The Development of an Expert System for Failure Analysis of Power Plant Components

Fred Starr

A Thesis Written in Submission for a PhD at The University of Surrey

March 2007

Dedicated to Maria Rosa Quintas Flór Starr
The Development of an Expert System for Failure Analysis of Power Plant Components

CONTENTS

Abstract

Chapter 1

Background to the Thesis

1.1 The Need for an Expert System
1.2 Thesis Aims
1.3 Expert System Benefits
1.4 Structure of the Thesis
1.5 Appendices, Presentations and Papers

Chapter 2

Literature Surveys on Steam Plant, Superheaters, Materials of Construction and Failure Mechanisms

2.1 Steam Plant Design and Operation
   2.1.1 Basic Principles
   2.1.2 Steam Plant Furnace Designs
   2.1.3 Burner Arrangements for Pulverised Fuel Furnaces and the NOx Problem
   2.1.4 Plant Derived Heat and Mass Flow Calculations

2.2 Steam Superheating and Superheaters
   2.2.1 Superheater Location
   2.2.2 Types of Superheater
      2.2.2.1 Radiant Superheaters
      2.2.2.2 Convective Superheaters
      2.2.2.3 Platen Superheaters
      2.2.2.4 Pendant Superheaters

2.3 Effect of Deterioration of Plant Components on Superheater Temperatures
   2.3.1 Feedheaters
   2.3.2 Furnace Air Leakage
2.3.3 Slagging of Furnace Walls
2.3.4 Fouling of Air Preheaters and Economisers

2.4 Superheater Materials of Construction
   2.4.1 Background
   2.4.2 New Martensitic Steels for Superheaters

2.5 Metallurgical Background to P91 Steel and Its Problems
   2.5.1 Basic Metallurgy of Power Plant Superheater Steels
   2.5.2 Physical Metallurgy and Heat Treatment of P91
   2.5.3 Problems with P91
      2.5.3.1 Stress Rupture Predictions
      2.5.3.2 Absence of Metallographic Changes for Temperature and Life Estimation
      2.5.3.3 Hardness Changes and Testing
      2.5.3.4 Cavitation
      2.5.3.5 Distinguishing Creep Type from Overheating Failures
      2.5.3.6 Impact of Nitrogen and Aluminium on Creep Strength
      2.5.3.7 Steam Side Oxidation Resistance
      2.5.3.8 Effect of Heat Transfer in Accelerating Oxidation Rates
      2.5.3.9 Welding and Type IV HAZ Cracking

2.6 Implications for Expert System Development

2.7 Descriptions of Metallurgical Failures in Superheaters and Related Phenomena
   2.7.1 Failure by Creep and Metallographically Based Temperature Indications
   2.7.2 Overheating
   2.7.3 Fireside Corrosion
   2.7.4 Slag Deposition and Slag Formation
   2.7.5 Erosion
   2.7.6 Weld Failures

Chapter 3

Expert Systems and Human Expertise

3.1 Predecessors of Expert Systems

3.2 Human Expertise and Error
   3.2.1 Characteristics of Human Experts
   3.2.2 Group Type Expertise and Its Problems
   3.2.3 What Makes an Expert?

3.3 Implications for an Expert System for Plant Failure Investigations
Chapter 4

General Issues in the Formulation of Expert Systems

4.1 Expert System Types

4.2 Design of Expert Systems for the Diagnosis of Failures

4.3 Knowledge Engineers and Domain Experts in the Building Expert Systems

Chapter 5

Flow Charts in the Design of an Expert System for Failure Analysis

5.1 Diagnosis of Failure Mechanisms and Identification of Root Causes

5.2 Flow Chart for Failure Investigation

5.3 Flow Chart for Superheater Heater Failure Investigation
   5.3.1 Activation of If...Then Rules (Failure Location /Visual Assessment)
   5.3.2 Activation of If...Then Rules (Plant and Equipment Design/Superheaters)
   5.3.3 Activation of If...Then Rules (Plant Data and Records/Superheaters)
   5.3.4 Activation of If...Then Rules (Plant Operating History)

5.4 Conclusions to Chapter 5 and the Formulation and Use of Flow Chart

Chapter 6

Formulation and Manipulation of If...Then Rules for Failure Analysis

6.1 Basic Procedures in Rule Formulation

6.2 Constructing and Cataloguing Glossary Terms

6.3 Glossary Types
   6.3.1 Semantic Glossary
      6.3.1.1 Qualitative Levels of Reliability of Conclusions
      6.3.1.2 Qualitative Levels of Compliance with Set Specifications or Treatment
      6.3.1.3 Qualitative Level of Affect
      6.3.1.4 Qualitative Level of Applicability
      6.3.1.5 Qualitative Effect of Change on a Problem
      6.3.1.6 Timewise Compliance or Frequency
      6.3.1.7 Semi Quantitative Difference to a Given Value
      6.3.1.8 Requirement to Take Action
6.3.2 Non-Quantitative Glossary
6.3.3 Quantitative Technical Glossary

6.4 More Detailed Analysis of Rule Build Up and Use
   6.4.1 Background to Example
   6.4.2 Fact Base and Data Input
      6.4.2.1 Problem Description
      6.4.2.2 Plant Information
   6.4.3 Inference Engine and the Failure Investigation
      6.4.3.1 Rules for Identification of the Failure Mechanism
      6.4.3.2 Rules for Estimating the Metal Temperature from Steam Temperatures
      6.4.3.3 Rules for Estimating the Metal Temperature using Parametric Methods
      6.4.3.4 Rules for Comparing the Temperatures Estimates to Decide on the Need to do More Detailed Laboratory Based Investigations
   6.4.4 Use of the Rules with the Example Investigation
      6.4.4.1 Establish Provisional Failure Mechanism as being Creep
      6.4.4.2 Calculation of Metal Temperatures
      6.4.4.3 Decision on Whether Root Cause is Plant or Material or Both
      6.4.4.4 Decision on Whether to Investigate the Plant Conditions or the Material

Chapter 7

A Probabilistic Approach Uncertainty in the Diagnosis of Failures

7.1 Probabilistic Rules

7.2 Conditional Probabilities for Root Cause Superheater Failure Investigations

7.3 Issues in the Application of Conditional Probabilities

7.4 Bayes’ Rules

7.5 Quantifying Evidence and Symptoms in Failure Analysis
   7.5.1 Quantifying Adjectival Descriptions
   7.5.2 Preliminary Assessment by Investigators and the Bayes Equation
   7.5.3 Methods for Quantifying Evidence Based Conclusions
      7.5.3.1 Aggregate P(E |F )Values and Weighting Factors
      7.5.3.2 Use of Individual P(E |F ) Values
Chapter 8

Plant Based Rules in Superheater Failure Investigations

8.1 Introduction

8.2 Billingsport-A Fictitious Test Model for Expert System Rules

8.3 Preliminary Flow Chart

8.4 Location of Superheater Failure

8.5 Rule of Thumb Estimates in Interpretation of Plant Data and Records
   8.5.1 Implications of Steam Temperatures and Plant Observations
   8.5.2 Superheater Tube Temperatures and Heat Transfer Rates
   8.5.3 Effects of Attemperation
   8.5.4 Excessive Flue Gas Temperatures

8.6 Design Factors
   8.6.1 Steam Drum or Once Through Systems
   8.6.2 Feedheaters and Economisers
   8.6.3 Excess Air, Flue Gas and Tempering Gas Recirculation
   8.6.4 Overheating and Thermal Shock

8.7 Plant Operating History
   8.7.1 Previous Failures and Operational Staff Awareness
   8.7.2 Operation at High Base Load Conditions
   8.7.3 Plant Cycling and P91
   8.7.4 Fuel and Burner Changes
   8.7.5 Maintenance, Instrumentation and Control Systems

8.8 Investigation at Billingsport Generating Plant
   8.8.1 Preliminary Assessment of Situation Using Expert System
   8.8.2 Steam Temperature Aspects at Billingsport
   8.8.3 Billingsport Operational Changes Leading to High Flue Gas Temperatures
   8.8.4 Evaluation of the Equipment as Root Cause of Superheater Failure
   8.8.5 Expert System Identification of Root Causes at Billingsport

   8.8.6 What Really Did Happen at Billingsport?

8.9 Conclusions to Chapter 8
Chapter 9
Failure Analysis of P91 Superheaters

9.1 Introduction

9.2 Flow Charts in Backroom Metallurgical Investigations

9.3 Flow Charts for P91 Metallurgical Failure Investigations

9.4 Assessment of Failure Mechanism
  9.4.1 Visual Assessment and Formulation of Initial Hypothesis
  9.4.2 Implications of Long and Short Term Creep Data for P91
  9.4.3 Implications for Bayesian Probabilistics
     9.4.3.1 Cavitation
     9.4.3.2 Hardness
     9.4.3.3 Lathe Boundary Precipitation
     9.4.3.4 Larson-Miller Parametric Estimates
     9.4.3.4.1 Larson-Miller Estimates in Validating Creep Failure Mechanism
     9.4.3.4.2 Larson-Miller Estimates to Verify Plant Data and Further Support Creep Failure Mechanism
     9.4.3.4.3 Larson-Miller Estimates to Highlight Other Failure Mechanisms and Causes
     9.4.3.4.4 Larson-Miller Estimates of Failure Time-Temperature Relationships
     9.4.3.5 Oxide Thickness

9.5 Application of Bayesian Rules in Identifying Failure Mechanisms
  9.5.1 Use of Japanese Superheater Failure as a Practical Example
  9.5.2 Bayesian Procedure to Identify Failure Mechanism

9.6 Application of Bayesian Analysis to Identify Root Cause of Japanese Superheater Failure
  9.6.1 Preliminary Steps to Authorise In-Depth Investigation
  9.6.2 Design Stress Issues
  9.6.3 Annealing and Tempering Treatments
  9.6.4 Alloy Composition and Effects of Strengthening Precipitates
  9.6.5 Steam Side Oxidation Induced Failures

9.7 End Result of Bayesian Identification of Metallurgical Root Cause

9.8 Conclusions to Chapter 9
Chapter 10

Discussion

10.1 Introduction

10.2 Results of the Thesis
   10.2.1 Procedures for Writing If...Then Rules
   10.2.2 Ability to Marshal Data
   10.2.3 Rule Grouping and Detailed Rule Formulation
   10.2.4 Bringing Together Conclusions

10.3 Technical Experts and the Knowledge Engineer

10.4 The Story Line Approach to Rule Formulation

10.5 Viability of Such an Expert System

10.6 Streamlining Expert System Development

10.7 Implications for the Use of P91 in Superheaters

10.8 Predicting the Effect of Oxide Growth on Tube Temperatures and Life

10.9 Stimulation of Clearer Thinking

Chapter 11

Final Conclusions and Future Work

Acknowledgements
APPENDICES

APPENDIX 1: Calculation of Steam and Gas Temperatures

APPENDIX 2: Spreadsheet for Calculation of Effect of Oxide Growth on Tube Temperature Increase and Reduction of Tube Life

APPENDIX 3: Trends in Heat Transfer Rates in Superheaters and Implications for Tube Wall Temperature Estimates

APPENDIX 4: Design Stresses for P91

APPENDIX 5: Visits to Drakelow and High Marnham Power Stations
PAPERS AND PRESENTATIONS

Baltica V Conference: Hotel Haikko Manor, Porvoo, Finland, June 20001:
Expert System for Failure Analysis in High Temperature Plant: F.Starr,
A. Shibli JE. Castle and R.Walker
- Conference Paper

Presentation to Surrey University Engineering Faculty: Guildford Feb 2002:
Development of an Expert System for Power Plant Failure Analysis:
F.Starr:
- Formal Presentation of Progress

Materials at High Temperature 21(3) Spring 2004
Potential Problems in the Identification of the Root Cause of Superheater
Tube Failures in 9Cr Martensitic Alloys: F.Starr, J. Castle and R. Walker
- Journal Paper pp 147-160

2nd International Conference on Boiler Tube and HRSG Tube Failures: Sheraton
Hotel, San Diego Nov 2004
Root Cause Identification of Superheater Tube Failures in 9 Cr
Martensitic Alloys: F. Starr, J. Castle and R. Walker
- Conference Paper
- Presentation

Materials and Components in Fossil Energy Applications (US DOE Newsletter)
No 162 Spring-Summer 2005
Problems in Identifying Root Causes of Superheater Failures in 9Cr
Steels
- Extended Summary of Materials at High Temperature Paper

International Workshop on Practical Applications of Age-Dependant Reliability
Models and Analysis of Operational Data, Fontenay, France Oct 2005 :
A Bayesian Approach to the Use of Evidence in the Identification of
Failure Mechanisms in Power Plant Superheaters: F.Starr, JE. Castle and
R.Walker
- Workshop Paper
- Power Point Presentation on Above
- Report on Presentation
Conference on Industry and Research Experience in the Use of P/T91 in HRSGs/Boilers: IOMMM, London Dec 2005
Steam Oxidation of T91 and Implications for Root Cause Failure Analysis: F. Starr, J. Castle and R. Walker:

- Paper
- Presentation
Abstract

The analysis of the mechanisms and causes of failures is a vital consideration in the safe and economic operation of power plants, but experts with the appropriate knowledge and background are becoming scarce. In consequence there is a need to develop an expert system which can encapsulate the human expertise that is needed in the investigation of power plant failures. In many cases more than one branch of technology and expertise must be brought to bear in an investigation, and a good expert system must reflect this.

The failure analysis of power plant superheaters forms a suitable basis for the development of an expert system, as superheaters are susceptible to failure by various mechanisms, including creep, overheating, creep-fatigue, fireside corrosion, erosion, and weld failures. In addition, the root causes of such failures result from the way a plant has been designed, built, or managed, as well as resulting from shortcomings in superheater materials of construction.

The focus on the shortcomings of P91 steel shows how the material of construction might contribute to the causes of failure. P91 is a 9Cr-1Mo martensitic alloy whose characteristics are different to the older low alloy carbon steels. This makes it a good test for questioning the assumptions underlying the formulation of the materials oriented If...Then rules in an expert system. Major issues with P91 are the absence of metallographic changes during component life, change in behaviour between medium and long term testing, and the severe affect that steam-side oxide scale has on raising superheater tube temperatures.

Methods for formulating If...Then rules are described. The need to incorporate adjectival and adverbial phrases into such rules is shown to be necessary to give qualitative, but consistent estimates of how reliable are conclusions. This technique is applied to a fictitious superheater failure, in which the operation of the flue gas dampers in plant is shown to be the root cause of premature failure, rather than the failure being induced by a changes in the type of coal or to a feed heater failure.

This "adjectival/adverbial" approach is itself novel, but the idea is taken much further to show how such phrases may be quantified using Bayesian probabilistics, to indicate, in numeral terms, how evidence from different sources can be used to support conclusions. This Bayesian method is applied to a superheater failure in a Japanese power plant, (reported in the literature), in which the failure mechanism was identified as being that of creep. The Bayesian method was also applied to the identification of the root cause which was shown to be due to a high rate of growth of the steam side oxide, in conjunction with a high rate of superheater heat transfer.

This overall conclusions are therefore is that the work has shown that information and knowledge on a complex domain can be systematically formulated into sets of If...Then rules, which will require, as a minimum, the use of adjectival and adverbial phrases which are of a semi quantitative type, to ensure consistency. More importantly Bayesian probability theory can be applied to this type of rule set to quantify the certainty of decisions taken by the expert system, and enable the expert system to bring together evidence from diverse sources.
Chapter 1
Background to the Thesis

1.1 The Need for an Expert System

The development of an expert system for the failure analysis of power plant equipment is becoming a vital necessity as the power industry changes. The fall in the number of power stations has led to a reduction in the numbers of people who have real expertise in power station technology. It is difficult to obtain actual figures of manpower, but the main UK laboratory, dealing with fossil fuel power generation, at Leatherhead in Surrey, run by the CEGB, closed in the early nineties. The regional laboratories belonging to the CEGB vanished even earlier. Laboratories in the coal industry, nuclear power and gas industries have shared this fate. Where any vestige remains, these new laboratories employ a fraction of the original numbers that worked in R&D. An indication of this is shown by the drop in Government R&D expenditure on energy which has fallen from about £260 million a year in 1987 to about £32 million in 2000, at year 2000 prices [1] The number of steam power stations on the UK mainland has fallen too from over 150 in 1979 to 10-15 today [2,3]. This is about the same number as were operating in the London area during the nineteen sixties. These steam plants are now largely responsible for meeting peak loads, so that they need to operate with the highest possible reliability and efficiency. This obviously becomes more difficult if those with expertise have left the industry.

There are other changes at work which is making the retention and development of experts and expertise more difficult. The reduction in the number of power plants that are needed has resulted in shrinkage in the manufacturing sector. Companies that have managed to stay in business have been forced to amalgamate. To reduce costs, groups that are perceived to be engaged in similar activities, such as in failure analysis, are rationalised.

All of this adds weight to an issue highlighted many years ago by Trevor Kletz who was at that time the leading expert in ICI on safety matters. He pointed out that “Organisations Have No Memory” and good safety procedures depend very much on the experience of individuals, and how well that experience is passed onto others who work for the organisation [4]. He advocated that supervisors and operators should be made to attend open discussions on accidents. But he also made the suggestion that better information retrieval systems should be devised, so that “people could readily locate details of previous incidents and recommendations that have been made”. The same issues come up when failures need to be investigated, as here too, the fact that organisations have no memory, makes failure investigation a problem.

One bright spot, as Kletzt indicated, is the development of information retrieval systems, of which expert systems are one example. Unfortunately, Kletz did not give any clues as to how such a system would be built or operated. A major issue is the conundrum, contained in the idea that organisations have no memory is that “Unless
you know which questions to ask, you will never get the right answer’. A really useful expert system must be configured to enable individuals, who do not know what questions to ask, and who have little experience of failure investigation, to be led towards identifying the root cause or causes of failures. Once the root causes are identified, measures can then be taken to avoid such problems in future. Or, if such failures cannot be avoided, plans can be made to mitigate their impact.

1.2 Thesis Aims

An “Expert System for Failure Analysis” has got to be built upon the expertise of human experts. Note the use of the plural. Failure investigation of power plant equipment is always a team effort, requiring input from various individuals. Some of these will be metallurgists, others will have experience with the operation power plant, and others will have had direct responsibility for the design of the type of equipment in question. These experts in their turn may have to rely on other specialists. Without the investigating team being properly aware of this, tens of thousands of man hours of experience will have been brought to bear on solving a problem. How can this depth of knowledge, in terms of operating experience and manipulation and evaluation of data, coming from different areas of technology, be put into a form which is accessible and useable to non-experts?

The conventional approach, used to construct expert systems, is for a “Knowledge Engineer” to interview a person who is an expert on a certain subject. The Knowledge Engineer has the responsibility of turning the expertise into a form which can be put into the shell of the expert system. Unfortunately the Knowledge Engineer usually has no real background in the subject area. Much time can be wasted because of this. Considering this in more concrete terms, in the case in point, the Knowledge Engineer will have to assimilate a diverse range of subjects, including high temperature steels, the combustion of coal, the assessment of the capability of the people operating a generating plant, etc. This is asking the impossible. A more fundamental issue comes from the expert himself. In many cases there is no clear “yes” or “no” answer. When the “unlikely to be”, “could be” or “probably be” responses are eventually given, what do these statements mean, and what was the thinking that differentiated “maybe” from “probably be”. This uncertainty often stems from the expert having to deal with rather fuzzy information, or having to weigh up different types of evidence from different sources. If the expert himself appears to be confused, even though he or she may know what is meant by these qualifications, this will cause difficulties for the Knowledge Engineer. All of this will slow down the interviewing process, at worst leading to the idea of building an expert system being dropped, at best leading to some complex issues being oversimplified or even being neglected altogether. The issues are:

Can the construction of this type of Expert System be streamlined by going directly to the expert? Indeed, given the fact that experts, by definition, know so many things, most of them of a disparate nature, is it really possible for the experts to formulate this knowledge into a new more coherent form, a form that is required by the mechanics of an Expert System?
These are the central questions of this Thesis. In answering these questions in the affirmative, the Thesis needs to show how this might be done. Obviously at some point the Knowledge Engineer has got to be involved. He or she is an expert in his or her own right. But is it really possible for the various experts to formulate their expertise in a manner that the Knowledge Engineer can use more easily?

The Thesis therefore consists of an investigation of the methods by which the information known to the experts can be transposed by the experts themselves into a form that can be used more directly by the Knowledge Engineer. To do this the experts will need to have some understanding of how an expert system is constructed. At its basis it consists lots of quite simple rules, each of which contains a nugget of technical information. The formulation of these rules requires a good deal of introspection and much of the thesis is given over to showing what is needed during these times when the expert is making up his or her own mind. But it is apparent that this process is not very different to what the expert must do when facing a new or little understood problem. Indeed such a problem is a perfect basis for showing how an expert system can be developed. Problems of this type are described in the Thesis and used to test out the ideas which have been developed.

Most failures of equipment on generating plant are due to the way that the plant was being operated, how it was designed, or were caused by some defect related to the materials of construction. When the root cause is mal-operation, it often becomes apparent that a number of things need to be fixed. It is also quite apparent, which of these is the priority. It is therefore reasonable to state the rules in language that are very close to ordinary speech, providing that consistency is used in defining how strong are the conclusions. With metallurgical investigations, the way in which the expert system must be used is more complex. There is still a need to put a level of confidence on the findings of specific parts of the metallurgical investigation. This is not too much of a problem. The real difficulty is to develop a technique by which conclusions from isolated observations (such hardness of a failed specimen, or the thickness of an oxide) can be brought together to make a convincing case for a specific failure mechanism. Bringing together evidence is something human beings, in general, do rather well. How one could get a machine to do it seems at first sight intractable.

Given this preamble we summarise the main intentions of this work, which are to show whether it is possible:

- To provide a procedure to break down complex ideas into quite simple statements, which then contain this information in a highly condensed form

- To marshal raw data and information from the literature, contacts, and personal experience to enable expert system rules to be formulated, each of which encapsulates specific pieces of information.

- To group these rules, so that they cover relevant aspects of power plant management, design, operation, fabrication, and materials of
construction, with the aim of using them to identify failure mechanisms and root causes.

- To devise a method of being able to put together the conclusions from sets of rules, when the evidence is weak and of disparate types from different sources

If the results of this work are to be useful, it is necessary to choose the right type of failure to use as an example around which the rules of the expert system can be developed. There are hundred of different types of failures that can occur on a power plant. Many of these are of a simple type and there would be little research in focusing on these, neither would the expert system from this example be of much use. Instead an expert system needs to be built around a component that can be prone to failures from a variety of different mechanisms; otherwise it will not be possible to discover the issues in building an expert system. Furthermore, in getting to the root causes of such failures with that component, the failures should be of the type that will necessitate a complex series of investigations. In essence the aim is to develop the procedures by which long chains of rules can be created in an expert system. Use of a simple failure as a paradigm (defined as a conceptual framework within which scientific theories are constructed) will lead to lead to a simplistic type of expert system, which will be deemed as trivial.

A component that has the necessary attributes of being likely to fail through a variety of mechanisms, because of specific types of operation, design or materials, is the superheater section on a power plant. This can act as the paradigm for investigation of rules relating to plant based failures. But the metallurgical investigations represent the greatest challenge in rule development. Hence, if a test for the ideas being developed is needed, what should be the superheater alloy around which the expert system should be formulated?

There is a strong commercial interest in the accurate diagnosis of the root causes of P91 superheater failures, as is becoming clear that there are problems with superheaters built using this class of alloys [5]. Some failures are solely due to the use of P91, but others are probably due a combination of factors, including the alloy itself and the design and operation of the superheater. Furthermore because of these concerns, the P91 issue is one that metallurgists, designers and power plant personal are willing to debate. This is vital in getting input from experts.

1.3 Expert System Benefits

What are the benefits of an “Expert System for Failure Analysis”? Providing that it is updated frequently, the system should:

- Enable technical staff to make quick but reliable assessments of failures and to take rapid remedial action.
- Minimise the need for specialised materials and engineering knowledge.
• Enable experiences to be shared with other users of the Expert System, via the Internet.

• Minimise space requirements for the storage of technical information.

• Permit the Expert System to be used as a Training Aid by academia at postgraduate level on materials and engineering courses, or by the Power Industry itself.

• Help move towards a Common Standard for the interpretation of failure mechanisms and remedial work.

It may also be remarked, in passing, that in the present culture in which “someone must be to blame” therefore “someone must pay”, the existence of a fully approved Expert System should greatly reduce the need for long drawn out litigation.

1.4 Structure of the Thesis

Because the thesis is intended to be of direct help to technical experts in condensing their knowledge in a highly structured way, the Thesis is arranged with this in mind, consisting of a number of chapters. Hopefully, in this way they will form a manual which others can use to develop their own approaches to a given field of technology. The underlying principle in the Thesis is to give specific examples of how an expert system of this type can be built up. This has been done by focusing on the types of failures that high temperature superheaters can experience, and how these can be induced through mal-operation of plant, design errors, and the shortcomings of superheater tube materials.

As noted there is considerable interest in P91 as material for superheaters, and this was one of the reasons for choosing this alloy. Hopefully the development of rules relating to the failure of this material will be of immediate interest in this area. But as P91 is a martensitic steel, and has somewhat different characteristics to the older superheater alloys. Hence the ability to construct rules is a very good test for the procedures that the author has developed.

There are eleven chapters in total, of which this is the first. Chapters 3, 4 and 5 are intended to give some background to what are Expert Systems, what is their structure, and how they can be used to work towards the solution of a problem. Chapter 2, entitled the “Literature Survey” contains much of the technical information which needs to be considered in building up the rules needed in this type of expert system.

Chapters 6 and 7 show the methods of formulating rules much more explicitly and in particular show methods by which “uncertainty” can be dealt with. Here again the approach is pragmatic. The expert who is going to try to formulate knowledge wants something that is simple for him or her to understand, and even more importantly wants something that the operator of the expert system will be able to understand, too. Hence, as far as possible the rules are based on standard English expressions, although such terms have to be defined and regularised. This is critical when
defining levels of confidence and belief about the reliability of the evidence or the conclusions that can be drawn from it. An even greater difficulty arises when conclusions have to be made on the basis of laboratory investigations, and this issue and its solution are covered in Chapter 7.

Chapters 8 and 9 move from the general to the particular and are used to develop and test out the ideas formulated in Chapters 5, 6 and 7. Chapter 8 focuses on the formulation of rules to tackle plant based failures, which are then used in a hypothetical investigation of a P91 superheater failure which apparently was caused by the type of coal. Chapter 9 develops example of the more complex rules which are needed in metallurgically based investigations of P91, where specific rules relating to plant problems or to a laboratory investigation of P91 are needed. These are applied to a superheater failure where a batch of P91 steel may have been defective.

Chapter 10 discusses the findings of thesis, which largely came out of the specific issues and topics covered in Chapters 3 to 9. It emphasises that a critical approach to the work has been taken at all stages, with the intention of delineating a practical approach to the construction of this type of expert system. Chapter 11 covers the conclusions.

1.5 Appendices, Presentations and Papers

The main appendices contain a description of methods of formulating data which is needed in the main body of the report. Also incorporated into this Thesis is one journal paper and five conference papers published during the development of this work. The journal paper was subsequently summarised in some detail in the American DOE/EPRI Materials Components Newsletter, a widely read publication that focuses on materials for advanced power plants. During the period when the Thesis was being formulated, the author also has published a number of other papers relating to power plant design, materials development, and process flow modelling of a flexible gasification system. These have not been included, but they all provided new insights into power plant issues.

References

Chapter 2

Literature Surveys on Steam Plant, Superheaters, Materials of Construction and Failure Mechanisms

2.1 Steam Plant Design and Operation

2.1.1 Basic Principles

The basic principle behind the design of fossil fuel steam plants is that coal, oil or gas are burnt to produce steam at high pressure and temperature. The steam is used to drive a set of turbines that, in turn, drive a generator. To improve plant output and efficiency the steam must be produced at the highest possible temperature and pressure, commensurate with the creep strength of superheater materials. At the moment most plants work at steam temperatures of around 540°C, with steam pressures in the region of 180 bar. A few plants run with temperatures of just under 600°C, the pressures in these systems are supercritical, that is the pressure is above 221 bar [1,2].

![Graph showing superheater pressures versus temperatures](image)

**Figure 2.1: Superheater pressures versus temperatures [Ref 9]**

Why is it that the production of superheated steam at high temperature so essential to plant efficiency? The simple response is that as the Carnot cycle indicates, a high inlet temperature into the steam turbine is needed if a respectable proportion of the heat in the steam is to be converted into work. To answer this more fully requires a somewhat deeper understanding of steam plant thermodynamics [3]. Essentially the expansion of steam through a turbine causes the steam temperature to drop, as heat is converted into work. Hence the work done is a function of the difference in pressure between that of the steam as it enters the turbine and that of the steam as it
leaves the turbine and enters the condenser. As the condenser pressure and temperature are fixed, typically being around 35°C and 0.05 bar, to ensure that as much heat in the steam is transformed in to work, it follows that if the plant is to take full advantage of a high steam temperature, the pressure must also be high.

To obtain the necessary degree of expansion steam pressures must increase exponentially with temperature. Figure 2.1 shows this relationship as it plots pressure against temperature for steam plants built between the 1920’s and the modern day. In actual fact steam pressures have risen even more rapidly than might be expected from a thermodynamic analysis, which focused solely on the benefits that superheaters bring [4]. This resulted from the introduction of reheating during the late thirties, which required plants to work at even higher pressures to get adequate expansion through each set of turbines.

In producing power from the combustion of fuel, the water is turned into steam in a boiler built into the furnace, using the heat from the burning fuel. The steam is then superheated in a set of heat exchangers using the heat in the flue gas (i.e. combustion gases from the furnace) in a flue gas duct. Having reached the specified
temperature the steam is directed into a HP (High Pressure) turbine. Expansion of
the steam through the turbine does work so the steam temperature drops. The steam
is then condensed and pumped back to the boiler. This arrangement is known as the
Rankine cycle, but has been modified quite considerably to improve output and
efficiency [5].

In practice the steam from the HP turbine is passed back to a further set of heat
exchangers called reheaters, where the steam is brought back to around 540°C. See
Figure 2.2. The reheated steam is then used to drive an IP (Intermediate Pressure)
turbine. On exiting from this, because the pressure is now quite low, around 5 bar,
the steam will then flow into a set of LP (Low Pressure) turbines where the outlet
pressure is around 0.05 bar. The steam exiting the LP turbines is condensed. The
condensate is pumped back into the plant as boiler feed water, being deaerated using
low pressure steam.

There are further departures from the simple Rankine cycle through the use of feed
heating, in which some steam is taken from the turbines and used to preheat the
boiler feed water. Some preheating is done during the deaeration stage, but the
amount of feed heating is limited since the pressure in the deaerators is close to
ambient. Most of the feed heating is done once the feed water has been pumped up
to the full plant pressure. See Figure 2.2. The process of feed heating improves plant
efficiency. Although the explanations for this effect are somewhat arcane, the feed
heating process in temperature/entropy terms comes closer to the Carnot cycle.
After the feedheating is finished, the water is heated still further in an economiser,
which utilises heat in the flue gas system.

2.1.2 Steam Plant Furnace Designs

The fuel for a steam plant is burnt in a furnace, the walls of which are lined with
tubes filled with water. In modern designs the tubes are joined to one another using a
fin like extension as shown in Figure 2.3. This is termed a water wall design. The
tubes can be vertical which implies very careful design to avoid some boiler tubes
being over heated whilst others do less work. This is one reason why some designers
prefer to run the tubes round the walls in a helical fashion, but there seems to be a
move against this type of design to vertical tubes which are internally ribbed to
ensure better heat transfer. The implications of these various designs for the
superheaters are not clear, but the general aim is to move to higher and higher rates
of heat transfer, implying that other things being equal harder working furnaces with
less margin if anything goes amiss.

The water is brought to the boiling point in the tubes, although there are two distinct
arrangements for drawing off the steam that is produced. In a once through furnace,
where the pressure is high (above 150 bar) the heating arrangements are such that all
the water in the furnace wall tubing turns into steam. The steam is passed over to the
superheater system proper where the steam is brought up to the desired temperature.

Older designs of plant are of the “steam drum” type. The steam drum is a cylindrical
vessel, roughly half full with water, which is at the saturation temperature, that is
just at the boiling point corresponding to the steam drum pressure. Fresh water from
the feedheating system enters the drum replacing the steam that goes off to the superheater. This fresh water, which is about as hot as the water in the drum, is used to flush the steam of contaminated solids. The boiler water from the drum itself is fed down to the tubing at the bottom of the furnace, via a “downcomer” pipe. As the water rises up the tubing it picks up heat and steam begins to be produced. However this water-steam mixture, from the furnace tubes, is led back to the steam drum. In this the steam separates from the water in the drum, the steam passing into the superheater system. The merit of this system is that any boiler water treatment salts or other dissolved solids in the boiler water stay in the water, and should not contaminate the steam. Obviously over time a build up of solids will occur. The level of these is kept to acceptable limits by blowing down the boiler (i.e. a partial draining off procedure), so that contaminated water plus the solids are taken off. The “blowdown” is replaced with fresh “makeup” water.

![Fig 2.3: Schematic of Water Wall Construction for Boilers](image)

In steam drum designs the flow of water from the drum to the furnace tubes, and then back up to the drum may have to be induced using a pump. It is then a called a “forced convection” or “fully pumped system”. If the density difference between the slightly cooler water coming from the drum and the mixture of steam and water in the furnace tubing is sufficient, a convective type flow will be established, needing no boiler circulation pump. Such a boiler is of the “natural circulation” type. Natural circulation becomes more difficult with higher pressure systems as the density difference between steam at pressure, and highly heated water becomes less.

As boiler pressures rise still further, there is more risk that the steam will be able to carry off the boiler water solids. Hence for modern pressure plants, the drumless system is used. Here the boiler water turns completely into steam within the upper section of the evaporator, before being passed to the superheaters. This procedure requires very high standards of water treatment in which the feedwater has to be extremely pure, otherwise solids would deposit on the furnace tube walls. Where the steam is close to or above the critical pressure of 221 bar, a once through boiler is mandatory. Obviously, in this case, the feedwater needs to be pumped into the boiler directly [6].
The type of fuel and burner arrangements heavily influence flue gas temperatures and the amount of carry over of erosive and corrosive slags and particulates, and have a direct affect on superheater performance and life. As Figure 2.4 shows that even the type of coal and the ash melting point can affect furnace proportions [7]. Modification to burners to reduce NOx emissions can have retrograde effect on superheater temperatures, as can changes from one fuel to another [8, 9, 10].
Not all the heat in the flue gases can be utilised through superheating, reheating of steam, and for heating of water in the economiser. Heat that remains in the flue gas is used to preheat combustion air going to the burners. Furthermore part of the flue gas may be recirculated back to the furnace to help control furnace temperatures and heat distribution [11,12]. See Figure 2.5

2.1.3 Burner Arrangements for Pulverised Fuel Furnaces and the NOx Problem

The most common arrangement is to mount the burners in rows at different heights, either on the walls of the furnace, or at the corners. Wall mounted burners can be used where the furnace is rectangular, with the burners being mounted on the long side of the rectangle. Burners of this type can be “front wall” mounted, so that the firing is from front to back, or the burners can be “opposed”, so that both the front and rear wall of the furnace have rows of burners. Whatever the method of mounting, swirling type burners are needed to give a short flame length to minimise impingement onto the opposing wall [13].

Corner, or “tangential” burners work quite differently. Here a long flame comes out at an angle to the sides of the furnace, from all four corners, thereby forming a vortex-like flame pattern when viewed from above. Corner burners are of the non-swirl type, as a long flame length is wanted and to ensure uniform heating, the cross section of furnace should be of a square rather than of a rectangular form [14]. A corner location enables the burners to be swung up or down to help control the relative heat inputs into the furnace or superheater. The need for good cross section can necessitate the division of the furnace by a set of tubes, containing either steam or water, so that two halves have a square shape. A split furnace can also lead to some unusual superheating arrangements. High Marnham power station, which is of this type, has the superheater positioned over one half of the furnace, with the reheater over the other [15].

Most pulverised furnaces in the UK are of the dry bottomed type whereby the ash, as it leaves the top of the furnace, is below the softening point. The wet bottomed furnace is somewhat like the cyclone variety, where the temperatures are maintained at a very high level, so as to melt the ash, which is then drained off from the bottom of the furnace. Pulverised fuel furnaces of this type are basically intended to deal with low melting point ashes. To assist in this the burners are mounted low down in the furnace box.

The current environmental issue is that of NOx formation, which has meant that many older boilers have had to have new sets of burners installed. “Staged combustion” is used wherein the fuel is initially only partially burned, resulting in a low flame temperature. As the flame progresses into the furnace, and has lost part of it energy by radiation, more air is added to complete the burning process. Unfortunately this can give problems with incomplete combustion. In front and rear wall fired systems this has led to the opposite walls being covered with deposits of a reducing and sulphiding nature [16]. It would also appear that the formation of CO has given rise to carburisation of the superheater tubing. This has given problems with both furnace walls and superheater tubing. With corner fired type furnaces, where the flames form a vortex, the addition of “over fire air” has brought the vortex
into the centre of the furnace, so that the walls are swept with clean air. The downside is that the vortex has tended to rise within the furnace so that the superheaters now run hotter [14].

2.1.4 Plant Derived Heat and Mass Flow Calculations

In assessing the mechanism and causes of failures of furnace, superheater and reheater tubing, an experienced plant operator will be aware of the implications of temperatures, pressures, steam and airflows. Deviations from the original design or operating conditions are particularly important, whether caused by the age of the plant, off-design operation, or changes in the type of fuel. On a real plant, however, it is impossible to measure all the relevant temperatures on a continuous basis, as temperatures and the corrosivity of the environment would burn out thermocouples. Most if not all of these observations will be qualitative.

Fortunately it is possible to estimate by calculation the temperatures at key points, such as at the furnace outlet, which can run up to 1350°C. This can be done using the fuel input, level of combustion air, amount of flue gas recirculation, and inlet flue gas and combustion air temperatures and the amount of steam generated in the furnace. Similar calculations can be done for the drop in flue gas temperature across individual tube superheater and reheater banks in the ductwork. This is done using the amount of heat absorbed by the steam in each bank [17, 18]. Appendix 1 describes the procedure by which this can be done. Formerly these calculations would be done by hand, but it is now possible to do them using commercially available process flow programs such as CHEMCAD or ASPEN. In the experience of the author these are perfectly reliable except in the region of the critical point of water. Fortunately in the final superheaters the steam temperature is well away from that of the critical point, 374°C, so that the properties are similar to those of a compressed gas. There can also be some problems, when using these programmes in estimating the flue gas temperature due to the ash in the coal turning into a molten slag.

These calculations can show whether the tube bank temperature is likely to be excessive. Pointers to this are high inlet and outlet flue gas temperatures, excessive temperature drops, high outlet steam temperatures and disproportionate use of attemperators to bring back temperatures to the design values. The heat load calculations could easily be incorporated into an expert system, and the results could be used to formulate heuristic If-Then rules to point to failure mechanisms and causes.

2.2 Steam Superheating and Superheaters

2.2.1 Superheater Location

As noted earlier the superheaters are located in the flue gas duct, after the furnace. They consist of sets of tubes about 50 mm in diameter placed across the duct to pick up heat from the flue gases. The use of the heat in the flue gases must, however, be shared with that needed for reheating steam. For this, and other reasons, the
superheater "coil" is not continuous but consists of several banks. The layout of these banks varies from plant to plant, but the essential principles are:

- **The flue gas temperature should drop as uniformly as possible as it passes from the entrance to the exit of the duct.**

- **The hottest sections, which are the secondary and tertiary banks, are positioned near the front end of the duct, whilst the cooler primary banks are near the back end.**

Although not the most efficient in terms of heat transfer, a lower temperature section of the superheater is usually positioned at the inlet to the flue gas duct to reduce the risk of fireside corrosion or creep. The secondary superheater will be used for this duty. In addition a set of shock tubes, containing relatively cold steam or water, may also be positioned at the furnace inlet to the flue gas duct.

Typical locations for the superheaters are shown in Figure 2.6, as depicted by the clear rectangular-like shapes. The hatched area represents the furnace box which contains the boiler tubes and burners. The duct which contains the superheater and reheater banks may be a simple extension of the furnace box, as with a "tower boiler" [19]. The most common alternative to this design is the two pass boiler in which the flue gas flows through a horizontal cross over duct, followed by a down coming duct, both of which are packed with tube banks. With the trend to supercritical operation, Siemens are promoting the horizontal boiler to reduce the amount of high cost austenitic and nickel based pipework [7].

![Figure 2.6: Relative Dimensions, Shapes and Superheater Positions for a 500 MW Boiler][8]

The tower system, according to Fleming, suffers from fouling of the shield and superheater tubes as they simply cross the furnace. With the pendant tube design,
which is that which is commonly used in two pass boilers, as slag accumulates, the weight of slag pulls or drags it off the tubing [20].

Although there is quite a lot of variation, a typical superheater system would consist of three distinct banks, in which the steam is gradually brought up to the turbine inlet temperature. The first or primary superheater, which takes saturated or near saturated steam, is positioned just before the economiser and sometimes after the reheater. It is therefore not a high temperature design issue, both steam and flue gas temperatures being in the 350-450°C range. Nevertheless, since the primary superheater uses finned tubing, erosion and fouling by dust, and low temperature corrosion may be problematic. The temperature differences between the flue gas and steam temperature in the secondary and final superheater are so high that bare tubes are adequate.

The steam from the primary superheater then enters the secondary superheater. This is situated at the exit to the furnace, directly receiving the hot flue gases. These are the range 1050°-1350°C for dry ash furnaces, depending on the how much heat is taken out of the flue gases by the evaporating section, the level of excess air and amount of flue gas recirculation. The steam and metal temperatures in the secondary superheater are relatively low, particularly if flue gas-to-steam heat exchange is parallel rather than counter flow. The aim is to keep metal temperatures down as far as possible to prevent creep and fireside corrosion [21].

The final superheater takes the steam up to the design turbine inlet temperature. French states that peak metal temperatures are designed to be about 40°C above the outlet steam temperature, for ferritic and martensitic alloys [22]. The National codes are in rough agreement with this, as summarised by Basu et al in Table 2.1 [18].

Table 2.1: Comparison of National Recommendations for Suggested Allowances for Superheater and Reheater Metal Temperatures [Ref 18 modified]

<table>
<thead>
<tr>
<th>National Code</th>
<th>German TRD</th>
<th>German TRD300</th>
<th>American ASME</th>
<th>Indian IBR</th>
<th>British BS1113</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiant Superheater</td>
<td>+50°C min or 30°C+3 times wall thickness in mm</td>
<td>+50°C min</td>
<td>No Recommendation</td>
<td>+50°C on max anticipated steam temp</td>
<td>+50°C at over 425°C</td>
</tr>
<tr>
<td>Convective Superheater</td>
<td>+50°C max or 15°C+2 times wall thickness in mm</td>
<td>+30°C min</td>
<td>No Recommendation</td>
<td>+39°C on max anticipated steam temp</td>
<td>+35°C at over 425°C</td>
</tr>
</tbody>
</table>
2.2.2 Types of Superheater

There are basically four different types of superheater design, radiant, convective, platen and pendant. Figure 2.7 shows the general configuration of each.

2.2.2.1 Radiant Superheaters

Radiant superheaters consist of tubes which line the sides of the furnace and duct, protecting these from heat. Most of the heating is by radiation from the flue gases.
This type of superheater is essentially part of the furnace box and can suffer during start up or when changing up to high loads, since the amount of radiant heating increases much faster than the steam flow [22]. For this reason all the codes build in bigger temperature margins for radiant than convective designs. See Table 2.1.

2.2.2.2 Convective Superheaters

In modern plants convective types are used on tower boilers. Here, a vertical duct, which contains the superheaters and reheat structures, is simply an extension to the furnace. The tubing for these units runs more or less horizontally across the duct with the flue gas passing over the tubes, thereby giving up its heat by convective heat transfer. The tubing consists of “S” bend tubes or sets of horizontal “U” bends in which the headers, which supply and receive the steam to the tubing, ar positioned at the sides of the flue gas duct. Spacers are placed between the tubes to prevent drooping, but vertical strings of steam-cooled tubing are also needed to support the tubes.

Since these types of superheater are truly convective, they behave in the classical manner in that, as boiler load drops, the degree of superheat and metal temperatures falls [22]. Fouling is a serious problem and it is vital to get the flue gas temperature down below the softening point of the ash before the flue gas encounters the tubing. Despite the use of shock tubing and wide inter-tube spacing on convective designs, if coal is used, slagging and fouling is a problem. Unless very well supported convective superheaters will tend to accumulate condensate during shutdown but this is much less of a problems than with platen or pendants designs [23].

2.2.2.3 Platen Superheaters

The platen tube superheater consists of a series of heat exchange surfaces, each of which has a wall-like appearance, set across a horizontal section of the flue gas duct, so that the flue gas flows between each of the platen “walls”. Each of the walls consists of sets of tubing, which are hung from inlet and outlet headers. In terms of heat exchange, platen superheaters are regarded as convective types. Platens produced by Mitsui Babcock are 90% convective 10% radiant [20]. This would imply that, as load dropped, so would steam temperature, as with the tower boiler superheaters. However CEGB experience is that where a platen receives the direct impact of the flue gases from the furnace, as in the case of the secondary superheater, the heat transfer, on the leading tubes, is primarily by radiation.

In simpler designs of platen tube superheaters, the shape of individual tubes is that of a “U”, although the bottom of the “U” can have a vee-like form, to fit with the shape of the duct. All structural supports are outside of the flue gas stream. Since the tubes hang straight down, bending moments, due to deadweight, are largely eliminated and the tubes are free to expand and contract. In more complex designs the tubes may be of a “W” form to reduce peak temperatures in the platen, although this nullifies one of the main advantages, in that the support of the tubes is quite simple in the “U” tube version. Because the tube lengths in a platen are different, the steam flows and peak tube temperatures in individual tubes can vary significantly.
Inspection of the schematic of the platen superheater in Figure 2.7 will show that there is some compensation in this arrangement, if the outer set of tubes is compared with the inner set. As the flue gas enters the superheater, hitting the leading set of tubes, the heat transfer rate at this point will be extremely high, and the flue gases are at their hottest at this point. As the flue gas progresses along the “walls” of the pendant, the temperature drops. As it exits the last set of tubes in the superheater, the flue gas is now at its coolest, but note that this tube contains the steam from the leading set of tubes. Conversely, with the centre set of tubes, the flue gas will have dropped in temperature to a mid-range value, since it is halfway way through the pendant. Hence the heat input to the inlet section of the centre set of tubes will be much lower than that in the leading or outer set. However the heat input to the steam on the exit section of tubing will be higher than the corresponding section on the outer set. It will also be apparent that the path length of each set of tubes is different, so unless chokes are fitted to the tube inlets of the centre tubes they will receive much more steam than the outer tubes, and tend to run cooler.

Because of temperature effects, individual tube strings tend to move out of the line of the platen. They then act as lead tubes, receiving a lot of heat. The tubes in the platen can be clamped into position by using a steam or water-cooled tube as a giant paper clip to prevent the tube moving out of line. In addition, by mounting stainless “knife and fork” blocks on the tubing, vertical movement is made possible, whilst sideways or out-of-line movement is made difficult. Unfortunately the blocks themselves give problems. Cracking can occur if nickel filler metal is used. The blocks tend to accumulate slag, so that fireside corrosion is accelerated at these points. A more modern technique is to weld a plate like membrane between the tubes in the tip region (i.e. parallel to the flue gas flow). This will help keep the tubes in line, but it could lead to stressing in the tip region and at the header, since the tubes will have lost some flexibility.

A principal shortcoming of platen superheaters is the accumulation of condensate in the legs after shut down. On start up this will block steam flow, leading to overheating of the lead tube and differential expansion between the legs. Once the condensate starts to boil it will flash over into the header, leading to header quenching [24,25]. Fortunately the outlet headers of platen superheaters are relatively small and act as subheaders, the steam from these passing to a main header, which tends to reduce the level of thermal shock and fatigue.

Platen superheaters are normally positioned at the entrance to the flue gas duct and therefore encounter the hottest gases coming from the furnace, which are likely to contain semi-molten slag and ash. They are therefore likely to be used as secondary rather than final superheaters in which the inlet steam temperature will be in the 350-400°C range. Furthermore, to keep the metal temperature down in the leading tubes, the steam is made to enter the superheater at this point. This arrangement is termed “parallel flow” as the flue gases and steam are basically travelling in the same direction from higher to lower temperature positions. It is not the most economic means of designing heat exchangers and is only reverted to when there are fears about the ability of a material to withstand high temperatures.
2.2.2.4 Pendant Superheater

Pendant superheaters can be regarded as vertical forms of convective superheater that are suspended from the top of the flue gas duct. They are in some respects similar to platen superheaters. The main difference is with header arrangements. With the platen type, a series of headers are needed, which lie parallel to the line of the duct, with each platen running between two sets of headers. With pendants just two main headers, in principle, are needed.

Thermal shock and fatigue of the headers is a real problem with pendant superheaters. As with platens the bottom legs of the tubes easily accumulate condensate. Hence in some modern designs instead of the outlets of the tubes all feeding into just one header, the tubes are grouped so that each group of tubes feeds into subheaders. These subheaders are of a smaller diameter and of a reduced wall thickness compared to the main header, into which these feed. This type of design reduces thermal fatigue in both the subheaders and main header.

Pendant designs are often used for the final stage of superheating, being positioned in the flue gas duct after the platen superheater. Flue gas temperatures will have moderated at this point and the need to shed slag becomes less important. Even so, as the steam temperature has now reached its maximum, there can be some risk of fireside corrosion.

2.3 Effect of Deterioration of Plant Components on Superheater Temperatures

Deterioration of some items of equipment will tend to raise superheater temperatures. Usually the effect is somewhat indirect, with repairs or cleaning of equipment having the opposite effect.

2.3.1 Feedheaters

If a feedheater perforates it may be necessary to by pass it, as feed water may be drawn back into the turbine, leading to blade damage. The loss of heat energy from the feedheater may have to be made up by increased firing, otherwise steam output will fall. Not all of the heat will be absorbed within the furnace. In consequence superheater temperatures will increase. With drum boilers even if there is no increase in the firing rate, superheater temperatures may rise due to the drop in steam production [26]. In addition there will be a tendency to increase furnace firing to maintain output, thereby pushing up superheater temperatures.

2.3.2 Furnace Air Leakage

Although the design level of excess air to the burners, even with coal firing, is only about 5-10%, the actual amount is more like 15-20%. Part of this is due to unburnt air coming back into the furnace with recirculated flue gas, but much of it is due leakage into the furnace. Leakage will increase with time due to failure of expansion joints, furnace movement leading to the opening up of gaps, and corrosion of the ductwork and the air preheater. The mass flow of combustion products will increase, which will tend to carry heat out of the furnace as flame temperatures will fall [27].
In addition there will be a tendency to increase furnace firing to maintain output, thereby pushing up superheater temperatures.

2.3.3 Slagging of the Furnace Walls

Excessive slagging of the furnace walls will reduce heat absorption and steam raising capacity. The heat which is produced has to go somewhere so that furnace outlet temperatures will tend to increase [28]. This subject will be dealt within more detail later in this chapter.

2.3.4 Fouling of Air Preheaters and Economisers

Fouling and corrosion of the heat transfer surfaces on the flue gas side of air preheaters and economisers will lead to a loss in thermal performance, so that the steam output will tend to deteriorate [29]. If the plant operator decides to accept this deterioration, there may be only a small increase in superheater temperatures, as there will be the facility of reducing the rate of flue gas recirculation or changing burner angle in corner fired furnaces. If output must be maintained, superheater temperatures will rise. The effects of a reduction in air preheat are more complex at low loads, since the reduced air preheat may give rise to combustion instability. Superheater temperatures in these conditions may be erratic and result in increased fouling of both the furnace and the superheaters tubing due to deposition of unburnt fuel

2.4 Superheater Materials of Construction

2.4.1 Background

The tubing in the final superheater sees the most severe combination of temperatures and pressures on the plant. For designs built between 1960 and 1990 temperatures and pressures were in the range 540°-565°C and 160-240 bar. Efforts were made in the 1960’s to use austenitic superheater tubing, headers, and connecting pipework to go to higher temperatures, but thermal fatigue was a big problem. Temperatures and pressure are again on the rise, the breakthrough being the use of strong martensitic steels for superheaters, reheaters, valves, pipework, and turbine rotors [30,31, 32].

Superheater tubes are between 50-100 mm diameter. Superheater headers are 0.5-1.0 m across. Given these parameters Cr-Mo-V, 2.25Cr-1Mo and 12Cr steels were adequate for plant running with steam temperatures up to 540°C, giving just-about acceptable wall thicknesses. Nevertheless, creep strength for all of these is on the borderline. For superheater tube and header materials, a very rough rule is that they should have a long term creep rupture strength in excess of 100 MPa at the design temperature. Table 2.2 shows that none of these older alloys really meet this criterion [30].

A big concern for both designers and operators is the selection of materials for superheater headers. Although these run at lower temperatures than the tubes, section thickness is considered excessive with the aforementioned alloys, as here too creep strength is only just sufficient. Furthermore, with the older materials, yield
strengths were low, so that if condensate quenching were to occur there would be a serious risk of cracking, particularly in the ligaments between the superheater tube stubs [33, 34]. Normal thermal stresses, caused by two shifting, that is shutting down the plant at night or at weekends, when the demand for electricity falls, were an added problem.

Table 2.2: 100000 Hour Stress Rupture Properties for Final Superheater Alloys [From Ref 30]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>500°C</th>
<th>540°C</th>
<th>580°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>CrMoV</td>
<td>170 MPa</td>
<td>100 MPa</td>
<td>46 MPa</td>
</tr>
<tr>
<td>2.25Cr-1Mo (&quot;T22&quot;)</td>
<td>135 MPa</td>
<td>78 MPa</td>
<td>34 MPa</td>
</tr>
<tr>
<td>12Cr (&quot;X20&quot;)</td>
<td>235 MPa</td>
<td>147 MPa</td>
<td>82 MPa</td>
</tr>
<tr>
<td>Type 321 Stainless</td>
<td>c.220 MPa</td>
<td>c.190 MPa</td>
<td>120 MPa</td>
</tr>
<tr>
<td>P91</td>
<td>165 MPa</td>
<td>148 MPa</td>
<td>120 MPa</td>
</tr>
</tbody>
</table>

As noted a major drawback of the austenitics was the tendency to thermal fatigue. The relative susceptibility to thermal fatigue of superheater alloys is given in Table 2.3, using data from Ref 10, and is best categorised by the "Merit Order Parameter R" which is given by:

\[ R = k \sigma_y \alpha^{-1} E^{-1} \]

Where \( k \) = Thermal Conductivity, \( \sigma_y \) = Yield Strength at Temperature, \( \alpha \) = Coefficient of Thermal Expansion and \( E \) = Young's Modulus using the units shown in Table 2.3[33].

Table 2.3: Physical Properties and Merit Order Resistance for Superheater Steels

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Conductivity (W.m.K(^{-1}))</th>
<th>Coefficient of Thermal Expansion (10^6).K</th>
<th>Young's Modulus (GPa)</th>
<th>Yield Strength At Temperature</th>
<th>Merit Order “R”</th>
</tr>
</thead>
<tbody>
<tr>
<td>T22</td>
<td>33</td>
<td>14.6</td>
<td>167</td>
<td>175MPa@500°C</td>
<td>2300</td>
</tr>
<tr>
<td>X20</td>
<td>26</td>
<td>12.3</td>
<td>198</td>
<td>250MPa@550°C</td>
<td>2700</td>
</tr>
<tr>
<td>Type 316</td>
<td>22.5</td>
<td>18.0</td>
<td>150</td>
<td>98MPa@600°C</td>
<td>800</td>
</tr>
<tr>
<td>P91</td>
<td>30</td>
<td>12.7</td>
<td>175</td>
<td>220(min)MPa@600°C</td>
<td>3000</td>
</tr>
<tr>
<td>P92</td>
<td>c.27</td>
<td>c. 12</td>
<td>c.180</td>
<td>c.300MPa@600°C</td>
<td>c.3750</td>
</tr>
</tbody>
</table>

As can be seen the R value of Type 316 is very low. De-rating was necessary in some really advanced plants utilising austenitics. Because of this experience steam temperatures settled back to 540°C for almost twenty years, and the two ferritic materials which came into use for superheater construction were "T22" (Fe-2.25Cr-1Mo) and "X20"(Fe–12-1Mo-0.3V) steels.
Because of this, a new header material called P91, based on a modified martensitic 9Cr steel, came into use during the late 1980s. This steel had a much better creep strength than the older alloys, so that header thicknesses could be reduced, itself contributing to improved thermal fatigue resistance. Note that the merit order of this alloy at 600°C is better than the older alloys at 550°C.

2.4.2 New Martensitic Steels for Superheaters

P91 is just about as good as the austenitic stainless steels at temperatures around 600°C and was first used for outlet superheater headers. It is now being used for superheater tubing as it is stronger than 2.25Cr (T22) and 12Cr(X20). An improved version of P91, P92, is being considered for use in pipework and headers. Here chromium and silicon are restricted to maximise strength, but compromising oxidation resistance. However, judging from the recent NPL Workshop at Teddington on Oxidation, where the focus was on the growth rate of steam side oxide in P91, it is unlikely that P92 will be used in superheaters.[35, 36].

Table 2.4: Elemental Composition of P91 Steel [Ref 39]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>%</th>
<th>C</th>
<th>Mn</th>
<th>B</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>W</th>
<th>Nb</th>
<th>N</th>
<th>Al</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>P91</td>
<td>Min</td>
<td>0.08</td>
<td>0.3</td>
<td>-</td>
<td>0.2</td>
<td>8.00</td>
<td>0.85</td>
<td>0.18</td>
<td>-</td>
<td>0.06</td>
<td>0.030</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0.12</td>
<td>0.6</td>
<td>-</td>
<td>0.5</td>
<td>9.50</td>
<td>1.05</td>
<td>0.25</td>
<td>-</td>
<td>0.10</td>
<td>0.07</td>
<td>0.04</td>
<td>0.40</td>
</tr>
<tr>
<td>P92</td>
<td>(approx)</td>
<td>0.07</td>
<td>0.45</td>
<td>0.004</td>
<td>0.06</td>
<td>9.0</td>
<td>0.5</td>
<td>0.2</td>
<td>1.8</td>
<td>0.05</td>
<td>0.06</td>
<td>&lt;0.02</td>
<td>--</td>
</tr>
</tbody>
</table>

2.5 Metallurgical Background to P91 Steel and Its Problems

2.5.1 Basic Metallurgy of Power Plant Superheater Steels

The earlier steels such as carbon-manganese and T11 and T22 steels have such a low alloy content that they behave in a very similar way to that of the simplest type of steel as represented by the well known iron-carbon equilibrium diagram as shown in Figure 2.8.

The diagram is of the eutectoid type, whereby below 723°C the stable phases are ferrite (α-iron) and cementite (Fe₃C). As the carbon content increases the cementite also increases, but up to about 0.7% carbon the carbide forms a lamellar eutectoid with the ferrite known as pearlite. These areas of eutectoid have the appearance, at low magnification, of small dark grains immersed in a network of light grey coloured grains of ferrite. The lamellar morphology gives a high surface area to volume ratio, which because of surface energy effects leads to the cementite spheroidising at temperatures between 400° and 700°C.

If these “carbon steels” are heated, on reaching 723°C, the pearlitic areas become unstable, the ferrite and cementite reacting to form carbon rich austenite grains. As
temperatures go even higher, ferrite become unstable, and depending on the carbon content a point is reached where the only phase remaining is austenite. At even higher temperature, just a little below the melting point of iron, austenite become unstable and a form of ferrite, delta ferrite, becomes the stable phase.

![Iron-Carbon Diagram](image)

**Figure 2.8: The Iron-Carbon Diagram**

If such an alloy is cooled reasonably slowly, the reverse changes, which are diffusion controlled, will take place, resulting in the same ferrite-pearlite morphology. The addition of percentage amounts of alloying elements slows up these diffusion reactions. Bainite will tend to form from the austenitic areas rather than pearlite, and as the cooling rate or the alloy content increases, the proportion of bainite in the final structure will also increase. Furthermore, if the material is quenched from the austenite region, an extremely hard phase, martensite is produced. Martensite is essentially unstable and in simple carbons steels will decompose into ferrite and carbide on being heated to temperatures of around 500°C.
For martensite to form, the alloy must be cooled reasonably quickly from the austenite phase field, and the alloy must be cooled to below the martensite start temperature. Both the minimum cooling rate and martensite start temperature are governed by the alloy content.

The addition of most common alloying elements, with the exception of carbon, nitrogen, nickel and manganese, destabilises austenite, reducing the size of the respective phase field in the equilibrium diagram. The phase field for both alpha ferrite and delta ferrite grow at the expense of that of the austenite, and if the alloy content is high enough, these two phase fields meet up. The austenite phase field, if it exists at all, is therefore confined to a small area, commonly known as the “gamma loop”. This greatly restricts the temperatures from which an alloy can be quenched.

2.3.2 Physical Metallurgy and Heat Treatment of P91

P91 is a development of the simple Fe-9Cr-1Mo or “P9” composition. This earlier material was allowed to cool slowly from the austenitising temperature, resulting in the formation of a ferrite-pearlite or bainitic structure, with a hardness of around 170 VPN. With P91 the alloy is air-cooled or “normalised”. This term can give rise to confusion, since a normalising treatment, with straight carbon steels, gives rise to ferrite and pearlite. But diffusional transformations in P91 are so sluggish that martensite forms instead. Martensite start and finish temperatures are just below 400°C and around 100°C respectively, the competing bainitic and pearlitic transformations taking well over an hour to commence [37].

![Figure 2.9: Phase Diagram for Iron-Chromium. Note the Austenite Loop [33]](image_url)
Small amounts of vanadium and niobium are added to the basic formulation of 9Cr-1Mo, which react with carbon and nitrogen. These precipitates pin the subgrain and lathe boundaries in the martensite, stabilising the structure for high temperature service, and impeding dislocation motion [38]. The specified composition is shown in Table 2.4.

To maintain a reasonably sized gamma phase loop during the solution annealing phase of the heat treatment, as Figure 2.9 shows, the chromium has to be restricted to levels which are below 10%. Quite minor changes, in composition or heat treatment, can bring the alloy into the austenite/ferrite phase region. Orr and Woollard indicate that the manufacturers, to prevent the formation of delta ferrite, try to work well within an envelope which has the “dimension” of about 3.4 to 6.3 “Nickel Equivalent” by 10.6 to 13.9 “Chromium Equivalent” [40]. If delta ferrite were to form the immediate effects would be a reduction in toughness and creep strength. See Figure 2.10

On cooling, the martensite is quite hard at about 400 VHN and is given a one hour tempering treatment at 750°-780°C, to reduce the hardness to about 270-200 VHN and to begin the precipitation of the carbo-nitrides [40]. M₂₃C₆ forms during the normalising and tempering treatment, this inducing a high proof stress. In service the carbide coarsens, but later in life V(CN) starts to precipitate and this maintains the interparticle distance so that strength is retained [41].

---

**Fig 2.10: Showing Desired Area of Compositions for P91 in Terms of Nickel and Chromium Equivalents [Ref 40]**
2.5.3 Problems with P91

P91 is a comparatively new material and as such presents problems both to the designer of superheaters and for the failure investigator. As will be seen, questions about the strength of this alloy, its oxidation resistance, and the long term performance of weldments are currently causing concern.

2.5.3.1 Stress Rupture Predictions

Most estimates of the long term creep rupture properties are based on the Larson-Miller parametric equation where for a constant stress

\[ P = T(C + \log t) \]

In this well known equation, \( P \) is the Larson-Miller Parameter, which is stress dependent, \( T \) is the absolute temperature in degrees Kelvin, and \( t \) is the time in hours. \( C \) is a constant which is used to modify the effects of the exposure time. Hence by running tests at an increased temperature it should be possible to accelerate the tests, in effect swapping temperature for time [42]. The commonly accepted value for \( C \) is 20, which is reasonable for the purposes of preliminary extrapolation, but as Furillo et al pointed out many years ago the \( C \) value is not fixed [43]. The other mainstream approach is to plot log stress against log time to failure and draw a smooth curve through the points using a Fourier series type expression. Typically the stress lines curve gently downward at long times as shown in Figure 2.11. The Fourier series approach can be developed further to give more complex expressions covering the whole range of temperatures, stresses and failure times, but such expressions only tend to become available after much data has been accumulated, and the use of the simpler Larson-Miller parametric approach is much more common.

Figure 2.11: Log Stress v. Log Time for P91 [34]
With P91 concern is beginning to be felt about possible over estimation of long term creep strength. The problem arises because, at the sort of stress and temperatures, which are used for long term extrapolation and for design stresses with P91, the slope of creep rate versus stress drops off quite markedly, compared to short term tests where the stresses are much higher as shown schematically in Figure 2.12. Unfortunately when an alloy is being developed it is necessary to make use of the shorter term higher stress data. Here the phrase “short term” is relative. Even a 30000 hour test would last around four years. But the effect is that if the slope does not change, once the stress level is below the kink in Figure 2.12, the estimated creep rate would have continue to drop of at a very rapid rate, giving a prediction of a very long and over-optimistic prediction of the creep life and long term strength.

![Log Creep Rate vs Log Stress](image)

**Figure 2.12:** Note very high stress sensitivity at high stresses

These uncertainties about the relationship between stress, temperature and component life will reveal themselves in the debate about the C term in the Larson-Miller equation for P91 steels. These, as noted, will influence the estimates about the long creep rupture properties needed for design purposes, with values of C tending to over estimate the strength and temperature capability. The choice of the correct value of C in failure investigations is also important, as this will impact on tube temperature estimates and therefore on possible failure mechanisms and root causes.

The preliminary extrapolations about the strength of P91 appear to have originated from the use of a value of C of around 35 [46, 47]. More recently, Kimura et al indicate up to 20000 hours that a parameter value of 38 is appropriate, but at longer times they suggest that a value of 20 gives a better fit [48]. Cerjak et al also have stated that the Larson Miller constant for long term tests is far too high. For a P91 alloy, these authors derive a best fit value of 31 for short term tests, but for longer term tests at lower stresses, they suggest that 22 is more appropriate [49]. For the complete range of high and lower stresses they quote a “polynomial derived value”
of 23.9. Similar observations about the stress dependence have been made elsewhere [50, 51].

How important are these differences in C value? The thinking that is required for the choice of C value in failure investigations is explored in Chapter 9, when the Larson Miller parameter is used to help identify the root cause of a superheater failure. In terms of estimating the temperature capability for design purposes, the results of extrapolation can be seen in Table 2.5, in which ASME have appeared to underestimated the strength at lower temperatures and over estimated at higher temperatures.

Table 2.5: 100000 hour Creep Rupture Strengths in MPa for P91
from
ASME, VdTÜV and EN Evaluations [34]

<table>
<thead>
<tr>
<th>P91 Evaluation Method</th>
<th>500°C</th>
<th>550°C</th>
<th>600°C</th>
<th>650°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASME</td>
<td>164</td>
<td>141</td>
<td>98</td>
<td>---</td>
</tr>
<tr>
<td>VdTÜV</td>
<td>253</td>
<td>162</td>
<td>90</td>
<td>---</td>
</tr>
<tr>
<td>EN</td>
<td>258</td>
<td>166</td>
<td>94</td>
<td>48</td>
</tr>
</tbody>
</table>

2.5.3.2 Absence of Metallographic Changes for Temperature and Life Estimation

Spheroidisation of iron based and chromium based pearlitic carbides is used to estimate average operating temperatures of low chromium and carbon steel tubing, which then can be used to give a rough estimate of tube life [53, 54, 55, 56]. Naskishiro et al showed that for a T22 steel (2.25 -1Cr) the range of spheroidised structures could be put into seven classes, but the temperature range in each class after about 20000 hours of exposure was of the order of 50 degrees [57]. However in the author’s experience a change of temperature, through the heated wall of a superheater tube of about 10°-20° C can be just about detected.

Spheroidisation is at best only semi-quantitative, but is useful in failure diagnosis of the lower alloys steels as it can show the extent of overheating of neighbouring tubes. It has the advantage that it is a non-destructive test that uses surface replication. As Figure 2.13 shows, for the pearlite containing steels such as T11 (Fe-1.25Cr-0.5Mo) the changes are very apparent [53]. Unfortunately, with the martensitic steels, there are no real changes in the optical microstructure over the life of the material. Fig 2.14 shows that after long term exposure of P91 and P92, the microstructure of these still has a distinct martensitic appearance [58, 59]. Ennis has suggested that the lathes of martensite lose their body centred tetragonal structure and revert to the body centred structure of true ferrite, there being no real changes in the microstructure while this happens [59, 38].
Fig 2.13: Effect of exposure to temperature on pearlitic structure of T11 steel (left top) leading to spheroidised structure (left bottom) (×300) [Ref 53].

Fig 2.14 (Right): Appearance of P91 (right top) and P92 (right bottom) creep test specimens at end of creep rupture testing. Note absence of cavities and maintenance of martensitic structure [Refs 58 and 59] (×500)
2.5.3.3 Hardness Changes and Testing

Changes in hardness due to sub-optical carbide coarsening and cavity growth can be used to estimate tube life directly in the low alloy steels of the T11 and T22 type [60,61]. Here the fall in hardness is due to the gradual coarsening of sub-microscopic carbides, the result of which is that at room temperature dislocation movement is less impeded. Even so there are practical problems in the application of this technique to well understood materials. Fleming has commented that there is a great deal of scatter with in-situ hardness testing [62]. Furthermore a serious problem is that the into-service hardness figures are not always available and can be distorted by stress relief of weldments etc. Such sub-optical changes are diffusion controlled, and are stress as well as temperature dependent. Bhadeshia et al have commented on the problems this causes for life assessment for the lower alloy steels [61]. The outcome is more certain when evaluating the life of steam turbine rotors, where due to the fall in steam temperature, there is drop in hardness along the rotor from the inlet section to the outlet. This obviates tempering induced effects, providing the rotor has been heat treated properly.

![Experimental data and Estimated curve](image)

**Figure 2.15: Relationship of Hardness and Creep Damage with Stress and Temperature [48]**

With P91 and P92 alloys, precipitate coarsening also occurs, reducing hardness, but in addition recrystallisation of the martensitic structure reduces the barriers to dislocation movement. Stress as well as temperature, in a similar manner to the low alloy steels, also appears to accelerate these changes in P91. Hence hardness changes are more enhanced in the gauge length of the specimens, where the stress is somewhat higher than in the specimen heads. Orlová et al found that in P91 the hardness in the specimen heads dropped fairly quickly to 230 VHN from the original value of 237 VHN, after which there was little further fall [63]. This may be a general phenomenon as the results on a 12Cr martensitic show the same head/gauge
effects [64]. The Orlova results showed that in a creep test at 600°C, which lasted some 16000 hours at a stress of 110 MPa, the hardness in the gauge length fell to about 190 VHN. This gives a drop of about 20%, which roughly corresponds to a fall of 25% reported by Bianchi et al in similar tests [65].

The experiments of Ishii et al on a martensitic forging with a chromium content of 10% have taken the hardness question much further. They found that as the failure time increases from about 3000 to about 28000 hours, the fall off in hardness was not so marked [66]. These results led to an equation that relates the hardness ratio (the ratio between the hardness as a result of creep divided by the hardness after tempering) to the creep life, as shown in Figure 2.15. For this purpose complex functions, which include the initial hardness, plus the stress and temperature dependence need to be taken into account. Presumably the same type of parametric equations could be developed for P91 and P92.

As noted earlier these falls in hardness in the martensitic steels are caused by a combination of recrystallisation effects as well as precipitation. On a research basis TEM techniques have been used to record such changes. Not unexpectedly, as with the hardness changes, the ageing effects on the microstructure are accelerated by stress. [63,64, 67]. Here it should be remembered that design stresses are extremely low compared to the stresses typically used in experimental tests.

2.5.3.4 Cavitation

As creep develops, in many materials, processes such as grain boundary sliding and the tendency for grain boundaries to act as "sinks" or traps for vacancies, lead to the formation of sub microscopic cavities at grain boundaries. Towards the end of the life of the component, the cavities grow and link up to such an extent that they form the optically visible fissures, which are one of the prime indications of creep. The concentration and shape of these cavities can be used to determine the necessity to repair components. Hence for this specific purpose cavitation is probably the best method for life assessment of the low alloy steels [60]. Unfortunately with P91 it is extremely difficult to detect cavitation until the material is very close to the end of its life [58]. This seems to be a typical view at this point of time.

2.5.3.5 Distinguishing Creep Type from Overheating Failures

In low alloy ferritic tubing long term creep failures will result in a highly fissured tube with some mild swelling, in which the failure is of the thick edge type. Where the temperature has been well in excess of the normal operating temperature, failure times can be in minutes. In these cases failures are normally of the thin lipped shark’s mouth type, as reported by French in his book, and Davidson and James on their internal guide for Power Gen [68, 69]. There is hint that this type of "overheating" failure occurs in the temperature region where the material is in dual phase austenite-ferrite condition, as Davidson and James state that above the upper critical point, the failures start to be of thick edge type. Furthermore Furtado and May report on a "sharks mouth" type superheater failure, which more detailed investigation indicated was more probably due to pure creep [70].
With P91, because of the sluggishness of diffusional transformations, and because the microstructure does not consist of discrete colonies of ferrite and pearlite, the dual phase region is not likely to form. In theory, in an overheating situation, the alloy could exhibit little ductility so that it might be difficult to decide on the failure mechanism, from visual evidence. The limited published data, however, suggests that the material exhibits tensile elongations of between 70 and 110% when tested at 1000°C., that is, within the austenitic region [71].

2.5.3.6 Impact of Nitrogen and Aluminium on Creep Strength

As with most high temperature alloys there is considerable scatter in the creep curves, some of which, in the case of P91, can be probably be traced to variations in heat treatment and composition. Because the shallow slope of log time/log stress creep curves, a minor increase in strength can increase life considerably. Conversely, an overoptimistic estimate of the design stress can lead to premature failures. Some of the causes of scatter are discussed below.

![Figure 2.16: Calculated Effect of Aluminium and Nitrogen on Creep Strength of a 9 Cr Steel [Ref 47]](image)

Providing that the upper range of austenitising temperatures are kept below the level at which delta ferrite appears, that is, c.1100°C, Orr and Burton report that the strength was increased by about 10% compared with material which was austenitised at 1050°C. This was ascribed to enhanced dissolution of V, Nb C and N which then became available for precipitation hardening when the alloy was subsequently tempered or was exposed at service temperatures. These authors also pointed out the significance of free nitrogen, as this forms strengthening precipitates with vanadium, the critical ratio being a ratio of 3.5 in the proportion of vanadium to nitrogen [72]. It is well known that excessive amounts of aluminium in plain carbon steels can tie up nitrogen leading to inferior creep properties [73]. Some quantitative
work has been done in Europe on this issue, albeit with turbine rotor steels, but Meyer states that the active nitrogen is given by the equation [74]:

\[
N_{\text{Free}} = N_{\text{Total}} - 0.52\text{Al} - 0.29\text{Ti} - 0.15(\text{carbo-nitride fraction})\cdot\text{Nb}
\]

Foldyna et al have calculated, as shown in Figure 2.16, using extrapolation techniques how the creep strength of martensitic alloys is affected by the combination of nitrogen and aluminium. In addition Brett has suggested that the reaction of aluminium and nitrogen will occur during tempering treatment, which these alloys receive after air hardening, particularly if the materials are overtempered. In such cases the into-service hardness is likely to be lower than expected [75]. The point is here is that over tempering is likely to promote the reaction of nitrogen and aluminium, preventing the former from reacting with elements such as vanadium, which would be critical in forming precipitates that would give a high hardness.

2.5.3.7 Steam Side Oxidation Resistance

Good steam side oxidation resistance is, as has been mentioned previously, vital in superheater tubes as the oxide will act as an insulating barrier, thereby raising tube temperatures. Thick oxide scales tend to spall or break off. Even small particles may erode the first stages of the high and intermediate pressure turbines. Larger flakes can drop down into the bottom loops of platen and pendant superheaters and reheaters, blocking steam flow, so that tube temperature again will increase. As noted, oxide spalling of P91 was a critical issue for discussion at the recent NPL/EPRI conference.
The shortcomings with the oxidation resistance of the P91 class of martensitics, and to an even greater extent those of the P92 class, stems from the need to obtain high strength. This can only be obtained by cooling the alloys from the austenitic range, and unfortunately the two elements which give good oxidation resistance, namely chromium and silicon are ferrite stabilisers and restrict the size of the gamma loop.

Because the oxidation properties of this material are on the borderline, a relatively thick oxide can grow on the inside of the tubing. Hence if a tube is under a heavy heat load, the insulating effect of the oxide will raise the tube temperature and cause premature creep. The magnitude of the temperature rise is proportional to the heat transfer rate in superheaters, the oxide thickness, oxide conductivity, porosity and adherence. Data for heat transfer rates is difficult to obtain but French shows a graph with rates varying from 19-63 kW.m$^{-2}$ and Husemann quotes 50-75kW.m$^{-2}$ [76, 77]. It should be noted that this is the steam side heat transfer rate, which is significantly higher than that on the flue gas side, the increase resulting from the difference between the inside and outside diameters of the superheater tubing.

Figure 2.17 shows a graph, calculated by the author, using data on from a paper by Husemann. It indicates that in the absence of heat transfer, or the formation of a thick oxide, a superheater tube, running at a constant metal temperature of 600°C, would use up about 1.6% of its life over a year. However at a heat transfer rate of 50kW per sq metre, the build up of the oxide scale gradually raises the tube temperature by about 17°C over a year. This progressive increase in temperature reduces tube life by about 4%. The assumption is that that the rate of metal wastage is about 0.1mm per year and this will give an oxide scale thickness of about 0.125 mm.

Figure 2.18: Effect of Chromium Content on Steam Side Oxidation Resistance at 600°C (lower curve) and 650°C (upper curve)

The oxidation rates shown in Figure 2.18 are a re-plot of oxidation rate data from a paper by Ennis et al in which the parabolic rate constants of ferritic and martensitic alloys in steam were converted to metal loss rates per annum [78]. It will be seen that between 8-11% chromium the oxidation resistance improves dramatically. However there appears to be a good deal of scatter in this region, which is due to
surface condition, the amount of oxide spalling, and the presence of silicon and, perhaps, manganese, according to these authors. These variations make it difficult to ascertain operating temperatures from oxide thickness measurements, something that is commonly done for other classes of high temperature materials. It is apparent from the graphs that if the material had a composition which had low resistance to oxidation, the rate of oxidation would double that is at 600°C, the rate of oxide growth would be 0.2 mm per year, rather than 0.1mm. This in turn would double the temperature rise that the tube would experience, and have a marked detrimental effect on the tube life.

![Figure 2.19: Effect of Si content on oxidation of NF616 alloys at 650°C for 1000 hours in steam [79]](image)

Figure 2.19, which used results taken from a paper by Tamura et al on the oxidation of various grades of NF616 (i.e. P92 type alloy) at 650°C in steam, suggests that there is also no definite point at which the level of silicon becomes protective [79]. Schütze et al consider that silicon, rather than forming a protective sublayer slows down the loss of chromium and may help in repassivation once oxide cracking and spalling occurs [80].

A critical number in both assessing metal temperatures in superheater tubes from oxide thickness is the increase in the rate of oxidation with temperature. Unfortunately there is a tendency to quote the parabolic rate constant when giving this figure, which in rule of thumb terms doubles every 10°C-20°C increase in temperature. However since the rate of oxide growth slows rapidly with time, the effect of temperature on the growth rate is relatively low. In the case of P91, it would appear that the growth rate doubles for every 30°-40°C increase in temperature [78, 81].
2.5.3.8 Effect of Heat Transfer in Accelerating Oxidation Rates

The calculations carried out in the previous section assumed that the oxide growth was determined by the original metal temperature, that is 600°C. However there is reason to believe that as oxide heated up, along with the tube material, it would tend to grow faster. Experienced colleagues at ERA at Leatherhead in Surrey and a FA Juelpich, in Germany, in the mid- to late nineties were concerned about such effects as any acceleration of the oxide growth rate would cause uncertainties in assessing metal temperatures.

Support is given to this view by Irwin who agrees that the effect of the increase in tube temperature is to accelerate, still further, the growth of oxide. A case investigated by him relates to a T22 superheater tube [82]. The steam temperature was 482°C, flue gas temperature 1093°C, and the mid wall tube temperature, before any steam side oxide began to grow, 542°C. Heat transfer rate was just under 95kW.m⁻². After three years of operation the tube temperature would have reached 580-590°C, pushing the remaining life down from about 30 to less than 10 years. Scale thickness after three years was about 200 microns.

**Figure 2.20: Tube Temperatures and Life Fractions With and Without Acceleration of Oxide Growth at 75kW.m⁻²**

The author has developed a spreadsheet model to quantify the magnitude of runaway oxidation and its impact on the creep life of superheater tubes. A copy of the
The parameters in the spreadsheet can be changed easily to take account of different rates of oxidation, thermal conductivity of the oxide, oxide growth rate laws, and the effect of temperature on the growth of oxide.

Figure 2.20 shows the runaway phenomena schematically in which a vicious cycle builds up between metal temperatures and oxide growth. In working out the final thickness of an oxide after an exposure of one year, it takes into account a number of factors. Typical values for each of these are shown below, which are based on the references given in Section 2.5.7

- **Oxide Thickness Temperature Gradient** (12.5°/100µm @ 50kW/m²)
- **Basic Oxide Growth Rate** (125µm/year @600°C)
- **Oxidation rate law** (prop to square root time)
- **Temperature Acceleration** (Doubles for every 30°C increase)
- **Initial Tube Temperature** (600°C)

The oxide thickness calculation was done in 1000 hour steps, with the temperature increase induced in the tube at the end of each step being used to calculate the increased oxidation rate in the ensuing step. The effect of these step changes in temperature on tube life usage was calculated using a Larson-Miller parameter approach for the effect of each 1000 hour exposure at the different temperatures.

To determine the actual value of the parameter it is necessary to make an estimate of the absolute life at the design temperature and to decide on the value of the Larson-Miller constant. Note that the absolute life is much higher than the design life as normally understood. Actual values used in the current version of the spreadsheet are:

- **Larson Miller Constant:** 31
- **Absolute Life:** 500000 hours at 600°C

In Figure 2.20, the dashed curves show the effect of the acceleration or runaway, at a heat transfer rate of 75 kW.m⁻², indicating that runaway increases the tube temperature by about 9°C after 8000 hours, compared to the oxidation rate being fixed at 600°C. Tube life suffers, runaway raising the life usage from 6.32% to 8.95%, as shown by the solid curves. Note that the runaway effect on temperature does not become really apparent until several thousands of hours have elapsed. However, the runaway effect becomes far more marked if the oxidation resistance decreases, especially when combined with high rates of heat transfer. Table 2.6 summarises these effects at heat transfer rates of 50, 62.5 and 75kW.m⁻², and also with oxidation rates higher and lower than those quoted above. For comparison, figures for the “no acceleration-no runaway effect” are included, in brackets, at the 100% level.
Table 2.6: Effect of changes in Oxidation Rate and Heat Transfer Rates on Tube Life after 8000 Hours Operation

<table>
<thead>
<tr>
<th>Oxidation Rate Compared to Standard at 600°C</th>
<th>Life Fraction Usage at Heat Transfer Rate of 50kW.m⁻²</th>
<th>Life Fraction Usage at Heat Transfer Rate of 62.5kW.m⁻²</th>
<th>Life Fraction Usage at Heat Transfer Rate of 75kW.m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>3.25%</td>
<td>4.00%</td>
<td>5.05%</td>
</tr>
<tr>
<td>100%</td>
<td>4.31% (4.03)</td>
<td>5.99% (5.15)</td>
<td>8.94% (6.32)</td>
</tr>
<tr>
<td>125%</td>
<td>5.99%</td>
<td>10.55%</td>
<td>21.64%</td>
</tr>
</tbody>
</table>

2.5.3.9 Welding and Type IV HAZ Cracking

Much of the HAZ (Heat Affected Zone) during welding receives an intercritical anneal, which prevents the material transforming completely back to martensite on cooling. Other regions of the HAZ close to unaffected parent material, heated to lower temperatures, do not transform to austenite during welding. They can however, be effectively over tempered. In both cases creep strength is impaired.

Transition welds could suffer from premature creep cracking because of carbon and nitrogen migration into or out of the P91 material. Repair welds will give similar problems, again because of carbon and nitrogen migration. The risk is likely to be higher with these, since the parent material will have aged considerably due previous in-service exposure [83].

2.6 Implications for Expert System Development for P91 Superheaters

The implications of this review of the properties of P91 in terms of the development expert system for the failure analysis of this material in superheaters has highlighted a number of issues relating to the use of P91/P92 martensitic steels in for superheater tubing. The specific difficulties would be at their most intense in having to determine the root cause of creep failures. Parker has drawn attention to possible problems in the use of P91, but Seliger and Gampe have also drawn attention to the related problem of estimating the creep life of this material [45, 84]. The main factors that need to be considered are:

- Reliable techniques are not available for estimating tube temperatures.

- Indirect methods will need to be used based on steam and flue gas side heat transfer calculations.

- Oxide formation on the steam side of superheater tubing could lead to a foreshortening of tube life of P91/P92 materials due to the relatively high oxidation rate of these alloys.

- There is the possibility of runaway oxidation at high heat transfer rates.
• Use of a high values of the Larson-Miller Constant for parametric extrapolations of the creep stress will lead to overestimation of operating temperatures of failed P91 tubing and may have led to an overestimation of the alloy capabilities.

A human expert would need to work through each of these issues in coming to conclusions about root causes, but in terms of this work the aim would be to assess whether a set of If...Then rules could be devised which would help in determining root causes. Any such effort should be done with the minimum of additional experimental investigations.

2.7 Descriptions of Metallurgical Failures in Superheaters and Related Phenomena

The main purpose of this part of the literature survey is to provide background information for use in Chapter 7, which is entitled “Dealing with Uncertainty in Failure Analysis”. The information given specifically relates to Section 7.5, in that chapter, which proposes a method by which the type of evidence that will be obtained in the course of laboratory and related investigations can be quantified. This quantified evidence is then used to support or disprove a particular hypothesis about the mechanism of a failure. This approach is taken further in Chapter 9 which covers “Metallurgical Failure Analysis of P91 Superheaters Using an Expert System” which also uses information from the literature survey. In addition some of this information is used in Chapter 8 which deals with “Plant Based Rules in Superheater Failure Investigations”.

Chapter 7 gives a full explanation of the procedures, but it uses a probabilistic method that is based on Bayes’ Rules. In this, an initial hypothesis, about the failure mechanism, is formulated, which is mainly based on the appearance of the failure, and in some circumstances on what the failure investigator is told about the operation of the plant. Confidence in these preliminary conclusions will range from strong to weak. The laboratory investigation will then begin to provide additional evidence, which will hopefully support the hypothesis. Some parts of the laboratory evidence will be very important; other parts will be less significant. Each of these pieces of evidence is then quantified and then added together, and, using the equations related to Bayes’ rules, is used to give an estimate of the probability of the initial hypothesis being correct.

Accordingly, in compiling this section of the literature survey, the focus is on:

• The typical appearance of various types of failures
• What supporting evidence comes from laboratory and backroom investigations
• What are the key pieces of evidence stemming from the operation of the plant
2.7.1 Failure by Creep and Metallographically Based Temperature Indications

Creep is the long term failure mechanism caused by the action of a reasonably uniform tensile stress on a component, at temperature. A component that is subject to creep undergoes continuous deformation, until it reaches a point where it fails by cracking. This implies that dislocations are constantly moving and being created under the action of stress. Associated with this process, vacancies are also being created which can aggregate at critical points in the microstructure such as grain boundaries [85]. The aggregation of the vacancies plus grain boundary sliding, results in the formation of cavities at the grain boundaries, which as discussed below, grow to form microcracks and fissures, until the component fails.

Here, it is important to realise, that in practice corrosion or erosion of superheater tubing will result in final failure by creep, as the wall thickness thins down and stress is increased. Furthermore, if the failure is on a straight length of the tube, away from any bending stresses, and the tube has begun to split in a longitudinal fashion, creep is almost certain to have been involved. Hence, if the failure is of the longitudinal split type, it is imperative for the investigator to make some preliminary calculations, using Larson-Miller parametric or other methods, to determine the metal temperature on the basis that the failure is totally due to a creep mechanism. This will give an over estimate, but this figure than will become the basis for comparisons with plant derived data, at an early stage or with other estimates based on laboratory information.

This preliminary assessment of temperatures will be based the hoop stress of the tube using the well known formula:

\[
\sigma = \frac{PD}{2t}
\]

Where \( \sigma \) is the stress, \( P \) is the pressure, \( D \) is the mid-wall diameter, and \( t \) is the wall thickness.

By the time a superheater tube has reached the point where it has failed, the walls of the fissures are often highly oxidised, and it is difficult to discern very much about the state of material. Photomicrographs of the structure are not very clear. If the material is a carbon steel, it is often decarburised. Any deformation which occurs is, broadly speaking, a result of the fissuring and there is comparatively little plastic flow of the grains. This leads to only a small reduction in wall thickness of the component; levels of overall creep elongation or tube diameter change are under 10%. French gives details of a low alloy superheater tube failure in which either the swelling was confined to the area in which the material had split or where the swelling was under 5% [86]. Similar remarks are made by Davison and James [87].

The other main visual clue that creep is the main cause is that the edge of the fracture is of the thick lipped type with no tendency to taper down [86, 87]. This is a result of the microcracks linking up. In practice low alloy ferritics that have failed prematurely by creep are often covered with a thick oxide on both the steam and flue gas side surfaces.
Fig 2.21: Showing Creep Failure in Bottom Bend of Pendent Superheater. Note Surface Fissuring Around Main Crack [86].

It follows the main visual clues in creep failures are the fissuring around the site of the failure and also a certain amount of swelling, which although limited is quite noticeable. Providing there is not too much corrosion, the amount of swelling can be measured with measuring tapes equipped with a Vernier scale. Where creep has occurred, and the problem is due to excessive flue gas temperatures or insufficient steam flow through the superheater as a whole, other tubes in the locality will also show some increase in tube diameter.

As noted, the gradual aggregation of vacancies leads to a type of porosity known as cavitation, which as it grows in size, orientates itself normal to the main stresses. At a comparatively late stage, the cavities join up to form micro cracks, mainly at the grain boundaries. The component will eventually fail; the appearance of the material around the failure site then consists of a mass of fissures, which originated from the growth and coalescence of the micro cracks. See Figure 2.21 [86]

This cavitation process gradually evolves until it leads to eventual failure. Hence various authorities, such as Neubauer and Wedel, Auerkari et al, Brear and Townsend have shown how the evolution and growth of the cavities can be
correlated with the life of the component. [89, 90, 91]. Table 2.7 shows the classification scheme established by Neubauer and Wedel, and shows how this relates to other schemes.

Table 2.7: Classification of Creep Induced Cavitation and Microcracking Phenomena

<table>
<thead>
<tr>
<th>Neuberger Classification of Damage State</th>
<th>Cavitation Description</th>
<th>NT TR 170</th>
<th>VGB-TW 507</th>
<th>1SQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>No cavities detected</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>B (Isolated Cavities)</td>
<td>Isolated cavities are detected.</td>
<td>2.1</td>
<td>2a</td>
<td>0/1</td>
</tr>
<tr>
<td></td>
<td>Not possible to deduce direction of maximum principle stress from damage</td>
<td>2.1</td>
<td>2b</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C (Oriented Cavities)</td>
<td>Cavities present, often with multiple cavities on same grain boundary. A clear alignment of damaged boundaries can be seen indicating axis of principle stress</td>
<td>3.1</td>
<td>3a</td>
<td>1/2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.2</td>
<td>3b</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D (Micro Cracking)</td>
<td>Cavities have reached the micro cracking stage and are on boundaries normal to the maximum principal stress. Some boundaries have separated due to inter-linkage of cavities so forming the microcracks</td>
<td>4.1</td>
<td>4</td>
<td>2/3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.2</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.3</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>E (Macro Cracking)</td>
<td>Cracking has reached the clearly fissured stage, whereby the micro cracks have joined together to form macrocracks</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Although cavitation assessment has been developed as a means of determining remnant life, it would seem that it only begins to be reliable at a comparatively late stage in the life of a component. Furthermore Brear and Townsend indicate that cavitation is best applied to weldment areas [91]. Henry et al essentially agree with this view, stating cavitation in ductile materials, as represented by the unwelded base material, only occurs relatively late in the life of a component [92]. Barros et al did not mention the use of this technique in attempting to assess the life of superheaters.
and reheaters, probably because from other evidence, including accelerated creep
tests, it appeared that less than 50% of the life of the tubing had been consumed.
These authors were also fairly dismissive about the reliability of hardness tests [56].
A useful rule of thumb has been suggested by Bezuidenhout et al, which is that, in
engineering terms, the component has exhausted its life when the number of cavities
reaches 1000 mm$^2$, although these authors also say that microcracking does not
begin until the number of cavities reaches several thousand per square millimetre
[93].

If a failure has occurred in a section of a tube away from a weld, the finding of
cavitation in the microstructure, is therefore very strong evidence that failure by
creep highly likely. As Chapter 7 shows, as a piece of evidence (such as the
symptom of a disease) becomes more and more restricted to whether an event has
occurred, the more reliable is the evidence. In the case of ductile materials, since the
cavitation only appears in the final stages of creep, cavitation becomes a very good
indicator.

A moot point is the time to failure that would give failures of the creep type. Creep,
as a high temperature failure mechanism, does shade into short term overheating
failures, as described below. The author, when investigating the use of a high nickel
wrought alloy Inco 617, found that it gave a classic creep failure appearance in a test
at 1100°C, which had lasted less than 1000 hours. This did not surprise one of the
internationally recognised experts on this type of material [94]. The author has also
seen creep failures on low alloys steel fired heaters after 4000 hours of operation. In
short, the appearance of the failure is more significant than the failure time.

The other indicators of creep, which are spheroidisation, hardness changes and
steam side oxidation, are much more indirect, and are basically used to show that
superheater tubing has been operating at temperature somewhat higher than the
design value. The results from these estimates can be utilised in a Larson-Miller
calculation.

Standardised methods for classifying the degree of spheroidisation have been
formulated. Table 2.8 comes from the paper by Nakashiro et al, which appears to
have based on CEGB reports from the sixties [57]. It is interesting to compare this
with the schematic pictures from the Brear and Townsend paper as shown in Figure
22, which also are CEGB derived [91]. But the table from the Japanese paper
includes an extra class (Class 7) whereby all the carbide has disappeared. In the
opinion of the author, this is not just the result of normal diffusion and
agglomeration processes, which would result in the carbide appearing as grain
boundary films, but it is due partly to decarburisation. As noted, the highly fissured
area, in the region of the main creep cracks, is often free from any carbides.
### Table 2.8: Spheroidisation Classes in Low Alloy Ferritics

<table>
<thead>
<tr>
<th>Spheroidisation Class</th>
<th>Degree of Spheroidisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Typical new tube structure of ferrite and fine pearlite.</td>
</tr>
<tr>
<td>2</td>
<td>Appearance of small particles of carbide at grain boundaries</td>
</tr>
<tr>
<td>3</td>
<td>Distinct indications of spheroidisation within pearlitic areas, but some carbide lamellae still present. More carbides at grain boundaries and some precipitation in grains</td>
</tr>
<tr>
<td>4</td>
<td>Spheroidisation in pearlitic areas almost complete but still grouped in original areas.</td>
</tr>
<tr>
<td>5</td>
<td>Spheroidisation complete and carbides are dispersed leaving little trace of original areas</td>
</tr>
<tr>
<td>6</td>
<td>Marked increase in size of spheroidised carbides due to coalescence</td>
</tr>
<tr>
<td>7</td>
<td>Carbide disappears</td>
</tr>
</tbody>
</table>

![Images of spheroidisation classes](image1.png)

**Figure 2.22: Schematic Showing Spheroidisation Morphology as Related to Class. Note that this Uses the CEGB Letter Type Classification System**

It will be apparent from Figure 2.22 that even in a material in which there are no problems with the initial microstructure, in that it consists of ferrite and pearlite, rather than martensite or bainite, there can be difficulties in assessing the class of spheroidisation. Classes 5 and 6 present particular difficulties in distinguishing the two...
As emphasised, the relationship between spheroidisation and life usage is not very good. Figure 2.23 taken from the paper by Brear and Townsend shows a schematic of the evolution of spheroidised structure. [91] The dotted lines correspond to whereabouts in terms of component life one might expect to find each one of the spheroidisation classes.

It will be apparent that Class 6 covers the last 60% of the component life. And given the difficulty with distinguishing Class 5 from Class 6, this combination covers 85% of the useable life. For the assessment of component life, spheroidisation is at best semi-quantitative. It follows that in failure investigations, a heavily spheroidised structure, since it suggests exposure to high temperature for significant amounts of time, would tend to support a creep failure mechanism, but this support would not be very strong.

Most authorities share this view and in general do not rely on spheroidisation as a means of estimating life. Mann, in investigating an overheated 1Cr-0.5 Mo superheater, which had been partly blocked by pieces from a broken attemperator, stated the formation of intraferritic M$_2$C (in low alloy steels) is the critical factor in providing creep strength. As its formation and degradation are more or less independent of spheroidisation, spheroidisation is not of great significance in his opinion. Indeed, Mann states that some tubes which had spheroidised had suffered only a minor reduction in life [95]. It is also apparent from his work that although, overheating had led to one of the tubes swelling by as much as 20%, the level of spheroidisation had only reached Class 4.

Spheroidisation becomes more useful in failure investigation in providing an estimate of tube temperature. For such a purpose, the estimate of temperature needs
to be reasonably accurate. A 20°C underestimate of the temperature will lead to an overestimate in the life by a factor of 2-3.

In terms of how accurate temperature estimates can be made, on the basis of spheroidisation, there are different views. In the opinion of the author, under conditions of high heat transfer rates, where the temperature difference between the hotter outside of the tube and the cooler inside, cannot have been much more than 10°C, it is just about possible to detect a difference in the amount of spheroidisation. However it is more difficult to determine absolute values. For the T22 class of steels, assessed in the work of Nakashiro et al, the range of spheroidisation classes for a 10000 and 100000 hour exposure is shown in Table 2.9. It will be seen that the range for each class is quite large, suggesting that the best that can be done is an accuracy of 40°C.

Table 2.9 : Temperature Range in °C Versus Spheroidisation
Class for T22 (2.25Cr-1Mo Steels)

<table>
<thead>
<tr>
<th>Class</th>
<th>10000 Hours</th>
<th>100000 Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Class 1</td>
<td>&lt; 460°</td>
<td>460-530°</td>
</tr>
<tr>
<td>Class 2</td>
<td>&lt; 490°</td>
<td>490-535°</td>
</tr>
</tbody>
</table>

Where it is possible to do accelerated laboratory-based spheroidisation treatments on steel from parts of the superheater that have not been significantly affected by heating, a higher level of accuracy is possible. Temperature estimates can then be made using a parametric equation, enabling a comparison to be made between microstructures obtained using the laboratory spheroidisation treatments, with those from the component under investigation. In the experience of the author the best that can be obtained using this technique is a figure that will have a plus or minus 10°C spread, even under the best conditions (that is where the component has failed within a short time). Turner and Drew claimed an even higher degree of accuracy. They stated that the temperature estimate from spheroidisation was within 8°C of that obtained from steam side oxide thicknesses [96]. The main problem with spheroidisation is that relies so much on the eye of the expert, and as no two as-received on unaffected microstructures are the same, nor is the thermal history ever the same, it cannot be the most reliable indicator of temperature.

For this reason more quantitative techniques for tube temperature or tube life are needed. Using the drop in hardness has possibilities, but the relationship between hardness and temperature is also not very good. The data in the Brear and Townsend paper, which utilised CEGB data shows that although with a T22 steel there is a pronounced drop in hardness from 180 VHN, with the start material, dropping down to 120 VHN near the end of the component life, the spread in hardness values is quite large. Using the stated tempering parameter, the spread, at a time corresponding to 100000 hours exposure would give a temperature range between 572° and 609°C. In the investigations by Turner and Drew, hardness measurements were clearly considered but the drop in hardness was so low that these workers did
not use the data in quoting temperature estimates. Smith suggests that hardness values give a "broad indication of the operating temperature" and are accurate within 15°C of the actual mean operating temperature [97]. However he suggests that the hardness results are most helpful in situations where ultrasonic based NDT is being used to measure the internal oxide thickness. The hardness results are especially helpful where the oxide derived temperature estimates are low, because the oxide has spalled off in those locations from which the oxide has spalled. However, even his results do suggest that hardness is fairly insensitive to temperature.

In discussing the use of hardness, Coade and Butler have suggested an extremely useful rule of thumb which was based on determinations from failed carbon steel and T22 tubing [98]. The hardness at failure for these materials was respectively 115-120 VHN and 120-120 VHN. These authors go on to say that if the hardness of such tubes have fallen below 125 VHN for carbon steel, and 135 VHN for T22, they should be immediately replaced.

As noted earlier providing the material is a low alloy steel, steam side oxidation thickness can be used to help estimate operating temperature. Metcalf shows that for a CrMoV steel the oxidation rate in air increases by a factor of 8 between 500 and 600°C. However, even after 10000 hours at 600°C the oxide thickness is only 28 microns thick [88]. In practice steam side oxide scales are thicker than this as steam is much more corrosive than dry air. In the tests carried out by Irwin, quoted previously, after about a year the oxide scale on a T22 tube had reached a thickness of about 100 microns. Over this time the tube temperature had increased from about 540° to 570°C [82]. Irwin also points out that if the overheating is very great and/or there is restriction in steam flow, the rapidly growing iron oxide, wustite, FeO will form.

The protective oxide scales, which form in steam, on low alloy steels, are of the duplex type. They consist of an inner layer of chromium-iron spinel, that is (Fe, Cr)\(_3\) O\(_4\), and an external layer of magnetite, that is Fe\(_3\)O\(_4\). If the oxide layer is of this type temperature estimates can be reasonably accurate, especially in sections of the superheater which are not subject to heat transfer. In some cases the oxide will be heavily laminated, consisting of fine interlayers of the spinel and the magnetite. Although plant cycling may lead to multilayer scale formation because of temperature changes, scale lamination can occur during long term constant temperature exposures. The mechanism is at least partly caused by the gradual distension of the tube as a result of creep, which assists in delamination of the scale at the scale metal interface, leading to the formation of new scale growth [99]. Under these circumstances, it is not really possible to estimate tube temperatures from the thickness measurements, although it might just possibly suggest that the tube was undergoing a significant amount of creep. However a thick oxide, whether it is of the simple duplex type or laminated, will suggest exposure to high temperature.

EPRl have published data which relate the growth of scales to time and temperature, and providing the scales are of the duplex, two layer type, and have not delaminated they can be used to estimate temperature. Figure 2.24, which is based on their data,
shows the relationship between time and temperature for growth of a 0.1mm steam side oxide scale on T22 steel [100]. As is usual in these cases, the data is based on accelerated tests with the results being correlated using a parametric equation of the usual type where:

$$P = 1.8T(20 + \log t)$$

There is a spread in the range of oxide thicknesses, which can be accommodated using a high and low value for the parameter P. For a 0.1mm scale thickness the high and low values of P are respectively, 36600 and 37400, thereby forming a band. It will be seen that this range gives a 20°C spread in the temperature estimate. This, one would guess, would be a deliberate decision by those who had the responsibility of correlating the results. Nakishiro et al concluded from their work, that whereas short oxidation tests were compatible with the upper part of the band, the longer terms tests would result in an overestimate of the operating temperature.

**Figure 2.24: Relationship between Time of Exposure and Temperature for Steam Side Oxide Growth of 0.1 mm Scale Thickness on T22 Steel**

It should be noted that these correlations cannot be used at temperatures much above 625°C, at which wustite becomes stable on this type of alloy, as the growth rate of this oxide is much higher than the normal protective scales. The dotted line shows the limit above which it is not practical to rely on oxide scale thickness. The graph also suggests that if wustite was to be detected, the material could only have been exposed to very high temperature for less than a few hundred hours.
These types of graphs can be used in conjunction with Larson-Miller parametric estimates to give limited support to the idea that thick oxides and creep go hand-in-hand. Obviously the stress level is important. A tube that was highly stressed could fail before oxidation had become significant. With such rule of thumb conclusions, an investigator can get an immediate idea of the likely design temperature from the wall thickness of a tube. In the temperature range under consideration materials are working close to their limits, as shown by Figure 2.25, and in general for the low alloy steels oxidation resistance is on the borderline.

Figure 2.25: Relative Wall Thickness for T22 Superheater Tubes at 160 bar Pressure at Metal Temperatures of 580°C and 540°C

Figure 2.26: Time and Temperature Combination for Steam Side Oxide Formation and Creep Failure in T22 Steel
Figure 2.26 quantifies the relationship. Here the time to creep rupture, at 600°C for T22 steel is set at 100000 hours. From this it is possible to estimate the time to failure for higher temperatures. The results are shown in the upper line in Figure 2.26. The lower line gives the time and temperature combinations to form an oxide that has thickness of 0.25 mm. The implications are therefore that in this case that even if such a thick oxide had formed it would not be very good evidence in support of creep failure. That is the time/temperature for this thickness of oxide to have formed is 20°C less than that required for creep to occur. Accordingly if the tube had failed by creep the stress levels would have been high. This should have been indicated by the wall section of the tube.

2.7.2 Overheating

In contrast to creep, overheating is characterised by a huge amount of deformation in the region of failure, where the tube balloons out, as a result of the internal pressure. It is a very high temperature failure mode, which occurs extremely rapidly, and, in superheaters is caused by steam flow being stopped. Boiler tubes, i.e. wall tubes in the furnace, can be prone to overheating failures, because of flame impingement from badly set up burners. Here very high heat transfer will result in the formation of steam in the tubes, which has a much lower cooling effect than boiler water.

A reduction in steam flow can be caused by large amounts of oxide which have formed on the inside of the tube, spalling off and falling down to the tube bends in pendant and platen superheaters. This is more likely to occur after a long period of operation when the oxide reaches an appreciable thickness, which will spall off when the plant has shut down. The other main cause of overheating is when condensate is trapped in the bottom of the tubes during a temporary shutdown. If the plant is restarted too quickly, the condensate does not have time to boil off and can form a seal preventing steam flow. One would guess that this latter problem is more likely with inexperienced operators or where some compulsion has been put on the operating staff to get the plant on line as quickly as possible.

Due to the deformation, there is a significant amount of wall thinning in the vicinity of the failure, and in most cases the lip of the failure is very thin as though the metal had been drawn down. The material is highly plastic and when the tube bursts the reaction of the escaping steam is to force the split apart, giving rise to the unmistakable shark or fish mouthed appearance as in Figure 2.27 [101].

The severe deformation and weakness of the material may be related to the fact that the temperatures are sufficiently high for a low alloy steel to be entering the austenite-ferrite zone. The effective grain size would be relatively small, which could enable the material to deform in a superplastic manner. At higher temperatures the phase field becomes fully austenitic, and grain growth would begin. This might account for the phenomenon, which some authors have commented on, that when the overheating is extreme, the edge of the failure is no longer thin lipped.

It is clear that it is so easy to recognise overheating failures that very little confirmatory evidence from the laboratory is needed. The focus of the work would be to identify the causes of the overheating. The bends in the failed and
neighbouring tubes will be X-rayed for oxide debris. If condensate blockage is suspected as the cause, questions will be asked about the operation of the superheater steam line drains, and the steam temperatures during start up will be examined. These ideally should show a gradual temperature rise on the outlet superheater header, indicating although condensate might have accumulated in all the tubes, this has slowly boiled away. There should be no rapid temperature drops, indicating that cold condensate had been left in a few tubes, which when coming to boiling point then flashes over.

![Figure 2.27: Typical Appearance of Overheating Failure](image)

2.7.3 Fireside Corrosion

Fireside corrosion of superheater is a high temperature phenomenon caused by the interaction of a layer of ash, which deposits on the surface of the tubes, with the tube material. The ash is an iron rich alumino-silicate, containing alkaline compounds, and forms a slag-like or highly sintered layer on the side of the tubes facing the gas flow. If the flue gas and the tube metal temperatures are high enough, the ash in
contact with the tube gradually changes in appearance and composition, so that it forms a white layer containing Na₃Fe(SO₄)₃ and KAl(SO₄)₂. Above about 540°C, this mixture of alkali trisulphates becomes molten and attacks the tubes [102, 103, 104, 105].

Table 2.10: Relationship Between Fireside Corrosion Rate and Gas and Metal Temperatures [105]

<table>
<thead>
<tr>
<th>Gas Temperature</th>
<th>Mid Wall Temperature</th>
<th>Low Alloy Ferritic</th>
<th>High Alloy Ferritic (Up 12% Cr)</th>
<th>Austenitic (347,316, Essette 1250)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>High Cl</td>
<td>Med Cl</td>
<td>Low Cl</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Cl</td>
<td>Med Cl</td>
<td>Low Cl</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High Cl</td>
<td>Med Cl</td>
<td>Low Cl</td>
</tr>
<tr>
<td>975°C</td>
<td>540°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>580°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>620°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>660°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>700°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1050°C</td>
<td>540°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>580°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>620°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>660°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>700°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1150°C</td>
<td>540°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>580°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>620°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>660°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>700°C</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Increasing temperature will destabilise the alkali trisulphates. Accordingly, in laboratory tests and in experimental plant trials, where test coupons or tubing are allowed to operate at temperatures far higher than normal levels, the rate of attack diminishes. A plot of corrosion rate versus temperature follows a bell shaped curve, peaking at about 650-700°C. In practice this type of behaviour seems not to be encountered; in the design of superheaters metal temperatures are kept as low as practical so as to minimise fireside attack.
Table 2.10 appears to be a more realistic picture, in which an increase in the temperature of either the flue gas or the metal temperature accelerates the corrosion rate. Table 2.10 also shows that a high chlorine level in the coal will enhance the rate of corrosion. The table was originally formulated by the CEGB and is based on UK coals, where the sulphur level in the coal is typically in the range 1-1.5%. The CEGB view appears to be that levels of sulphur above 2% will only have a small effect on the increasing the rate of corrosion. But today, the few remaining UK coal fired stations run on imported low sulphur and chlorine coal.

The formation of these compounds, in the white layer, requires the presence of a high level of sulphur trioxide in the deposit, circa 500 ppm. It is now considered that this gradually accumulates in the ash layer by a catalytic mechanism, which involves the oxidation of SO₂ within the deposits themselves [102]. But a minimum level of sulphur dioxide, in the flue gas, will be needed to form sufficient sulphur trioxide. In this respect the correlation developed by Shigeta et al shows that the corrosion rate is roughly linear with the concentration of SO₂, but tailing off as the concentration reaches 5000 ppm [104]. In the UK the levels of SO₂ in the flue gas are in the 1200 ppm range (0.12%), but major problem in this country has stemmed from the use of coals which have high levels of chlorine.

This kind of operational information, characterised by Table 2.10, can be incorporated into the Fact Base of an Expert System, and is extremely useful in relating the rate of attack to the flue gas and metal temperatures. If the steam temperature is kept below about 540°C, this should keep the rate of corrosion to an acceptable level, with the higher alloy materials. This kind of data can also be used in rule-of-thumb estimates about what are likely to be the design flue gas temperatures at various points in the systems.

But none of the usual superheater alloys is really resistant and either chromium coatings, overlay claddings, or shields need to be used if the temperatures are high. Hence Table 2.10 presents a rather disappointing picture in which there is not that much improvement in going from low alloy steels to stainless. The significance of this, for the P91 type steels, is that as competitors to the austenitics, they might be chosen (unthinkingly) to operate in conditions where corrosion could be significant. However most of the CEGB experience was with 12Cr type, which do form a genuine chromia rich spinel and a 9 chrome material may be somewhat less resistant than might be expected. Some confirmation of this is given in a paper by Wyatt which suggests from operating experience, that the corrosion rate becomes excessive at metal temperatures above 580°C [107]. Table 2.11 is based on results from this paper.

One effect that might have to be considered is the possible interaction of a high rate of steam side oxidation and fireside attack in P91 tubing. As has been described, when tubes are subjected to high rates of heat transfer, the insulating effect of the oxide will be to increase tube temperatures. This could possibly push material to a level where fireside corrosion rate is much higher. Inspection of Table 2.10 shows that each temperature band has a spread of 40°C.
Table 2.11: Data from the Wyatt Paper on Experience with 9 Cr-1Mo Alloys [107]

<table>
<thead>
<tr>
<th>Station</th>
<th>Position</th>
<th>Estimated Temperature</th>
<th>Exposure Time</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stourport B</td>
<td>Secondary Superheater</td>
<td>545-580°C</td>
<td>100000 h</td>
<td>None</td>
</tr>
<tr>
<td>Stourport B</td>
<td>Secondary Superheater</td>
<td>545-580°C</td>
<td>30000 h</td>
<td>None</td>
</tr>
<tr>
<td>Drakelow C</td>
<td>Outer Triflux Section</td>
<td>c.500°C</td>
<td>29,595 h</td>
<td>None</td>
</tr>
<tr>
<td>Bankside</td>
<td>Experimental in Secondary Superheater</td>
<td>c.550°C</td>
<td>22000 h</td>
<td>c.0.2mm attack</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c.575°C</td>
<td>22000 h</td>
<td>c.0.3mm attack</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c.590°C</td>
<td>22000 h</td>
<td>c.0.5mm attack</td>
</tr>
<tr>
<td>Uskmouth B</td>
<td>Final Reheater Pendant</td>
<td>593-660°C</td>
<td>c. 48000h</td>
<td>9 Cr Mo V alloy has lost half corrosion allowance (6mm????)</td>
</tr>
</tbody>
</table>

The information in the Wyatt paper suggests that 12 Cr alloys tended to fail due to creep or overheating due to temperature excursions during light up, but the Bankside trials suggested that corrosion resistance was slightly better than the 9 Cr series.

![Fig 2.28 Fireside Corrosion schematic. Note humped appearance of deposits on incoming side of tube](Fig 2.28 Fireside Corrosion schematic. Note humped appearance of deposits on incoming side of tube)
The combination of metal and flue gas temperatures, are therefore indicative of fireside corrosion. However, the presence of the white layer, containing the alkaline trisulphates, is a very good indicator of this mode of attack. In addition the presence of "wastage flats" in the 2' o' clock or 10 o' clock positions on the tube are also indicative of fireside corrosion. See Fig 2.28

The suggested mechanism for this is that a thick deposit of ash forms on the leading face of the tube, which then gives some protection to the tube, reducing the tube temperature over this region. The flats form at the sides tubes where the depth of the ash falls away, although it is still present at this point. In practice not all tubes will show flats as much will depend on the local aerodynamics and on the frequency of soot blowing. However as the front face of the tube will collect the ash and received the maximum rate of heat transfer, the back face of the tube will be virtually unaffected.

2.7.4 Slag Deposition and Slag Formation

As described in the previous section the deposition of ash on the superheater can result in fireside corrosion, but heavy deposits of ash and slag are a precursor to fireside corrosion. Ash and slag deposition of have both direct and indirect effects. Ash deposits on the superheater are more likely to form if the sodium oxide content of the ash is high as this gives a sticky ash, but the basicity of the ash is also involved. There are several definitions of slag basicity, but a common one is that of the base-to-acid ratio (B/A). Hence the fouling index \( F_1 \) is given by [108]:

\[
F_1 = (B/A) \times \frac{Na_2O}{Na_2O}
\]

Where:

\[
B = Fe_2O_3 + CaO + MgO + K_2O + Na_2O
\]

\[
A = SiO_2 + Al_2O_3 + TiO_2
\]

The sodium oxide content and fouling index can be related to fouling tendency as shown in Table 2.12.

Table 2.12: Superheater Ash Fouling Characteristics

<table>
<thead>
<tr>
<th>Na_2O</th>
<th>Fouling Index</th>
<th>Fouling Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 0.5%</td>
<td>Less than 0.2%</td>
<td>Low</td>
</tr>
<tr>
<td>0.5 -1.0%</td>
<td>0.2 - 0.5</td>
<td>Medium</td>
</tr>
<tr>
<td>1.0 - 2.5%</td>
<td>0.5 - 1.0</td>
<td>High</td>
</tr>
<tr>
<td>More than 2.5%</td>
<td>More than 1.0</td>
<td>Severe</td>
</tr>
</tbody>
</table>

Slag deposition results from the melting of the ash when the pulverised coal burns. If the slag deposits on the evaporator tubes it will disrupt heat transfer. This is a commonplace but it is commented on specifically by Lopéz et al [109]. The disruption is mainly caused by the insulating effect of the slag layer, but light coloured slags with a high calcium content reflect the heat and this too can inhibit heat transfer. Furthermore, deposition of slag around burners may affect burner performance causing partially burnt pulverised fuel to be carried to the top of the furnace.
The reduced absorption of heat by the evaporator will increase flue gas temperatures, and can lead to slag deposition on the superheaters at the furnace exit. In consequence superheaters that are further down the flue gas duct are more likely to suffer from ash deposition and fouling. Naturally, the increased flue gas temperatures will tend to exacerbate fireside attack.

Deposits of slag will not necessarily form a uniform coating on furnace or on superheater tubes. With the latter "Gas Laneing" will occur whereby sections of a superheater are blanked off by the accumulations of slag. In some circumstances, slag can slowly work its way down the outside of the pendant tubes and then form a solidified mass between the bottom of the pendants and the floor of the superheater duct. Such masses are very difficult to remove.

In assessing whether slagging is likely to be a problem, the simplistic approach is to compare the temperature of melting point of the slag to that of the local environment, but as slags have no definite melting points, a number of rules of thumb, using various correlations, have been developed [108,109,110]. Most of these rules are based on the slag composition, which is given in terms of the proportions of oxides that result from the presence of Si, Al, Ca, Fe, Na, Ti, Mn and P.

These oxide based compositions are used to create functions such as the slag basicity, iron index, the sum of the Fe$_2$O$_3$ plus CaO contents, and the slagging factor. All of these provide some sort of correlation with the severity of slag deposition. The compositions can also be used to produce viscosity correlations. The two main viscosity figures that are quoted are the temperature at which the slag has a viscosity of 250 poises, and the slag viscosity at a temperature of 1426°C (2600°F). These figures can then be used to give rule of thumb estimates of the propensity towards furnace slagging, but unlike the other correlations, they can, in principle, be used to indicate how it might be possible to eliminate slagging by dropping the flue gas temperature.

The Multi-Viscosity Index or MVI figure attempts to take these viscosity correlations a stage further, and one which more applicable to the slagging of evaporator tubes. The MVI is based upon the recognition that the presence of iron under reducing conditions can significantly lower the viscosities of slags [111]. This is well recognised phenomena in coal gasification systems where the viscosity correlations assume that the iron is present as FeO rather than Fe$_2$O$_3$. The thinking behind the MVI is that after a thick slag layer has formed, the innermost layers will be in a reduced condition. Accordingly the MVI is based on the temperature at which the viscosity is 250 poises under oxidising conditions, that is on the outer surface of the slag, but also takes into account the temperature at which the viscosity is 10000 poises under reducing conditions. The latter figure can be thought about as the ability of the slag to sinter and form a material that is much more solid than liquid. In addition a "correction factor" is used in the equation, which is based on the average of the temperatures at which under oxidising and reducing conditions the viscosity is 2000 poises.
The thinking behind all these different viscosity levels is partly to take into account how the presence of iron affects the slag under oxidising and reducing conditions. It also takes into account how well the slag will stick on to the tubes as it gradually accumulates. A number of correlations of ash composition and temperature have been developed, which can then be used to calculate the temperatures required to estimate the MVI. One of the standard viscosity correlations for oxidised slags is that of Watt and Fereday, but others are available [112, 113,]. For slags in the reduced condition, correlations are also available [114,115].

It is clearly helpful in thinking about what is actually going on if we have some idea of which “liquids” to which these three sets of viscosities correspond. Table 2.13 shows a representative set [116].

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Viscosity in Poises (P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water @ 20°C</td>
<td>0.001</td>
</tr>
<tr>
<td>Olive Oil @ 20°C</td>
<td>0.84</td>
</tr>
<tr>
<td>Glycerine @ 20°C</td>
<td>14.8</td>
</tr>
<tr>
<td>Honey @ 20°C</td>
<td>100</td>
</tr>
<tr>
<td>Chocolate Syrup @ 20°C</td>
<td>250</td>
</tr>
<tr>
<td>Ketchup @ 25°C</td>
<td>980</td>
</tr>
<tr>
<td>Peanut Butter @ 20°C</td>
<td>2500</td>
</tr>
<tr>
<td>Glass in Workable State</td>
<td>10000</td>
</tr>
</tbody>
</table>

The MVI equation is stated below and includes “fs” the average of the temperatures, under reducing and oxidising conditions, at which the viscosity is 2000 poises [111]. These correction factors are shown in Table 2.14.

\[
MVI = \frac{(T_{250\,\text{Oxid}})}{(54.1. \, \text{fs})}
\]

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>1038</th>
<th>1093</th>
<th>1149</th>
<th>1204</th>
<th>1260</th>
<th>1316</th>
<th>1371</th>
<th>1427</th>
<th>1482</th>
<th>1538</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correction Factor (fs)</td>
<td>1.0</td>
<td>1.3</td>
<td>1.6</td>
<td>2.0</td>
<td>2.6</td>
<td>3.3</td>
<td>4.1</td>
<td>5.2</td>
<td>6.6</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Inspection of the MVI formula also shows that the bigger the difference between the $T_{250\,\text{Oxid}}$ and the $T_{10000\,\text{red}}$ the greater the value of the index. This is in keeping with the practical observation that slags with a very long softening range are difficult to remove. Slags which have a short range, either tend to form a slag that forms an ash, which will not stick to the tubes, or if the temperature is a little higher will produce a slag which easily drips of the tubes.
It is standard practice for coal suppliers to state the \textquotedblleft Slagging Index\textquotedblright\ Temperature (SI) of the ash. The tests were originally experimentally based and were used to determine the temperatures at which a small cone of ash begins to deform (IDT) and the temperature at which the ash coalesces to form a hemispherical droplet (HT). All these figures can now be calculated from the composition. The slagging index is given by a weighted average of the two temperatures, as follows:

\[
SI = 0.8 \text{ IDT} + 0.2 \text{HT}
\]

The slagging index does give some feel for the situation which might develop at the outlet to the furnace box, where the flue gas first encounters the secondary superheater. The slag is likely to stick onto the superheater if it is at temperature somewhere between the point at which the ash sinters to give a solid mass, but is at a temperature below the point at which slag drains feely enough to run off the tubes. In some respects it is a crude version of the MVI.

Table 2.15 shows the slagging index, MVI and the slagging factor and how they can affect furnace performance [108,111]. The slagging factor is given by multiplying the base-to-acid ratio by the sulphur content of the coal. Here the argument is that because the sulphur in coal is present as pyrites, during combustion this forms iron oxide which has a very strong fluxing action. This correlation works for many Northern Hemisphere coals, but the iron in coals from South of the Equator is present as a carbonate. In this case the \textquotedblleft iron index\textquotedblright\ is more relevant and is given by multiplying the base-to-acid ratio by the ferric oxide content of the ash.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
\textbf{Likelihood of Slag Problems} & \textbf{Slagging Index Temperature} & \textbf{MVI} & \textbf{Slagging Factor} \\
\hline
Severe & Less than 1050°C & More than 1.11 & More than 2.6 \\
\hline
High & 1050°C-1230°C & 0.55-1.11 & 2.0-2.6 \\
\hline
Medium & 1230-1340°C & 0.277-0.55 & 0.6-2.0 \\
\hline
Low & More than 1340°C & Less than 0.277 & Less than 0.6 \\
\hline
\end{tabular}
\caption{Relationship of Slagging Index Temperature, MVI and Slagging Factor to Likelihood of Slag Problems [108, 111]}
\end{table}

Today slag prediction programmes are available, such as the web-based \textquotedblleft Coal Calculator\textquotedblright\ from Ultra Systems, which by giving weight to the various correlations aims to predict whether any particular ash is likely to give problems. An example is shown in Table 2.16 [110]. The data used in this particular example is that of a typical present day British coal from Harworth Colliery [117].
Table 2.16: Slagging and Fouling Estimates for Harworth Coal Based on the Coal Calculator

<table>
<thead>
<tr>
<th>ASH ANALYSIS</th>
<th></th>
<th>%</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>SiO2</td>
<td>50.8</td>
<td></td>
</tr>
<tr>
<td>Alumina</td>
<td>Al2O3</td>
<td>26.1</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>Fe2O3</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td>CaO</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>MgO</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>Na2O</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td>K2O</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>TiO2</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn3O4</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>S</td>
<td>0.00001</td>
<td></td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P2O5</td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

| Sulphur in coal    | S     | % db | 2.25|

### Ash Deposition - Some common indices

<table>
<thead>
<tr>
<th>Index</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base/Acid ratio</td>
<td>0.28</td>
</tr>
<tr>
<td>Iron Index</td>
<td>4.02</td>
</tr>
<tr>
<td>Multi-Viscosity Index</td>
<td>1.06</td>
</tr>
<tr>
<td>Critical Viscosity @ 1426°C</td>
<td>313</td>
</tr>
<tr>
<td>T250 Temperature</td>
<td>1348</td>
</tr>
<tr>
<td>Iron + Calcium</td>
<td>15.7</td>
</tr>
<tr>
<td>Slagging Factor Rₚ</td>
<td>0.62</td>
</tr>
<tr>
<td>Fouling Factor Rₚ</td>
<td>0.22</td>
</tr>
</tbody>
</table>

### Ultra-systems' recommendations**

Values calculated here are normalised to: <5 = "Good", >10 = "Bad"

<table>
<thead>
<tr>
<th>Index</th>
<th>Weighting Factor</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe₂O₃ x B/A</td>
<td>1.0</td>
<td>17.2</td>
</tr>
<tr>
<td>MVI</td>
<td>0.8</td>
<td>10.7</td>
</tr>
<tr>
<td>CV1426°C</td>
<td>0.6</td>
<td>10.0</td>
</tr>
<tr>
<td>Fe₂O₃ + CaO</td>
<td>0.4</td>
<td>13.7</td>
</tr>
<tr>
<td>B/A</td>
<td>0.2</td>
<td>9.5</td>
</tr>
<tr>
<td>OVERALL</td>
<td>13.1</td>
<td>Bad</td>
</tr>
</tbody>
</table>

The section of the Coal Calculator entitled “Ash Deposition” covers many of the correlations discussed above. The section of the table entitled “Ultra-systems recommendations” is a weighted average of some of these correlations. In this case the overall view is that the slagging characteristics of Harworth coal are bad, but the ash fouling propensity is moderate. The Harworth coal appears intermediate in properties from those used in the past by the CEGB, but in practice coals are often blended to give a suitable compromise between the price and the effect on plant performance and maintenance.

It is obviously more helpful if the tendency to form slag can be related to the flue gas temperature. Cooler flue gas will tend to solidify high melting point slags. Juniper, who has developed the Coal Calculator referred to above, considers that both the “Slagging Index Temperature” and the temperature at which the viscosity is 250 poises to be fairly useless in predicting how changes in flue gas temperature affect slagging behaviour.

His verdict is not too surprising. The need to know the 250 poises temperature was originally used to determine whether it was going to be easy to drain off the molten slag from bottom of a slag tap furnace. The main criterion was that this temperature should be below 1426°C (2400°F), otherwise slag flow would be difficult.
Figure 2.29: Relationship between Viscosity at 1426°C and Likelihood of High Flue Gas Temperatures Causing Slagging Problems [110]

Juniper favours using the slag viscosity at 1426°C as a criterion, as displayed in Figure 2.29. His results were based on actual experimental runs in a boiler. The black squares are tests where slagging was encountered, the white squares are where the ash was powdery. This graphical information can be transposed into a look up table which would allow the Inference Engine in the Expert System to make decisions about whether one coal was better than another and to give a rough guide to safe flue gas temperatures. See Table 2.17.

Table 2.17: Look Up Table for Effect of Slag Viscosity on Maximum Flue Gas Temperature

<table>
<thead>
<tr>
<th>Viscosity Range (Poises)</th>
<th>Below 500</th>
<th>500 to 1000</th>
<th>1000 to 1500</th>
<th>1500 to 2000</th>
<th>2000 to 2500</th>
<th>2500 to 3000</th>
<th>3000 to 3500</th>
<th>3500 to 4000</th>
<th>Above 4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Flue Gas Temperature</td>
<td>1200°C</td>
<td>1225°C</td>
<td>1260°C</td>
<td>1300°C</td>
<td>1325°C</td>
<td>1350°C</td>
<td>1380°C</td>
<td>1400°C</td>
<td>1425°C</td>
</tr>
</tbody>
</table>
Figure 2.30: Relationship between Iron Index and Likelihood of High Flue Gas Temperatures Causing Slagging Problems [110]

A similar type of graph can be formulated using the iron index, although here there is a problem for the human expert in devising simple to remember rules based on this graph since the iron index axis is logarithmic. See Figure 2.30. This is much less of a problem for expert systems, of course, but, on the basis that furnace temperatures can be up to 1300°C, and in terms that a person could expect to remember:

- Anything above 2 is going to be very bad
- Values between 1 and 2 are highly likely to give problem

Values have to be somewhat lower than 1 if problems are to be avoided. The Coal Calculator table does not include the Slagging Index as Juniper does not think that this is very useful. Some of the problems with the Slagging Index can be seen by comparing its predictions about slagging behaviour of a low iron UK coal with those of the Coal Calculator. See Table 2.18. In this case the IDT was 1150°C and the HT was 1400°C. This results in a slagging index temperature of 1200°C. On this basis Table 2.18 would suggest that slagging will be severe, but most of the parameters in the Coal Calculator indicate that the slagging characteristics are good to moderate. The only exception is the MVI figure, which does seem to be rather high given the low iron content of the slag and the high silica level. The Coal Calculator assessment for a high iron coal is shown in Table 2.19. This data is used in Chapter 8.
### Table 2.18: Coal Calculator Results for Low Iron UK Coal

<table>
<thead>
<tr>
<th>ASH ANALYSIS</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>SiO₂  %</td>
<td>49.4</td>
<td></td>
</tr>
<tr>
<td>Alumina</td>
<td>Al₂O₃ %</td>
<td>29.2</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>Fe₂O₃ %</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td>CaO %</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>MgO %</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>Na₂O %</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td>K₂O %</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>TiO₂ %</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn₃O₄ %</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>SΟ₃ %</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P₂O₅ %</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Sulphur in coal</td>
<td>S % db</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>

**ASH DEPOSITION - Some common indices**

<table>
<thead>
<tr>
<th>Index</th>
<th>Weighting Factor</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base/ Acid ratio (B/A)</td>
<td></td>
<td>0.87</td>
</tr>
<tr>
<td>Iron Index (Fe₂O₃ x B/A)</td>
<td></td>
<td>13.02</td>
</tr>
<tr>
<td>Multi-Viscosity Index (MVI)</td>
<td></td>
<td>2.52</td>
</tr>
<tr>
<td>Critical Viscosity @ 1426°C (CV)</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>T250 Temperature (°C)</td>
<td></td>
<td>977</td>
</tr>
<tr>
<td>Iron + Calcium (Fe₂O₃ + CaO)</td>
<td></td>
<td>37.0</td>
</tr>
<tr>
<td>Slagging Factor (Rs)</td>
<td></td>
<td>1.74</td>
</tr>
<tr>
<td>Fouling Factor (Rf)</td>
<td></td>
<td>0.78</td>
</tr>
<tr>
<td>OVERALL</td>
<td></td>
<td>40.6</td>
</tr>
</tbody>
</table>

**Ultra-systems' recommendations**

Values calculated here are normalised to:

- <5 = "Good",
- >10 = "Bad"

**References:** Juniper LA. 1996. Ash Deposition Indices

---

### Table 2.19: Coal Calculator Results for High Iron UK Coal

<table>
<thead>
<tr>
<th>ASH ANALYSIS</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>SiO₂  %</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Alumina</td>
<td>Al₂O₃ %</td>
<td>20.2</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>Fe₂O₃ %</td>
<td>20.7</td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td>CaO %</td>
<td>16.3</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>MgO %</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>Na₂O %</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td>K₂O %</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Titanium</td>
<td>TiO₂ %</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn₃O₄ %</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Sulphur</td>
<td>SΟ₃ %</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P₂O₅ %</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Sulphur in coal</td>
<td>S % db</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

**ASH DEPOSITION - Some common indices**

<table>
<thead>
<tr>
<th>Index</th>
<th>Weighting Factor</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base/ Acid ratio (B/A)</td>
<td></td>
<td>0.87</td>
</tr>
<tr>
<td>Iron Index (Fe₂O₃ x B/A)</td>
<td></td>
<td>18.02</td>
</tr>
<tr>
<td>Multi-Viscosity Index (MVI)</td>
<td></td>
<td>2.52</td>
</tr>
<tr>
<td>Critical Viscosity @ 1426°C (CV)</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>T250 Temperature (°C)</td>
<td></td>
<td>977</td>
</tr>
<tr>
<td>Iron + Calcium (Fe₂O₃ + CaO)</td>
<td></td>
<td>37.0</td>
</tr>
<tr>
<td>Slagging Factor (Rs)</td>
<td></td>
<td>1.74</td>
</tr>
<tr>
<td>Fouling Factor (Rf)</td>
<td></td>
<td>0.78</td>
</tr>
<tr>
<td>OVERALL</td>
<td></td>
<td>40.6</td>
</tr>
</tbody>
</table>

**Ultra-systems' recommendations**

Values calculated here are normalised to:

- <5 = "Good",
- >10 = "Bad"

**References:** Juniper LA. 1996. Ash Deposition Indices

---

*Revised: Workshop on Impact of Coal Quality on Thermal Coal Utilisation, CRC for Coal Utilisation, Brisbane.*
2.7.5 Erosion

Most erosion problems occur on the lower temperature section of the flue gas duct where the temperatures have dropped and the fly ash has become sufficiently hard to act an erodent. But with superheaters and furnace wall tubing, erosion is a result of mal-operation of the soot blowers, which are used to blow deposits of ash and slag of tubing. Soot blowers often used steam as a blast, but air and water can be used. A typical soot blower arrangement consists of a retractable lance which can be pushed into the furnace when required. The length of the sootblower moves across the surface of the tubes, so that the nozzle can spray its fluid at high velocity onto slagged surfaces.

Over-frequent use of the soot blowers will lead to erosion because of material that is entrained by the flow. This will be pieces of solidified slag, but in steam soot blowers the erodent can be water droplets, if lines are wet. A dry erodent simply wears the surface away, but if this is due to water droplets the surface will have a sculpted appearance. However there are other clues. Wear will be related to the position of soot blower, especially if has tended to get stack in one position when it is pushed into the flue gas duct. Other tubes in the same location will also tend to show signs of erosion. Naturally there will be little sign of deposits or oxides.

Because of the risks of erosion casual soot blowing is to be discouraged and ideally should only be used when steam temperatures begin to dip. On the other hand if soot blowing is not done sufficiently often, sintering of the slag can make subsequent removal difficult.

2.7.6 Weld Failures

The most critical welds in superheater tubes are butt welds in superheaters that are used to join lengths of tubing and should always be of the full penetration type. Slightly less critical are the welds for connecting the tubes into the superheater headers. These are made using nozzle type connectors, and can be of the partial or full penetration type. Attachment welds are less important and are often of the fillet type. See Figure 2.20.

Many causes of weld failure in superheater tubes and their connections are not difficult to recognise, and are caused by bad workmanship.

For butt welds the appearance and usual possible causes of failure are:

- **Porosity in weld**: Poor welding technique, dirty conditions, damp rods,
- **Misalignment**: Badly aligned tubes
- **Poor weld profile**: Poor welding technique
- **Arc strikes**: Poor welding technique

Nozzle type welds also tend to suffer from these problems.
Failures of attachment welds are easy to recognise, but can have a variety of causes. One key feature is the attachment plate acting as a heat transfer fin, or as a point at which corrosive deposits can collect.

The appearance and possible causes of attachment weld failures is:

- **Overload**: Evidence of ductile failures
- **Creep failure of the tube, attachment or weld**: Typical creep cracking of microstructure
- **Fireside corrosion**: Localised attack with high temperature ash deposits
- **Over penetration**: Dip in surface and evidence of weld breakthrough on bore

None of these would require a deep metallurgical investigation, although if failure mechanism was that of creep or fireside corrosion the possibility that the plant may have been the root cause needs to be investigated. But when a tube has failed due to poor welding technique, the most important question is whether this is representative of the general standard of welding on that piece of equipment.

Where weld cracking has occurred, this will require metallographic investigation and is differentiated into the following classes:

**Type I**: Wholly in weld and might be due to hydrogen

**Type II**: Starts in weld but propagates into HAZ

**Type III**: Starts in HAZ but propagates into parent
**Type IIIa:** Cracking is in the HAZ, very close to the fusion line, due to carbon migration into the fusion zone. It is known to occur in CrMoV welded with T22 steel. Could possibly occur if P91 and X20 is welded to a lower alloy steel.

**Type IV:** Failure in the parent metal but often used to describe failure in the intercritical zone of the parent which is next to the visibly transformed section of the HAZ. That it is in a section of the HAZ that has been subject to a tempering treatment.

With respect to P91 and its use in superheaters, it is Type IV cracking which is causing most concern at the present time, as it can lead to unpredictable butt weld type failures, in headers, after some tens of thousands of hours of exposure. Fortunately, in superheater tubes, the axial stress due to pressure is half the hoop stress, accordingly the risks of Type IV failures caused by pressure alone are low.

The causes of Type IV cracking are still a matter for discussion, but Type IV cracking is associated with changes in the HAZ during the welding process, and possibly overageing effects induced by either stress relief and/or in service exposure. The starting structure is tempered martensite, which as has been emphasised needs to be in an optimum state of precipitation before it enters service. Any disruption of the start structure will be detrimental. Hence an obvious possibility is that a partial transformation of the HAZ to austenite occurs during the weld temperature cycle. This would create a microstructure which contained fine grains of martensite. The other possibility is that the HAZ is simply subject to a combination of thermal induced strain, which in combination with the temperature cycle leads to a structure which will rapidly overage.

**References**

1. Marlow, BA. “Steam Turbines” pp 1267-1314 in Kempe’s Engineers Year Book 2002 ed Stevens, CMP Information Ltd


8. Singer, JG “Fig 1 pp 7-3 in Fossil Power Systems”, c/o Combustion Engineering Inc 1981


15. Starr, F. “Notes on Visits to High Marnham and Drakelow-24th Feb 2003”


20. Fleming, A. personal information on discussing “Indian Power Plant Fouling Problems” March 2003


23. Bogart, D. at Innogy Ltd Swindon “Personal information obtained in discussing HRSG and other types of superheater” March 2002

24. Pearson M of Pearson Associates frequent discussions about the causes of thermal fatigue and related matters over the period 2000-2004


27. “Steam Temperature Control by Excess Air” pp 12.14 in “Steam: Its Generation and Use” Babcock and Wilcox 1975


30. “High Temperature Steels, Austenitic Steels and Ni-Fe-Cr Alloys” pp 4-7 c/o Vallourec and Mannesmann Tubes 1989


35. “NPL/EPRI Workshop on Steamside Oxidation” held at the National Physical Laboratory, UK. September 2003


37. Section 6.3 “Transformation Behaviour” The T91/P91 Handbook c/o Vallorec and Mannesmann Tubes info.service@tvmtubes.de


39. The T91/P91 Handbook c/o Vallorec and Mannesmann Tubes


45. Parker, J” Practical Experience with Advanced Steels” pp 304-320 4th Int.Conf. on Advances in Materials Technology for Fossil Power Plants Hilton Head Island, South Carolina, c/o EPRI 2004


47. Foldyna, V. Kuboň, Z. Jakobová, A and Vodák, V “Development of Advanced High Chromium Ferritic Steels”, pp 73-92 Microstructural
Development and Stability in High Chromium Ferritic Power Plant Steels ed Strang and Gooch, IOM 1997


52. Data Sheet 434 R –Designation T91/P91 “High Temperature Steels, Austenitic Steels and Ni-Fe-Cr Alloys” c/o Vallorrec and Mannesmann 1989


54. Toft, LH. and Marsden, RA.” The Structure and Properties of 1% Cr-0.5% Mo Steel after Service in CEGB Power Stations” pp 276 Structural Processes in Creep ISI 1961


59. Ennis, P.J., Photomicrographs of P92 Stress Rupture Specimens at 650°C/82MPa/13306h exposure and consequential discussions


62. Fleming, A. of ETD Ltd: Personal communication to the author Feb 2004


67. Ennis, P.J., Zielińska-Lipiec, A. and Czyszka-Filemonowicz, A. “Quantitative Comparison of Microstructures of High Chromium Steels for Power Stations” pp 135-143 ibid

68. French, D.N. “Case Histories 2.1 to 2.10” pp 59-95 Metallurgical Failures in Fossil Fuel Boilers Willey 1982

69. Davidson, J.K. and James, D.P. “Effective Use of Boiler Tube Failure Outages” pp 33-44 c/o Power Technology Ltd UK1993


75. Brett, S. “The Creep Strength of Weak Thick Section Modified 9 Cr Forgings” pp35-44 ibid

76. French .DN “Section on Effects of ID Scale” pp 205-209 in Metallurgical Failures in Fossil Fired Boilers Wiley 1982


78. Ennis, PJ. Quadakkers, WJ Fig 4 in “The Effects of Oxidation on the Service Life of 9-12% Chromium Steels ” p 461 Advanced Heat Resistant Steels for Power Generation ed Viswanathan and Nutting IOM 1999


80. Schütze, M. Renusch, D. Schorr, M. “Parameters Determining the Breakaway Oxidation Behaviour of Ferritic-Martensitic 9Cr Steels in H₂O Environments” Corrosion Engineering Science and Technology 2004

81. Scarlin, B. Slide 25 “Dampfoxidation” from Internet Presentation entitled Werkstoffentwicklung für Hochtemperatur-Dampfkraftanlagen, Nov 2001

83. Fleming, A. and Shibli, A. of European Technology Development Ltd – 
Personal Information given at various times.

84. Seliger, P and Gampe, U “Life Assessment of 9 Cr Components” OMMI 
Vol2 (Issue 1) 2002 www.ommi.co.uk

85. Weertman, J and Weertmann JR ”Mechanical Properties Strongly 
Temperature Dependant” pp 983-1010 Physical Metallurgy RW.Cahn , 
North Holland 1970

86. French. DN Chapter on “Failures of Boilers and Related Equipment” p 610

87. Davison. JK and James. PJ. Section on Long term Creep in “Effective Use of 
Boiler Tube Failure Outages” pp 35-38 Power Technology Centre, Powergen 
1993

88. Metcalf. E “ Oxide Characterisation for Life Prediction” p168 Surface 

by Means of Replicas” ASME Int. Conf. on Advances in Life Prediction 
Methods, Albany ,USA 1983

90. “State of Art Report on Lifetime Analysis of Boiler Tubes” VTT Research 
report No TUO74-021828 ,VTT Technical Research Centre, Finland Oct 2003

91. Brear. JM and Townsend .RD “Modern Approaches to Component Life 
Assessment –Damage Degradation and Defects“ c/o ERA Technology Ltd, 
Leatherhead UK c.1994

92. Henry .JF, Ellis. FV and Viswanathan. R “ Field Metallography for Plant 
Life Extension” pp 13-26 Microstructural Science , ed Blum, French, 
Middleton and Vander Voorte, ASM International 1987

93. Bezuidenhout. MEJ, Beukes. D and Van Heyl. FH “ Assessment of the 
Condition and Refurbishment of the Main Steam Pipework at Hendrina 
Power Station” pp17-27 Conference on Operating Pressure Equipment, 
Mercure Hotel, Brisbane, Australia April 1997 pub. Institute of Metals and 
Materials Australasiasia Ltd 1997

94. Starr. F “Discussions with P. Ennis of FA Juelich about performance of 
Inconel 617 tube stubs for a header for a closed cycle gas turbine heat 
exchanger” circa 1991.

95. Mann. SD. “Metallurgical Assessment of Superheater Tubes” pp 361-366 
Conference on Operating Pressure Equipment, Mercure Hotel, Brisbane, 
Australia April 1997 pub. Institute of Metals and Materials Australasiasia Ltd 
1997

97. Smith, JJ "Determination of Remaining Life of Boiler Tubes by Non-Destructive Methods" pp 239-244 Conference on Operating Pressure Equipment, Mercure Hotel, Brisbane, Australia April 1997 pub. Institute of Metals and Materials Australasia Ltd 1997


105. CERL Publication "The Control of High Temperature Fireside Corrosion" ed Baker et al 1974


111. Stultz, SC and Kitto, B “Steam” Babcock and Wilcox 1992


118. “Analysis of Coal Ash and Fusion Characteristic” Table.1.16 p.70 Volume E Modern Power Station Practice, Pergamon Press 1992

119. Davison, JK and James, PJ pp 67-71 “Effective Use of Boiler Tube Outages” c/o Power Technology 1993

120. “Soot Blower Basics” Engineering Threads 605-133988

121. Davison, JK and James, PJ pp 15-16 and pp30-31 “Effective Use of Boiler Tube Outages” c/o Power Technology 1993
122. Foundation Level Course LMF 101/ Plant Operation Damage and Assessment Issues c/o ETD Ltd:
CHAPTER 3

Expert Systems and Human Expertise

3.1 Predecessors of Expert Systems

A number of Expert Systems have been developed for use in the engineering field. Expert systems are so closely linked in with the use of computers, that this has tended to obscure the fact that these are just another tool that enables mankind to tame and control nature. Unfortunately, due to weaknesses in technical content, poor insight about potential users, and lack of user friendly-ness, many have done little except gather dust. Hence Expert Systems have not had the impact their supporters once predicted. But the basic aim of an expert system is to enable us to store vast amounts of information, in such a way that we use it to make rational decisions quickly and cheaply.

In one sense information is being codified. This codification of information and its accessibility is intended to enable the mass of individuals who make up the engineering, legal, financial, and medical professions, most of whom have no special insights beyond their own limited sphere of activities, to improve their productivity and to ensure that the correct course of action is being taken. Many of the problems in getting hold of the right sort of technical information can be seen in the development of the “handbook”, which can be regarded as a hard copy analogue of an Expert System.

The forerunner of the handbook, in the late medieval period, was the vade mecum, which contained rules of thumb of good engineering practice. This was a handwritten compilation, put together by a skilled craftsman or engineer of works. It was intended to help secure his personal position, or that of his Guild, in a given area of technology. It might well have taken a lifetime to produce. One of the main impediments to wide circulation was the need to copy out the contents by hand. Putting the information into book form was therefore a major step forward compared to even earlier techniques when information was recorded on scrolls. Looking for information in a long piece of scroll, or writing in new data, would have been quite impractical. The book was such a breakthrough in the supply of information that its use has become a metaphor in its own right. Hence good access to information makes it “an open book”, or a lack of understanding about it makes it “a closed book”. Unfortunately the closed book metaphor applies to too many expert systems as they are tedious to use and impossible to amend.

With the arrival of printing it became feasible to produce the handbook in its modern form. With printing, many copies can be published, at a reasonable cost, for those interested in a specific craft or branch of engineering. The handbook helped to accelerate technical progress and standardise common approaches to engineering problems. The writing and formulation of such a book does, of course, require the author and his colleagues to make free with their own special insights. In so doing
there has always been the conflict between the benefits to the community of putting knowledge into the public domain, and the loss of competitiveness to the individual or organisation that this implies. This is still a major problem today, which proponents of expert systems barely recognise.

Printing too, as a technique, brought problems of its own. Unless an institution or wealthy individual was willing to subsidise publication, high production costs would limit circulation. At one time, indeed, circulation was also impeded by the ability of the practical engineer to read. There are analogies in this with expert systems. Even thirty years ago the programming of computers was a difficult and specialised activity. The personal computer was yet to be invented. Fortunately the situation has now changed with the incorporation of easy-to-use software, and the ability for the individual to make changes on a PC or laptop.

With respect to the opportunity to make changes to the content of technical literature, a major shortcoming of printed books was (and is) the reluctance of both publishers and authors to update the work. It is more profitable to produce reprints than new editions. By 1979, for example, Mark's "Hand Book for Mechanical Engineers" had gone through sixty-eight printings since its inception in 1916, but it was only up to its seventh edition. This was not a problem with the vade macum, which can be updated by hand, whenever the need arises. Ideally, the best type of expert system should have the facility for the user to input his or her experience, and this is something that the designers of the expert system should strive for. For an expert system for failure analysis it requires that the computer software should be easy to use and flexible. It also requires that a clear account be given of the methods used to formulate the If...Then rules by which it operates.

Even the best handbooks and other technical literature tend to be used only a few times before those sections of interest to the user become fixed in the memory. Hence it is comparatively rare for a practicing engineer to make use of hand or textbooks on a day-to-day basis. Once a specific subject or topic has been learnt, most of us will never look into that subject again, relying on personal contacts and practical experience to keep up to date. Similar issues can occur with expert systems. After using the system for just a few times, the ideas that it carries become incorporated in the memory of the user, and once that happens the machine will be left switched off. To ensure that the expert system will continue to be of service, it needs an updating facility and needs to pack in a high density of information. In principle this is something which computer based systems are able to offer.

Books tend to get re-used when a new problem comes up. When this happens the engineer will often turn back to a book to refresh his or her ideas in coming to a solution. Note that the book itself rarely provides a complete answer to the problem. Written information and data is combined in the mind of the engineer with knowledge garnered from experience, plus any information about the problem itself. Often in reaching a conclusion, the engineer will test his or her preliminary analysis against other information that has been overlooked or discounted in the initial analysis. Accordingly conclusions will be iterated until a final solution is obtained. See Fig 3.1.
This ability to weigh up evidence is something that the written word can rarely do. The closest that a book can come to making a judgement about a problem is through the use of equations, which can predict whether a given solution is practical. A fairly simple case would be one indicating whether a pipe with a given wall thickness could withstand the pressure. Equations in a sense distil experience and go beyond the rule of thumb predictions by practical men. Initially it would be necessary for the engineer to look up the mechanical properties of the materials of construction. Nevertheless after a few months the engineer would "know" whether a pipe was suitable or not. If equations or mechanical property data had to be used in validating the conclusions, this would be very much part of the bureaucratic procedures associated with equipment design.

Somewhat closer to techniques, which are used in simple expert systems, is a flow chart giving a set of yes/no questions. These are used to help inexperienced people deal with, for example, the failure of a car to start, whether major do-it-yourself activities are safe, or how to work out income tax demands. Nevertheless, even when the flow chart is complex, if it is used just a few times, the procedures fix in the memory.
3.2 Human Expertise and Error

3.2.1 Characteristics of Human Experts

Experts, it would seem, are no different from ordinary individuals in the way in which they go about their activities. James Reason in his book dealing with "Human Error" suggests that humans have three main approaches to overcoming "Problems". These can be characterised as a person doing and thinking on a "skill based", "rule based" or "knowledge based" performance level [1]. Some examples of such are shown in Table 3.1.

<table>
<thead>
<tr>
<th>Level</th>
<th>Normal Life Example</th>
<th>Power Plant Example</th>
<th>Metallurgical Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skill Based</td>
<td>Making tea</td>
<td>Replacing gasket</td>
<td>Etching a sample</td>
</tr>
<tr>
<td>Rule Based</td>
<td>Paying bills on time</td>
<td>Conditioning of boiler water</td>
<td>Assessing safe life of tube</td>
</tr>
<tr>
<td>Knowledge Based</td>
<td>Planning a holiday</td>
<td>Implications of two shifting</td>
<td>Designing new creep resistant alloy</td>
</tr>
</tbody>
</table>

There is some overlap between these different performance levels, but it is obvious from the examples given in the table that activities associated with the skill based level are limited in scope, although they rely on "rules". For example when making tea one needs to ensure that the kettle is switched on, or, in replacing a gasket in a leaking joint on a steam pipe that it is of the right type, or when etching a metallographic sample, that the etch will suit the alloy.

Problems involving rule based levels tend to be more complex, with the variety of rules tending to change with the occasion. Here, in the payment of bills, one would need a whole set of rules covering any short term difficulties with the family finances. In a boiler plant, most station chemists would follow a set of rules about taking a boiler water sample, analysing it and then having to decide what chemical dosing the boiler water would need. Similarly, rule based calculations about the safe life of a tube would need to take into account known problems, such as whether the tube is heated, as in a superheater, or just carrying high steam at temperature and pressure.

Finally a problem, at a knowledge based level, may involve a good deal of guesswork, as not all the information is available and the new rules may need to be made up as one works through the problem. For example in the planning of a holiday one will need to guess how much time it would take to recover from a flight. To give a more technological example, in the context of power plants, the issues needed in switching to two shift from base load operation are very complex and are plant specific. In the metallurgical field, the problems in designing a new alloy are legion. Although thermodynamic programs help to judge what phases may appear, they do not say anything about the morphology of the precipitation, what levels of embrittlement will be associated with a given precipitate, or whether precipitate formation will interfere with heat treatment or forging. This is where true
expertise and experience begins to show, not least in being able to discount those things that are likely to be easy, with the expert focusing on those which will create real difficulties.

An expert differs from the non expert in that, within his or her area of expertise, a much greater range of rule based concepts can be brought into play without much thought. Hence an expert can make an assessment of the situation, or carry out any physical activities associated with a job much more rapidly than the non-expert. Most of us will have had personal experience of how quickly we can analyse situations in our own field, and how slowly we do jobs with which are outside of our line of expertise. Indeed, even when we have finished such a job, being non experts, we may not be able to apply the final but critical If-Then rule which will be of the type:

“If it works in a certain fashion Then the job is done”.

The rapidity with which an expert can come to conclusions is not only due to the number of rules which he or she can bring into play. It is also due to the way that the expert can think about the problem in an abstract way and put the problem into a well understood rule based context. James Reason quotes examples from chess and other games where an experienced player is able to see, after just a glance at the board, where groups of pieces could be good for defence or attack. Similarly an experienced failure investigator, when he sees a burst pendant superheater tube will start to ask questions about plant start up procedures, and whether any condensate may have been blocking steam flow through the tube. When working at this rule based level, it would appear that the expert, because he is able to fit the problem into a well understood context is able to bypass some of the intermediate rules, on the assumption that he will know the answer to these. This is one reason why his thinking processes are so rapid.

An expert can make serious errors, however, if he deduces that a problem falls into a well known class and this deduction is wrong. Misreadings of this type usually stem from a blind following of the rules and familiarity breeding contempt. In the experience of the writer such mistakes tend to occur when the expert is being pressurised into making a quick assessment of the situation, without having the time to make additional checks. James Reason comments that when an expert makes such mistakes the consequences can be profound. The failure due to intergranular corrosion of a Type 316 austenitic stainless pipe as occurred at plant operated by British Gas, back in the early eighties, illustrates the kind of difficulty which can occur. The initial prognosis was that the failure, based on the location its location, near a tee-piece on the steam line, was caused by stress corrosion cracking, which is the most common cause of failure of austenitic stainless in gas making plant. Stress corrosion tends to be a fairly localised form of cracking. It is rectified by cutting out the affected section of pipe and replacing it with a new piece.

Would an expert system have made any difference? This is equivalent to saying what questions should have been asked, but were not. Some of the questions which might have put the expert onto the right track and would have been:
If Steam_Leaks are From Crack Then Stress_Corrosion, Intergranular_Corrosion, or Thermal_Fatigue are possible

If Plant_Cycling is NO Then Thermal_Fatigue Is NO

If Pipe is above 400°C Then Stress_Corrosion is NO

If Type_316 Then material could be Sensitised is YES

If Type_316 Then state Time_Temperature_History

If time is 5000 hours is YES and temperature was 475-625°C is YES Then Type 316 will Sensitise

State conditions which might lead to any significant form of aqueous corrosion of sensitised material (which are):

a. Long exposure time
b. Wet insulation
c. Marine/Sea coast conditions
d. Polluted atmosphere
e. Corrosive condensate inside pipe
f. Galvanic effects

If (a and b ) plus (either c, d, e ) Then Corrosion_Risk is high

If Type 316 is Sensitised Is YES and Corrosion_Risk is High Then Intergranular_Corrosion is Probable

If Intergranular_Corrosion is possible Then examine Other_Pipework for Leaks

This is a fairly simple set of rules which would have revealed that intergranular corrosion was at least as high a probability as that of stress corrosion and all of the pipework needed being replaced not just a small piece. In this case the corrosion was caused by the coastal environment and wet insulation

Ideally the true expert will know all the questions that need to be asked. But when a job become very complex or unusual, the analysis will move to the knowledge based level. Reason states that when moving onto this plane, the speed of the expert slows down to that of the non-expert, as the formulation of the solution depends on cut-and-try methods. In this, the expert, using what knowledge he has, tries something to solve a particular part of the problem. If this idea works the assumption is made that this particular mode of thinking will eventually lead to a solution. Accordingly the term cut-and-try does not really indicate the length of the process involved, which might be better described as the following series of actions:
• Thinking, with varying degrees of desperation, about how the problems might be solved
• Coming up with a possible solution
• Finding out what is needed to apply the proposed solution
• Whether the solution is practical in the circumstances
• Getting together the hardware, personnel and time to try out the solution
• Trying the solution
• Deciding whether or not it has given a positive answer to the problem

As one of the problems with cut-and-try methods is identifying how a problem might be solved one virtue of a good expert system is that it will supply a range of options, which the average expert may not have thought about trying, or even known that they exist.

3.2.2 Group Type Expertise and Its Problems

No one person is likely to have all the expertise needed to solve a complex industrial problem. In practice issues involving failure of power plant equipment will involve a group of “experts”. Groups of this type are often made up of individuals, who will not be completely unbiased. Manufacturer’s representatives are often involved, with the intention of keeping any blame away from the design and construction of the equipment. Those individuals who represent operating or maintenance staff will be keen to show that their team did nothing wrong. With power plant problems, it is highly likely that a technical expert, quite often a metallurgist, may be present. He or she will be there to try to identify the mechanism of the failure and suggest how this might have originated, but his or her real expertise is likely to be strictly limited. When the question of root causes arises, the metallurgist will often rely very heavily on what the other members of the group are prepared to contribute, which as we have noted can be quite biased. If the opinion of the technical expert appears to fit in with the sort of answer the rest of the group finds “helpful” the deliberations will stop, even though harder and more pointed questions will reveal serious weakness in the story. When these deeper questions about root causes arise, people with much greater technical insight should be called. This often does not happen because:

• The consensus is that the problem has been solved, mechanism and root cause having both been identified, with the plant being put back to work satisfactorily

• The root cause has been identified and some other party, not privy to the discussions, has been held to blame, and may have to accept financial responsibility

• Enough time has been spent on this issue already, even though there is no clear solution

• The members of the group did not realise that there were important issues still to be addressed
• It is in the interests of the group, or a leading member of it, for the investigations to go no further

• There is over-representation by one group of technical experts who tend to focus on a limited aspect of the problem

A comprehensive expert system would be free from such bias. The author knows of a situation in which a fairly simple failure of a gas main, reviewed in some detail by a group of Gas Industry and Pipe Maker Experts, led to a legal case which dragged on for some eight years, before the true facts were discovered.

3.2.3 What Makes an Expert?

We have briefly reviewed some of the ways in which experts or groups of expert can go wrong. Hopefully an expert system will be immune from these problems. Even where a problem has apparently to be treated on a knowledge based level, a good expert system should be able to speed up thought processes, as its set of rules will contain much more knowledge than what the average expert is able to carry in his head.

Looking at the way an expert goes about the job helps us to see what is desirable in an expert system. Figure 3.2, which shows the main characteristics of a human expert, emerged after discussions between my supervisors and me. The arrows show how the different aspects of a person's expertise become apparent as a job progresses. Starting at the left hand side of Figure 3.2, we only regard a person as an expert if he is deeply knowledgeable about his speciality and has a track record of having used his expertise in a practical way. Here the term "practical" is used in a catholic manner. For instance a welding expert would not necessarily have to do any welding to prove his expertise, but he would have a deep understanding how welders go about their job and the mistakes they are likely to make. Moving round Figure 3.2, once an expert is on the job, we expect him to ask questions, to listen to the replies and then without fuss, weigh up the evidence, and take appropriate action. Sometimes, to the consternation of the non-experts the advice is "don't worry...do nothing". This sometimes takes more experience and courage than doing something.

The different types of lettering in the diagram represent the types of actions and thought processes that are going on as the expert does his or her job. On the left hand side of the diagram, the boxes with red lettering represent the prior knowledge and experience that an expert should have. The boxes with the black lettering are indicative of the physical activities that we see when the job is actually being done. This can be talking to people, telling technicians and craftsmen what should be done, supervising their work or actually doing the work required. The boxes in green italics cover activities which relate to the job after it has been completed. These include an ability to explain or demonstrate why the job was done in this specific way, how long things are likely to last, whether he or she found anything new out or developed new techniques. Finally, as the boxes with the blue lettering show, after the expert finishes his work, relevant information will be filed away in his or her memory for deployment on the subsequent jobs.
What Makes an Expert?

Forgets Nothing          Learns

Explains How Conclusion was Reached

Organised Memory

Deeply Knowledgeable

Predicts Future Correctly

Practical Experience

Highlights Root Causes

Overcomes People or
Technology Derived Obstacles

Solves Problems

Can evaluate and combine disparate forms of information

Not Frightened To Take Action Or Leave Things Alone

Listens

Questions

No Fuss

Has New Insights

Figure 3.2: Schematic of the Thought Processes and Activities of an Expert

Any questions that the expert puts to other people or to him or herself need to be put in such a way that a clear answers should emerge to each, such that the expert is able to weigh up the evidence for and against a particular hypothesis. Here it should be noted that in many cases the answers to specific questions will not be yes or no. Many are going to be of the “maybe” type or “don’t know” or “won’t say”. Part of
the art of the expert is to utilise this type of rather vague and, at times, deliberately misleading information.

After these preliminary steps, we would expect at the very least, that the expert to have solved the problem. But if the problem has simply required the blind application of rules, we may not be overly impressed. Our faith in the expert increases, if the expert:

- Has new insights which relate to the job
- Highlights root causes of the problem
- Predicts the future correctly, assuming that changes are or are not made
- Can explain to colleagues, working on the same or related problems, how the conclusions were reached

Here it is worth pointing out that when there has been an equipment failure, the tendency will be to focus on the technical features of the case. However a real expert will recognise that failures by individuals are often part of the root cause, and diplomacy is often part of an expert’s expertise. How this could be incorporated into an expert system is a moot point!

Related to this issue is the tendency of organisations and individuals to not provide the information and equipment that is needed to do a full investigation. Sometimes there are good reasons for this. It can be costly to obtain data, or to get the more detailed expertise to evaluate such information. More often than not, it has to be said, the lack of cooperation stems from individuals who have preconceived opinions about the causes of a failure, or worse still, have something to hide. It is possible that something of this type was happening in the Japanese superheater failure discussed in Chapter 9. In such a case a real expert will adopt a “Plan B” approach and get the information that is required by some other route.

As was noted, at the end of the job, the expert will file away the most important features of it in his memory. More detailed matters will be included in a report, but the expert should remember in outline at least, what are the contents. An ability to recall related incidents is yet another feature of a human expert. Indeed, although we may be willing to forgive an expert for being in general a forgetful person, we expect him to have at all times the facts at his fingertips.

These, then are the core values these we expect an expert to possess. In practice, experts rarely work completely on their own when doing failure analysis. They might be part of a formal group, as described earlier, when they will receive positive guidance for other members of the team investigating the failure. Alternatively, they might be working by themselves, feeding their insights and conclusions through to someone who has overall responsibility for the investigation. In both cases, the expert will be getting some background information about the failure and some feedback about his own input. The expert should be able to assess the usefulness and reliability of this information, thus his knowledge should extend to a reasonable
extent outside of his own field. This can be difficult for the individual to do, but it should be reasonably easy to incorporate this into an expert system.

3.3 Implications for an Expert System for Plant Failure Investigations

The shortcomings in older forms of information storage systems and the way that expert can fail have been reviewed in some detail as it formed the basis for much of the thinking behind the Thesis.

An important conclusion was that the Expert System should contain complex information, often in the form of look-up tables of data and equations which can be brought into play automatically. This would go beyond normal human capabilities, and ensure that the Expert System would continue to be used and developed.

The Expert System also needs to have some of the attributes of the vade mecum in that it can be continually be improved and added to. For this one needs to set down the methods by which new rules can be introduced into the System.

A major conclusion was that the Expert System needs to go beyond the metallurgical issues that relate to power plant failures. It should cover other areas of technology which are significant in the design and operation of power plant. In this way it will combined the best features of group type expertise.

References

CHAPTER 4

General Issues in the Formulation of Expert Systems

4.1 Expert System Types

There may be confusion in what is meant by an Expert System. This has arisen, in part, from the interest in Artificial Intelligence, and the rapid development of computer based information retrieval and manipulation systems [1].

Data retrieval packages are the most common and basic form of system which use artificial intelligence, and can be of various degrees of sophistication. An example of such is that of the "Petten Databank" which includes quantitative information relating to creep crack growth [2]. This however is more useful in the prediction of component life rather than in failure analysis. MPA in Germany is, however, developing a data retrieval system which could be helpful in failure investigations, as it is intended to predict the risk of power plant equipment failures from different causes. It does this by looking at the time to failure of different power plant components [3].

Data retrieval packages can be used in conjunction with neural networks, which are another form of artificial intelligence. One definition of these comes from the paper by Silverman, who states that:

"A Neural Network is a computational system which can learn patterns of behaviour between input and output information, in the absence of a specific model"[4].

Such networks are, at present, best used as genuine research tools where complex amounts of semi-reliable data need to be correlated. In failure analysis they might eventually be used to correlate the effect of trace elements on creep ductility, creep strength and oxidation resistance, but they essentially an ancillary tool.

Hypertext, has been considered by some to be a form of expert system. These work by picking out key words and phrases from information that is stored in an electronic form. Hypertext is of undoubted help in searching relevant literature, or when "trawling the Internet" using a search engine such as Google. Roberge has advocated the use of hypertext packages to process corrosion information to improve coating selection [5].

But this is not how an expert system works, as the use of hypertext is highly dependant on the knowledge of the person who uses it. Missing out a key word can lead to a significant loss of information. A more important drawback is that once the information has been downloaded, the user has still to interpret it. He or she simply has to go back to the literature or handbooks in a slightly more sophisticated way, using a search engine, rather than looking through the index of a book or reading the abstract of a paper. Nevertheless hypertext can help in the development
of an expert system, since it is able to generate a very large amount of information that an expert can use in formulating If...Then rules.

In the future, however, one could envisage a neural network being used in conjunction with the Expert System. Providing that there are many users of an Expert System for power plant component problems, it should be possible to record anomalous failures along with the specifics of plant performance and the detailed design of components. This would suggest that an Expert System should have some means of downloading “inexplicable occurrences” into a data bank, for future evaluation. Again this would bring the Expert System closer to how a real human being operates.

The true type of expert system is one which is based on the use of syllogisms or If...Then rules, to marshal sets of evidence, so that conclusions can be reached. Compared to the other forms of artificial intelligence described above, expert systems are intended to be used by relatively untrained people. This enables them to carry out complicated and time consuming tasks with confidence. In expert systems questions are asked of the user, and based on the information which he or she inputs, plus information already embedded in the system, the Expert System will lead the person to a definite conclusion. A good Expert System will also have embedded within it a facility for checking whether the input data sounds reasonable.

To summarise, these various computer-based programmes, sometimes viewed as Expert Systems, are used by different personnel. Quite specific types of question are required, as inputs, if the various programmes are to work. Conversely as outputs, they give distinct types of answer. These differences can best be illustrated in Table 4.1

**Table 4.1: Types of System using Artificial Intelligence**

<table>
<thead>
<tr>
<th>Programme Type</th>
<th>Operator/User</th>
<th>Quality of Question</th>
<th>Quality of Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Retrieval</td>
<td>Middle-Management or Technical Staff</td>
<td>Precise for Forecasting</td>
<td>Arithmetically Reliable Only</td>
</tr>
<tr>
<td>Hypertext</td>
<td>Expertly Trained Personnel</td>
<td>General Information</td>
<td>Fuzzy but Intelligible</td>
</tr>
<tr>
<td>Neural Network</td>
<td>Experienced R&amp;D Staff</td>
<td>For Concept Development and Pattern Learning</td>
<td>Precise but Initially Unintelligible</td>
</tr>
<tr>
<td>Expert System</td>
<td>Technicians</td>
<td>Precise for Required Action</td>
<td>Reliable but Unintelligible</td>
</tr>
</tbody>
</table>
The suggestion in Table 4.1 that Expert Systems give “Reliable but Unintelligible” answers may be regarded as controversial. The aim of an Expert System is to replace a human expert with an operator or user who has lower levels of training or more generalised experience. It follows that the reasoning behind some of the responses, provided by the Expert System, can be unintelligible, initially at least to the person using the system. It is at this point access to a data retrieval system, or a hypertext program, may be vital to give the necessary back up and confidence in the use of an expert system.

The same problem, of course, can occur when one human being deals with another. If there is an obvious lack of understanding or belief by the non-expert, it behoves the expert to call upon previous experience, relevant literature, or other authorities in the field, if he or she is to get his or her arguments accepted.

4.2 Design of Expert Systems for the Diagnosis of Failures

Most of the published papers on expert systems are not helpful in showing how to construct an expert system. Exceptions to this are those by Emenike on pipe line corrosion, and Castle and Baker on XPS spectrum diagnosis, where there is an attempt by the respective authors to show how the system is built up from the basic rules [6,7]. However it was felt more profitable, in building up an expert system, to work from textbooks on the subject. The two which were found to be of most use were those of Parsaye and Chignell and that by Jackson [8,9]. The review that follows is based on these books. The book by Parsaye and Chignell was found to be especially helpful and major part of the work in the first year was to work through this book, translating the ideas in it into pieces of thinking that can be incorporated into an expert system.

The essence of an expert system is, however, that is uses “heuristic rules” to produce conclusions which have a good chance of being correct. The term heuristic, in this case, indicates that the rules have been derived from experience and are basically of a qualitative or semi-quantitative type. Rules of this type are incorporated into the Inference Engine of the expert system. They are formulated in terms of two valued logic that is:

If (A) Then (B)
If (Not A) Then (B)
If (A) Then (Not B)
If (Not A) Then (Not B)

When using an expert system, the person operating it will be asked questions which originate from the Inference Engine. The input data comprises the Fact Base upon which the Inference Engine can work. In using the information the Inference Engine may have to use subroutines, particularly when the input data is of the numerical type. For example in assessing whether a creep failure is a likely mechanism, the
Inference Engine will need plant operating pressure, details of pipe dimensions and the time to failure. One subroutine would work out the hoop stress in the pipe, the other would go through a Larson-Miller calculation to estimate the operating temperature. Given this calculated operating temperature, the expert system would then begin to seek other information that would support that temperature estimate. Figure 4.2 shows this procedure as a schematic.

The conclusions produced using one rule will lead to the activation of others. Hence an expert system must be designed so that a sequence of questions will lead through to the correct analysis or conclusion. Where the issue under investigation is fairly straightforward, for example in picking out a lump of stainless steel from a heap of scrap, the questions can be arranged in “Frames” In a frame, a limited set of questions are asked in one frame, and based on the results, lead on onto another, as shown in Figure 4.3, which shows the sequence of actions needed which lead to the identification of a material:

A shortcoming of frame systems is that the categories in each frame need to be carefully thought through, otherwise some things may be overlooked. How would “leather” fit into the above scheme? The results of a frame determined investigation may lead to what seem to be ambiguous conclusions. In the example there are two different routes which lead to the identification of a material as a ferritic stainless steel, depending on whether the material was rusted or not.
More importantly frame systems can also start to fail when intermediate or final conclusions have to result from the interaction of information from different areas of expertise. In our case, where a plant operator needs to make a quick decision on the mechanism or causes of a superheater failure, there is no obvious route between what the failure looks like, probable operating temperature and experiences with other plants. Nevertheless all would be relevant to the diagnosis.

The alternative is the use of chains or networks made up of If-Then Rules. Chains are more able to allow the expert system to retrace its steps if it becomes clear that the preliminary conclusions are at variance with some of the facts. Chain systems are of the forward, backward or mixed chain type, the latter combining aspects of the first two. With "Forward Chaining Systems" the system branches out as follows from the initial set of questions, as shown below. See Fig 4.4.

Such systems are useful in making a decision about a reasonably complex matter, such as what type of pulverised fuel burner to buy, where, cost, output, fuel flexibility, etc are important factors. The problem with this is that one might have
ten different burners to evaluate and much time would be wasted on examining each type.

The converse of these “Backward Chaining Systems” are best used when attempting to justify an observation, for example “Is the failure due to creep?” As one works through the rules, in a backward chaining system, the evidence for the assumption becomes more and more conclusive, but at any point a question could be asked whose response could negate the original assumption. Only when the final rule containing all the “figure ones” had been reached, as in the schematic example shown in Figure 4.5, would the original assumption have been proved. In a backward chaining system negative answers should lead to back tracking, to suggest a new preliminary assumption.

In concrete terms Rule 1 would start the procedure by conjecturing that the failure was due to creep, and the subsequent rules would cover all the visual, metallographic, hardness and life estimation type tests that would be needed to support this conjecture. The final rule, as a “Goal”, Rule 1.1.1.1, would state that as the tests had produced confirmation of a creep mechanism, Rule 1 had been proved. Negative answers would lead to the postulation of other mechanisms such as thermal fatigue, or overheating type failures. The main objection to backward chaining is that, as can be seen, it needs an expert to decide what is going to be Rule 1, which somewhat defeats the point of an expert system. Nevertheless backward training concepts are helpful in designing a system.

A way out of the impasse, of needing an exert to decide which hypothesis should be tested, would be for the expert system to set up a list, in order of probability of mechanism which might cause a certain piece of equipment to fail. For superheater the list would be:

![Diagram of Backward Chaining Type Expert System]
Creep
Overheating
Fireside Corrosion
Fireside Erosion
Fatigue
Poor construction

For a boiler tube the listing would be

Waterside Corrosion Fatigue:
On Load Corrosion
Fireside Corrosion
Fireside Erosion
Oxygen Pitting
Poor construction

For each of these a few key questions of the “go/no go” type would be needed. Assuming the answers were of the “go” type, the questions would pass on to more in depth questions concerning the mechanism of attack. If the responses to this initial set of questions, about a mechanism, gave a negative answer, the expert system would then back-track, to set up preliminary questions for the next most likely mechanism.

Back tracking can also be used in identifying the root causes of failures. Figure 4.6 shows a hypothetical situation in which the way the plant is being operated might be responsible for the failure. In this example, two shifting would lead to creep fatigue of the headers or tube attachments, whereas long term operation, at somewhat over the design temperature would probably lead to creep, but excessive over-firing could lead to a short term superheater type failure. These are referred to as Mechanisms 1, 2 and 3, respectively. The flow chart indicates that the Mechanism 1 rules are “fired” first. If all of these sets of rules answers to “yes”, the conclusion is that the root. However, if any of the rules in the Mechanism 1 chain gave negative answers the system would backtrack back, this leading to the activation of the Mechanism 2 rules.

All of this works very well assuming that each answer gives an absolutely clear “yes” or “no” answer. In this classical form of expert system, if all the questions relating to a mechanism or a cause, were of a confirmatory nature, at the end of each set the expert system would state that the specific mechanism had been proved. In practice there are often a lot of “maybe” type answers or situations where the evidence or data is not available, hence a strong positive or negative response cannot be given. Similarly until detailed laboratory investigations are complete, perhaps backed up with an in depth review of factors such as the local stress distribution, temperature gradients or corrosion rates, it will be impossible to be categorical about whether the failure mechanism is creep fatigue caused by the plant having to two shift. If the response to the first of the Mechanism 1 questions is “no”, the Mechanism 2 rules about creep would then be activated.
If equipment_age > 5 years is yes
   And failure is crack
Then fire Mechanism_Rule_1 first

**Mechanism Rule 1**

If plant is two_shifting
Then fire
low_cycle_fatigue_rules in turn

If failure is at tube_manifold or pipe_hanger
Then fire next
Low_cycle_fatigue_rule

If initial_part_of_crack shows limited branching
Then fire next
Low_cycle_fatigue_rule

If rudimentary low_cycle_fatigue_calculation is Yes
Then assume failure is low_cycle_fatigue caused by two shifting

**Mechanism Rule 2**

If not plant is two_shifting
Then fire
creep_failure_rules in turn

If tube shows bulging_and_fissuring
Then fire
next creep failure rule

If microstructure_and hardness_observations indicate creep
Then assume failure is creep

If Larson_Miller_calculation is yes
Then failure is creep caused by higher_than_design temperatures
4.3 Knowledge Engineers and Domain Experts in the Building Expert Systems

The classical way to construct expert systems is to get someone skilled in their design, that is a Knowledge Engineer, to interview a Domain Expert. The domain expert is someone who has experience of the technology under review and can help to create the Knowledge Base. The knowledge base encapsulates know-how in appropriate form, which the Inference Engine can manipulate. Jackson, in discussing how an expert system was intended to improve a telephone system network, stated that:

*An expert was procured and trouble shooting knowledge was elicited through a series of interviews. The expert would describe a problem solving heuristic. A knowledge engineer would formulate this into an if-then rule expressed in English. This formalisation was then examined by the domain expert to see if it corresponded with his intuitions and experience. If this was not the case the knowledge engineer would reformulate the rule until it was acceptable.*

In building the Expert System and thinking how the Inference Engine will sequence the If-Then questions both the domain expert and knowledge engineer will need to consider the set up of the Fact Base. In our case the Fact Base would contain the input information relevant to each failure. This is part of the User Interface and needs to be well thought out otherwise it will be difficult to use and may result incorrect information being entered.

Developing the Inference Engine, etc, is time consuming, especially given the need for the domain expert and knowledge engineer to interact in the manner described. Typically only two major rules can be formulated a day. But Parsaye and Chignell suggest that if the domain expert has some knowledge of expert systems, it should be possible to dispense with the knowledge engineer, at least in writing If-Then rules and in design of the system. This has been the approach used in this work.

Whether the expert system involves the knowledge engineer in framing the rules or not, each If-Then rules will be of the type *If X Then Y*. Clearly it is necessary to define X and Y for each rule. X and Y can be phrases rather than single nouns. Parsaye and Chignell state that these need to be incorporated into a knowledge structure, where X and Y do the following within the If-Then rules:

**Naming, Describing, Organising, Relating Constraining**

In formulating phrases to describe specific Xs and Ys actions it is often necessary to use groups of words. The convention is that a lower case hyphen is used to link the words, as with the phrase "Convective_Superheater". Accordingly it would be correct to state the following If-Then rule:

*If plant Steam_Flow increases Then Convective_Superheater_Temperature will decrease*

However the following rule would be gibberish in the expert system, as the first word after "Then" is "convective" which is not in the glossary of terms
If plant Steam_Flow_Increases Then convective Superheater_Temperature will decrease

There is also a need to outline methods by which the system tracks through the rules and links the conclusions together. We also need to consider the type of user interface, and the format of an explanation facility. A vital necessity, in our case, is the ability to up-date the knowledge base in the system, either by the original domain expert or by the system users. Given these issues rather than to concentrate on the mechanics of entering If-Then rules in to an experts system shell, and given the background of the author it seems more appropriate to investigate the issues in formulating the rules and showing how they can be combined in a logical sequence to simulate the behaviour of a real human steam plant failure investigator.

1. Winston. PH. "Artificial Intelligence" Addison-Wesley 1993
4. Silverman.DC "Corrosion Prediction from Laboratory Tests Using Artificial Neural Networks" pp 3430-3444 NACE 12th International Corrosion Congress. NACE 1993
5. Roberge. PR "Transforming Computerised Information for its Integration into a Hyper Tutorial Environment “ pp 3404-3411 ibid
Chapter 5

Flow Charts in the Design of an Expert System for Failure Analysis

5.1 Diagnosis of Failure Mechanisms and Identification of Root Causes

No failure investigator could properly do his or her work without accurately diagnosing the mechanism of superheater failure. For this, "backroom" and laboratory investigations by various specialists are often needed. Such investigations will normally involve removal of parts of the superheater, metallography of the failure site and examination of deposits. Backroom investigations will often involve the need for calculation. For superheater failures these would normally encompass Larson-Miller or creep-fatigue calculations about plant life, but they might also entail assessments of rates of heat transfer, an attempt to work out superheater temperatures from furnace conditions, and in some instances, finite element calculations. Ideally the people doing the backroom investigations should make their own visit to the plant to see exactly where in the superheater the failure had occurred, but this is not always possible.

For the expert system one of the main issues with the backroom observations, in determining the mechanism of failure, is the need to bring the results of a diverse set of observations together, so that they point towards a given failure mechanism. This aspect in the design of an expert system will be covered in detail in subsequent chapters.

The diagnosis of failure mechanisms is not an end in itself. By accurately diagnosing the type and mechanism of failure, it becomes possible to link this back to a set of root causes. Having identified the root causes, in most cases it will become possible to avoid such problems in future. Or, if problems cannot be prevented completely, it will be practical to avoid significant and costly consequences. These include a "forced outage", whereby the plant has to shut down when it is in the process of generating electricity. The most serious consequence would be the destruction of significant sections of the plant and loss of life.

The moot point with root causes is how far back one needs to go in identifying the real root cause. But in a sense all causes of equipment failures are man made. One of the biggest complaints of late, in the power generating field, have come from operators of combined cycle gas turbine plants. The heat recovery steam generators (i.e. boilers and superheaters) in such plants are notorious for failing as a result of fatigue, induced during frequent startups as engendered by two shifting. Most of these problems could have been avoided by more careful design, ensuring the better drainage of condensate. However most combined cycle plants have been designed to operate as base load units in which there would be just two or three scheduled start ups a year. Hence the real root cause could be the decision to operate the plants on a two shift basis so that the heat recovery steam generator has to go through a severe temperature cycle each day. Going even further back into final causes, the need to
switch to two shift operation would have originated in such factors as changes in the price of natural gas, or the use of nuclear plants for base load power.

It is apparent that each of these decisions, be they about the design of the plant, how it was operated, the price of fuel, the resolve to “go nuclear”, would all have been made by human beings, usually quite unaware of the consequences of their actions. It would be possible to construct an expert system which went right back to where the problems originated. The operators of a power plant are more concerned with the basic issue of what was the mechanism of failure, and whether it points towards the cause being that of plant operation, equipment design or materials of construction. Once the expert system has thrown light on these matters it will become possible for operators to take preventative action.

5.2 Flow Chart for Failure Investigation

In this thesis the intention is to focus on how the rules needed to build an expert system come into being. The eventual focus of the work is an expert system that could deal with the root causes which stem from problems caused by superheater material and those which might have resulted from the operation or design of the power plant.

Figure 5.1 shows that the same basic set of activities are needed in the investigation of any failure, wherever it might occur on a plant. The work associated with this thesis has shown that the formulation of such flow charts is a vital factor in the process of setting down If...Then rules. In each flow chart the consideration of various topics, identified in the boxes, can be used to devise a number of If...Then rules, each encompassing a nugget of information. In producing the flow charts, they need to be sufficiently detailed to promote thinking about the formulation of a set of If...Then rules about each factor that might have some relationship to the mechanism or cause of the failure.

Some examples of If...Then rules, which stem from the use of the flow charts, will be given later in this Chapter. Nevertheless, it will become apparent that simply composing the rules is not adequate for an expert system. A special vocabulary needs to be designed. In addition, methods are required whereby the conclusions of If...Then rules can be brought together. The detailed techniques which relate to adapting the way in which people would normally say or write the rules are covered in Chapters 6 and 7.

Returning to the flow chart in Figure 5.1, the first step is to determine what is the nature of the failure and on which piece of equipment it has occurred. The next stage is to determine whether there was anything in the plant operating conditions and history that could give some indication as to why that particular component failed. Even at this stage it is likely that a review of the way in which the plant has been operated, maintained, or inspected will often point to the likely failure mechanism, and in conjunction with this, the root cause. In such cases there would be no need for an in depth investigation. Conversely although it may be possible to make an intelligent guess about the failure mechanism, backroom and laboratory work will be needed to verify this hypothesis. The outcome of these more detailed investigations
will point back to some aspect about the way the plant is operated, as a root cause, or else point to some deficiency in the design of the component or its materials of construction. Until these are rectified, his type of failure will continue.

Figure 5.1: Activities in Identifying Power Plant Failures
Figure 5.1 suggests that the expert system would start by asking which piece of equipment had failed or had been suffering from problems. The fact base, for this section, would be set up as two sets of tables, one for the water/steam system and the other for furnace and furnace ancillaries. On ticking off the appropriate section of the table, the expert system would begin to activate rules specific to failures and problems in that that piece of equipment. As shown earlier, a power plant can be thought of as two distinct assemblies of equipment. There one set in which water is treated, turned into steam, with the steam being used to produce power, before it is condensed and returned back to the boiler. The second set is where the fuel is prepared for combustion, mixed with air for firing, combusted, with the products of combustion being used to heat boilers and superheaters etc. The rules for each of these are shown below.

The preliminary set of rules for the water steam system are as follows:

- If problem Water_Treatment Then activate Water_Treatment_Rules
- If problem Feed/Drain_Lines Then activate Feed/Drain Line_Rules
- If problem Pumps Then activate Pump_Rules
- If problem deaerator Then activate Deaerator_Rules
- If problem Feedheater Then activate Feedheater_Rules
- If problem Economiser Then activate Economiser_Rules
- If problem Boiler/Evaporator Then activate Boiler/Evaporator_Rules
- If problem Steam_Lines Then activate Steam_Line_Rules
- If problem Superheater Then activate Superheater_Rules
- If problem Reheater Then activate Reheater_Rules
- If problem Valve Then activate Valve_Rules
- If problem Turbine Then activate Turbine_Rules
- If problem Condenser Then activate Condenser_Rules
- If problem cooling tower Then activate Cooling_Tower_Rules

The preliminary set of rules for the water steam system are as follows:

- If problem Fans Then activate Fan_Rules
- If problem Air_Preheater Then activate Air_Preheater_Rules
If problem Coal_Mills Then activate Coal_Mill_Rules
If problem Burners Then activate Burner_Rules
If problem Furnace Then activate Furnace_Rules
If problem Flue_Gas_Duct Then activate Flue_Gas_Duct_Rules
If problem Flue_Gas_Recirculation Then activate Flue_Gas_Recirculation_Rules
If problem Gas_Tempering Then activate Gas_Tempering_Rules
If problem Precipitator Then activate Precipitator_Rules
If problem Combustion_Air_Fan Then activate Combustion_Air_Fan_Rules

5.3 Flow Chart for Superheater Heater Failure Investigation

Figure 5.2 shows how this process of investigation might be applied to superheater failures, in which a much more detailed flow chart emerges. The flow chart, or “Superheater Diagnosis Tree” outlines the procedure for diagnosing failure mechanism and identifying the root causes. The flow chart began to emerge after the formulation of some preliminary If-Then questions, when it could be seen that distinct groups of questions were emerging. The top half of the tree, down to the box labelled “Provisional Conclusions on Failure Mechanism and Cause” basically covers the activities that senior technical staff of a plant would carry out to begin to ascertain the mechanism and cause of a failure of a superheater.

The lower half of the flow chart, below the provisional conclusions box includes the backroom and laboratory activities, which would only begin to be activated if plant people think that there is something quite unusual about the failure, or if it appears that this type of failure is tending to occur unexpectedly across a large number of plants.

Notice, however, the discontinuous line to the extreme right of the flow chart, which leads to and through a box entitled “Simple Repair”. Quite often, no real investigation is made by plant personnel after a failure. Proper investigations are made only when the repair does not work. Similarly, the operators, having come to some provisional conclusions about the nature of the failure, normally put in hand measures to avoid future problems. If these are successful, there will be no need for backroom work. However, if failures continue to occur, more in depth work will be needed. In this a major input to peoples’ thinking, will be the knowledge that the preventative measures were not successful. This information becomes part of the plant history.
Investigate Superheater

Failure Location
  - Design Features
  - Plant Data and Records and NDE
  - Operating Schedule
  - Control and Operability
  - Repairs and Modifications
  - Industry Wide

Tubes
  - Headers and Connections
  - Visual Assessment

Headers and Connections
  - Visual Assessment
  - Superheater

Superheater
  - Furnace
  - Water/Steam Side

Furnace
  - Side

Visual Assessment
  - Potential Failure Mechanisms

Potential Failure Mechanisms
  - Provisional Cause based on Plant Design Data and History

Provisional Cause based on Design Features
  - Provisional Cause identified but Confirmation Needed
  - Cause Not Identified or Unusual/Repetitive

Identify Root Causes of Failure and Other Symptoms

Lab Based Identification of Failure Mechanism
  - Agreement between Lab, Calculations History and Repairs etc

Calculations and Stress Analysis based on Lab Failure Mechanism Data, Plant Records and History
  - Non-Agreement between Lab, Calculations History and Repairs

Repairs and Changes Effective
  - Repairs, Mods Operational Changes
  - Repairs and Changes Non-Effective

Mechanism and Cause Obvious

Provisional Conclusions on Failure Mechanism and Cause

Fig 5.2: Superheater Failure Diagnosis Tree
As with plant type investigations distinct groups of If-Then questions began to emerge in the backroom and laboratory sections. However the main difference is that because there is more information to hand, the responses to some of the questions in this laboratory phase will cause back-tracking, so that ideas about mechanisms and root causes may need to be revisited and rechecked. The main difficulty that emerged, however, during the initial stages of formulating If...Then rules in this research, is the problem of putting diverse pieces of evidence together in support of a specific hypothesis of what the failure mechanism might be. This involves getting the expert system to do similar action to what an expert does in “weighing up the evidence”.

There are four fairly distinct pieces of information on which plant personnel would rely when investigating failures. Hence there are four different groups of If...Then questions. These correspond to:

- **Failure Location**
- **Design Factors**
- **Plant Quantitative Data and Records**
- **Plant Operating History**

As shown schematically by the chart, for a major piece of equipment, such as a superheater bank, it will be necessary to have separate sets of If...Then rules, depending whereabouts on the equipment the failure has occurred. The principal locations on a superheater where failure might be expected are on the tubes and the header.

### 5.3.1 Activation of If...Then Rules (Failure Location /Visual Assessment)

- **If** problem on superheater_tubes **Then** activate_rules for superheater_tube_failure_mechanisms_visual_assessment

- **If** problem on superheater_header **Then** activate rules for superheater_header_failure_mechanisms_visual_assessment

### 5.3.2 Activation of If...Then Rules (Plant and Equipment Design/Superheaters)

- **If** superheater_design_and_construction information available **Then** run_rules to assess failure_implications

- **If** furnace_design and operating_characteristics available **Then** run_rules to assess failure_implications
5.3.3 Activation of If...Then Rules (Plant Data and Records/Superheaters)

If furnace_side_records available enter data Then run rules
to assess failure_implications

If water/steam_side_records available enter data Then run rules
to assess failure_implications

5.3.4 Activation of If...Then Rules (Plant Operating History)

If current_and_past_plant_operating_schedule available Then run rules
to assess failure_implications

If industry_wide_knowledge available Then run rules
to assess failure_implications

If plant_control_operability available Then run rules
to assess failure_implications

If repairs_modifications available Then run rules
to assess failure_implications

5.4 Conclusions to Chapter 5 and the Formulation and Use of Flow Charts

This chapter has shown the importance of formulating flow charts to help clarify the thinking that is needed in formulating suitable If...Then questions. The flow chart reveals how the questions can be grouped into sets of questions which relate to specific issues. With this thesis all the flow charts originated from setting down a few If...Then questions about failure investigation which then stimulated the author into thinking about how these could be grouped. Having formulated the main flow charts, it would seem that these could easily be modified to cover most other types of failure investigation. Once the appropriate issues have been identified, and incorporated into a flow chart, this will stimulate the thinking about what If...Then questions are needed.

The flow chart for superheater failures has confirmed the initial view that investigations normally fall into two distinct phases. The first phase is where the operators make an on-site diagnosis of the failure based on a visual assessment, the way the plant operates and information that they know from elsewhere. The second phase covers the backroom and laboratory activities.

The final message of this Chapter is that If...Then rules will need to be written in a fairly specialised way if they are to be used in an expert system, and that in some manner they need to overcome the shortcomings of the two valued logic of If...Then rules. This issue will be addressed in the Chapter 6 which follows immediately, and the techniques which are formulated will have direct application in the establishment of root causes. The other issue which has been touched on in this Chapter is the techniques whereby the output from If...Then rules needed in laboratory
investigations can be marshalled together to build up a convincing case to support a specific failure mechanism. This issue will be covered in Chapter 7. Without an understanding of the techniques for rules formulation, as provided by Chapters 6 and 7, there would be little point in setting down the rules. Accordingly the majority of the rules that have been formulated for plant induced problems will be set down in Chapter 8. Chapter 9 contains the type of rules that will be needed where the superheater material (P91) is considered to be a root cause of premature failures.
Chapter 6
Formulation and Manipulation of If...Then Rules for Failure Analysis

6.1 Basic Procedures in Rule Formulation

To progress the development of ideas in this thesis, on a number of occasions various examples of If...Then rules have been quoted, without clarifying how they are created. It now becomes necessary to set down the process of rule formulation.

The basic principle is that all If...Then rules are based on two valued logic, that is:

\[
\begin{align*}
\text{If } (A) & \text{ Then } (B) \\
\text{If } (\neg A) & \text{ Then } (B) \\
\text{If } (A) & \text{ Then } (\neg B) \\
\text{If } (\neg A) & \text{ Then } (\neg B)
\end{align*}
\]

In these rules A is either a word or set of phrases that form the “argument” and B is a word or set of phrases that cover the consequences or “predicate”.

The building blocks of an expert system consist of sets of If...Then rules which cover the knowledge, thought processes and actions of experts in the field. Accordingly, in this case, the aim should be to formulate well considered, but heuristic knowledge about metallurgical failures into If...Then equations similar to those above.

Let us analyse what might be needed in formulating the sets of rules that would be part of a typical superheater failure investigation. One such set of rules would be that needed to estimate the likely mean operating temperature of a P91 superheater tube. The assumption is that the superheater had failed after 25000 hours. To solve this problem the expert will utilise the ideas set down in the italicised paragraph. It contains many of the words, phrases, numbers and equations that might be useful in forming If...Then rules, and these are highlighted in bold.

\[
\begin{align*}
\text{On the basis that the failure time of a P91 superheater tube is 25000 hours an estimate of the failure temperature can be obtained using a method of extrapolation using the Larson Miller parametric equation, on the assumption that the failure is due to a creep failure mechanism.}
\end{align*}
\]

The equation is of the form: 

\[
P = (T+273)(C + \log t)
\]

Where:

- \(P\) = Parameter for each stress level, \(T\) = Test Temperature in degrees Kelvin,
- \(C\) is the Larson-Miller constant which modifies the effect of the time \(t\) at which creep failure occurs.
In addition the value of the **LM-Parameter** for the design stress of 65MPa is **32305** and the L-M Constant in this case is **31**. The temperature in degrees Kelvin is given by adding 273 to the calculated failure temperature. The design life was **100000 hours**.

Without going into several pages of description, much of which would be repetitive, it is impossible to record every one of the thought process that an expert uses in formulating his or her attack on this problem. But it shows that it is necessary to consider the use of certain key words, phrases, and numbers such as “determine”, “creep failure”, “P91”, “L-M Parameter”, “superheater” “calculation”, numbers such as “273” and “32305” suitable If...Then rules are to be formulated. Not all of these words and phrases would need to be used in constructing the rules, and there will be others that have to be used which do not necessarily feature in the italicised section.

This paragraph illustrates the problems in trying to use a Knowledge Engineer to formulate the rules from scratch as many of these words and phrases would be unknown to him or her. Even if the Knowledge Engineer was familiar with these expressions, they are used by the expert used in a highly specific way. This semantic problem is exemplified by the word “creep” and the phrase “creep failure”. The dictionary definition of “creep” is defined as moving along in a very slow and very silent fashion. The phrase “creep failure” is likely to give even more problems to the knowledge engineer as the phrase appears to incorporate the colloquial use of the word “creep”, meaning an untrustworthy and unsavoury individual. It is therefore apparent that definitions will be required for the majority of such words and phrases used by the expert. Hence it is essential that the domain expert formulates the If...Then rules, rather than to produce these through a series of discussions with the knowledge engineer. Whatever the case, whether the expert does the bulk of the work in rule formulation, or does this through the intermediary of the knowledge engineer, there will be a need for a glossary of terms. As the range of failures and equipment grows, the expert system the glossary or glossaries will become more extensive.

Turning back to rule formulation the approach that seems to be necessary is to start with the core of the procedure that is needed to solve the problem. From this “core rule or procedure” the expert needs to work forwards and backwards from this point. That is a series of rules will lead up to the core rule, which would be needed to initiate it. After the application of the core rules, another series begins to which will eventually lead through to the consequences. In the case of the P91 superheater failure nothing can be done until the expert decided to make use of the following rule, which is:

\[
\text{If superheater tube is P91 Then use P91 L-M Parameter to calculate T Metal Larson Miller Parameter Derived}\]

In this case “T Metal” refers to the metal temperature and “Larson Miller Parameter Derived” states that this was used using the appropriate parameter. In
addition to this the first part of the If...Then rule makes it clear the data relating to P91 under the stated conditions would have to be used.

Hence one would need other If....Then equations such as:

\[
\text{If stress is 65MPa} \quad \text{Then} \quad \text{look\_up parameter\_value corresponding to 65MPa and put in parametric\_equation}
\]

In this case the parameter value would be 32305

In addition the Expert System would state the value of the constant C on the basis that the failure was short term, For this it needs to work out the time\_failure\_ratio ( i.e failure time divided by design life) and would need to state:

\[
\text{Calculate time\_failure\_ratio and use to assess C}
\]

In this case C is 0.25.

Hence the new If....Then rule is

\[
\text{If time\_failure\_ratio less than 1 is YES Then C is 31 and put in parametric equation.}
\]

The final major decision that needs to be made

\[
\text{Calculate T\_Metal\_Larson\_Miller\_Parameter\_Derived using Larson\_Miller\_subroutine for}
\]

Failure time =25000 hours
C=31
P = 32305
Therefore t = 639°C

It is assumed that the subroutine would subtract 273 from the answer before carrying out the order to “print result on screen”.

Hopefully it will now be reasonably clear how to create individual If...Then rules for each of the actions needed to determine the temperature of the superheater. Essentially, just as a human expert would, the process is broken down into a series of steps, each one of which becomes an If...Then rule. Furthermore each of the rules utilises the words and processes, which a human expert would have to use, in forming the arguments and predicates. It also appears that the rules follow a logical sequence, but in forming this sequence it is necessary to identify the core idea around which the sequence can be constructed.
6.2 Constructing and Cataloguing Glossary Terms

As noted earlier many of the words and phrases that have to be used in the If...Then rules were the same or similar to those in the italicised text. In using these words they are often combined with others, joining them with a lower case hyphen or hyphens where a number of words and numbers have to be combined. The expert system recognises these as unique words, which make up the glossary of terms that substitute for the A and B in the arguments and predicates in the If...Then rules.

For the knowledge engineer who is incorporating the glossary into the expert system software it is necessary to distinguish how these terms are used. The three basic types of term that are used in logic are “constants”, “expressions”, and “variables”.

**Constants** are terms that are fixed and refer to a particular subject or object. In this case typical examples would be:

- superheater_tube
- failure_time
- P91
- failure_time

P91 is one of those terms that could conceivably cause problems to the knowledge engineer. It needs to be made clear, in the glossary, that this is where a letter, either on its own or in combination with a figure, relates to a specific object. In compiling the history of a plant an expert system will encounter many such examples, as specific pieces of equipment are identified by sets of letters and numbers.

**Expressions** are a term of an alphanumeric type. There are several such examples in the above set of If...Then rules. Expressions can consist of a single number, such as temperature in degrees centigrade, or the L-M parameter values. In these cases the expression is of the “single” type. Alternatively they can be an “arithmetic expression” of the type X plus a constant, as in \((K_{05} - 273)\). “Function expressions” are more complex, as with parametric equation \(P_{23} / (C_{23} + \log t_0)\).

Both constants and expressions are fixed when used in argument-predicate statements and need to be defined properly in the glossary of terms and written down in the correct manner.

**Variables** have a more generic character and behave rather like the use of “X” and “Y” in an algebraic equation.

In the example given although the problem, which has been considered, is that of a superheater tube, the Larson-Miller parametric equation applies to any high temperature component that can fail by creep. Hence “X” in the second If...Then rule, in the previous section, could apply to gas turbine blades, structural members in the wings of Concorde, light bulb filaments, as well as parts of superheaters.
In general it is clear to the expert whether the word that are being used are of the constant, expression or variable type.

### 6.3 Glossary Types

#### 6.3.1 Semantic Glossary

The previous section have shown that an expert system which deals with failures will need to incorporate a glossary of terms which can be used in individual If...Then rules in which they substitute for the argument “A” and the predicate “B”. This leads to quite complex rules of the following type.

\[
\text{If plant is load following Then load following is possible cause of header cracking}
\]

\[
\text{If failed tube is in high heat flux area Then high heat flux is probable cause for creep failure}
\]

It will be seen that these two examples incorporate the words “high”, “possible” and “probable”. This is a method of getting over one of the problems of two valued logic in that it gives Yes/No answers. Words and phrases like “high” are defined in the semantic glossary and give what might be termed “levels of truth”. The levels of truth are adjectives or adjectival phrases which indicate just how much credence can be put on the level of reliability or applicability of a certain observation or conclusion. Because of the nuances associated with these terms, it has necessary to create a semantic glossary, which ranks the terms in a non-quantitative manner.

Obviously a shortcoming of this approach is that there is a measure of judgement, which has to be used. For example in the rule given above, which refers to “high heat flux”, ideally the word “high” should be ideally be quantified in terms of kW/sq. metre. This can be done in many cases as the author shows in Chapters 7 to 9 in which the basic aim is help decide on failure mechanisms and causes using Bayesian probabilistics.

Caution needs to be exercised in this respect, as the author’s use of Bayesian probabilities is intended to develop a system whereby the Inference Engine simulates the ability of people to weigh up evidence. It is not intended to be used to estimate failure probabilities.

If we assumed that “improbable” corresponded to a 0.05 probability, what exactly does this mean? If we were talking about motor car reliability, it would mean that if a million cars a year were produced, around 50000 of them would break down. Probability estimates are easy to apply to mass production items. For a power plant we do not have a million plants, we just have the one under investigation. So, supposing that an If-Then rule threw up the figure of 0.05 as the probability of a forced outage a superheater failure which could be reduced by taking appropriate action, what would be the likely response of the plant manager? He would almost certainly ask “What does this mean in English? We would then be back to using words like “improbable”, and depending on what sort of character was the plant...
manager, or his financial constraints, attitudes to safety etc this verbal statement would be the mainspring of whether or not he would not take preventative action.

Kirkstieger (a senior colleague at the DG-JRC where the author works), in recent one-to-one discussions has pointed out that this type of probability estimate is used in risk analysis. He emphasised, however, that the degrees of probability with risk tend to be ranked in terms of orders of magnitude. This is helpful when assessing the danger from an oil refinery or nuclear plant. Estimates like this would be quite helpful in deciding whether an accident would cost millions, tens of millions or hundreds of millions to fix. Such estimates can also be useful in deciding how many square kilometres around a plant might be affected by toxic or radioactive emissions. But here again this use of the probabilities is on too course a scale. We need to think of the various classes in the semantic glossary as covering a set of probabilities which run from 1 to 100, with 1 being impossible and 100 being certain. The nearest analogy would be the odds on betting on individual horses. Here, it should be noted, even a “rank outsider” has a reasonable chance, and the “favourite” does not always win. The pieces of evidence in failure investigations are of this type.

Nevertheless, as the investigation proceeds, it becomes more important that various theories be backed up by quantitative data and calculations. The interesting thing about such calculations and data is that the significance of these has usually to be interpreted in an extremely heuristic or rule of thumb manner. That is heat transfer figures or temperature calculations, for example, still have to be “interpreted” by the expert and set against his or her experience. By and large, then, certainly at an early stage in the investigation adjectival and adverbial words and phrases are useful in an expert system, and overcome to a large extent the two valued logic problem. It also appears that in the determination of root causes, the semantic, non quantitative glossary is satisfactory.

As such, the discussion on how to quantify evidence is reserved to the following chapter which deals with uncertainty. In this a conditional probability approach is developed, making use of Bayes’ rules in a pragmatic, but hopefully understandable fashion.

The components of the Semantic Glossary are given below:

6.3.1.1 Qualitative Levels of Reliability of Conclusions

<table>
<thead>
<tr>
<th>Impossible</th>
<th>Improbable</th>
<th>Possible</th>
<th>Probable</th>
<th>Certain</th>
</tr>
</thead>
</table>

6.3.1.2 Qualitative Levels of Compliance with Set Specifications or Treatment

<table>
<thead>
<tr>
<th>No or Bad (Does not Comply)</th>
<th>Poor</th>
<th>Fair</th>
<th>Yes or Good (Does Comply)</th>
</tr>
</thead>
</table>
6.3.1.3 Qualitative Level of Affect

None or Insignificant ➞ Little or Small ➞ Moderate ➞ Strong or Severe or High

6.3.1.4 Qualitative Level of Applicability

Cannot be applied (Not_to_be_relied_on) ➞ Perhaps_can_be_applied
(Not_very_reliable) ➞ Can_be_applied (Reliable)

6.3.1.5 Qualitative Effect of Change on a Problem

Eliminated ➞ Decreased ➞ Unchanged ➞ Increased ➞ Unmanageable

6.3.1.6 Timewise Compliance or Frequency

Never ➞ Infrequently ➞ Sometimes ➞ Usually ➞ Always

6.3.1.7 Semi Quantitative Difference to a Given Value

Low (Lower) ➞ Intermediate (Similar) ➞ High (Higher)

6.3.1.8 Requirement to Take Action

Imperative ➞ Desirable ➞ Questionable ➞ Unnecessary

6.3.2 Non-Quantitative Glossary

The Non-Quantitative Glossary is intended to be used as part of the expert system, whereby the system is made to react in a specific way using “If...Then” rules. In addition, the Glossary gives brief explanations about what the words or phrases are intended to mean.

In the actual “If...Then” rules, the words and phrases are written in the expert system style so as to signal that the rules should operate in a certain way. For example “furnace_conditions” should start to activate rules which will deal with how the furnace has been operated.

To keep the Glossary within a manageable size and to make the “If...Then” rules more reader friendly, the Glossary adopts a commonsense attitude in listing them. Furthermore to prevent over-duplication with, for example header metal
temperatures, these are listed in the Glossary as Header_Metal_Temperatures (Boiler, Superheater, Reheater)(Inlet, Outlet)

**Typical contents of the non-quantitative glossary are as follows:**

*Actual_Inlet_Steam_Temperature*: The actual steam inlet temperature to a superheater

*Actual_Outlet_Steam_Temperature*: The actual steam outlet temperature from the superheater

*Affect_On_Failure*: Relates to whether some phenomenon will have caused the failure mechanism or the time to failure

*Alloy (Superheater_Tube, Super_Header, etc)*: Alloy from which component is made

*Activate*: Go to rules regarding this subject

*Air_Preheater*: Heat exchanger usually of a regenerative type used to preheat combustion air to the furnace

*Ascertain*: Find out more details

*Ascertain_Similar_Plant_Mechanisms_or_Causes*: Used when a plant that is broadly similar to the design has experienced the same type of failures as the ones under investigation

*Average_Operating_Equivalent_Operating_Hours*: This is used to give a plant operator a very rough estimate of the equivalent time that a superheater has been under load

*Attemperator*: A device which is used to control superheater and reheater temperatures by spraying in water into the inlet or outlet of the superheater. The attemperator can be classified as an attemperator1 (outlet primary superheater), attemperator2 (outlet secondary superheater) attemperator3 (outlet tertiary superheater) and if fitted attemperator4 (outlet primary reheater)

*Base_Load_Operation*: Operation of the plant at or near the design output of the plant with little or no load_following or two_shift_operation

*Bending_or_Whipping*: Sometimes occurs due to failing around of a superheater tube after a sudden burst or split has occurred and can be wrongly supposed to be the cause of failure

*Boiler_Circulating_Pump*: A pump used to circulate water on a forced circulation boiler or one used during the start up period of certain natural circulation or once through boiler boilers

*Bowed*: Bending of header or pipe due to thermal expansion, condensate carryover or failure of supports

*Brittle_Fracture*: Catastrophic type of cracking of heavy section components such as headers, drums and turbines rotors usually occurring around room temperature under conditions of high stress

*Burner_Arrangement*: General description of arrangement of burners in furnace

*Burner_Set_Up*: Arrangement of those burners that are operating in a furnace

*Burner_Row*: Describes which row of burners in the furnace are operating and is characterised by Top, Middle or Bottom
Burner_Orientation: Describes, where applicable the direction in which burners are pointing and is characterised by Upwards, Level, Downwards

Burner_Type : Type of burner

Carry_Out_Test : Advise operator to do appropriate tests

Calculate : Do necessary calculations

Circumferential_Weld: Weld which is used to join two tube like components end to end

Coal_Calculator : Method for calculating slagging and fouling tendency of coal

Coal_Type : Basic description of coal. For example bituminous, lignite, ash content

Coal_Source: Area or country from which coal was mined

Component_Replaced : A component that was replaced. The failure time and cause of failure will need to be identified, and whether a new design or material was used in its construction

Component_Repaired : A component that was repaired. The failure time and cause of failure will need to be identified. The form of repair will need to be stated.

Complies_With_Design : This is usually part of a phrase in which stating the piece of equipment will state how well it complies with the design operational parameters, such as pressure temperature or flow rate, etc

Condensate_Build_Up: Accumulation of condensate during start up and shut down which can lead to blockage of steam flow, quench cracking or distortion

Confirm_Agreement_With : A method by which towsees of conclusions can be compared

Convective_Superheater: In modern designs a superheater in which the tubes are placed laterally across the flue gas duct, thereby absorbing heat by convection. In older designs a unit which was positioned in the furnace outlet, whereby the steam flowed through looped or S bend tubes gradually picking up heat. In both cases the design is optimised to pick up convective heat, so the flow round individual tubes enhances turbulence and heat transfer.

Contributory_Factors: Factors which may contribute to the cause of failure, which need to be followed up once the evidence from the main line of investigation becomes weak or inconclusive.

Control(Difficult to): Aspect of plant operation which is difficult to control

Cracks or Cracking: Failure or pre-failure of a component associated with cracks, wherein there is little or no deformation away from the cracks themselves. Cracks can be classified as wide_cracks, narrow_cracks, intergranular_cracks or transgranular_cracks

Creep: A mechanism of failure due to the effects of a constant level of stress at high temperature, which will eventually lead to the failure of the component through a combination of deformation, fissuring and cracking. Most high temperature components are designed to last a specific time at the design temperature, typically 100000 or 225000 hours for steam plant. However there is always a large factor of safety so that under the specified conditions the life is significantly longer. In practice many components will fail before the specified time due excessive temperatures or stress. An alternative term for creep failure in this context is stress rupture failure.

Creep_Fatigue: A failure mechanism in which relatively long periods at high temperature, where the material is exposed to a change in strain due to the imposition of pressure forces or dead load loads, which lead to creep, are interspersed with much shorter periods in which the imposed stresses first
accelerate and then reverse the direction of strain. Short period failures, are characterised as being due to low cycle fatigue, are primarily caused by thermal expansion effects, and occur when the equipment is below design temperature. The main effect of creep fatigue is to reduce creep life compared to operation under base load conditions (cf creep and fatigue).

Creep Failure Causal Rules: A method of initiating the rules which are used to evaluate the results of backroom and laboratory investigations

Current: Indicates that after the reliability of a particular sensing point has been verified through consultation with past base load plant records or other data, the current data can or should be used in diagnosing the mechanisms or root cause of failures.

Deaerator: A drum-like pressure vessel which uses steam or water at high pressure to remove oxygen from the feed water. Oxygen removal must be supplemented by chemical methods

Definite Cause: Applies where there is no doubt what is the cause of the problem. See Unknown Cause

Deformation: In this context, a form of damage to the component that is usually local to the vicinity of the failure region, where the component has experienced an increase in length or diameter in the direction of the main stress.

Design: A word added, in various ways to a specific statement, or operating factor which indicates that these were the intended plant operating limits

Design Change: Significant modification plant equipment or materials

Design Life: Intended life of equipment as sold to customer

Design Tube Stress: Stress in tube at operating pressure excluding corrosion allowance

Design Inlet Steam Temperature: Intended inlet temperature to superheater

Design Outlet Steam Temperature: Intended outlet temperature to superheater

Design Steam Inlet Pressure: Intended inlet steam pressure to superheater

Design Steam Outlet Pressure: Intended outlet steam pressure from superheater

Different: Something which is different

Downstream: Location of component, equipment or failure position with respect to another piece of equipment

Distortion: Permanent deformation of equipment, assembly or component caused by thermal expansion and or failure of support or bad design of support or equipment

Duplex Tube: Tube in which the outer surface is a corrosion resistant high grade austenitic or nickel based alloy, whereas the inner surface is a lower grade creep resistant austenitic or ferritic alloy.

Economiser: A heat exchanger in the flue gas train which is used to extract heat from the flue gases after the reheaters but before the air preheater

End Cap Weld: Circumferential weld used to join the end cap to the header tube

Enthalpy: Energy available in a substances, in this case a fluid which is composed of pressure/volume energy and temperature energy. Enthalpy in gases and liquids increases uniformly as temperature increases and therefore temperature changes can be used to estimate relative changes in
heat input. When water turns into steam latent heat effects give a big changes in enthalpy and steam tables need to be used.

Equivalent Operating Hours: The equivalent number of hours at the design temperature as calculated using a Larson-Miller Parameter or Manson-Haferd or other parameter.

Erosion: Wear of equipment caused by impact of high velocity steam or water flows which may or may not be entraining solid particles or liquid droplets.

Excess Air: The percentage of air over that needed for complete combustion.

Fatigue: A failure mechanism that is due to frequent reversals of stress, in which the number of cycles to failure is over 100. In a power plant, the changes in stress are caused by changes in through wall temperature gradients or by the restraint that a component may suffer when it attempts to change its length as a result of thermal expansion or contraction. As such the fatigue is of a low cycle nature. It is convenient to differentiate fatigue from creep-fatigue whereby the effect of fatigue is to accelerate the creep and is restricted to high temperatures. Both phenomena lead to cracking with little deformation.

Failure Appearance: A visual clue which is indicative of a specific failure mechanism. Numbers are added to this to indicate specific types.

First Failure: First failure on equipment.

Flue Gas Temperature Viscosity Parameter: This is based on the slag viscosity at 1426°C, which is then used to set a safe flue gas outlet temperature.

Latest Failure: Failure before one being investigated.

Failed Tube or Header etc: Refers to component or equipment that has failed.

Failure Cause: Cause of failure.

Failure Implications: Factors which would result in a given type of failure mechanism.

Failure Mechanism: Underlying mechanism which led to the failure, for example creep or stress corrosion.

Failure Location: Position on equipment where failure took place.

Failure Region: Region close to location of failure, but ideally not suffering from fissuring, carburisation or decarburisation.

Feedheaters: Heat exchangers which take steam which is extracted from the steam turbines or which use waste steam from a turbine driven boiler pump and use the heat energy to preheat boiler feed water. As with feed pumps they are classified as being either HP or LP feedheaters.

Feed Pumps: Pumps used to force water in to boiler drum. They are divided into LP feed pumps, used before the deaerator, and HP pumps used after the deaerator and before the HP feed system/economiser.

Fireside Corrosion: Generic term for attack by ash or slag on superheater tubing. The attack involves the formation of a molten alkali iron trisulphate layer, which accelerates sulphidation and oxidation of the tubing. In some cases carburisation may be present.

Fireside Corrosion Module: Set of more detailed assessments brought into use when there is some evidence that the failure was caused by fireside corrosion.
Fissuring: Failure or prefailure associated with the formation of a large number of fine cracks at the surface and within the body of the component. The large number of the cracks may result in deformation of the component. The larger fissures may join up to cause total failure of the component by cracking or leakage.

Flue_Gas_Recirculation: The proportion or percentage of flue gas which has been recirculated back to the furnace.

Fuel: Whether coal, oil or natural gas. Individual types of fuel have their own characteristics.

Furnace_Conditions: Factors which can be measured using standard instrumentation or assessed visually which would affect heat transfer in the furnace and need to be checked out to establish the root cause of superheater failure. They would include excess_air, flue_gas_recirculation, gas_tempering, burner_arrangement, fuel, etc.

Furnace_Design_and_Operating_Characteristics: Type of furnace, fuel

Furnace_Side_Records: Quantitative information about furnace_side_conditions

Furnace_Slagged: Excessive slag covering of water wall or other evaporative heat transfer surfaces. This will reduce evaporative rate and hence furnace throughput, leading to higher than expected flue gas temperatures

Gas_Tempering: A type of flue_gas_recirculation admitted near the top of the furnace to reduce superheater temperatures and increase heat transfer to the reheater and economiser.

Gradients (Header, Tubes): Temperature gradients which are likely to form along headers and/or over tubes bundle across a duct. They are classified as near_uniform, arch_shaped, saucer-shaped and W_or_M_shaped

HAZ: Heat Affected Zone in the parent metal, alongside the weld deposit, which is often weaker and liable to crack due to non optimum microstructure

Header_Metal_Temperatures (Boiler, Superheater, Reheater) (Inlet or Outlet): These are measurements of the header material itself and are taken from wired on thermocouples every 1-2 metres along the header. See also peak_metal_temperature

Heat_Transfer_Coefficient: A function somewhat similar to thermal conductivity of a metal in which the basic ability of a flowing gas or liquid to impart heat to a solid surface. It is normal given in the number of kilowatts of heat transferred to a square metre of surface given a one degree Kelvin temperature difference.

Heat_Transfer_Rate: The amount of heat energy entering tubes or furnace walls and is given either quantitatively as kW.m² or qualitatively as low, intermediate or high

High_Velocity_Steam_Escape: Escape of high velocity steam which will cause erosion or reaction force on component leading to bending or whipping.

Inadequate_Materials : Materials which are not good enough for the proposed operation

Internal_Deposits_Present: Material from steam or water which has accumulated on internal surfaces of superheater, reheater or boiler

Laboratory_Investigation: Investigation of failure in laboratory, which may follow plant_investigation. Need for this is identified with an adjective.

Load_Following: A mode of operation when the plant alters output to meet variation in load demands or to correct for frequency problems
Low NOx Burners: Burners which operate using staged combustion to reduce levels of NOx. They will accelerate furnace wall corrosion and possibly induce CO attack of superheaters.

Metallurgical Significance: A phrase intended, in conjunction with the appropriate adjective, to show whether the foregoing observations suggest that there amiss with the material in the context of strength, and oxidation resistance.

Method (This): A technique used to produce a data point when the normal method is unreliable or unavailable.

Modify Operational Procedures: Change operating practices and plant conditions to attempt to overcome problems.

Old Plant: Obsolete design of plant.

Operating and Not Operating: Refers to equipment that would influence plant behaviour or measurements.

Operation Change: Change in type of operation, for example from base to peak load.

Open Burst: Large opening in tube usually due to overheating or severe erosion, which can result in a high velocity jet of steam which can lead to tube bending or whipping erosion of nearby tubes. See also wide crack.

Operational Change: Significant change in mode of operation.

Parent Metal: Material which belongs to component which has been welded and is outside of the HAZ.

Provisional Failure Mechanism: Initial Assessment of mechanism of failure based on Failure Appearance.

Pendant or Platen Superheater: Superheater which consists of a series of heat exchanger tubes usually of “U” or “W” form, arranged to form a wall like arrangement, with the tubes hanging downwards, set parallel to the flue flow. Although much of the heat transfer is by convection, the line-like arrangement of the tubes does not maximise convective heat transfer in the way that a true convective superheater does.

PF Mill: Pulverised fuel mill.

Plant Conditions Actual: A phrase used to indicate actual conditions in the plant.

Plant Complies With Design: An extended version of the Complies With Design phrase, which will usually have the adjectival phrases, well, poorly etc, added.

Plant Investigations: A phrase which when qualified using adjectival phrases will state how necessary it is to carry out plant investigations.

Provisional Creep Mechanism: Is a preliminary goal based on visual assessment.

Plot Graph: An instruction to plot a simple graph, of for example, header temperatures versus thermocouple position.

Pump: See specific type of pump.

Quench Cracking: Cracking of the internal surfaces of headers and tubing caused by relatively cool condensate coming into contact with hot surfaces, leading to shallow tensile cracking.
Radiant Superheater: Wall or ceiling mounted superheater which utilises radiant heating.

Record(s): Records of relevant information about the suspected failure cause and/or the results of the investigation.

Recurring Problem: A problem or failure which tends to reoccur on the equipment under investigation or on similar units elsewhere.

Reheater: Heat exchanger in the flue gas system which is used to reheat relatively cool steam exiting the HP turbine back to temperature. There are usually a series of reheaters situated between the superheaters 2 and 3 and the economiser.

Relevant Data: Information that could be helpful to this and future investigations.

Removed Immediately: Removal of failed or problematic component or equipment before it is subject to further damage by operation of the plant or by corrosion if left standing at room temperature for a long period.

Repair equipment: Repair equipment.

Risk or Risks: A term which is used in helping to identify how a change is likely to influence a specific failure mechanism.

Root Cause: The real cause of the problem which, if rectified, will eliminate or reduce future occurrences.

Root Cause Plant: Root cause is due plant design, type of operation, or a none-performing piece of equipment or operator failure.

Root Cause Material: Root cause is either due to some basic shortcoming in the material connected with its metallurgy, heat treatment or composition or use of wrongly specified material.

Root Cause Both Plant Material: A combination of both of the above.

Seam Weld: A weld, which runs longitudinally along a pipe, which was used to fabricate the pipe from a piece of plate. In some cases, following subsequent rolling, the position of the weld may not be apparent.

Shields: Device used to protect tubes from excessive heat transfer or the effects of slag and ash deposition.

Shielded Tubes or Unshielded Tubes: Tubes with and without shield. The effect of shielding is to reduce heat transfer to the shielded tubes, with the result that downstream unshielded tubes may suffer.

Similar Plant: Plant which is of the same basic design and designed by the same manufacturer, although there may be differences, due to the availability and cost of equipment and recognition that later units have needed design changes.

Sliding Pressure Control: A mode of varying plant output where steam pressure is controlled by changing the feed pump pressure and output.

Spread: Range of values around the specified or expected value given as a plus and minus (±) quantity.

Starts: Number of starts, qualified by whether these are cold, warm or hot starts.

State On Screen: A command asking for significant results to be displayed on the monitor.
Steam Drum: Cylindrical pressure vessel used on steam drum systems to separate the steam from the water

Steam_Drum_Temperature: A temperature which is governed by the saturation pressure of the water in the drum, and whose value can be determined from steam tables. It can be measured from a thermocouple as SD_TA or calculated from steam tables as SD_TA_sat

Steam_Flow_Superheater (1, 2, 3): The flow of steam through the superheater which originates from the boiler. The overall蒸汽_Flow Superheater_(1, 2, 3) is that flow, plus additional steam due to operation of the attemperator.

Steam_Flow_Reheater: The flow of steam through the reheater which originates from the outlet of the HP turbine. The overall Steam_Flow_Reheater_(1, 2, 3) is that flow plus additional steam due to operation of the attemperator.

Steam_Separator or Steam_Cyclone: Device used on once through boilers to separate steam from water droplets by a vortex inducing system

Stress: Stresses are classified into specified_stress and excessive_stress

Superheater: Heat exchangers used to heat high pressure saturated steam from the evaporating section of the furnace. There are usually at least three in series with the Superheater 2 facing the outlet of the furnace and Superheater 3 being the hottest.

Superheater_Design_and_Construction: Type of superheater, number and materials of construction

Superheater_Header_Failure_Mechanisms_Visual_Assessment: Simple examination by plant personnel of failed equipment with, if possible, some internal inspection by intrascopes and cutting up of tubing

Superheater_Pressures 1, 2 or 3: Refers to pressures at the inlet and outlet of the respective superheaters

Superheater_Pressure_Drop 1, 2 or 3: Refers to the pressure drops from inlet to outlet of the respective superheaters

Superheater_Temperatures_Inlet or Outlet (1, 2, 3): Refers to steam temperatures at the inlet and outlet of the respective superheaters

Superheater_Temperature_Rise (1, 2, 3): Refers to steam temperature increase from inlet to outlet of the respective superheaters

Superheater_Tube_Bank: Refers to the collection of tubes which make up the superheater

Superheater_Tube_Straight_Length: Phrase indicating tube failed along straight section of tube

$t$: A time in hours, but sometimes used to identify the specific equation that need to be used

$t_{failure}$: Failure time in hours

T: A letter indicating temperature to which other descriptive words will be added

T_Design_Superheater_Rise: Design temperature increase from inlet to outlet of superheater

T_Metal_Larson_Miller_Derived or T_Metal_LMP_Derived: Temperature based on the failure time and design stress using the Larson Miller parameter for the material in question
T_Metal_Superheater_Design: Design metal temperature. Usually this is not known and has to be estimated.

T_Metal_Temperature_Steam_Derived: An estimated metal temperature based on the steam inlet and outlet temperatures.

T_Actual_Superheater_Rise: The actual temperature increase from inlet to outlet of the superheater.

Temperature_Assessment_Module: A module which is brought into play when the preliminary assessment indicates creep.

Temperature_Distribution_Header: Temperature distribution across a tube bank or along a header etc. Although the qualitative temperature distribution may be in the form of actual figures, these, when given by the IF.... THEN rules, can only be used as trends. This is due to uncertainties caused by type of material and the fact that the plant has been subject to cycling. The quantitative rules are used where a plant has not been cycling and where the temperature estimates based on hardness or oxide thickness are recognised to be reliable.

Thickness (Tube_Wall or Steamside_Oxide): Thickness where appropriate.

Throttle_Control: A mode of operation where the boiler and superheater are maintained at a constant pressure but the pressure into the turbine is altered to vary plant output. In this mode the steam pressure in the plant remains constant, unlike when running under sliding_pressure_control.

Time_Failure: Failure time.

Time_Failure_Ratio: The ratio of the failure time to the design life and may be needed to ascertain a suitable value for "C" in the Larson-Miller equation.

Tube: A word added to other statements indicating that the data or observation was related to the superheater tube.

Tube_Longitudinal_Crack: A fairly narrow crack running along the length of the tube which could indicate a creep failure.

Tube_Crack_Faces_Main_Heat_Flow: Position of crack probably indicating that the crack was temperature related and indicating final failure by creep if the crack is fairly narrow and longitudinal.

Tube_Bulged: Visible bulging of tube which if associated with operation at temperature, and no cracking or narrow cracking or fissuring will indicate creep.

Tube_Fissured: A series of fine cracks which are present when a tube has finally failed by creep.

Tube_Wasted: Visible wear of tube caused by erosion or reasonably uniform external corrosion due to fireside attack.

Tube_Deposits: Deposits on tubes which could indicate fireside corrosion.

Tube_White_Deposits: White deposits found close to surface of tube and are strong indicators of fireside attack.

Tube_Side_Facets: Worn facets on either side of tube not facing direction of flue gas flow and are good indicators of fireside corrosion.

Tube_Fish_Mouthed_Split: Wide open crack associated with extreme thinning of wall as a result of deformation at temperature. This is a good indicator of an overheating type failure.
Tube_Circumferential_Crack: A crack running around the circumference of a tube and is likely to be associated with a weld defect

Two_Shift_Operation: A mode of operation when the plant is started up in the morning and shut down at night

Uneven_Temperature_Distribution: Typically along a header or across a tube bank

Unaffected_Material: Material apparently unaffected by heat and remote from failure_region

Unknown_Cause: Where it is impossible to ascertain why a problem has occurred. See Definite_Cause

Unknown_Mechanism: Where the mechanism of failure is unknown at this point in the investigation although the cause may be conjectured

Upstream: Location of component, equipment or failure position with respect to another piece of equipment

Water/Steam_Side_Records: Quantitative data on boiler pressures and temperatures etc

Weld: Common method of joining two components by a fusion technique

Weld_Cracking: Cracking of a weld or in the vicinity of a weld. Weld cracking is described as

Type I: Wholly in weld and might be due to hydrogen

Type II: Starts in weld but propagates into HAZ

Type III: Starts in HAZ but propagates into parent

Type IIIa: Cracking is in the HAZ, very close to the fusion line, due to carbon migration into the fusion zone. Known to occur in CrMoV welded with T22 steel. Could possibly occur if P91 or X20 is welded to a lower alloy steel

Type IV: Failure in the parent metal, but often used to describe failure in the intercritical zone of the parent that is next to the visibly transformed section of the HAZ. The implication is that the failure will have occurred in a section of the HAZ which has been overtempered.

Visual_Assessment: When the appropriate mechanism is under review this activates the specific set of visual indicators relating to the mechanism in question

Weld_Deposit: The material deposited from the welding process

Weld_Failure: Failure due in some way to the weld

Weld_Quality: Whether welding has been done properly so that there is an absence of blowholes or cracking in the Weld_Deposit, post weld cracking in the heat affected zone, and good fusion between the two components without excessive penetration etc.

6.3.3 Quantitative Technical Glossary

The quantitative technical glossary will come into use when it is necessary for the expert system to carry out a sub-routine to make some kind of quantitative prediction
AR Hardness Ratio: Measured Hardness in Failure Region / Hardness of As Received Material if figures available

Larson-Miller Parameter: Parametric equation of the type where temperature can be estimated assuming that the time to failure (t Failure h) and stress are known, viz P = T(C+log t). To determine P it is necessary to decide on an appropriate value of C and the actual or design stress σ.

This will result in an expression such as:

T_P91_t_Failure_25000_Superheater_P91_31_65_MPa_LMP_Derived the value of which can be obtained using a sub-routine which will refer to a look-up table or calculated using an equation.

Tempering Test Check: A check to assess whether the material has been properly heat treated. This consists of a one hour austenitising treatment at 1060°C on four separate specimens, followed by a tempering treatment for 2 hours at 720°, 740°, 760° and 780°C. Suggested hardness figures for material that is within specification, would be for each of these temperatures 265, 250, 235 and 220 VPN.

6.4 More Detailed Analysis of Rule Build Up and Use

6.4.1 Background to Example

The earlier examples given in this chapter show the process by which an expert begins to formulate his rules in a predigested form, but a Knowledge Engineer will need to take this approach much further when incorporating the rules into the Expert System. That is the rules would need to be machine readable, utilising simple statements or rules such as “calculate”, “using” “substitute” as well as If...Then rules, in requesting the program to move to the next step. These statements would also make use of the words and phrases as detailed in the glossary. Some of these statements relate to the input data, with such information being stored semi-permanently in the Fact Base of the Expert System. The rules, which allow this data to be manipulated to produce conclusions, would be stored in the Inference Engine.

This section of the thesis therefore shows, in more detail, how this might be done using a set of illustrative “modules” intended to solve an example problem, each module of which containing sequences of Rules. This hypothetical example covers a situation in which a superheater failure has occurred, and the aim is to show how machine readable rules might be written, firstly to identify what is the mechanism of the failure, and secondly to decide on whether the root cause is due to the conditions in the plant, or whether the actual cause was material based.

Some of these machine readable statements and rules will lead to either positive or negative conclusions, that is either YES or NO, which either effectively end this phase of the module or lead onto another set of questions. To ensure that the Expert System runs properly, one option is to consider the results of each of these questions as a goal. Depending on whether the answer is “YES” or “NO”, this will activate the required branch of the Expert System.

The sequence of rules that is required for this module is given below, but typical examples of a sequence of Goal-type rules would be:

...
Goal_1a is Provisional_Creep_Mechanism_Proved is YES

If Goal_1a is YES Then Activate Temperature_Assessment_Module

If Goal_1a is NO Then Activate Fireside_Corrosion_Module

The aim of this set of modules, each of which will lead to a “goal” are in this example:

- To identify, provisionally, the failure as creep from visual observations (YES or NO) as Goal_1a, and to distinguish it from other possible failure mechanisms which would be Goals_1b, 1c, 1d, and 1e
- On the assumption that failure is by creep, to estimate, from the time to failure, the metal temperature
- To compare this with the metal temperature as derived from the superheater steam temperatures
- To decide whether root cause is with the plant – Goal_2a (NO or YES)
- To decide whether root cause is with the material – Goal_2b (NO or YES)
- To decide whether route cause is with both the plant and the material – Goal_2c (YES or NO)
- To decide whether to carry out a wholly plant based investigation to determine root cause – Goal_3a (YES or NO)
- To decide whether to carry out a detailed laboratory investigation to determine root cause – Goal_3b (YES or NO)
- To decide whether to carry out both a plant based and a laboratory based investigation – Goal_3c (YES or NO)

It should be noted that the operator of the expert system would not be expected to suggest what could be the possible failure mechanism, in the opening phase of the investigation. This is the job of the Expert System, which as will be described in more detail in Chapter 7, does this by making use of some simple visual observations about the state of the failed component. Accordingly, the opening module of the Expert System would contain a set of questions that would contain sets of modules relating to each failure mechanism. Each of these can be categorised as Goal 1a, 1b, 1c, etc as shown below:

Goal_1a is YES If Provisional_Failure_Mechanism_is_Creep
Goal_1b is YES If Provisional_Failure_Mechanism_is_Fireside_Corrosion
Goal_1c is YES If Provisional_Failure_Mechanism_is_Erosion
Goal_1d is YES If Provisional_Failure_Mechanism_is_Overheating
Goal_1e is YES If Provisional_Failure_Mechanism_is_Weld_Failure

On the basis of the visual findings, the Expert System would then activate the appropriate module, behaving exactly like an experienced human investigator who would endeavour to ascertain whether the root cause stems from the plant or from the material.

The input data, statements, and If...Then rules can all be regarded as equations within the Expert System and are enumerated as such.

6.4.2 Fact Base and Data Input

Each new failure should start with an input from the investigator. This details basic information in a standardised form that can be drawn on, as needed, to set values for Objects used in the Rule set.

The assumption is that the Expert System contains much information in the Inference Engine in the form of rules and calculation procedures which utilises data that has been into the Fact Base. The Fact Base will include sets of key words which will relate to equipment items, and would require the operator to input which equipment and components are under evaluation, along with basic design and operating data such as steam temperatures, pressures and flows. In a real example the Fact Base would also include much more qualitative information on, for example, the state of the furnace, whether there were any leaky tubes, whether the plant was cycling etc.

6.4.2.1 Problem Description

The Expert System would ask the operator a series of questions in English, but the information would be stored in the following form as data in the Fact Base

Failure Equipment is Superheater [1]
Failure Component is Superheater_Tube [2]
Failure Location is Superheater_Tube_Straight_Length [3]
Time of Failure is Time_Failure_Time (25000 hours) [4]

6.4.2.2 Plant Information

The tube materials is P91 [5]
Design Life is Time_Design_Life (100000 hours) [6]
Design_Tube_Stress (65 MPa) [7]
Obviously the properties of the alloy which are being investigated are important and the operator would be required to state the name or code number of the alloy. In this case the material is P91, hence a set of rules would begin with the statement:

\[
\text{If P91 is YES} \ldots \ldots
\]

It also seems likely that some, if not all of this data could be permanently stored in the Fact Base/Inference Engine for use when required. However information that would be relevant to the investigation and which is easy to ascertain would be steam temperatures and pressures, fuel flows, steam flows and excess air. In this example only the data relating to steam temperatures are considered. This input data is turned into the following objects.

- **Actual Inlet Steam Temperature** is \( T_{\text{Actual Inlet}} \) (505°C)
- **Actual Outlet Steam Temperature** is \( T_{\text{Actual Outlet}} \) (565°C)

The provisional determination of the root cause of the failure is very dependent on the visual appearance of the failure. Accordingly in this case the operator of the Expert System is required to enter a set of Failure Appearances which are then used to make an assessment about the mechanism by the Inference Engine. In this case the input information consists of Failure Appearances 1 to 10. In the examples given, to clarify the situation, the YES or NO response that the operators would have given to the failure appearance questions is highlighted in blue for clarity.

- Failure Appearance 1 is Tube Longitudinal Crack is YES
- Failure Appearance 2 is Tube Crack Faces Main Heat Flow is YES
- Failure Appearance 3 is Tube Bulged is YES
- Failure Appearance 4 is Tube Fissured is YES
- Failure Appearance 5 is Tube Wasted is NO
- Failure Appearance 6 is Tube Deposits is YES
- Failure Appearance 7 is Tube White Deposits is NO
In human term this would be done by requesting the operator to highlight the most significant words and phrases which are mentioned Tables 7.3 to 7.8 as shown in Chapter 7. Each of these phrases categorises a specific failure mechanism. Obviously an absence of a specific phrase suggests that the failure was not caused by that specific mechanism.

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>30%</td>
<td>Bulging or swelling of tube up to about 10% increase in diameter. Any thinning of tube is fairly limited and uniform, and corresponds to the general swelling.</td>
</tr>
<tr>
<td>Probable</td>
<td>60%</td>
<td>Main longitudinal crack surrounded with fissures. Bulging of tube in area of crack. Some evidence of wastage due to fireside corrosion or erosion. Alternatively indications from severity of bulging and more open crack an overheating failure.</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>90%</td>
<td>Fairly narrow main longitudinal crack surrounded with fissures. Crack position faces hottest flue gas or radiation source. Some mild bulging of tube in area of cracking and away from this. Significant simple oxidation but no serious wastage. Plant has reached significant proportion of over 70% life based on operating hours.</td>
</tr>
<tr>
<td>Certain</td>
<td>99%</td>
<td>Fairly narrow main longitudinal crack surrounded with fissures. Crack position faces hottest flue gas or radiation source. Some mild bulging of tube in area of cracking and away from this. Significant simple oxidation but no serious wastage. Plant close to end or beyond end life based on LM parameter estimates.</td>
</tr>
</tbody>
</table>

A copy of Table 7.3 is shown above, and as Chapter 7 will describe, tables such as this are really intended to assist with a Bayesian probabilistic approach to bringing together evidence from various sources. But here, the main use of the Table 7.3 is to allow the highlighting of certain words and phrases, which are needed at this initial stage of making a preliminary assessment. The aim is to pick out the main features which could give support to the idea that the mechanism is could be of the creep type. In contrast to when the Table is being used in the Bayesian analysis, it does not really matter in which particular section of the Table the words are located. The
important thing is that they tend to point very strongly towards a given failure mechanism.

6.4.3 Inference Engine and the Failure Investigation

As noted in Section 6.4.1 the investigation fails into three main modules, the first of which is to identify the mechanism as being that of creep. The second module is to decide whether, from a comparison of the temperatures, as estimated from the steam temperatures, and those from a Larson-Miller parametric estimate, as to whether the plant or the material was the root cause. The third module is to decide whether a laboratory investigation is required.

The rules, and calculation procedures relating to these modules, would need to be stored permanently in the Inference Engine, and would be brought into play when the data was put into the system. Clearly there are three sets of rules of rules for each of the different modules and the form of these is shown in the following subsections.

6.4.3.1 Rules for Identification of the Failure Mechanism

The aim of the preliminary failure investigation is determine a provisional failure mechanism, so that the appropriate module can be activated. This is best done through a set of rules which relate to the appearance of the failure.

To start the process the Expert System, having ascertained that component which failed was a superheater tube, would get the operator to input information about the visual appearance. The rule would be:

If failure component is superheater tube
Then activate Failure_Appearance_Rules for Superheater_Tube_Failure

[25]

These rules would be based on If...Then statements such as:

If Failure_Appearance_1 is tube_longitudinal_crack
Then Provisional_Failure_Mechanism is Creep

A similar procedure can be used for other creep failure mechanisms such as that of Rule 16. Hence:

If Failure_Appearance_2 is Tube_Crack_Faces_Main_Heat_Flow is YES
Then Provisional_Failure_Mechanism is Creep
The converse of this rule is of course:

If Failure_Appearance_2 is Tube_Crack_Faces_Main_Heat_Flow is NO
Then
Provisional.Failure_Mechanism is NOT Creep

Stated more succinctly these two sets of rules would be:

If Rule 16 is YES Then Provisional.Failure_Mechanism is Creep

And

If Rule 16 is NO Then Provisional.Failure_Mechanism is NOT Creep

On this basis a set of rules based on the YES or NO responses to Rules [15] to [24] can be formulated as follows which relate to a specific Failure_Appearance:

6.4.3.2 Rules for Estimating the Metal Temperature from Steam Temperatures

The intention here is to use the outlet steam temperature to provide a rough guide to what is likely to be metal temperature. This is done by adding 40° C onto the outlet steam temperature. This value will need to be modified if the temperature rise through the superheater is significantly different from the design value. Hence a comparison has to be made between this and the design temperature rise. Hence there are two new objects to be described. These are:

T_Metal_Temperature_Steam_Derived

(which is the metal temperature derived from the steam temperature which in this case is the outlet steam temperature plus 40° C)

T_Actual_Superheater_Rise

(which is the actual superheater temperature rise derived from the inlet and outlet temperatures)

In this case using the data about the design temperatures and actual steam temperatures the values of these two objects can be stated on the screen. This will be done by the Inference Engine which will need to contain a set of instructions using a small sub-routine to determine these values. Hence the following sets of rules.

Calculate T_Metal_Temperature_Steam_Derived [26]

State value T_Metal_Temperature_Steam_Derived on screen [27]
Calculate $T_{\text{Superheater Rise Actual}}$
(using equation $T_{\text{Actual Outlet}}$ minus $T_{\text{Actual Inlet}}$) [28]

State value $T_{\text{Superheater Rise Actual on screen}}$ [29]

To assess how the actual temperature rise through the superheater compares with the design temperature rise it is necessary to state and calculate

Calculate $T_{\text{Design Superheater Rise}}$
(using the equation $T_{\text{Design Outlet Steam Temperature}}$ minus $T_{\text{Design Inlet Steam Temperature}}$ [30]

| Inlet Steam Temperature | Outlet Steam Temperature Above Design by $-10^\circ$ to $-5^\circ$ | Outlet Steam Temperature Above Design by $-5^\circ$ to $+5^\circ$ | Outlet Steam Temperature Above Design by $+5^\circ$ to $+10^\circ$ | Outlet Steam Temperature Above Design by $+10^\circ$ to $+15^\circ$ | Outlet Steam Temperature Above Design by over $+15^\circ$
|-------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------
| Above by $10^\circ$ - $20^\circ$ | Improbable | Improbable | Probable | Certain | Certain |
| Above by $0^\circ$ - $10^\circ$ | Improbable | Possible | Probable | Almost Certain | Certain |
| Below by $0^\circ$ - $10^\circ$ | Impossible | Improbable | Improbable | Possible | Probable |
| Below by $10^\circ$ - $20^\circ$ | Improbable | Possible | Probable | Probable | Almost Certain |
| Below by $20^\circ$ - $30^\circ$ | Probable | Probable | Almost Certain | Almost Certain | Certain |
| Below by $30^\circ$ - $40^\circ$ | Probable | Almost Certain | Almost Certain | Certain | Certain |
| Below by $40^\circ$ | Probable | Almost Certain | Certain | Certain | Certain |

The Inference Engine would then need to use a modified form of Table 8.1 from Chapter 8, which is reproduced above to decide whether the "$40^\circ$C plus outlet steam temperature" is a good guide to the likely metal temperature. A rule would need to be written which states that, when the design temperature rise and the actual temperature rise are similar (as in this case), the $40^\circ$C plus rule can be used. Obviously if the inlet steam temperature departs from the design conditions, as the discussion in Chapter 8 suggests, it becomes more necessary to carry out actual heat transfer calculations rather than rely on rule of thumb estimates.
6.4.3.3 Rules for Estimating the Metal Temperature using Parametric Methods

The aim is to determine the metal temperature based on the actual life using a Larson-Miller parametric calculation. This will utilise the time to failure, a parameter value which is derived from the stress, and a C value that depends on whether the failure is of the premature type. Obtaining these figures is a preliminary step. As before equations must be stated. These include what might be regarded as a general statement:

The Larson Miller derived metal temperature could be stated as:

\[
T_{\text{Metal LMP Derived}}
\]  

There is no simple rule of thumb for calculating the Larson Miller derived temperature which will require the manipulation of the Larson-Miller equation as a sub-routine, using the appropriate values. /

The calculation of the temperature will depend on the metal, the Larson Miller constant (C) and the design stress. In addition for the calculation to proceed the actual time to failure (t_Failure_h) must be known. In this case the metal is P91 and h, the failure time is 25000 hours, and \( \sigma \) is 65 MPa. The actual parameter value for the stress level and the material will need to be acquired from a data set or look up table (unless the expert system has access to a Fourier type equation which relates the parameter value to the stress). In this case the parametric value is 32305. (see Table 9.17)

Furthermore, in this case the value of C is dependant on the “time_failure_ratio” which is the ratio of the failure time to the design life. When the failure ratio is less than 1, the failure is premature and a C value of 31 should be used. Hence it is necessary to do the following

**Calculate Time Failure Ratio**

(using Time Failure Ratio = Time Failure_Time divided by Time Design Life)

\[
[32]
\]

The rules relating to this calculation are:

If P91 is YES

Time Failure Ratio less than 1 Then C is 31 in parametric_equation

\[
[33]
\]

If If P91 is YES and \( \sigma \) is 65 MPa Then parameter is 32305 in parametric_equation

\[
[34]
\]
Using the appropriate parametric value, Larson-Miller constant and time to failure this will result in an equation of the type, where as indicated earlier. The next step is:

\[
T_{\text{Metal LMP Derived}} = \left( \frac{32305}{31 + \log 25000} \right) - 273
\]  

6.4.3.4 Rules for Comparing the Temperature Estimates to Decide on the Need for More Detailed Laboratory Based Investigations

The final aim of these modules is to decide on whether the subsequent investigations should be plant based, laboratory based, or a combination of both. The thinking behind the rules is that if the metal temperatures, as derived from the steam temperatures, are similar to those of the design conditions, it is unlikely that the premature failure has been caused by the operation of the plant, and the material is defective. Alternatively if the estimated metal temperatures, as derived from the steam temperatures are higher than the design temperatures, and agree with the parametric estimates, it is likely that the plant is at fault.

The third case is when the steam temperature estimates are different to the design conditions, but do not agree with the parametric estimates. This would suggest that there is something amiss with the plant, and also with the material. An example of such is where the steam temperatures are higher than design, leading to excessive tube temperatures and wastage of the tube because of fireside attack. The combination of high metal temperatures and reduced wall thickness would result in a greatly reduced time to failure.

These rules are partly based on Table 9.17 in Chapter 9, which states whether the temperature differences between the two sets of estimates warrants further investigation. Table 9.17 is shown below. It would be helpful if this table could be shown on the monitor, or could be called up by the operator to enable him or her to see the implications of any differences in the temperature estimates.

<table>
<thead>
<tr>
<th>Temperature Discrepancy L-M Value minus Plant Value</th>
<th>Significance</th>
<th>Requirement for Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>More than +30°</td>
<td>High</td>
<td>Imperative</td>
</tr>
<tr>
<td>+30° to +15°</td>
<td>Moderate</td>
<td>Desirable</td>
</tr>
<tr>
<td>+15° to +10°</td>
<td>Little</td>
<td>Questionable</td>
</tr>
<tr>
<td>Less than +10°C</td>
<td>Insignificant</td>
<td>Unnecessary</td>
</tr>
</tbody>
</table>

The initial step is to decide on whether the plant is at fault through a comparison of the design and actual conditions. The initial aim is to decide how well the design
metal temperature and that estimated from the steam conditions, as these will give an indication of whether the plant is at fault or not. Hence:

Calculate $T_{\text{Metal\_Steam\_derived}} - T_{\text{Metal\_Superheater\_Design}}$  

In determining the significance these temperature discrepancies, a set of rules can be formulated to cover this aspect. These are based on the discussion in Section 8.5.1 of Chapter 8 which relates to how excessive steam temperatures might induce creep is also helpful in drawing up the rules. These rules would be internal to the Expert System and would not be displayed. They are:

**If** $T_{\text{Metal\_Temperature\_Steam\_Derived}} - T_{\text{Metal\_Superheater\_Design}}$ is $-5^\circ$ to $+10^\circ$

**Then**

Plant_Complies_With_Design_Well and Plant_Conditions_Actual have Insignificant_Affect_On_Failure  

[37]

**If** $T_{\text{Metal\_Temperature\_Steam\_Derived}} - T_{\text{Metal\_Superheater\_Design}}$ is $+10^\circ$ to $+20^\circ$

**Then**

Plant_Complies_With_Design_Fairly and Plant_Conditions_Actual have Moderate_Affect_On_Failure  

[38]

**If** $T_{\text{Metal\_Temperature\_Steam\_Derived}} - T_{\text{Metal\_Superheater\_Design}}$ is above $+20^\circ$

**Then**

Plant_Complies_With_Design_Conditions_Poorly and Plant_Conditions_Actual have Severe_Affect_On_Failure  

[39]

Follow-on rules from Rules 37 to 39 would relate to whether the plant should be investigated would be:

**If** Plant_Conditions_Actual have Insignificant_Affect_On_Failure

**Then**

Plant_Investigations_Unnecessary  

[40]

**If** Plant_Conditions_Actual have Moderate_Affect_On_Failure

**Then**

Plant_Investigations_Desirable
If Plant\textsubscript{Conditions Actual} have Severe\_Affect\_On\_Failure
Then
Plant\_Investigations\_Imperative

These results would be displayed on the monitor.

Notice at this stage the expert system has only been making use of the conditions in the plant. However unlike a human investigator the Expert System would be beginning the opening phase of assessing whether there is something amiss with the P91 material. Here the relevant factor is the difference between two different methods of estimating the metal temperature. The first step is to calculate these:

\textbf{Calculate} T\textsubscript{Metal LMP Derived}

Using this approach four sets of rules, partly based on the table above can be stated

\textbf{If} T\textsubscript{Metal LMP Derived} minus T\textsubscript{Metal Temperature Steam Derived} is more than +30°
\textbf{Then}
Metallurgical\_Significance is high

\textbf{If} T\textsubscript{Metal LMP Derived} minus T\textsubscript{Metal Temperature Steam Derived} is +30° to +15°
\textbf{Then}
Metallurgical\_Significance is moderate

\textbf{If} T\textsubscript{Metal LMP Derived} minus T\textsubscript{Metal Temperature Steam Derived} is +15° to +10°
\textbf{Then}
Metallurgical\_Significance is little

\textbf{If} T\textsubscript{Metal LMP Derived} minus T\textsubscript{Metal Temperature Steam Derived} is less than +10°C
\textbf{Then}
Metallurgical\_Significance is insignificant

The appropriate results would be displayed on the monitor.

The final issue that needs to be decided is whether the problem is due to the plant and also to the material. This is easy to solve, since, if this is the case, the Expert System will indicate that both aspects will need a fuller investigation.
6.4.4 Use of the Rules with the Example Investigation

6.4.4.1 Establish Provisional Failure Mechanism as being Creep

As discussed above it is now possible to do this using the results of rules 15 to 24. This can be done in the following way:

If Failure_Appearance_1 is Tube_Longitudinal_Crack is YES Then
Provisional_Failure_Mechanism is Creep

As noted earlier this statement is becoming cumbersome and would be better expressed as:

If rule 15 is YES Then Provisional_Failure_Mechanism is Creep

Similarly the Expert System can also ascertain:

If rule 16 is YES Then Provisional_Failure_Mechanism is Creep
If rule 17 is YES Then Provisional_Failure_Mechanism is Creep
If rule 18 is YES Then Provisional_Failure_Mechanism is Creep
If rule 19 is NO Then Provisional_Failure_Mechanism is NOT Erosion
If rule 20 is YES Then Provisional_Failure_Mechanism is Fireside_Corrosion
If rule 21 is NO Then Provisional_Failure_Mechanism is NOT Fireside_Corrosion
If rule 22 is NO Then Provisional_Failure_Mechanism is NOT Fireside_Corrosion
If rule 23 is NO Then Provisional_Failure_Mechanism is NOT Overheating
If rule 24 is NO Then Provisional_Failure_Mechanism is NOT Weld_Failure

The Expert System now evaluates the answers and finds the following.
Gaol_1a is YES since Rules 48, 49, 50, 51, are YES (i.e. is Creep) [58]
Gaol_1b is NO since Rule 52 is NO (i.e. is NOT Erosion is NO) [59]
Gaol_1c is YES since Rule 53 is YES (i.e. is Fireside_Corrosion) [60]
Goal_1c is NO since Rules 54, 55 are NO (i.e. is NOT Fireside_Corrosion) [61]
Goal_1d is NO since Rule 56 is NO (i.e. is NOT Overheating) [62]
Goal_1e is NO since Rule 57 is NO (i.e. is NOT Weld_Failure) [63]

Goal_1a has four “YES” answers, whereas most of the other Goals have “NO” answers, apart from Goal_1c, that for fireside corrosion which has one “YES” and two “NOs”.

On this basis the Expert System directs the analysis down to the module which is intended to identify whether the material or the plant is the root cause of the failure. A sub-routine would be needed to direct the Expert System into using the rules associated with the creep set of rules.

Hence:

If Gaol_1a is YES Then calculate
T_Metal_Temperature_Steam_Derived
And
T_Metal_LMP_Derived

6.4.4.2 Calculation of Metal Temperatures

The first step is to estimate the metal temperature from the steam temperature. This is done from:

Calculate T_Metal_Temperature_Steam_Derived
(using the equation T_Actual_Outlet plus 40° [26]

Which gives T_Metal_Steam_Derived = 605°C

This calculation is only really valid if the actual temperature rise through the superheater is equal to the design temperature rise. Hence it is necessary to:

Calculate T_Design_Superheater_Rise [30]
Calculate T_Actual_Superheater_Rise [28]
This is a comparison between the design value and actual value of temperature rise. As the design temperature rise was 60° and the actual temperature rise was also 60° there is no need for complex calculations.

The actual rule relating to this would be:

If T_Design_Superheater_Rise is between $-5°$ to $+5°C$
Then
complex_heat_transfer_calculations are unnecessary
and $T_{Metal\_Steam\_Derived} = 605°C$

[64]

The second part of the assessment is to calculate the metal temperature using the Larson-Miller parameter. This requires the appropriate look up table to be identified. As indicated earlier this requires the use of some additional If….Then rules which stem from the material and the time to failure. In this case the set of rules are:

**Calculate** Time_Failure_Ratio
(using Time_Failure_Ratio = Time_Failure_Time divided by Time_Design_Life)
[32]

The actual Time_Failure_Ratio is 0.25 hence:

If P91 is YES and
Time_Failure_Ratio less than 1 Then $C = 31$ in parametric_equation
[33]

If If P91 is YES and $σ$ is 65 MPa Then parameter is 32305 in parametric_equation
(as determined from the look-table or an equation)
[34]

It is now possible to calculate the estimated temperature based on the parametric estimates:

**Calculate** $T_{Metal\_LMP\_Derived} = 639°C$

This figure should be printed on the monitor.

6.4.4.3 Decision on Whether Root Cause is Plant or Material or Both

As stated earlier the aim now is, using these various temperatures estimates and the design value, to determine, which of the following goals have been achieved. These are:

- To decide whether Root_Cause_Plant (YES or NO) – Goal_2a
- To decide whether Root_Cause_Material (YES or NO) – Goal_2b
To decide whether Root_Cause_Both_Plan_Material (YES or NO) – Gaol_2c

(nb: “NO” is equivalent to “No Problem”)

Hence to decide on whether the plant is at fault it is necessary to:

Calculate $T_{Metal\_Steam\_Derived} - T_{Metal\_Superheater\_Design}$ [36]

After carrying out this calculation it will be seen that the result corresponds to Rule 37 as the temperature difference between the design and temperature as calculated from the stream conditions is only $+5^\circ C$. Hence:

If $T_{Metal\_Temperature\_Steam\_Derived} - T_{Metal\_Superheater\_Design}$ is $-5^\circ$ to $+10^\circ$

Then Plant_Complies-With_Design_Conditions_Well and Plant_Conditions have Insignificant_Affect_On_Failure [37]

This brings us to how Goal_2a might be stated. There are various ways of doing this but a verbal statement is best, using the key phrase:

Plant_Complies-With_Design_Conditions_Well

(notice the use of the word “well”, which distinguishes the rest of this phrase from other design conditions). According we can write:

Goal_2a is NO If plant_complies_with_design_conditions_well

(nb: “If Goal-2a is NO” when there is a no problem with the plant)

For other conditions as represented by equations we can state respectively:

Goal_2a is YES If Plant_Complies With_Design_Conditions_Poorly
Goal_2a is YES If Plant_Complies With_Design_Conditions_Fairly

(nb: “If Goal-2a is YES” when there is a problem with the plant)

To assess Gaol_2b we need to determine the difference between the temperatures as estimated those from the parametric estimates and from the steam conditions. Hence:

$T_{Metal\_LMP\_Derived} - T_{Metal\_Steam\_Derived}$ is more than $+30^\circ$

Then metallurgical_significance is high
If \( T_{\text{Metal\_LMP\_Derived}} \) minus \( T_{\text{Metal\_Steam\_Derived}} \) 
is \(+30\)° to \(+15\)°

Then
Metallurgical\_Significance is moderate

If \( T_{\text{Metal\_LMP\_Derived}} \) minus \( T_{\text{Metal\_Steam\_Derived}} \) is \(+15\)° to \(+10\)°

Then
Metallurgical\_Significance is little

If \( T_{\text{Metal\_LMP\_Derived}} \) minus \( T_{\text{Metal\_Steam\_Derived}} \) 
is less\_than \(+10\)°C

Then
Metallurgical\_Significance is insignificant

In this case the steam derived metal temperature was 605°C but the parametric estimate was 639°C. Hence the temperature difference was 34°C and the metallurgical\_significance is high.

In a similar manner to the writing of Goal 2\_a, we can write:

Goal\_2b is NO if Metallurgical\_Significance is insignificant

[65]

Here again “NO” is equivalent to “No Problem”

In all the other cases Goal\_2b is YES. This basically says that it would be worth doing laboratory investigations to a greater or lesser extent as there is something slightly peculiar about the behaviour of the material.

Turning now to the final situation where both the plant conditions and the material are suspect, this would occur if both Gaol\_2a and Gaol\_2b are YES.

Hence:

Goal\_2c is YES if Gaol\_2a is YES and Goal\_2b is YES

[66]

To emphasise this point we can also write even more strongly that:

Goal\_2c is NO if Gaol\_2a is YES and Goal\_2b is NO

[67]

Goal\_2c is NO if Gaol\_2a is NO and Goal\_2b is YES

[68]

6.4.4.4 Decision on Whether to Investigate the Plant Conditions or the Material

It is now possible to use the set of Goals 2a, 2b or 2c to decide on whether to investigate the plant conditions or to do laboratory investigations. To reiterate what was stated in Section 6.4.4.1 from the set of bullets regarding the sequence of goals, when we come to the third set of goals the aims are:
• To decide whether to carry out a wholly plant based investigation to determine root cause – Goal_3a (YES or NO)

• To decide whether to carry out a detailed laboratory investigation to determine root cause – Goal_3b (YES or NO)

• To decide whether to carry out both a plant based and a laboratory based investigation – Goal_3c (YES or NO)

The set of Goal 2s lead onto the corresponding set in Goal 3s. For example if the first of these is written out in full, we have:

If Goal_2a is YES (because Plant_Complies_With_Design_Conditions_Poorly is YES)

Then

Goal_3a is YES (which is Plant_Investigations are needed)

The converse of this is:

If Goal_2a is NO (because Plant_Complies_With_Design_Conditions_Well is YES)

Then

Goal_3a is NO (which is Plant_Investigations are not needed)

To simplify these types of expressions it is necessary to state the third set of goals explicitly, as follows.

If Goal_3a is YES Then Plant_Investigations are needed [69]

If Goal_3b is YES Then Laboratory_Investigations are needed [70]

If Goal_3c is YES Then Both_Plant_Investigation_Laboratory_Investigations are needed [71]

The converse of these statements is

If Goal_3a is NO Then Plant_Investigations are not_needed [72]

If Goal_3b is NO Then Laboratory_Investigations are not_needed [73]

If Goal_3c is YES Then Both_Plant_Investigation_Laboratory_Investigations are needed [74]

If Goal_2a is YES Then Goal_3a is YES [75]

If Goal_2b is YES Then Goal_3b is YES [76]
If Gaol _2c is YES Then Goal _3c is YES  

[77]

If Gaol _2a is NO Then Goal _3a is NO  

[78]

If Gaol _2b is NO Then Goal _3b is NO  

[79]

If Gaol _2c is NO Then Goal _3c is NO  

[80]

In this case there is a need for metallurgical investigation because the discrepancy between the steam derived estimates and the parametric estimates of the metal was so high then, Goal _2b is YES. From this we can state in harmony with Rule 75:

\[\text{If Gaol}_2\text{ is YES Then Goal}_3\text{ is YES}\]

It then follows that:

\[\text{If Gaol}_3\text{ is YES Then Laboratory Investigations (are needed)}\]

[81]

This conclusion would be printed out on the screen. However the necessity for laboratory investigations increase as the difference in the metal temperatures derived from the parametric estimates increase. The Expert System will be able to advise on the need for this using the following rules:

\[\text{If Laboratory Investigations Then evaluate Rules 83, 84, 85}\]

[82]

These If...Then rules are also based on Table 9.17 which was previously used to decide whether the plant was at fault or the materials was at fault. However the same difference in the temperature predictions can be used to decide on whether worth doing an investigation of the material. If the temperature difference is stated in words and the temperature difference was more than 30°C, this would have the form:

\[\text{T-Metal LMP-Derived minus T-Metal Temperature Steam-Derived is more than +30°}
\text{Then}
\text{Significance is High and}
\text{Laboratory Investigations are Imperative}\]

[83]

In this case the discrepancy is 34°C, hence the equation would comply with Rule 83. This result and the others, where the temperature difference is not so pronounced can be written as:
If T_Metal_LMP_Derived minus T_Metal_Temperature_Steam_Derived is $+30^\circ$ to $+15^\circ$ 

Then

Significance is Moderate and
Laboratory Investigations are Desirable

[84]

If T_Metal_LMP_Derived minus T_Metal_Temperature_Steam_Derived is $+15^\circ$ to $+10^\circ$

Then

Significance is Little and
Laboratory Investigations are Questionable

[85]

This effectively leads onto the questions arising out of the laboratory investigation. As Chapter 7 will show this is an important issue in itself, and the issues which arise, although related to the mechanics of rule formulation, bring up some rather different issues.
Chapter 7

A Probabilistic Approach Uncertainty in the Diagnosis of Failures

7.1 Probabilistic Rules

By their nature heuristic rules entail a good deal of uncertainty. Grappling with uncertainty is as much a problem in expert systems as it is life itself. If -Then rules, of their nature, give yes/no answers, working on “two-valued” logic. We need devices which can contend with the fact that rule of thumb responses sometimes cannot give even a definite “maybe” let alone a “yes or no” answer to most If...Then questions.

In this respect Parsaye and Chignell have a chapter on “Uncertainty”, which covers elementary forms of the Bayes’ Theorem [1]. Jackson goes into the subject in a somewhat deeper fashion in a chapter on “Representing Uncertainty” which is also concerned with the concept of “Conditional Probabilities” and Bayes’ theorem, but cover, in addition, some aspects of set theory and fuzzy logic [2]. The main concerns of both of these authors are that of quantifying heuristic rules, dealing with simple probabilistic concepts in expert systems, and bringing together the tentative conclusions of several heuristic rules, when the probabilities are known. It was necessary to investigate the mathematics underlying these ideas and the following proved helpful

The Venn diagram, which is integral to set theory and fuzzy logic, can be used to introduce the concept of conditional probabilities. In the example shown, this particular Venn diagram consists of a rectangle, which is supposed to include all sets of coloured balls. For clarity only the sets of red and blue coloured balls are shown.

![Venn Diagram showing separate sets of red and blue balls](image)

Figure 7.1: Venn Diagram showing separate sets of red and blue balls

In Figure 7.1 there are two independent sets red and blue balls. In a sense we can reach into the Venn diagram and pick out red balls, blue balls, or balls of a different
colour by choosing from the surrounding areas. However the Venn diagram can also be used to illustrate the possibility of a cause producing an effect. This can be shown by joining the two sets to one another, as in Figure 7.2.

Figure 7.2: Venn diagram showing that the two sets of red and blue objects have been used to create a mixed set

There are two mathematical expressions that describe the joining of the two areas. The combined area produced by the joining is termed the “union”, as exemplified by the area enclosed by the thick line. The mathematical form is denoted by:

\[
\text{Red } \cup \text{ Blue}
\]

The area of overlap, that is the hatched area, is termed the “intersection” of red and blue and is denoted by:

\[
\text{Red } \cap \text{ Blue}
\]

The intersection is, in a sense, a mathematical abstraction. Another way to think about the intersection is that it gives an idea of the amount of mixing that is going on between the red and blue ball areas. If there is a lot of mixing, the area of intersection is greater.

In probability theory, the greater the overlap between the red and blue areas, that is the area of intersection, the more confident we can be that there is some cause and effect relationship between the two. Taking the analogy further, this cause and effect relationship could suggest a game, whereby if a blue ball was picked out one might then be given a red ball as a present. The more the two areas overlap, the greater the chance one would be given a red ball. That is, the picking out of a blue ball will have been the cause of being given a red ball.

In most complex situations, as in real life, there is never one-to-one relationship between cause and effect. In the Venn diagram, the bigger the overlap between the red and blue, the greater the chance of being given a red ball, if a blue one is found first. For one to be given a red ball every time, the two areas on the Venn diagram
would need to overlap completely and would need to be exactly the same size and shape. If the two areas did not intersect, as was shown in Figure 7.1, one would never be given a red ball if a blue one was found.

The size of the areas in the Venn diagram indicate the probabilities of the two types of coloured ball being found. It is therefore apparent that there is less chance of finding a red ball rather a blue one. The probabilities of these are characterised, mathematically, as:

\[ P(\text{red}) \quad \text{and} \quad P(\text{blue}) \]

The probability of finding red and blue balls together, which is designated the total probability, is given by the area of the intersection, that is:

\[ P(\text{red} \cap \text{blue}) \]

\( P(\text{red} \cap \text{blue}) \) and \( P(\text{blue} \cap \text{red}) \) are both governed by the area of the intersection, and are equal to one another.

The probability of being presented with a red ball, having first picked out a blue ball, is characterised by the expression \( P(\text{red} \mid \text{blue}) \), which in words should be stated as "probability of red given probability of blue". It follows that \( P(\text{red} \mid \text{blue}) \) is governed by:

The area of the intersection = \( P(\text{red} \cap \text{blue}) \)

The size of the blue area = \( P(\text{blue}) \)

Which leads to the first law of conditional probabilities.

\[ P(\text{red} \mid \text{blue}) = \frac{P(\text{red} \cap \text{blue})}{P(\text{blue})} \]

\( P(\text{red} \mid \text{blue}) \) is termed the "conditional probability" as the probability of being given a red ball partly depends on the finding a blue ball first, and also on the how strong is the probability of actually being given red ball if a blue one has been found.

If the game was reversed, so that if one is given a blue ball, when a red ball is found first, gives a different set of probabilities, which is denoted by:

\[ P(\text{blue} \mid \text{red}) = \frac{P(\text{red} \cap \text{blue})}{P(\text{red})} \]

Note that the chances of being given a blue ball if red one is found first, that is \( P(\text{blue} \mid \text{red}) \) would be much less than being given a red ball, if a blue ball is found first, that is \( P(\text{red} \mid \text{blue}) \) even though the area of intersection is the same. This follows from the fact that the red area is smaller than the blue area, indicating that there is much less chance of picking up a red ball.
Accordingly although the intersection area is the same for both cases:

\[ P(\text{red} | \text{blue}) = \frac{P(\text{red} \cap \text{blue})}{P(\text{blue})} \]

Does not normally equal

\[ P(\text{blue} | \text{red}) = \frac{P(\text{red} \cap \text{blue})}{P(\text{red})} \]

From these two expressions we can derive Bayes’ rule by making use of the fact that:

\[ P(\text{red} \cap \text{blue}) = P(\text{red} | \text{blue}) \cdot P(\text{blue}) = P(\text{blue} | \text{red}) \cdot P(\text{red}) \]

Hence Bayes’ rule

\[ P(\text{red} | \text{blue}) = \frac{P(\text{blue} | \text{red})}{P(\text{red})} \cdot \left[ P(\text{blue} | \text{red}) \right] \cdot \left[ \frac{P(\text{red})}{P(\text{blue})} \right] \]

This indicates the probability of being given a red ball, after a blue one has been picked, is partly determined by the chance that if a blue is picked first, a red one will be given, and also by the ratio of the probabilities of finding red and blue balls together.

### 7.2 Conditional Probabilities for Root Cause Superheater Failure Investigations

To reiterate, the conditional probability \( P(\text{F} | \text{E}) \) is given by the probability an event \( \text{F} \), and a symptom or cause \( \text{E} \), are normally found together. That is:

\[ P(\text{F} | \text{E}) = \frac{P(\text{F} \cap \text{E})}{P(\text{E})} \]

Note that the fact that an event occurs alongside a possible cause does not imply the two have to be connected. That a superheater has failed by creep is not necessarily related to the fact that the superheater has been overheated. Although overheating is the most common form of creep failure, creep failures can be caused by the equipment having been operated beyond its design life, or having been caused by a deficiency in the materials of construction.

The can be illustrated with the Venn diagram in Figure 7.3, which is supposed to represent all forms of superheater failure, the rectangle itself representing all possible causes of failure. Hence the probability for the rectangle \( P(\text{All Forms of Failure}) \) is 100%. As overheating is a major contributor to superheater failures, it encompasses 40% of the diagram, as represented by the elongated grey patch.
The roughly circular darker patch, in the centre of the diagram, represents the fact that about 15% of superheater failures are caused by creep. Note that although the creep patch overlaps the overheating region, part of it lies outside. This indicates that some creep failures, as previously stated, have nothing to do with overheating.

In this case, assuming that we have good reason to know that overheating is occurring on a plant, and that a failure has occurred, we can use the concept of conditional probabilities to work out how probable it is that the overheating might have caused the creep failure. In this case, the failure is the event (F) and the cause (E) is overheating.

If, as shown in the diagram the probability that creep and overheating are found together in 10% of all failure cases, then:

\[ P( F \cap E) = 0.1 \]

The diagram also shows that overheating is associated with 40% of all failures, accordingly

\[ P(E) = 0.4 \]

Applying the conditional probabilities rule then

\[ P(F | E) = \frac{P(F \cap E)}{P(E)} \]

\[ P(F | E) = \frac{0.1}{0.4} = 0.25 \]

In other words, if a failure has occurred and overheating has been noted from temperature records, or operating staff statements, etc, then the chances that it had caused the creep would be 25%.
Overheating is a symptom that something is wrong or will be going wrong. However, as noted above, overheating is a phenomenon that does occur quite frequently on power plants and can play a part in other types of failure, such as erosion, creep-fatigue, and high temperature corrosion. Figure 7.4 shows this schematically, as the overheating area intersects these alternative failure mechanisms, besides that of creep. However, some superheater failures, such as stress corrosion, are not related to overheating and have other causes, and lie outside of the overheating area.

It follows that where a cause is one that can be associated with many failure mechanisms, it is not sensible to assume that if it is occurring it would lead it a definite form of failure. What may be termed the back calculation enables us to determine $P(E | F)$, which is the strength of the relationship between the event and it probable cause. Because the area of intersection between creep and overheating is such a high proportion of the area for creep, there is a very good chance that the overheating will have led to the creep failure. Therefore from the equation:

$$P(E | F) = \frac{P(E \cap S)}{P(E)}$$

and using the same probabilities as in the previous example:

$$P(E | F) = \frac{0.1}{0.15} = 0.67$$

This indicates that if we have definitely decided that the failure is of the creep type, there is a 67% chance that the superheater is being overheated. This would be the kind of conclusion a failure investigator would make, having determined that the failure was of the normal creep variety. It could be argued that these conditional probability rules result in a kind of circular argument. However, in the first case the failure investigator would only have the observations that the superheater had been...
running hot. He would not have even seen the failure. Hence at this stage his conclusions about the failure mechanism would be quite tentative.

Figure 7.4 also shows that there is a small amount of overlap between the creep and the high temperature corrosion area. In practical terms this would mean that fireside corrosion had led to a loss of wall thickness, thereby raising the stress and increasing the chances of a failure by creep. That is both fireside corrosion and overheating will have contributed to being root causes of the failure. However, as the fireside corrosion is accelerated by the overheating, it is necessary to determine how strongly this was influenced by the overheating.

Where fireside corrosion and overheating have helped to cause a creep failure we can write:

\[
P ( \text{creep} \mid \text{corrosion} \cap \text{overheating} ) = \frac{P(\text{creep} \cap \text{corrosion} \cap \text{overheating})}{P(\text{overheating})P(\text{corrosion} \mid \text{overheating})}\]

The intersection area of all three phenomena is about 1% of the total area, so that

\[
P (\text{creep} \cap \text{corrosion} \cap \text{overheating}) = 0.01
\]

\[
P(\text{overheating}) \text{ as previously } = 0.4
\]

\[
P(\text{corrosion} \mid \text{overheating} ) \text{ that is the probability of overheating being a cause of fireside corrosion is given by } \frac{P(\text{corrosion} \cap \text{overheating})}{P(\text{overheating})}. \text{ Since the intersection between fireside corrosion and overheating is about 0.07 then:}
\]

\[
P(\text{corrosion} \mid \text{overheating} ) = 0.07/0.4 = 0.175
\]

Therefore \[ P ( \text{creep} \mid \text{corrosion} \cap \text{overheating} ) = 0.01/ (0.4) \cdot (0.175) = 0.142 \]

These two results show that there is real possibility, given the sizes and amounts of interaction shown in the Venn diagram, that wastage due to fireside corrosion has been a cause of creep.

One real merit of the Venn diagram technique is that once it is understood, it becomes easier to set down on paper how various causes might interact with one another. Once the areas have been put down in a schematic fashion it becomes possible, using spreadsheet, to adjust the probabilities and the levels of interaction so that sensible levels of cause and effect will result. That is human experts can test or evaluate different values for probabilities until the results of each conditional probability calculation begin to fit in with their experience.

### 7.3 Issues in the Application of Conditional Probabilities

As shown above some of the issues in the application of conditional probabilities can be demonstrated using simple models based on Venn diagrams. But there are
conceptual problems in using conditional probabilities. As will be shown, although, they can be used, with some caution, to help determine the root cause of plant based failures, when it comes to using causal evidence to determine failure mechanisms, Bayes' rules seem to be more appropriate.

Figure 7.5: Showing relative probabilities of a failure type and a cause

The problems in applying conditional probabilities need to be recognised when designing expert systems. Some of the initial difficulties are shown in Figure 7.5. In these, the left hand circle represents the probability that a specific type of failure (F) has occurred and the right hand circle represents the probability that this particular root cause (C) will have happened.

In all of the diagrams the circle partially overlap. The amount of overlap shows the chances of the root cause having led to the failure. Note that amount of overlap is critical and this partly depends on the diameters of the two circles. If the ratio of the area of overlap to the area of the cause is the same in all cases, then the conditional probability \( P(\text{Failure} \mid \text{Cause}) \) would be the same in all cases. In Case 1, the diagram indicates that this type of failure is very common, but the root cause does not happen that often. Hence the rule of conditional probability shows that there is a reasonable chance that it will have been the cause. The chances of this will increase with the amount of overlap.

In Case 2, the small size of the left hand circle indicates that this type of failure does not happen very often, but the possible cause happens frequently. One way to think about this is that this cause happens a lot of the time, but does not always lead to this type of failure.

In Case 3, both this type of failure and the possible cause happen a lot of the time. It follows that when there is a good degree of overlap the there will be a strong connection between the failure and possible cause. In Case 4 although the size of the circles is smaller than in Case 3, here again if there is good overlap there will be a strong connection between failure and possible cause. Neither failures nor causes
happen very often, but when the cause does occur there is a good chance it will lead to the failure.

A further set of schematic Venn diagrams can also clarify the relationship between failures and causes. See Figure 7.6. Here the aim is to show the effects of intersection on the relationship between cause and effect. Here the circle representing the failure is hatched and the circle representing the cause is left clear.

![Figure 7.6 Showing effect of 100% intersection of failure probabilities and root causes.](image)

It will be seen that with Case 5, the overlap, or intersection, between the failure and cause is large. It follows from the equations of conditional probability that there it is highly probable that this particular cause will have led to the failure. If the two circles had coincided exactly, that is complete intersection, the probability of the cause having led to the failure would 100%. With Case 6 although the area of the circles and the intersection areas are smaller, once again, if there had been complete overlap, the probability of the cause leading to the failure would have been would been 100%.

Accordingly for both Case 5 and 6

\[
P \left( \text{Failure Type} \mid \text{Root Cause} \right) = \frac{P \left( \text{Failure Type} \cap \text{Root Cause} \right)}{P \left( \text{Root Cause} \right)} \text{ is close to 1}
\]

The strong relationship between this particular type of failure and this particular cause, can be shown by assessing how strongly the failure points back to a possible cause, by calculating \( P \left( \text{Root Cause} \mid \text{Failure Type} \right) \). When the two probabilistic circles coincide fully, this "backwards equation" will "point" back, 100%, to the root cause (i.e probability of 1) or:

\[
P \left( \text{Root Cause} \mid \text{Failure Type} \right) = \frac{P \left( \text{Failure Type} \cap \text{Root Cause} \right)}{P \left( \text{Failure} \right)} = 1
\]
Cases 7 and 8 are more likely to occur in practice, where the probability of a given type of failure is not the same as the probability of the cause. With Case 7, the cause does not happen very often, although this type of failure happens a lot. This would suggest that the cause, when it does occur, will always induce this type of failure. Indeed, in this case as the area of intersection is equal to the probability of this particular root cause, it has a 100% probability of giving a failure of this particular type. An example of such a cause would be the installation of an ordinary carbon steel pipe in a superheater instead of a steel with good creep resistance. This would invariably lead to a premature creep failure.

In Case 8, there is also complete overlap, but the chances of the root cause occurring are much higher than the incidence of this particular failure type. It follows that:

\[
P(\text{Failure Type} \mid \text{Root Cause}) = \frac{P(\text{Failure Type} \cap \text{Root Cause})}{P(\text{Root Cause})} < 1
\]

Here the opposite situation prevails, in which this type of failure is quite uncommon, although the cause happens frequently. In colloquial terms, people are “constantly getting away with it”. For example, designers and operators often neglect drainage of superheaters, which leads to the build up of condensate during shutdown periods. On start up the cold condensate will be carried through the system leading to thermal shock and eventual failure of tube stubs and headers, but only if there are enough shutdowns and restarts. It is only because most materials are quite resistant to thermal shock that this type of failure is not as common as it might be. The tie up between cause and effect is shown by running the equation backwards in which case:

\[
P(\text{Root Cause} \mid \text{Failure Type}) = \frac{P(\text{Failure Type} \cap \text{Root Cause})}{P(\text{Failure Type})} = 1
\]

An experienced failure investigator will be aware of these cause and effect considerations, when evaluating failure causes, and will try to avoid jumping to conclusions. Situations that are typified by Cases 7 and 8 can present real difficulties with expert systems, but some help can be obtained by running the chains of evidence backwards. This is something people can do, and something like this could be built into the failure diagnosis package.

In practice, there is usually, if a failure has occurred, more than one possible root cause. The elimination of some of the possibilities represents positive evidence in support of the actual root cause.

The other main difficulty in the application of conditional probabilities is that it is apparent from the equations, as the probability of the root cause increases, the probability that it is the cause of the event decreases. Although, as discussed earlier, it is possible to argue that as the likelihood of a root cause falls, it becomes more possible to tie this to a specific type of failure, this would be a puzzle to many experts trying to set up their own system. As discussed earlier, overheating tends to produce creep failures. The problem in designing an expert system which would utilise this information is that if the user puts into the system the fact that a plant is
suffering badly from overheating, the expert system would calculate that the chance of creep failure occurring was low, that is:

\[ P(\text{creep} \mid \text{overheating}) = \frac{P(\text{creep} \cap \text{overheating})}{P(\text{overheating})} \]

It would possible to compensate for the probability that the equipment having overheated by increasing the probability of an intersection occurring as shown in the Venn diagram in Figure 7.7.

\[
\begin{array}{c}
\text{F} \\
\text{C}
\end{array} \quad \Rightarrow \quad \begin{array}{c}
\text{F} \\
\text{C}
\end{array}
\]

**Fig 7.7:** Showing proposed method of compensating for an increase in the cause (C) of a failure (F) by increasing intersection.

This makes engineering sense, but it calls for a judgement to be made how quickly the intersection should grow compared to the growth in the probability of overheating. This can be illustrated using Bayes rule, which in this case can be stated as:

\[ P(\text{creep} \mid \text{overheating}) = P(\text{overheating} \mid \text{creep}) \cdot \frac{P(\text{creep})}{P(\text{overheating})} \]

To demonstrate the increase in the likelihood that creep has been caused by the overheating, as the probability of overheating increases it is necessary to either (i) increase the ratio of the probabilities of creep to overheating, that is \( \frac{P(\text{creep})}{P(\text{overheating})} \) or (ii) to increase the probability that if creep has occurred this does also suggest that overheating is likely to occur, that is \( P(\text{overheating} \mid \text{creep}) \) needs to increase.

Part of the problem come from the underlying idea that in these equations that we are dealing with events that are completely probabilistic. That is all terms in the conditional probabilities and Bayes’ equations are related to statistical considerations. In failure analysis only some functions have these probabilistic connotations. Clearly \( P(\text{creep} \mid \text{overheating}) \) has a statistical or probabilistic character, as although overheating does cause creep, it is not the only cause. Similarly \( P(\text{overheating} \mid \text{creep}) \) suggests that if creep has occurred it is sensible to investigate whether the plant has overheated, although again a creep failure can have occurred without any overheating.

However, the fact that creep has occurred is not really a probabilistic event. We can determine with a high degree of certainty whether the failure mechanism is that of creep, so it no longer become a probabilistic event in normal statistical term. That is
we have not looked at 1000 superheaters failures and stated that 100% of them have failed by creep. We are dealing with just one failure and the failure probability has a heuristic nature. Similarly we can also determine, with a reasonable degree of heuristic confidence, whether or not the plant is overheating. The conclusion must be that, in using conditional probabilities for root cause identification, they are not altogether helpful and need to be used with caution. In many cases they can be dispensed with, using simple If....Then rules to work through to the root cause. Probabilistic ideas become more helpful when weighing evidence in support of failure mechanism. Here, concepts based on Bayes rules will be shown to be very helpful if they are manipulated in the right way.

7.4 Bayes' Rules

Bayes' rules stem from the equations of conditional probability, in which the probability of an intersection of an event, such as a superheater failure mechanism (F) and a symptom or evidence that points to this type of failure (E), then is $P(F \cap E)$ is equal to both:

$$P(F|E).P(E) \text{ and/or } P(E|F).P(F)$$

Rearranging these two expressions:

$$P(F|E) = \frac{P(E|F)P(F)}{P(E)} \cdots \cdots \cdots \cdots (3)$$

In this case $P(F|E)$, which is the "posterior" probability of failure mechanism being diagnosed correctly, is related to the prior probabilities of the following:

$P(E|F)$ = Conditional probability with which the evidence is normally associated with this type failure mechanism

$P(F)$ = Prior probability of the failure mechanism being that which caused the failure

$P(E)$ = Prior probability that this type of evidence comes to light in the course of investigations

(* The terminology associated with Bayes' rules is not very obvious to modern readers. "Posterior" in this context means the conclusion that could be made after ( nb after-behind-posterior are all synonyms) all the evidence was assimilated and manipulated. "Prior" in this case refers to information which comes to light or which is accepted as being correct at the start of the investigation)

Bayes' rule, in this form, is essentially that used in the equations for conditional probability described earlier, and have the same counter intuitive difficulty that, as the frequency of the evidence increases, the probability of the failure being diagnosed by the evidence falls. However, the frequency of the evidence $P(E)$ can be replaced by an expression which takes into account of the fact that there may be evidence or symptoms which either do not support the hypothesis or will lead up the event, that is:
\[ P(E) = P(E|F)P(F) + P(E|\text{Not } F) \cdot P(\text{Not } F) \] \hspace{1cm} (4)\\

\( P(E|\text{Not } F) \) quantifies the probability that the evidence is not associated with the failure mechanism. \( P(\text{Not } F) \) is the probability of other failure mechanisms other than the one that is being investigated. The "Not Event" in eqn (4) may be thought of, in Venn diagram terms, as being related to those zones of the diagram that are outside of the type of mechanism being investigated.

Accordingly
\[ P(F|E) = \frac{P(E|F)P(F)}{P(E|F)P(F) + P(E|\text{Not } F) \cdot P(\text{Not } F)} \] \hspace{1cm} (5)

In most texts Bayes' equation is discussed in the context of statistical probabilities and Waner gives a good example of the use of eqn (5) in deciding how likely it is that an athlete has, in fact, been taking drugs, despite his denials, but who has tested positive. In the example given, 10% of the team are considered to be taking drugs. But the test for drugs has some problems. For 95% of the time it will identify those athletes who are taking drugs, but miss 5%. It also will categorise 15% of athletes who are not taking drugs, as drug takers. If the event (F) in this case is the drug test, and (E) are athletes who are taking drugs, then

\begin{align*}
P(E|F) & \quad \text{positive test for real drug takers} = 0.95 \\
P(E|\text{Not } F) & \quad \text{positive (incorrect) test on non drug takers} = 0.15 \\
P(F) & \quad \text{proportion of drug takers on the team} = 0.1 \\
P(\text{Not } F) & \quad \text{proportion of non drug takers on the team} = (1-0.1) = 0.9
\end{align*}

From equation (5), using these values, one can calculate that \( P(F|E) \), which is the likelihood that the athlete, who tested positive, is actually a drug taker, is 0.4130 or just over 40%.

In this case \( P(E|\text{Not } F) \) is known, but in many situations it would be necessary to assume that
\[ P(E|\text{Not } F) = P[1-P(E|F)] \] \hspace{1cm} (6)

And
\[ P(\text{Not } E) = 1-P(F) \] \hspace{1cm} (7)

Hence it is possible to write eqn (5) as:
\[ P(F|E) = \frac{P(E|F)P(F)}{P(E|F)P(F) + [1-P(E|F)] \cdot [1-P(F)]} \] \hspace{1cm} (8)
The author considers eqn (5) and perhaps to an even greater extent eqn (8) as being much more useful in the analysis of failures than eqn (3) as they explicitly recognise the importance of contradictory evidence in making a judgement about P(F|E). These forms of the Bayes’ equation also avoid the apparent contradiction that as the probability of cause occurring or the reliability of evidence increases, the probability of event being related to the cause or evidence falls.

Using eqn (8) the probability that the “raw” evidence points to the event or failure mechanism P (F | E), can be plotted in terms of P (E | F), that is how often the evidence can normally be associated with the failure mechanism, and how frequently the event or failure mechanism occurs. Figures 7.8 to 7.11 are of this type, where the vertical axis entitled “Probability of Evidence Indicating Failure Mechanism” is equivalent to P (F | E). In each of the figures the levels of P (E | F) are shown in the boxes at the side of the graphs. The frequency of occurrence of the failure mechanism forms the horizontal axis.

Fig 7.8: Probability of Correct Indication of Failure Mechanism at High Levels of Reliability of Evidence

Figures 7.8 and 7.9 are of the basic type and show the relationship between the likelihood of failure by a specific mechanism and how reliable is the evidence that indicates the failure mechanism. Some surprising conclusions emerge. The topmost curve in Figure 7.8 is one where the evidence is 99% reliable, that is it is “extremely good”, at predicting the failure mechanism. Nevertheless, it will be seen that the failure has to be quite common before we can be reasonable confident that the failure is of a particular type. Indeed for this “extremely good evidence” to predict the failure mechanism with a certainty of 95%, more than 15% of the failures would have to be of that specific mechanism. In practical terms this could mean getting the
wrong result 1 time in 20. Indeed the implications of the curves in Figure 7.8 are that for failure mechanisms that are relatively infrequent, very strong evidence would be needed before one could definitely say that the failure was of that particular type.

It also follows, as shown by Figure 7.9, where this type of evidence does not give very good support to this type of failure mechanism, it actually reduces the probability that the failure mechanism has been properly identified.

Table 7.1 shows more clearly the relationship when the evidence is 99% reliable but the failure mechanism varies between 1% and 5% of failures. When the failure mechanism only happens one in a hundred cases, the overwhelming evidence only points to a 50% probability of that type of failure having occurred. Perhaps one way to look at this is there is at least some evidence which support this particular hypothesis even though such failures only rarely occur.

Table 7.1: Relationship between Correct Indication of Infrequent Failure Mechanism when Evidence is Extremely Good

<table>
<thead>
<tr>
<th>Failure Mechanism Frequency P(F)</th>
<th>0.01</th>
<th>0.02</th>
<th>0.03</th>
<th>0.04</th>
<th>0.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of Evidence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indicating Failure Mechanism</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P(F</td>
<td>E) when P(E</td>
<td>F) is 0.99</td>
<td>0.50</td>
<td>0.67</td>
<td>0.75</td>
</tr>
</tbody>
</table>

This situation can occasionally occur in human relationships. We have all been in situations where, although the evidence may be absolutely positive, we cannot believe that someone we know quite well would have behaved quite so badly or stupidly. A similar situation can arise in the field of technology where equipment or software which has a well proven record of reliability is initially held not to be responsible for major accident. Only after all other possibilities have been exhausted, and after the equipment is tested under the conditions that have led to the accident, can we be reasonably sure that it was the cause. Even so failure investigators will often qualify their findings on the “balance of probabilities”. That is, other causes of failure seem even less likely.

In our case these considerations are somewhat academic. As will be demonstrated Bayes’ equations, in Expert Systems, are used somewhat differently to the way they tend to be used in probabilistic determinations. The effect of this is that only high levels of failure frequency, \( P(F) \) are used in the Bayes’ equations in Expert Systems. The more important question is how well such evidence, that might be available, ties in with a given failure mechanism. For example high levels of steam side oxidation will normally suggest high operating temperatures, which could point to a creep failure mechanism. However high temperatures can be associated with other failure mechanisms.

Figure 7.9 deals with the situation where the evidence is not very good at pointing to a particular type of failure. The curves show, not surprisingly, that the evidence is fairly useless at identifying the failure mechanism unless this is a very common
cause of failure. If the evidence was only 40% accurate in failure diagnosis, for it to be a reasonable good predictor, this type of failure would have to be occurring very frequently. If we were looking for an “almost certain” conclusion (see below) this type of failure would have to be responsible for about 14 out of 15 failures. In fact the results show that poor quality evidence points away from a specific type of failure not towards it.

Fig 7.9: Probability of Correct Indication of Failure Mechanism Correctly at Low Levels of Reliability of Evidence

Figures 7.10 and 7.11 show the situation when the evidence in support of a specific mechanism may be contradicted by evidence in support or another mechanism.

Figure 7.10 shows a typical failure analysis situation in which the evidence that supports a particular mechanism is not very conclusive, having a probability of being right of only 70%. The supposition is that there is an alternative mechanism, where the evidence in its support has a reliability of respectively 20, 30 and 40%, as shown by the three curves. When the evidence in support of the alternative mechanism is 30%, this is equivalent to the lowest of the curves in Figure 7.8, which was derived using an expression based on P(1-F). If the evidence is support of the alternative failure mechanism is not strong, at 20%, this actually strengthens the argument in support of the initial hypothesis of the cause of the failure. This is equivalent to a human expert having run through some of the alternative ideas and finding so little support for them that he or she is left with only one conclusion, however dubious this might be. If however, the evidence supporting the second mechanism is greater than (1-F), in this case when the support is 40%, then this weakens the argument in support of the first mechanism.
Fig 7.10: Effect of Evidence in Support of an Alternative Failure Mechanism on where the Likelihood of the Primary Mechanism is only 70%.

Figure 7.11: Showing Situation Where the Evidence in Support of the Second Mechanism is Stronger than the First Mechanism.

Figure 7.11 shows the situation where the evidence in support of second mechanism is much stronger than that of the first mechanism. Here the second mechanism has a fixed probability of being correct of 70%, whereas the reliability of the first mechanism falls from 40, down to 20%.
Quantifying Evidence and Symptoms in Failure Analysis

As might be supposed, most of the discussion about the use of conditional probabilities and Bayes Rules is related to the use of hard statistical data, in which the probabilities of events, symptoms and evidence can be quantified. The example given earlier in which the likelihood that an athlete was a drug taker was assessed is quite typical gives a similar example based on DNA evidence being used to identify a criminal. The closest example to that of failure analysis, is that used in MYCIN as discussed by Jackson [2]. This is an expert system program to decide which antibiotic should be used to combat bacterially induced blood infections. In so doing MYCIN quantifies the ways in which the organism reacts to staining, its shape and its aerobicity. These characteristics are given “certainty factors” which relate to how closely they correspond to, for example, whether the bacteria are rod or egg shaped.

In MYCIN the critical value that is used from these certainty factors is taken to be the minimum value. This is not the way failure investigators work as they combine the evidence from each set of observations, heuristically, rather than rely on just one maximum or minimum value. Jackson comments that this approach does not always agree with straightforward probabilistic analysis, but nevertheless appears to have given good results. Much of his subsequent discussion, which includes a critique of other approaches, is based on the manipulation of these certainty factors and how they might be used to point to a course of action. A major failing of his discussion is a critique of the methods by which the certainty factors were quantified.

The same kind of shortcoming is also seen in a long article in the “Stanford Encyclopaedia of Philosophy” on Bayes’ Theorem, which reviews a number of ways in which the evidence can be assessed using the theorem [3]. Indeed the usual tendency is for writers to assume that the relevant probabilities have been quantified, with little or no discussion on how heuristic, or rule of thumb observations might be turned into numbers. What follows, therefore is an attempt to show how this might be done, in failure analysis, basing this as far a possible on the Bayes’ equation and the type of graphs generated in the previous Section. The parameters that need to be quantified are:

- Adjectival Descriptions
- Methods of Deciding of Probability of Failure Mode
- Relationships Between Evidence and Possible Failure Mechanisms

The intention is to do this in the clearest possible fashion, so that similar procedures can be used in other types of failure analysis.
7.5.1 Quantifying Adjectival Descriptions

One of the merits of the Figures 7.8 to 7.11 is that they help show, in pictorial terms, what is the probabilistic reality of some of the things which people say. As mentioned above, the statement someone is “99% certain that the evidence points to a particular failure mechanism” does not necessarily mean that the conclusion is 99% likely to be correct. Bayes’ theorem shows that such a statement is only likely to be true if that specific failure mechanism is reasonable common. Similarly, for a failure mechanism to be impossible, it would need the failure mechanism to be relatively uncommon. Hence when we categorise evidence, and state its quality or reliability using verbal or heuristic expressions, it is necessary to gauge where these might be situated on the graphs shown above.

It was pointed out in Chapter 6 because of the inflexibility of the If...Then rules, it is necessary to create a semantic glossary, which has to be used in conjunction with the rules. This overcomes a major shortcoming of the rules, which are of the two valued logic type, giving “Yes” or “No” responses, producing statements such as “If X is Yes Then Y is Yes” or “If X is No Then Y is Yes”. Such rules imply that if “X” was the evidence, and the evidence is absolutely reliable, the conclusion “Y”, of the rule, is also absolutely reliable. The glossary therefore contained sets of adjectives and adjectival phrases that could be used to express the degree of confidence in evidence or conclusions. The most important of these, termed the “Qualitative Level of Reliability of Conclusions or Evidence” is shown below:

<table>
<thead>
<tr>
<th>Adjectival Reliability of Evidence</th>
<th>Probability of Evidence Being Correct</th>
<th>Evidence points to Failure Mechanism (Mechanism Frequency= 0.7)</th>
<th>Evidence points to Failure Mechanism (Mechanism Frequency=0.9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impossible</td>
<td>0.1%</td>
<td>0.2%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Improbable</td>
<td>5%</td>
<td>10.9%</td>
<td>32.1%</td>
</tr>
<tr>
<td>Possible</td>
<td>30%</td>
<td>50%</td>
<td>79.4%</td>
</tr>
<tr>
<td>Probable</td>
<td>60%</td>
<td>77.8%</td>
<td>93.1%</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>90%</td>
<td>95.5%</td>
<td>98.7%</td>
</tr>
<tr>
<td>Certain</td>
<td>99%</td>
<td>99.6%</td>
<td>99.9%</td>
</tr>
</tbody>
</table>
These values of probability, for each level of reliability, have been formulated, by the author. Having quantified these probabilities, it then becomes possible to use them to assess how correct was the initial view on what was the failure mechanism.

Inspection of Table 7.2 shows that the relationship between the various levels of reliability and their quantification is not symmetrical. This is deliberate, as the values are designed to fit in with what are likely to be the probabilities that people might give in weighing up evidence in support of a given failure mechanism.

7.5.2 Preliminary Assessment by Investigators and the Bayes Equation

Assuming a superheater has failed, and it is then sent to a metallurgical laboratory, the failure investigation will basically be done to confirm what the team, who are investigating the failure, think is the failure mechanism. Only rarely is the laboratory work done without anyone having a clue as to what might be the cause. Essentially the work is carried out to either prove or disprove this preliminary view on what is likely to be the failure mechanism.

In practice this preliminary view will be largely based on a visual inspection of the failure and, in some cases, on what has been said about plant operations. This information can be treated as being how likely it is that the failure is of a certain type. It should have a fair degree of being correct, otherwise the team will be on a “wild goose chase”. It can therefore be identified as being similar in properties to “F” in Bayes’ equation. The probability of F, that is P(F) can be decided on by how good is the preliminary visual evidence. This is not too difficult to establish in the case of superheater failure mechanisms. For each type of failure there are one or two pieces of **overriding visual evidence** that point towards the failure mechanism. For example, creep failures in a superheater tubes are characterised, by the type of the crack. This will be relatively tight and will be surrounded by smaller fissures in the metal. In addition the tube will be slightly swollen around the failure.

When the visual evidence for creep is very good, the investigating team would probably conclude that it was “almost certain” that the failure was by creep. Quantifying the “almost certain” using the criteria discussed above would suggest that the probability of a creep failure was 90%.

In making this initial visual assessment, only four categories of “reliability of conclusions” are needed in practice, as there is no point in investigating unlikely or improbable failure mechanisms. The four sets are:

- Possible
- Probable
- Almost Certain
- Certain

Of these the most commonly used are likely to be “Probable” and “Almost Certain”. The “Possible” case would tend to be used when although creep might have occurred there is strong evidence that there are other failure mechanisms at work. The “Certain” category is also likely not be used in practice; it is included as it helped in the formulation of table of descriptions. Table 7.3, is one such table and shows how the appearance of a creep failure would relate to the categories stated
above. In formulating the descriptions, it is best to consider the extremes, that is the “Certain” and “Possible Categories” first. Note that to be realistic, the visual observations are supported, where possible, by information about how the plant operated, as this too will give pointers to possible failure mechanisms.

These Tables can be used as stated, to produce heuristic or Bayesian probabilities as described. They can also be used, through the process of highlighting key word and phrases, to enable the Expert System to make an initial qualitative assessment which would be helpful in the initial stages of the investigation. This was previously done in Section 6.4 of Chapter 6, and the highlighted phrases in the Tables below refer to the examples used at time.

**Table 7.3: Quantification of Reliability of Conclusions in Visual Assessment of Creep Failures**

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Bulging or swelling of tube up to about 10% increase in diameter. Any thinning of tube is fairly limited and uniform, and corresponds to the general swelling.</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Main longitudinal crack surrounded with fissures. Bulging of tube in area of crack. Some evidence of wastage due to fireside corrosion or erosion. Alternatively indications from severity of bulging and more open crack an overheating failure.</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Fairly narrow main longitudinal crack surrounded with fissures. Crack position faces hottest flue gas or radiation source. Some mild bulging of tube in area of cracking and away from this. Significant simple oxidation but no serious wastage. Plant has reached significant proportion of over 70% of its life based on operating hours.</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Fairly narrow main longitudinal crack surrounded with fissures. Crack position faces hottest flue gas or radiation source. Some mild bulging of tube in area of cracking and away from this. Significant simple oxidation but no serious wastage. <strong>Plant close to end or beyond end of life</strong> based on LM parameter estimates.</td>
</tr>
</tbody>
</table>

In a similar manner tables can be constructed for the other failure mechanisms in superheaters. In the case of a superheater that has failed by overheating the only categories are “Certain” and “Almost Certain” as the morphology of this type of failure is so definite. Lower categories of overheating failures would tend to merge into genuine longer term creep failures.
### Table 7.4: Quantification of Reliability of Conclusions in Visual Assessment of Fireside Attack Failures

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Deposits have produced attack but no particular characteristics, and final failure has been due to creep or overuse of soot blowers. Some ash on superheaters. Temperatures not known</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Heavy deposits of ash on front side of tube facing on coming gas flow. Considerable amounts of ash on superheater bundle. Flue gas temperatures could be high at this point. General attack associated with creep failure</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Heavy deposits of ash on front side of tube facing on coming gas flow. Considerable amounts of ash on superheater bundle. Flue gas temperatures and tube temperatures could be high at this point. Not much attack on the front side of tubes. Attack stronger on sides of tube</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Heavy deposits of ash on front side of tube facing on coming gas flow. Considerable amounts of ash on superheater bundle. Flue gas and tube temperatures known to be high. Deposits show the white layer. Not much attack on the front side of tubes. Attack is on side producing “side facets” on tube in cross section, leading to a wear through type hole at this point</td>
</tr>
</tbody>
</table>

### Table 7.5: Quantification of Reliability of Conclusions in Visual Assessment of Erosion Failures

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Some thinning or wastage on front side of tube facing erosion source but failure was by creep</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Wastage type failure possibly a combination of soot blower erosion and fireside attack</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Strong evidence from direction of possible erosion flow whether from soot blowers or steam blast from local failure that the failure is by wear or wastage. Need for frequent soot blowing.</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Strong evidence from direction of possible erosion flow whether from soot blowers or steam blast from local failure that the failure is by wear. Need for frequent soot blowing. Temperature records suggest overuse when few deposits are present.</td>
</tr>
</tbody>
</table>
Table 7.6: Quantification of Reliability of Conclusions in Visual Assessment of Weld Failures

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Circumferential failure are common on this component but no real evidence</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Circumferential failure could have been at a weld but weld location is not certain</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Circumferential failure has occurred and is definitely associated with weld and in fusion or HAZ. Signs of lack of fusion or porosity</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Circumferential failure has occurred and is definitely associated with weld and in fusion or HAZ. Failure associated with cracking, lack of fusion or porosity. Material known to suffer Type IV cracking and similar failures reported from plant</td>
</tr>
</tbody>
</table>

Table 7.7: Quantification of Reliability of Conclusions in Visual Assessment of Overheating Failures

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>See Creep</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>See Creep</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Wide fish mouth split type failure with evidence of thick lips and indications from plant records of flow starvation</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Wide fish mouth split type failure with thin lips</td>
</tr>
</tbody>
</table>
### Table 7.8: Quantification of Reliability of Conclusions in Visual Assessment of Creep Fatigue Failures

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Cracking at reheater/superheater to outlet manifold tube junctions or other areas where temperature gradients are likely to occur during plant cycling and temperatures in creep range. Plant reaching end of normal life and has been a base load unit. Desuperheater used occasionally to control excessive temperatures.</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Cracking at reheater/superheater to outlet manifold tube junctions or other areas where temperature gradients are likely to occur during plant cycling and temperatures in creep range. Plant has not cycled frequently. Shape would result in thermal shock on hot restarts. HAZs susceptible to Type IV failures. Desuperheater used frequently to control excessive temperatures.</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Cracking at reheater/superheater to outlet manifold tube junctions or other areas where temperature gradients are likely to occur during plant cycling and temperatures in creep range. Plant has cycled frequently and temperatures in creep range. Shape of superheater would result in thermal shock on hot restarts. HAZs susceptible to Type IV failures.</td>
</tr>
</tbody>
</table>

### Table 7.9: Quantification of Reliability of Conclusions in Visual Assessment of Thermal Fatigue Failures

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Cracking at reheater/superheater to inlet manifold tube junctions or other areas where temperature gradients are likely to occur during plant cycling and temperatures below creep range. Plant reaching end of normal life and has been a base load unit with some cycling.</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Cracking at reheater/superheater to inlet manifold tube junctions or other areas where temperature gradients are likely to occur during plant cycling and temperatures in creep range. Plant has cycled frequently. Shape would result in thermal shock on hot restarts.</td>
</tr>
</tbody>
</table>
7.5.3 Methods for Quantifying Evidence Based Conclusions

In practice, having decided upon a likely mechanism of failure, using the visual clues discussed in Section 7.5.2, to decide what is the value of $P(F)$, much of the subsequent failure investigation is heavily dependent on laboratory based metallographic and analytical work, but it also supported, where necessary, with calculations. This results in a number of disparate pieces of evidence, which in general the human expert does not have too much difficulty bringing together in making a conclusion. In some way the expert system needs to be able to do something similar.

The procedure which is suggested, basically involves evaluating each piece of evidence, and assessing how it might support, using previous example of a creep failure. Creep failures are particularly good illustration of how this might be done. Normally, when a superheater tube has failed by creep, there are significant metallographic changes, the superheater tube increases in diameter, and depending on the steel, there can be an appreciable growth in the thickness of the oxide. Most importantly, calculations will show that the material has reached the end of its life, as determined by a parametric estimate using stress and temperature.

It would be unprofessional for a human expert to base his or her judgement on one piece of evidence alone, but it is clear than some pieces of evidence are more important than others. The amount of microcracking and fissuring is much more significant in the identification of creep than how much the material may have oxidised. The weighting factor accorded to microcracking (which is classed as a cavitation based phenomena) would be much higher than that of oxidation.

In the final assessment, all the pieces of evidence need to be brought together in some manner. One approach is to combine all the evidence to give an overall $P(E|F)$, as will be discussed in Section 7.5.3.1. The problem is that of combining evidence in this way invariably leads to $P(E|F)$ values that are very close to or excess of 1 (unity), which almost always suggest that the initial failure assessment was “Certain”. This can be overcome to some extent by using weighting factors.

The other approach is to utilise each piece of evidence independently, testing it using Bayes' rules. The advantage of this approach is that each $P(E|F)$ value will be less than 1, so overconfident predictions will not occur. The problem then is to find an acceptable way to combine these values.

7.5.3.1 Aggregate P(E|F) Values and Weighting Factors

The aim, in building up the laboratory based evidence in a rational manner is to give each piece an appropriate weight so as to determine its value in the function $P(E|F)$. In this case $P(E|F)$ is the probability that a particular piece of evidence indicates a creep mechanism. These weighting factors do need to be determined by a human expert first of all, and it is important to state the method which underpins the quantification. The principle upon which this is done is to suppose that if, and only if, this particular piece of evidence was available, and the evidence was very good, how much weight should be given to that piece of evidence.
For example, as fissuring is a very good indicator of creep, the weighting factor given to this should be around 80%. Conversely, the presence of a thick oxide is not a good indicator, per se, for creep. It would just suggest that a tube had been running hot for a long period. Hence, the weighting factor, in this case should only be 0.1.

<table>
<thead>
<tr>
<th>Evidence</th>
<th>Weighting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spheroidisation</td>
<td>0.4</td>
</tr>
<tr>
<td>Cavitation</td>
<td>0.7</td>
</tr>
<tr>
<td>Larson-Miller Calculations</td>
<td>0.5 - 0.8</td>
</tr>
<tr>
<td>Tube Swelling</td>
<td>0.2</td>
</tr>
<tr>
<td>Steamside Oxidation</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 7.10 lists the pieces of laboratory based evidence that would be needed in building up the case for creep and the maximum weighting factor that should be accorded for each. In determining $P(E|F)$, each of these weighting factors are multiplied by the reliability of the conclusions.

Tables 7.11 to 7.15 show the "Creep Failure Conclusion Reliability" for the observations and calculations that have to be made. If we suppose that the metallographic assessment showed that the materials had reached Stage 3 in terms of spheroidisation, as shown in Table 7.11, this equates to this evidence giving possible support to a creep failure. The term "possible" in probability terms was previously defined as being equal to 0.3. As Table 7.9 gives the maximum weighting factor for spheroidisation in $P(E_{creep} | F_{creep})$ as 0.4, on this occasion the contribution that the spheroidisation makes to $P(E_{creep} | F_{creep})$ is quite small, that is 0.3 times 0.4 = 0.12.

Here there are some points which need to be made. Normally the contribution that stems from the spheroidisation observations would be added to those from cavitation, Larson-Miller calculations, etc. The somewhat ambiguous observation, based on spheroidisation, whilst not in itself giving much support to creep, would, in practice, be supplemented by other observations.

If it is assumed that there were only spheroidisation observations available, it would still be possible to proceed, but the significance is greatly affected by the strength of the original assessment that the failure was by creep. If the visual evidence had suggested that the creep failure was in an "Almost Certain" category, (having a probability of 0.9), eqn (6) can be applied as follows:
\[ P(F|E) = \frac{P(E|F)P(F)}{P(E|F)P(F) + P(E|F)^cP(1-F)} \]

And where \( P(E|F) = 0.12 \) and \( P(E) = 0.9 \)

\[ P(F|E) = \frac{(0.12)(0.9)}{(0.12)(0.9) + (0.88)(0.1)} = 0.55 \]

That is that the probability of creep having been the mechanism of failure, despite the weaknesses of the spheroidisation evidence is 55%. Transposing this back to the adjectival descriptions, as outlined in Table 7.2, this implies that the chances that the failure is due to creep is quite close to “Probable”. If the visual evidence had been weaker, indicating that it was only “Probable” that the failure was of the creep type (i.e. 60% confidence), the same spheroidisation evidence would have indicated that the chances of failure being due to creep as being only 16%. Table 7.2 indicates the chances of the mechanism as being due to creep as being in between “Improbable” and “Possible” This shows how the laboratory evidence can be used in an expert system to help support or contradict the initial hypothesis.

**Table 7.11: Possible Spheroidisation/Creep Indications**

<table>
<thead>
<tr>
<th>Spheroidisation Class</th>
<th>Degree of Spheroidisation</th>
<th>Creep Failure Conclusion Reliability</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Typical new tube structure of ferrite and fine pearlite.</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>Appearance of small particles of carbide at grain boundaries</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Distinct indications of carbide spheroidisation within pearlitic areas, but some carbide lamellae still present. More carbides at grain boundaries and some precipitation in grains</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Spheroidisation of carbides in pearlitic areas almost complete but still group in original areas.</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>Spheroidisation complete and carbides are dispersed leaving little trace of original areas</td>
<td>Almost Certain</td>
<td>0.9</td>
</tr>
<tr>
<td>6</td>
<td>Marked increase in size of spheroidised carbides due to coalescence</td>
<td>Certain</td>
<td>0.99</td>
</tr>
<tr>
<td>7</td>
<td>Carbide disappears</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Each one of Tables 7.11 to 7.15 has been set up in a pragmatic manner and no undue effort was made to keep the tables absolutely consistent. In Table 7.10 some of the spheroidisation classes have been run together, as it is considered that much the same conclusion would emerge from both of the classes in indicating their support for a creep failure. In drawing up Table 7.12, which deals with cavitation and microcracking, the view is that it is often difficult to identify cavities in the early stages of creep. Furthermore these sophisticated cavitation measurements are really intended for life assessments, hence the "probable" classification is left out. Nevertheless if microcracking and fissuring are detected, this is extremely strong evidence for creep. Hence, as Table 7.10 indicates, cavitation observations are given a high weighting.

Table 7.12: Possible Cavitation/Creep Indications

<table>
<thead>
<tr>
<th>Neuberger Classification of Damage State</th>
<th>Cavitation Description</th>
<th>Creep Failure/Life Conclusion Reliability</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>---</td>
<td>No cavities detected</td>
<td>Impossible (No detectable creep)</td>
<td>0.001</td>
</tr>
<tr>
<td>B (Isolated Cavities)</td>
<td>Isolated cavities are detected. Not possible to deduce direction of maximum principle stress from damage</td>
<td>Improbable (Creep occurring but not close to end of life)</td>
<td>0.05</td>
</tr>
<tr>
<td>C (Oriented Cavities)</td>
<td>Cavities present, often with multiple cavities on same grain boundary. A clear alignment of damaged boundaries can be seen indicating axis of principle stress</td>
<td>Possible Creep definitely occurring but not close to end of life</td>
<td>0.3</td>
</tr>
<tr>
<td>D (Micro Cracking)</td>
<td>Cavities have reached the micro cracking stage and are on boundaries normal to the maximum principal stress. Some boundaries have separated due to interlinkage of cavities so forming the microcracks</td>
<td>Almost Certain (If material has not failed it would have done in few months)</td>
<td>0.9</td>
</tr>
<tr>
<td>E (Macro Cracking)</td>
<td>Cracking has reached the clearly fissured stage, whereby the micro cracks have joined together to form macrocracks</td>
<td>Certain (If material has not failed, failure would be imminent)</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Table 7.13 Possible Steamside Oxidation/Creep Indications (For Low Cr Ferritic Alloys)

<table>
<thead>
<tr>
<th>Amount of Oxidation</th>
<th>Creep Failure Conclusion</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10 μ</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>10-100 μ</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>&gt;100 μ</td>
<td>Probable</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 7.10 showed at two different weighting factors are given to the Larson-Miller calculations. The lower is where there is a strong element of guesswork in estimating the metal temperature. This could be out by up to 50°C, if the instrumentation is poor and the operating staff have no feel for what might be going on. In this case the weighting factor would be 0.5. If it was possible to determine temperature reasonably accurately from skin temperature thermocouples, heat transfer estimates or dependable calculations based on oxide thickness, the reliability of the Larson-Miller estimates would be very good. The suggested weighting factor in this case would rise to 0.8. The actual relationship between the failure time and how close this ties in to the failure time as estimated by the parameter is shown in Table 7.14

Table 7.14: Possible Larson Miller Parameter/Creep Indications

<table>
<thead>
<tr>
<th>Failure Time as Fraction of LM Parameter Estimate</th>
<th>Creep Failure Conclusion</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10%</td>
<td>Impossible</td>
<td>0.001</td>
</tr>
<tr>
<td>10-25%</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>25-50%</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>50-90%</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>90-120%</td>
<td>Almost Certain</td>
<td>0.9</td>
</tr>
<tr>
<td>&gt;120%</td>
<td>Certain</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 7.15: Possible Tube Swelling/Creep Indications

<table>
<thead>
<tr>
<th>Amount of Swelling</th>
<th>Creep Failure Conclusion</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1%</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>1-3%</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>3-10%</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>&gt;10%</td>
<td>Check Overheating Rules and Tables</td>
<td></td>
</tr>
</tbody>
</table>
Each of these probabilities of the reliability of evidence is then multiplied by the appropriate weighting factor and then added together to determine \( P(E \mid F) \). Table 7.16 shows how this can be done in the evaluation of a failure where the visual evidence indicated that it was a “Probable” creep failure. That is \( P(F) \) was 0.6.

**Table 7.16: Example Table Showing Aggregation Method of Determining \( P(E \mid F) \) for a Creep Failure**

<table>
<thead>
<tr>
<th>Type of Investigation</th>
<th>Level</th>
<th>Probability</th>
<th>Weighting Factor</th>
<th>Weighted Individual ( P(E \mid F) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spheroidisation</td>
<td>Probable</td>
<td>0.6</td>
<td>0.4</td>
<td>0.24</td>
</tr>
<tr>
<td>Cavitation</td>
<td>Almost Certain</td>
<td>0.9</td>
<td>0.7</td>
<td>0.63</td>
</tr>
<tr>
<td>Larson-Miller</td>
<td>Probable</td>
<td>0.6</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube Swelling</td>
<td>Possible</td>
<td>0.3</td>
<td>0.2</td>
<td>0.06</td>
</tr>
<tr>
<td>Oxidation</td>
<td>Possible</td>
<td>0.3</td>
<td>0.1</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**AGGREGATE \( P(E \mid F) = 1.2 \)**

Because the aggregate \( P(E \mid F) \) in this case in Table 7.16 is greater than 1, the calculations of \( P(F \mid E) \) using a combination of the initial visual assessment and the laboratory based evidence indicate that it is “Certain” that the failure is by creep. That is the probability is 100%. The actual value of \( P(E \mid F) \) is 1.2 and resulted, to a large degree, from the cavitation assessment. This simply reflects the fact that microcracking and fissuring are the features which are considered to characterise creep failures. However if, for some reason the crack area had been destroyed or lost, we could still use the other pieces of evidence. The aggregate total for \( P(E \mid F) \) would then fall to 0.57 and \( P(F \mid E) \) would now be 0.665, which would indicate that the probability that the failure was due to creep was somewhere between possible and almost certain.

Clearly despite the simplicity of this approach, a major difficulty results from by adding the \( P(E \mid F) \) values together. This will almost always tend to lead aggregate totals that are close to or even above 1, and happens even when the individual values have been weighted. The end result is that there is strong possibility that although the individual pieces of evidence are weak, when aggregated, this appears to be overwhelming. For this reason a better approach is required.
7.5.3.2 Use of Individual P(F|E) Values

Table 7.17 uses the same information obtained from the laboratory and backroom investigations as was utilised in Table 7.16 and in the related Bayesian calculations. Accordingly P(F) is assumed to be 0.6.

The main difference is that weighting factors that were used in Table 16 are dispensed with, so that the individual probabilities (for spheroidisation, cavitation, etc) are now equal to P(E|F). These can then be incorporated into a Bayes’ equation in which P(F) is 0.6. Table 7.17 shows the results of his approach.

Table 7.17: Table Using Individual P(E|F) Values for Different Types of Laboratory Evidence to Determine Failure Mechanism

| Type of Investigation | Level          | Probability P(E|F) | Visual Evidence P(F) | Failure Supported by Evidence P(F|E) |
|-----------------------|----------------|-------------------|----------------------|------------------------------------|
| Spheroidisation       | Probable       | 0.6               | 0.6                  | 0.69                               |
| Cavitation            | Almost Certain | 0.9               | 0.6                  | 0.97                               |
| Larson-Miller         | Probable       | 0.6               | 0.6                  | 0.69                               |
| Tube Swelling         | Possible       | 0.3               | 0.6                  | 0.39                               |
| Oxidation             | Possible       | 0.3               | 0.6                  | 0.39                               |

Average P(F|E) = 0.63

Taking all five values, the average P(F|E) is only 0.63, corresponding to level that is close to “probable” putting these values back into words. The outcome is surprisingly low, but this is largely due to the fact that in this hypothetical example, the amount of oxidation and tube swelling were set at deliberately low values.

If faced with such a situation a human expert would be likely to discount these two negative results and concentrate on the more important observations. This an expert system could do, reporting the results as follows.

If average P(F|E) is 0.63 Then creep_failure_mechanism is just probable

In addition If best creep_failure_guide is cavitation and P(F|E) is 0.97 Then cavitation indicates creep_failure_mechanism is close to certain
To the author, the focusing on the best piece of evidence, seems to imitate one of the worst features of human behaviour, and one should try to use all the evidence that is available. Furthermore, in some cases the best evidence (viz cavitation) may have been lost. Hence it is imperative to find a quantitative method, based on the Bayesian probabilities that can combine evidence. As has been shown simple averaging techniques are not sufficient, and aggregation methods are no better.

A way through this impasse is to divide the average by some factor that takes into account the number of pieces of evidence. Because this approach is somewhat crude it needs to be fairly conservative, and it is suggested that two of the pieces of evidence should be discounted. Hence the average \( P(F \mid E) \) would be divided by some function of \( (N-2) \) where \( N \) is the number of pieces of evidence (which are taken to be 3 or more). The procedure can be regarded as a method of discounting two of the weakest pieces of evidence. In terms of the overall function is suggested that 0.95 be taken to power of \( (N-2) \). Accordingly in situations where there is a good deal of slightly dubious evidence, the \( P(F \mid E) \) value which would be produced by the Expert System would be:

\[
\text{Average } P(F \mid E) \text{ divided by } 0.95^{(N-2)}
\]

The function \( 0.95^{(N-2)} \) is termed the “Evidence Volume Factor”. The results of this procedure are shown in Table 7.18.

### Table 7.18: Evidence Volume Factor v. Number of Pieces of Evidence

<table>
<thead>
<tr>
<th>Number of Pieces of Evidence</th>
<th>Evidence Volume Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>0.90</td>
</tr>
<tr>
<td>5</td>
<td>0.86</td>
</tr>
<tr>
<td>6</td>
<td>0.81</td>
</tr>
<tr>
<td>7</td>
<td>0.73</td>
</tr>
<tr>
<td>8</td>
<td>0.69</td>
</tr>
</tbody>
</table>

In the case under discussion, there were five pieces of evidence, giving an Evidence Volume factor of 0.86. Dividing this into the average \( P(F \mid E) \) of 0.63 this raises the value to 0.73. In words this puts the likelihood that the failure having been caused by creep as being halfway between “Probable” and “Almost Certain”.

It would seem that the technique of using individual \( P(F \mid E) \) values is more flexible and closer to the way in which people think than the aggregate approach. Since individual values are available it can pick on those which are more important and
highlight these as an output from the Expert System. In other cases where there is a
lot of evidence, but none of the can be regarded as being critical, the weight of this
can be taken into account using the evidence volume factor.

References


3. Riley. KF, Hobson, MP and Bence. SJ “Mathematical methods for Physics
and Engineering” Cambridge University Press 2000

people.hofstra.edu/faculty/Stefan_Waner/RealWorld/tutorialsf3/unit 6-6.html 2005

plato.stanford.edu/entries/bayes-theorem 2005
Chapter 8

Plant Based Rules in Superheater Failure Investigations

8.1 Introduction

The next two chapters of this thesis, Chapters 8 and 9, represent the culmination of the work and build upon the thinking that has gone on earlier. To reiterate, as part of the literature survey, Chapter 2 provided much of the raw data and background information that is needed in building up an Expert Systems. Chapter 3 only has had an indirect influence on the work, and was written to help show what we ought to expect of an Expert System, focusing on the need for it to be able to tackle hard questions and to be capable of being updated. Chapter 4 reviewed the types of Expert Systems, helping to set the scene for the sort of Expert System that would be needed.

Chapters 5, 6 and 7 explicitly showed the procedure by which these rules can be constructed for this type of Expert System. It was necessary to do this, as the methods by which rules are formulated are not something that is made clear in most descriptions of expert systems. The author had to build up these procedures himself. In this respect the process of developing of If...Then rules has analogies in the design and construction of experimental apparatus to test a specific scientific hypothesis.

Summarising the contents of these later chapters, Chapter 5 outlined the use of flow charts as a precursor to the formulation of If...Then rules. Chapter 6 discussed one of the main shortcomings of rules of If...Then rules, which is that, in their basic form, they only produce Yes/No answers. Chapter 6 indicated that one solution to this difficulty is the incorporation of adjectival and adverbial words and phrases into the rules. These have the ability to modify bald “Yes” or “No” answers into statements that reflect the probability of the conclusions being correct. Chapter 7 went on to show that verbal type If...Then rules, although incorporating adjectival and adverbial phrases, cannot easily be used to put together evidence from different sources. This becomes a real problem when there are multiple types of evidence, none of which in themselves are conclusive. This is most likely to occur in laboratory and background investigations, when the evidence might consist of an initial visual appreciation, optical microstructural changes, alloy compositions, use of parametric equations, and heat transfer rates, etc. Hence Chapter 7 showed how to turn such evidence into quantitative probabilistic statements, which can then be used in Bayes’ Rules. This simulates how a human expert is able to combine evidence using fuzzy, non-quantitative information.

In this Chapter, which deals with plant based failures, it will be shown that If...Then rules using adjectival and adverbial words and phrases are adequate when the root cause of a failure originates from some shortcoming in the operation, design, or maintenance of a plant. Of course many plant based failures stem from a number of causes, and an Expert System will need to recognise this. Some causes will be more important than others, and the adjectival and adverbial type of If...Then rule should
be able to give the necessary weighting to each of these contributory factors. In the real world, all of these potential causes of the failure ought to be fixed, otherwise the problem is likely to reoccur. Clearly the more important is a specific root cause, the more vital it is to fix it. For example, some failures are caused by a lack of experience by the operating staff. Re-training is therefore critical. However, it is also likely that shortcomings with the control system have been contributory causes and these too will need to be improved, otherwise some other person will repeat the mistake. But just changing the control system will not prevent failures if the operators do not know how to use it properly.

As was indicated in Chapter 1, investigations of superheater failures can be categorised as being those which are passed on to laboratory based personnel and those which dealt with on in the plant technical experts. Laboratory investigations are initially focused on the need to confirm the mechanism of failure. But plant based investigations do not normally wait until the preliminary laboratory findings are known. They begin once a tentative assessment of the cause of failure has been made. The immediate aim of the plant investigations is to give support to this initial assessment, or where they do not, they are intended to suggest laboratory and background work that would focus on alternative mechanisms. However, the main aim of the plant based investigations is to seek out any shortcomings in plant operations, maintenance procedures, or design problems, as these would represent root causes. Note that factors such as high steam or flue gas temperature are not root causes in themselves. These will have resulted from a malfunction of the furnace or its ancillaries, which need to be put right otherwise similar failures will occur in future.

8.2 Billingsport - A Fictitious Test Model for Expert System Rules

An unfortunate feature of Expert Systems is that, if they are to truly encompass the expertise of human experts, especially when covering plant derived root causes of failures, the procedures tend to be rather prosaic and repetitive, and it can be difficult to see how this might relate to a practical situation. To help overcome the ennui in working through a great many If...Then rules, most of which seem quite trivial, and not related to the real world, a hypothetical failure in a generating plant has been created as a means of showing how an Expert System approach could be used in a real failure situation. The fictitious plant is supposed to be located near imaginary town of Billingsport, somewhere in the UK. The circumstances under which the superheater failed, is based on the way the power generating sector has developed over the past twenty years in the UK and in the USA.

The investigation of this failure forms a test case for plant based rules, most of which are initially formulated in Sections 8.3 to 8.7 in this Chapter, although some information and rules come from Chapters 2 and 9. These issues are described in Sections 8.3 to 8.7 and they are stated to exemplify the large number of factors that need to be taken into account. Some of this information is then used in solving the Billingsport superheater failure and the investigation of the failure is described in Section 8.8. In addition Sections 8.3 to 8.7 also give some verbal background as well as rules which is pertinent to the investigations Billingsport.
Not all of the information which is incorporated into these Sections will be used in the Billingsport Investigation, but they do show the range of issues that have to be covered in building an expert system.

The background to this hypothetical failure is given below in italics, and contains the kind of technical information that a human expert would be given by the plant management, before the expert actually visited the site. In addition the expert would also be aware of how the generating sector and company had changed over the years, and how the local management had responded to these changes. This information is also given as background. What is particularly important in this example is the effort by senior management to try to put the blame on the material, P91 steel, rather than on possible problems at plant level.

In any real investigation, as the investigation progresses, further questions are asked and expertise brought in at appropriate points. The same is true for an Expert System. Accordingly, not all the information that is needed to identify root causes is given in the following text. New information, which is germane to the failure investigation, will appear as the Expert System works through its set of questions. This new background information is also given in italics at appropriate points in Section 8.8.

**Superheater Failure at Billingsport Generating Plant**

*This coal fired power plant had been service for about eleven years, and was of a conventional design running with a steam temperature of 545°C and at 165 bar. For the first five years it ran as a base load unit, but then, owing to the fall in natural gas prices, the plant was put on to a two shift and load following cycle. After about three years of this type of operation the top header in the final superheater was found to have cracked. This had been constructed of a thick section P22 material, and the view was that the thermal cycling was leading to nozzle cracking. There was also a suspicion that some operators were not managing the start up properly, and had permitted header quenching to occur. In support of this view there had been one incident where a tube had burst during start up.*

The availability of P91 in the form of pipe and tubing gave the opportunity to upgrade the superheater. Because of commercial considerations, the redesign was done by the original constructors, who agreed that the choice of P91 would be ideal for a plant that would be subject to cycling. The original plant specifications were used in the redesign process. Hence the whole of the final superheater was replaced on the basis of new-for-old; that is the design life of the tubes was 100000 hours. (The header was given a design life of 225000 hours). A recommendation, which was accepted, was to upgrade the superheater instrumentation, so that the operating staff would
have a better idea of the steam temperatures during normal operation, and more importantly, during start up.

Unfortunately, these modifications occurred at a time when the Energy Regulator was changing the rules about how electricity prices would be governed. Previously a pool system had been in place, which, although giving a fair return to the owners of plants that were being operated on a two shift or part time basis, was felt to be giving excessive payments to the operators of base load nuclear and CCGT plant.

There was considerable uncertainty about what was to come, but the feeling was that due to the incompetence and lack of technical understanding of the Regulator, both base load and two shift plant would lose out. At the same time, top management in the company, which was now through to its fourth ownership/restructuring in six years, had been awarding themselves excessive salaries. And to keep shareholders quiet, dividends had been kept at a high level. To pay for this, operating and maintenance budgets had been cut, and it was made clear to local management that their jobs were on the line, unless their plant was getting a 15% return.

The immediate effect was panic at both HQ level and at Billingsport. It was essential to get the plant back to work, and cut budgets wherever feasible. Hence, all non essential maintenance and inspections were shelved. There was some thought about leaving off the instrumentation on the new header. Fortunately this still went ahead, since contracts for the installation had been signed. Furthermore the plant management argued with HQ that if there was another, "unexplained failure" of the superheater, the plant would have to be taken off line, with the company having to buy replacement power off the market.

The plant was actually recommissioned a few days before schedule, and worked on a two shift basis for the next two years. The plant was a little more profitable than expected, as the new regulations were reasonably favourable to everyone. But during this period staffing levels were cut and maintenance was contracted out. Older, more experienced operating staff were given the "option" of early retirement, as the costs for this came from the pension scheme. The original management team, who had been with the plant since the beginning, and had looked after the recommissioning, also took the retirement option.

With respect to the new set of people, there was a feeling, at all management levels, that to remain on the plant for a long time was professional suicide. Head office, working on acquisitions and sales of overseas power generating companies, was the
place to be. What with the job cuts and the fact that much of the
management was absent for most of the time, away on business-
type courses, the place was virtually deserted compared with the
old days. The only new position was that of the energy sales
manager who spent all day, and every day, bidding into the power
market. This was vital for a generating plant that was two shifting.

A big reversal came with the huge increase in oil and gas prices,
making it viable for a coal fired plant to go base load again. But
others in the generating system had the same view, so profitability
was still tight. The reduced number of start ups was a reason for
cutting manpower still further.

Generating efficiency was slightly down on the design value, even
though the plant was run at design steam temperatures and
pressures. There was some toleration of this since it was
accepted the plant was over ten years old and maintenance had
been skimped. Electrical output was actually just on design,
however, so there were few complaints from head office.

Things were going very well until one day last winter, a tube in the
final superheater burst. The failure was catastrophic in the sense
that the tube actually whipped around smashing into neighbouring
tubes increasing the repair costs. The time at failure was 25000
hours. The plant was down for two months, with the company
having to buy in power at around £1000000 a day. The
company's shares began to slide downwards in response, and
questions were being asked about the way the company was
run.....the organisation had made enemies with some of its former
staff who were giving off-the-record briefings to the newspapers.

By this time people in the power plant world had heard the news
that P91 and T91 were not quite the godsend that its protagonists
had hoped. Head office wondered if at least part of the costs and
all of the blame could be off-loaded to the tube manufacturers.
One of the few technical experts in head office (she was a
software designer), suggested that before undertaking legal
action, it might be best to investigate the background to the failure
as thoroughly and objectively as possible. Sadly, as a result of the
clear-out of manpower, the people involved in the modifications to
the plant had long gone, so she also suggested buying in an
expert system which could investigate power plant superheater
failures. This would avoid the messy business of having to deal
with people.
8.3 Preliminary Flow Chart

Figure 8.1 shows a “Superheater Failure Diagnosis Tree”, which covers the inputs that would or could be needed in identifying the causes of superheater failures. In practice the laboratory and plant based investigations run more or less in parallel. Although the tree starts from a box called “Superheater Failure” in running an expert system, there would be a number of preliminary stages, leading from the type of plant, then through to equipment type. This secondary stage would include the systems encompassing electrical equipment, controls, combustion side, water treatment, and steam raising, etc.

The process and progress of an investigation depends very heavily on what the failure looks like. This visual assessment is the first real step in the investigation. In Figure 8.1 a series of short thick arrows, on the left side of the diagram, lead down to the initial visual assessment. As noted in Chapter 7, each of the main mechanisms of failure of a superheater will tend to have its own characteristic appearance.

Not all the aspects of plant investigation shown in Figure 8.1 would have to be activated. When a superheater failure occurs, the plant management have the option of not doing any investigations at all; the superheater can simply be repaired without further ado. Hence one of the minor arrows coming out of the superheater failure box leads down to “Repairs”, bypassing all of the plant based investigation boxes. If the repair is successful that is the end of the matter. If not, the failure will need to be properly investigated at the plant and laboratory level. This is shown by the lettering in the box entitled “Repairs and Changes Non-Effective” being set in bold, with an arrow from this leading back to the box entitled “Investigation Needed”. It will be noted that there are a small number of such boxes in the figure, which indicate that a deeper assessment or reassessment is required at these points. Obviously a failure that did reoccur would provide valuable clues as to mechanisms and root causes. An important set of if ...Then rules which would relate to this would be:

\[
\text{If} \quad \text{failure was Component Replaced or Component Repaired} \\
\text{Then} \\
\quad \text{state Failure Time Repair as } t_2_{\text{repair}} \\
\quad \text{and} \\
\quad \text{Failure Time First Failure as } t_1_{\text{first failure}} \\
\]

\[
\text{If } t_2_{\text{repair}} \text{ is similar to } t_1_{\text{first failure}} \\
\quad \text{and} \\
\quad \text{Operating Change or Design Change since First Failure is No} \\
\quad \text{Then} \\
\quad \text{Same Failure Mechanism is probable} \\
\]

\[
\text{If } t_2_{\text{repair}} \text{ is not similar to } t_1_{\text{first failure}} \\
\quad \text{and} \\
\quad \text{Operating Change or Design Change since First Failure is Yes} \\
\quad \text{Then} \\
\quad \text{Other Failure Mechanism is possible} \\
\]
Provisional Assessment on Failure Mechanism and Cause

Superheater Failure

Investigation

Design Factors

Plant Data and Records and NDE

Plant Operating History etc

Operating Schedule

Control and Operability

Repairs and Modifications

Industry Wide Knowledge

Tube Failure Locations

Headers and Connections

Visual Assessment

Visual Assessment

Superheater

Furnace

Furnace Side

Water/Steam Side

Water/Steam Side

Plant Data and Records and NDE

Operating Schedule

Control and Operability

Repairs and Modifications

Industry Wide Knowledge

Fig 8.1: Superheater Failure Diagnosis Tree

Provisional Failure Mechanism based on Visual Assessment

Provisional Failure Mechanism based on Visual Assessment

Provisional Cause based on Plant Design Data and History

Provisional Cause based on Plant Design Data and History

Provisional Cause Identified but Confirmation Needed

Laboratory Examination

Lab Based Identification of Failure Mechanism

Lab Based Identification of Failure Mechanism

Calculations and Stress Analysis based on Lab Failure Mechanism Lab Data, Plant Records and History

Calculations and Stress Analysis based on Lab Failure Mechanism Lab Data, Plant Records and History

Non-Agreement between Lab, Calculations History and Repairs etc

Non-Agreement between Lab, Calculations History and Repairs etc

Successful Identification of Root Causes of Failure and Failure Prevention

Simple Repair

Repairs, Mods and Operational Changes

Repairs and Changes Effective

Repairs and Changes Non-Effective

Mechanism and Cause Obvious

Agreement between Lab, Calculations History and Repairs etc

Calculation and Stress Analysis based on Lab Failure Mechanism Lab Data, Plant Records and History

Successful Identification of Root Causes of Failure and Failure Prevention
Note also that the upper half of Figure 1 contains sets of the boxes that are in blue or in red, covering the essential preliminary investigation which would relate to a superheater tube failure. The blue arrows and boxes refer to work that a metallurgist would be expected to do. The red arrows cover the investigative work of plant personnel. The results of these two sets of investigations may come together at some stage, hence the arrows and boxes become green from this point onwards. At this time the laboratory work should be providing more support for the proposed failure mechanism and helping to point towards root causes. If the failure is of a serious type, the work will involve calculations, probably using data from plant records and design data. As will be seen in Chapter 9 this type of in-depth work will be needed in investigating some types of P91 superheater failures.

Four fairly distinct pieces of evidence will be utilised by the plant personnel in examining whether the operation of the plant will have contributed to cause of the failure. Hence there are four different groups of If...Then questions. These correspond to:

- **Failure Type and Location**
- **Plant Quantitative Data and Records**
- **Design Factors**
- **Plant Operating History**

### 8.4 Location of Superheater Failure

Even before proper investigations have begun, the type and location of the failed component will have given some indication of the probable cause, and, with somewhat less certainty, the mechanism. Hence each of these equipment types would be subdivided into the specific parts. Figure 8.2 shows how the parts of the steam raising system might be grouped. Each of these can be broken down into its different elements. With the superheater, there are three main components that need to be identified in formulating appropriate If...Then rules.

These individual groups of equipment would provide “nests” for specific If...Then rules relating to issues that could impact on other parts of the generating plant. For example problems with combustion equipment such as coal mills, burners, or air preheaters, will tend to increase superheater temperature, and the If ...Then questions relating to these would point to root causes of superheater failures. In formulating the categories there will be some overlap between these pieces of equipment. A clear case in point is the superheater system, which can either be regarded as part of the combustion system or part of the steam raising equipment.

The specific part of the superheater that failed would also give an indication about the mechanism and therefore about potential root causes. Tube failures are likely to have been caused by excessive temperatures, fireside side corrosion, or erosion. Header failures tend to be caused by thermal cycling, with the welded area around nozzles tending to fail prematurely. However, even in the absence of thermal cycling, the HAZ sections in welds can susceptible to Type IV cracking. Conversely, unless there is some serious defect in plant operation, it would be unlikely for the header to fail by simple creep. Failures of attemperators are broadly
due to design problems, but more importantly, if they go badly wrong they can induce thermal stress failures in the headers, or if parts break off, it can lead to local blockage of the steam flow.

![Figure 8.2: Grouping of Steam Raising Equipment](image)

It follows therefore, that as soon as a failure has occurred, it is worth getting the Expert System to ask if there is any visual confirmation of the supposed failure mechanism which would tend to be associated with the position in the superheater where the failure happened. An in-depth analysis of plant information and records would be premature at this stage so only basic information would be requested. Hence, if the failure was on a superheater tube the If...Then questions to be asked would be:

If Failure is Superheater_Tube  
Then  
activate Visual_Assessment_Failure_Rules  
for  
Creep, Overheating, Fireside_Corrosion Erosion, Weld

Furthermore

If failure is on Superheater_Tube  
Then  
activate T_Metal_Temperature_Steam_Derived
where $T_{\text{Metal Temperature Steam Derived}}$ is the metal temperature estimated from the steam temperatures.

If the failure has occurred on a header the initial rules stemming from this particular location are:

- If Failure is Superheater_Header
  Then
  activate Visual_Asseesment_Failure_Rules
  Nozzle , End_Cap , In_Header

- furthermore
  If Failure is Superheater_Header
  Then
  activate rules Cyclic_Operation

### 8.5 Rule of Thumb Estimates in Interpretation of Plant Data and Records

A fully developed Expert System would need to contain steam tables to enable it to make accurate estimates of the heat inputs to feedheaters, the economiser, the evaporator, superheaters and reheaters. In addition, the Expert System should also be able to work out theoretical flue gas temperatures from a knowledge of the air flow, flue gas composition, and fuel input to the plant. But even without this information, it is possible to make some intelligent guesses about what is going on in a plant, using some rule of thumb estimates. This is the procedure used in this section.

#### 8.5.1 Implications of Steam Temperatures and Plant Observations

The most obvious indication that something is amiss is that outlet steam or flue gas temperatures are excessive, as these are often symptomatic of many types of root causes of superheater tube failures. Excessive steam or flue gas temperatures are critically important in creep, but they also have direct significance in governing the extent of fireside corrosion, and indirectly, of soot blower erosion. However, although temperatures may be within design limits, there can still be problems with superheater materials. For instance, if the inlet steam temperature to a superheater was low, this might mean that the superheater had to work harder to get the outlet steam temperature up to the design values. This will impact on heat transfer rates and tube temperatures. The insights into this aspect of superheater temperatures will only emerge as a result of more in depth investigations involving heat transfer calculations. It is therefore important to prevent the Expert System jumping to conclusions in the way that people sometimes do.

In spite of this it is possible to come up with some rules of thumb for steam temperatures, which would alert the Expert System to possible problems caused by the tube running at too high a temperature. A practical difficulty would be that if the steam temperatures are excessive, the attemperator is likely to be in use to keep the
HP turbine inlet temperature at an acceptable level. This would distort the outlet temperature readings and a vital If... Then rule would be:

\[
\text{If Attemperator is In Use and is Not For Normal Operation} \\
\text{Then} \\
\text{Calculate Supereheater Heat Transfer Rates using Programme}
\]

From the outlet header steam temperature it is feasible to state the following rules for creep, providing that the alloy is P91, which tends to be used in borderline situations, providing the attemperator is not in use. The basis for these rules was covered in Chapter 2 where the importance of high temperatures in affecting creep and fireside corrosion were highlighted, but the subject is discussed in even more detail in Chapter 9. The rules are:

\[
\text{If Steam Temperature is Design Plus (0 -5 °C)} \\
\text{Then} \\
\text{Creep Failure due to Steam Temperature is improbable}
\]

\[
\text{If Steam Temperature is Design Plus (5-10°C)} \\
\text{Then} \\
\text{Creep Failure due to Steam Temperature is possible}
\]

\[
\text{If Steam Temperature is Design Plus (10 -20 °C)} \\
\text{Then} \\
\text{Creep Failure due to Steam Temperature is probable}
\]

\[
\text{If Steam Temperature is Design Plus (20 -35°C)} \\
\text{Then} \\
\text{Creep Failure due to Steam Temperature is almost certain}
\]

\[
\text{If Steam Temperature is Design Plus (35-50°C)} \\
\text{Then} \\
\text{Creep Failure due to Steam Temperature is certain}
\]

Note that these particular rules are only intended to alert the Expert System that something is amiss, but there will definitely be a need for more data and calculations, since outlet steam temperatures have only an indirect relationship to tube temperatures. Hence a cautionary rule, which takes care of the fact that either the steam flow is excessive or there has been a design error, can be stated as follows:

\[
\text{If Steam Temperatures and Flue Gas Temperatures and Steam Flow} \\
\text{are Within Design, but Metallurgical Root Cause is NO} \\
\text{Then} \\
\text{calculate Superheater Heat Transfer Rates}
\]
Because P91 is a superheater material that is known to be on the borderline in terms of creep strength, it is likely that the temperatures of steam and metal temperature on the outlet header will be monitored along its length. The If...Then rules which relate to the steam temperature of the individual tubes, in predicting the likelihood of creep, would be basically similar to the ones given for the steam outlet temperature. Of much greater importance is that these figures give the temperature distribution across the header. If the was very irregular then this would point to the fact that there was a bad distribution of steam or that the flue gas was tending to channel in some manner. Taking these temperatures in conjunction with a high steam temperature associated with the failed tube an If ...Then rule would be:

If Temperature_Distribution_Header varies by more than 40°C
Then
Investigate_Causes of Temperature_Distribution_Header

As discussed in Chapter 2 it is extremely difficult to get in situ estimates of superheater tube temperature because the furnace environment is so aggressive. It is not that easy, either, to get a good estimate of the temperature of the flue gas entering the superheater bank. Recourse may be needed to indirect techniques, which will be discussed in the following section, but again a useful rule of thumb would be, for the condition of the flue gas:

If Furnace Exit Superheater Slagged Then Flue Gas Temperatures are probably_high
and
Calculate Superheater Heat Transfer Rates and Superheater Tube Temperatures
and assess Fireside Corrosion and Creep

Severe slagging of the evaporator tubes would also tend to promote high superheater tube temperatures, as heat transfer into the furnace would be poor. Hence two additional rules of thumb are:

If evaporator is Slagged
Then
Flue Gas Temperatures are probably_high
And
Calculate Superheater Heat Transfer Rates and Superheater Tube Temperatures

8.5.2 Superheater Tube Temperatures and Heat Transfer Rates

Once more formal investigations have begun to ascertain whether a plant is somehow at fault have begun, the ideal procedure is to ascertain the absorption of heat by the steam as it passes through the failed superheater. This data can then be used to produce an average heat transfer rate, and a tube metal temperature. This calculation relies on the mass flow of steam, and the heat contents (enthalpies) of the mass of steam at the inlet and outlet of the superheater tubes. From the tube dimensions it is then a relatively simple matter to estimate the average heat transfer
rate. This figure can be used in conjunction with the outlet steam temperature to give a reasonably good indication of peak metal temperatures, although because the heat input will vary round the circumference of the tubes there will be some uncertainties due to this. Such estimates can be characterised as back room investigations done by specialists.

But this is not the way that people investigating failures work. The first inclination is to try to use the plant data that is immediately available, and this is the approach used here. Hence it is appropriate to think about using rule-thumb-estimates. When used with caution, these estimates can be helpful if the root cause is plant based. Such rule-thumb-estimates are not really relevant to a proper identification of metallurgical root causes. In such cases more detailed estimates of heat transfer rates may be necessary.

Rule-of-thumb estimates about metal temperatures always have a degree of uncertainty since heat transfer rate can change from the inlet to the outlet of the superheater. This is especially true if the flow through the superheater is of the parallel flow type. Such an arrangement is favoured when the material is working close to it limits, either in terms of mechanical properties or high temperature corrosion resistance. Here the relatively cool inlet steam enters the superheater at the point where the flue gas is hottest. Because of the large temperature difference heat transfer rates are high at this point, but the cooling effect of the steam should keep metal temperatures down. Of equal importance is the heat input across a superheater bank, which can change as the furnace output alters. The resulting steam temperature profile can change from an “M” shape to a “W” shape or vice versa. Nevertheless the assumption has to be that the designer will try to utilise the properties of the material to its fullest extent so that the same rule of thumb estimates which relate metal temperature to steam temperatures can be made whatever the type of superheater that is being made. The only difference that one might expect is that on a counterflow design, the peak metal temperature would be close to at the outlet of the superheater. With a parallel flow design the metal temperature should be more or less constant throughout the length of the tubing, with the position of the peak temperature depending on local flue gas conditions.

In modern systems, as would be typical of a P91 superheater, it is common to instrument the header along its length, giving a reasonably good idea about the steam temperature of individual tubes. In such cases it is reasonable to assume that the peak average metal temperature will be about 20-40°C, above this, although, this figure is very approximate. This subject is discussed in more detail in Chapter 9, which goes into backroom investigations in more detail.

Estimates of metal temperature become much less accurate if only the temperature of the steam as it leaves the header is known. Accordingly in such cases the actual spread in metal temperatures could be anything from 20° to 60°C and such a range cannot be used at all to identify either failure mechanisms or metallurgical root causes.

Steam temperatures which are higher than design will almost certainly indicate that some thing is amiss, and the set of If...Then rules that were set down in the previous
section are helpful in this respect. In themselves they need to be utilised in conjunction with other information to identify plant based root causes.

It may be considered that low steam temperatures should not be a cause for concern. However, if inlet temperatures are low, the superheater will have to be working harder than usual. Given the fact that the temperature rise through the superheater is not likely to be much more than 60°C, if the inlet temperature is down by more than 10°C, this would imply a need for the heat transfer rate to be increased by 15-20%. Table 8.1 shows some rule-of-thumb relationships between inlet and outlet temperatures and what they might mean in terms of metal temperature exceeding the design values.

<table>
<thead>
<tr>
<th>Inlet Steam Temperature Below Design</th>
<th>Outlet Steam Temperature Above Design by -10° to -5°</th>
<th>Outlet Steam Temperature Above Design by -5° to +5°</th>
<th>Outlet Steam Temperature Above Design by +5° to +10°</th>
<th>Outlet Steam Temperature Above Design by +10° to +15°</th>
<th>Outlet Steam Temperature Above Design by over +15°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°-10°</td>
<td>Improbable</td>
<td>Improbable</td>
<td>Improbable</td>
<td>Possible</td>
<td>Probable</td>
</tr>
<tr>
<td>10°-20°</td>
<td>Possible</td>
<td>Possible</td>
<td>Probable</td>
<td>Probable</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>20°-30°</td>
<td>Probable</td>
<td>Probable</td>
<td>Almost Certain</td>
<td>Almost Certain</td>
<td>Certain</td>
</tr>
<tr>
<td>30°-40°</td>
<td>Probable</td>
<td>Almost Certain</td>
<td>Almost Certain</td>
<td>Certain</td>
<td>Certain</td>
</tr>
<tr>
<td>40°</td>
<td>Probable</td>
<td>Almost Certain</td>
<td>Certain</td>
<td>Certain</td>
<td>Certain</td>
</tr>
</tbody>
</table>

The Expert System would need to ask a series of questions about temperatures, which would result in the following types of If... Then statements basing the results on Table 1, examples of which would be incorporated into the Fact Base along with the look up tables.

If Inlet_Steam_Temperature is 10°-20°C Below_Design and Steam_Temperature_Rise is 60°C and Outlet_Steam_Temperature is between -5°C and +5°C of design Then Above_Design_Metal_Temperatures are possible and check Superheater Heat_Transfer_Rates
Obviously sets of these tables need to be formulated for the main ranges of superheater temperature rise. There is an argument for having just one basic table in the Expert Systems which would give the temperature rises in terms of percentage increases.

8.5.3 Effects of Attemperation

Bringing steam temperatures under control by use of the attemperator, that is injecting feedwater into the steam at either an inlet or outlet header, can, as indicated earlier, mislead an investigator into thinking that everything is okay. The usual aim of this procedure is to bring the steam temperature down to the limits required by the turbine or the next superheater. If a spray attemperator is used, the injection of feedwater may be used as a normal method of increasing the power output from the plant at high loads, as extra steam is produced.

Clearly if the feedwater is injected into the steam in the outlet header, this would suggest that the steam temperature is too high, and it is then a relatively simple matter to ascertain what the outlet steam temperature actually is, either by turning off the attemperator for a short time and doing an actual measurement, or by calculating this temperature using the steam and feedwater flows.

If an inlet attemperator is used, the outlet steam temperature indications may also be high. The obvious problem is that extra heat is needed to evaporate the water, which can imply higher metal temperatures and heat transfer rates. In addition it is unlikely that the spray of water along the inlet header will be even so that some tubes will receive more than others. Hopefully on modern plants the monitoring of steam temperatures from individual tubes, or groups of tubes going into subheaders will reveal these anomalies.

The appropriate If...Then rule is:

If Attemperator is Operating
Then check Outlet_Superheater_Steam_Temperatures Without_Atemperator
or Calculate Superheater_Metal_Temperatures

8.5.4 Excessive Flue Gas Temperatures

One of the most likely causes of high metal temperatures results from problems with flue gas temperature, distribution and rate of flow. As discussed in Appendix 1 a change in the flue gas temperature has much less effect on the superheater tube temperature than that of a change in the steam temperature. In terms of a typical superheater constructed in P91 steel, because the alloy is so close to its limits, flue gas temperatures of more than 75°C above the design should give rise to concern. Heat transfer rates could then be up to 25% higher than the designer has calculated, even if the temperature distribution across the superheater was uniform. This would raise metal temperatures by about 10-15°C. That is if the design skin temperatures of the superheater was 600°C, the metal temperature could be up to 615°C, This would
have a significant affect on the life, reducing this to about a quarter of that anticipated.

A problem for the operator is that it will probably be impossible to measure the flue gas inlet temperature at the inlet to the high temperature superheater, but it should be practical to measure the flue gas temperature further down the duct, after the superheater, using spot readings, even if continuous monitoring is impractical. Since most of the temperature drop in the flue gas is due to heat absorbed in the superheaters, reheaters and economisers, a high temperature further down the flue gas system will point to something being wrong. From these temperature recordings, plus a knowledge of the steam and flue gas flows it will be possible to work out average heat transfer rates and metal temperatures.

The flue gas temperature at furnace exit should be in the range 1000° to 1200° to ensure that there is a balance between steam raising, superheating, avoidance of fireside corrosion, and slag build up on the shock tubes and secondary superheater. Hence an important criterion is therefore how close is the flue gas temperature to the ash softening point. If this is exceeded the ash will stick to the tubing. The flue gas temperature should be below this or the secondary superheater will start to foul. In general with most coals, this temperature should be under 1200°C.

This kind of rough estimate can be helpful in trying to assess root causes, where high flue gas temperatures are involved. Since a designer would also be trying to keep fireside corrosion in check throughout the flue gas train, the combination of flue gas and metal temperatures that this implies, also provides an indication of what the design temperature conditions are likely to be. Quantitative data such as this can be incorporated in the Fact Base and used by the Inference Engine. Section 8 of this Chapter shows this procedure at work in the Billingsport investigation.

8.6 Design Factors

8.6. Steam Drum and Once Through Systems

The most significant split in the design of a steam system is whether it is of the steam drum or once through type. With the former, the steam exiting the steam drum tends to be at fairly constant temperature, as this is governed by the drum pressure. That is, the temperature of the steam is determined by the saturation pressure. Modern plant, which would be more likely to use P91 for the final superheater, utilises once through boilers, in which the water turns to steam, as it travels through the tubes of the evaporator. The steam temperature in once through designs is not fixed, dropping away at low steam outputs. Accordingly, a steam separator is employed to remove significant quantities of water droplets that have been carried over by the steam.

The more important issue, assuming the plant is running base load, is that reduced steam temperatures, pressures or steam flows can indicate that something is amiss. All of these factors would point to a reduced heat input to the evaporator, which, if the coal burn is normal, will be inducing high flue gas, and possibly high superheater temperatures.
8.6.2 Feedheaters and Economisers

Feedheaters are heat exchangers that are used to preheat the feedwater, thereby improving the efficiency of the steam cycle. They utilise extracted steam taken off various points of the reheat and low pressure turbine sets, and a typical plant would have up to eight extraction points and feed heaters to suit. The hot water from feed heaters enters the economiser, which is also used for bringing the feedwater up to a temperature suitable for use in the evaporator. The economiser makes use of the heat in the flue gases, and is situated in the flue gas duct, before the air preheater. In the case of drum boilers, the economiser can be used to raise a certain amount of steam. But there will be problems if the economiser is not designed for “steaming”, since the formation of steam pockets can disrupt steam flow, leading to water hammer. In the extreme, the formation of a big steam pocket can stop water flow altogether.

Low pressure feedheaters utilise the direct injection of low pressure steam into the feed water to remove oxygen, and are effectively part of the deaeration units, but the feedheaters situated after the deaerator operate with feed water at boiler plant pressure. Various types of heat exchanger are used on the high pressure feedheaters, but a common design is of the hairpin shell and tube type. Thermal shock, during start up, is a problem with this type of feedheater, resulting from the effects of severe temperature gradients in thick metal tube plates. Clearly the thermal cycling which happens during two shift operation gives a fatigue component, but in addition, water conditions tend to be poor during two shifting, so the problem is more one of corrosion fatigue.

If a high pressure feedheater cracks badly, it may have to be bypassed, since the feed water is at much higher pressure than the steam coming from the reheat and low pressure turbines, and the feedwater could find its way back to the turbines. Obviously, if a feed heater has to be taken out of service, steam production will fall. In some cases it would be possible for the economiser to supply more heat, although this will have implications for the amount of air preheat. Hence whatever happens, if an attempt is made to maintain output, more fuel has to be burnt in the furnace and flue gas temperatures will start to rise.

In assessing the root cause of failures, it is therefore necessary to assess feedheater performance and this is best done by asking the ESO to list the feed heaters and state what are the design and actual operating temperatures. A pertinent If...Then question is therefore;

\[
\text{If Flue\_Gas\_Temperature is high} \quad \text{Then} \\
\quad \text{list Feedwater\_Heaters} \\
\quad \text{and Design\_Feedwater\_Temperatures and Actual\_Feedwater\_Temperatures}
\]

8.6.3 Excess Air, Flue Gas and Tempering Gas Recirculation

Much of the heat that is transmitted within the furnace is as a result of radiation from particulates and luminous flames. The amount of radiation is governed by the fourth
power of the absolute temperature, so relatively small changes in the flame
temperature can make a lot of difference. Decreasing the air preheat to the burners
will reduce temperatures, but increasing the level of excess air, or increasing the rate
of flue gas recirculation can also be used to bring down the furnace temperatures.
Whereas decreasing the air preheat reduces the energy input to the furnace,
increasing the excess air or flue gas recirculation works by changing the thermal
mass of the products of combustion.

Because of reduced in-furnace temperatures, less heat will be radiated to the tubes,
and other things being equal, steam production will suffer. Conversely, since less
heat is taken out of the furnace more heat will be available in the flue gas duct.
Superheaters, reheaters and economisers, further down the duct, tend to benefit most
from high levels of excess air or recirculation, since they rely on convective heat
transfer and the increase in gas velocity improves this.

![Figure 8.3: Schematic of Flue and Tempering Recirculation Showing Top and
Bottom Injection Points (Flue Gas Fans and Air Preheater are Omitted)](image)

Increasing the excess air level is detrimental to plant efficiency, so good shift
personnel will make use of the flue gas recirculation system to control temperatures.
Flue gas recirculation, as the term implies, consists in abstracting a portion of flue
gas either before or after the air preheater, and re-injecting the flue gas back into the
furnace, either at the furnace bottom or at its top. Figure 8.3 shows a schematic of the system.

When the flue gas is injected back in the boiler at the bottom it is termed “flue gas recirculation”, and because of the thermal mass effects it will obviously cool off the furnaces gases. Flue gas recirculation is therefore most useful if the evaporator is tending to receive too much heat. As discussed, one of the consequences is that superheaters, reheaters and economisers will run hot. Buoyancy effects tend to move the point of peak radiation from the flames upwards in the furnace, adding to the increased rate of convective heat transfer. If the coal which is being fired produces a low melting point ash, considerable quantities of slag can be carried over onto the secondary superheater, causing it to corrode and interfere with its heat transfer performance.

If the temperature of the secondary superheater is too high, another form of flue gas recirculation is needed. This is often termed “gas tempering”. Here the recirculated flue gas is admitted closer to the top of the furnace box. In addition to cutting flue gas temperatures, it should, ideally, cool them to the point whereby any slag that is carried over from the furnace will solidify, preventing it from depositing on the superheaters.

To be quite certain of stopping slag build up in the furnace and slag deposition on the secondary superheater, both flue gas recirculation gas tempering may have to be used. Operation of both sets of dampers calls for some judgement and understanding on the part of the shift personnel, but it may be impractical to keep altering the position of the dampers if the plant is continually changing output.

Tables 8.2 and 8.3 summarise the likely effects. The difference between the two Tables results from the evaporator tubes in the furnace tending to become heavily coated with slag, despite the use of bottom-fed flue gas recirculation. In terms of quantifying adjectival phrases it is difficult to quantify the effects of damper positions on heat input to the furnace and on flue gas temperatures, but the writer suggests:

**Furnace heat transfer (on the basis of the design conditions):**

- **None:** Less than 0.9 Design
- **Small:** 0.90-1.0 Design
- **Moderate:** 1.0- 1.10 Design
- **Severe:** More than 1.10 Design

**Flue Gas Temperatures**

- **None:** 1150°C or below
- **Little:** 1150-1225 °C
- **Moderate:** 1225-1300 °C
- **High:** 1300°C and above
## Table 8.2:
Effect of Damper Position on Furnace Conditions with Non-Slagging Coal

<table>
<thead>
<tr>
<th>Door or Damper</th>
<th>Position</th>
<th>Coal</th>
<th>Furnace Heat Input Compared to Design</th>
<th>Likelihood of High Outlet Furnace Flue Gas Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue Gas Recirculation Open</td>
<td>Non Slagging</td>
<td>Moderate</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Gas Tempering Open</td>
<td>Non Slagging</td>
<td>None</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>Flue Gas Recirculation Closed</td>
<td>Non Slagging</td>
<td>Severe or High</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>Gas Tempering Closed</td>
<td>Non Slagging</td>
<td>Severe or High</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

### Table 8.3:
Effect of Damper Position and on Furnace Conditions With Slagging Coal

<table>
<thead>
<tr>
<th>Door or Damper</th>
<th>Position</th>
<th>Coal</th>
<th>Furnace Heat Input</th>
<th>Likelihood of High Outlet Furnace Flue Gas Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue Gas Recirculation Open</td>
<td>Slagging</td>
<td>Small</td>
<td>Little</td>
<td></td>
</tr>
<tr>
<td>Gas Tempering Open</td>
<td>Slagging</td>
<td>Small</td>
<td>Moderate/High</td>
<td></td>
</tr>
<tr>
<td>Flue Gas Recirculation Closed</td>
<td>Slagging</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Gas Tempering Closed</td>
<td>Slagging</td>
<td>Moderate</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>Flue Gas Recirculation Closed</td>
<td>Slagging</td>
<td>Moderate</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>Gas Tempering Open</td>
<td>Slagging</td>
<td>Moderate</td>
<td>Moderate</td>
<td></td>
</tr>
</tbody>
</table>
As noted, all the superheaters will tend to run hot with flue gas recirculation, including the final superheater, which is usually the second one along the flue gas duct. Overheating of the final superheater, when using flue gas recirculation, may be exacerbated if the coal is of the slagging type, since the secondary superheater may be slagged. In this situation the furnace already has a reduced heat input and the use of flue gas recirculation will restrict heat pick up by the evaporator still further. The temperature of the flue gases can then be very high.

8.6.4 Overheating and Thermal Shock

As described in Chapter 2 there are four types of superheaters, radiant, convective, pendant and platen. Radiant tube superheaters line the walls and roof of the upper reaches of the furnace where it turns into the flue gas duct. The other three types of superheater are positioned in the flue gas duct itself to intercept the flue gas flow.

Radiant superheaters tend to receive a great deal of radiant heat from the burners and glowing ash particles even when little steam is being generated. The flow of steam, under these conditions, is not high enough to give good cooling; hence failures are more likely under these conditions. It follows that failures in radiant superheaters tend to result from long periods of part load or stop start operation. If a failure has occurred, inspection of the records of inlet and outlet steam temperatures and flows, and a comparison with previous start ups should indicate whether an over-hasty start up is a root cause. With convective designs, creep and fireside corrosion failures will be associated with long periods of operation at base load. Under these circumstances the flue gases will be very hot, and although steam flows are high, metal temperatures also tend to be high. If there are weaknesses in the welds, either due to poor weld quality or a Type IV problem, failures could occur at any time after a few tens of thousands of hours of operation had elapsed, although creep and fireside corrosion would be more likely.

8.7 Plant Operating History

Perhaps the most important question that an investigator can ask is “Has this type of failure happened before?” Figure 8.4 shows a flow chart that can be used to clarify why it is that something has happened now, rather than earlier.

This sort of question should not only lead to an outline of the circumstances of the previous set of failures, but the response will also test how carefully the failure mechanism and its root cause have been diagnosed. But the corollary of this, “Has it happened before?” query, is a question that is asked less often. This question is, “If it hasn’t happened before, why has it happened now, and was such a failure expected?” Such a question can lead almost directly to the failure cause, as operational changes, equipment and control system unserviceability, or the unforeseen effects of adding new equipment can affect the way in which the superheater operates.
Superheater Failure has Happened Before Without Other Changes

Yes

Re-occurred After Long Period of Operation Without Other Changes

Yes

Design Error or Operating Shortcoming

No

Only Occurred After Operating Change or Staff Change Without Other Changes

Yes

Load Increase or Decrease Plant Cycling Fuels, etc will Affect Superheater or Furnace Or Due to Inexperienced Staff

No

Only Occurred After Equipment Became Unserviceable

Yes

Equipment Malfunction Affects Superheater or Furnace Inexperienced Staff do not Recognise Problems

No

Only Occurred After New Equipment Fitted

Yes

New Equipment Will Affects Superheater or Furnace or gives Re-commissioning Problems Inexperienced Staff do not Recognise Problems

Figure 8.4: Flow Diagram Showing Sequence of Questions to be for Ascertaining Root Causes
8.7.1 Previous Failures and Operational Staff Awareness

Note that the third block in 8.4 highlights how the inexperience of operating staff can be a root cause of failures. The times when this is most likely to happen is either during commissioning, when the most stupid errors are made from top management downwards, or alternatively when the shift personnel staff are presented with an operational change, such as two shifting. In some cases shift personnel will be reluctant to admit that their lack of knowledge or experience could be the root cause of the failure. Can an Expert System expose this difficulty?

Table 8.5: Shift-to-Shift Variations in Starting Up a Two Shifting Power Plant

<table>
<thead>
<tr>
<th>Factor</th>
<th>Andrew's Shift</th>
<th>Jim's Shift</th>
<th>Alan's Shift</th>
<th>Michael's Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Steam to HP Turbine</td>
<td>50 mins</td>
<td>150 mins</td>
<td>100 mins</td>
<td>75 mins</td>
</tr>
<tr>
<td>S/H Drains Closed</td>
<td>30 mins</td>
<td>140 mins</td>
<td>80 mins</td>
<td>50 mins</td>
</tr>
<tr>
<td>Initial Steam Flow</td>
<td>20%</td>
<td>20%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>Initial Pressure</td>
<td>80%</td>
<td>90%</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>60%</td>
<td>50%</td>
<td>75%</td>
<td>80%</td>
</tr>
<tr>
<td>Bottom Burner Row Lit</td>
<td>5 mins</td>
<td>5 mins</td>
<td>5 mins</td>
<td>5 mins</td>
</tr>
<tr>
<td>Middle Burner Row Lit</td>
<td>80 mins</td>
<td>200 mins</td>
<td>90 mins</td>
<td>40 mins</td>
</tr>
<tr>
<td>Top Burner Row Lit</td>
<td>40 mins</td>
<td>200 mins</td>
<td>150 mins</td>
<td>100 mins</td>
</tr>
<tr>
<td>Pressure Fluctuation</td>
<td>30bar at 45 mins</td>
<td>10bar at 210 mins</td>
<td>5bar at 70 mins</td>
<td>5bar at 45 mins</td>
</tr>
<tr>
<td>Temperature Fluctuation</td>
<td>80°C at 45 mins</td>
<td>30°C at 210 mins</td>
<td>10°C at 70 mins</td>
<td>10°C at 45 mins</td>
</tr>
<tr>
<td>Time to Full load</td>
<td>90 mins</td>
<td>240 mins</td>
<td>180 mins</td>
<td>120 mins</td>
</tr>
</tbody>
</table>

Supposing that a failure has, in fact, taken place after a change to two shifting, what an Expert System can do, in these circumstances, is ask pertinent questions, such as:

If there are Serious Steam Temperature Pressure Fluctuations in during Some Start Ups state Steam Drains Operation, Burner Light Up Schedule Time From Burner Light Up To Steam Production

The Expert System would need to contain a table similar to that of Table 8.5, which would enable it to make this shift-to-shift comparison. Constructed in the right way this could allow the Expert System to make some valid conclusions about the failure cause.

Inspection of the columns in Table 8.5 shows real differences between the shifts. Andrew's shift went for a very quick start up and was prepared to take chances. There is a distinct possibility that overheating will occur with this procedure, simply because of this. More importantly the steam drains, which when open, will increase steam flow, and help carry off accumulated condensate were closed too early. It is
noteworthy that a severe pressure and temperature fluctuation occurred shortly after this. As mentioned above, the firing up of the top burner, in an attempt to reach a high steam temperature was not good, either. Jim’s shift went to the other extreme, whereby they were extremely cautious, so that theoretically overheating should not have been a problem. The concern here must be that they allowed the steam pressure to reach a high level before the steam was admitted to the turbine. More importantly, the temperature was low, so that there a strong possibility that condensate would be present in the superheaters.

Table 8.6: Probabilities of Various Actions as Contributing to an Overheating Failure

<table>
<thead>
<tr>
<th>Contribution to Overheating Failure</th>
<th>Andrew’s Shift</th>
<th>Jim’s Shift</th>
<th>Alan’s Shift</th>
<th>Michael’s Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to Steam to enter HP Turbine</td>
<td>Probable</td>
<td>Improbable</td>
<td>Improbable</td>
<td>Possible</td>
</tr>
<tr>
<td>S/H Drains Closed</td>
<td>Almost Certain</td>
<td>Improbable</td>
<td>Improbable</td>
<td>Improbable</td>
</tr>
<tr>
<td>Initial Steam Flow</td>
<td>Possible</td>
<td>Possible</td>
<td>Improbable</td>
<td>Improbable</td>
</tr>
<tr>
<td>Initial Pressure</td>
<td>Probable</td>
<td>Probable</td>
<td>Improbable</td>
<td>Improbable</td>
</tr>
<tr>
<td>Initial Temperature</td>
<td>Probable</td>
<td>Probable</td>
<td>Improbable</td>
<td>Improbable</td>
</tr>
<tr>
<td>Bottom Burner Row Lit</td>
<td>Improbable</td>
<td>Improbable</td>
<td>Improbable</td>
<td>Improbable</td>
</tr>
<tr>
<td>Middle Burner Row Lit</td>
<td>Improbable</td>
<td>Probable</td>
<td>Improbable</td>
<td>Possible</td>
</tr>
<tr>
<td>Top Burner Row Lit</td>
<td>Almost Certain</td>
<td>Almost Certain</td>
<td>Possible</td>
<td>Impossible</td>
</tr>
<tr>
<td>Pressure Fluctuation</td>
<td>Almost Certain</td>
<td>Probable</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>Temperature Fluctuation</td>
<td>Almost Certain</td>
<td>Probable</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>Time to Full load</td>
<td>Possible</td>
<td>Improbable</td>
<td>Improbable</td>
<td>Possible</td>
</tr>
</tbody>
</table>

The procedures used by Alan’s and Michael’s shifts are much better. Table 8.6 shows how in qualitative terms these factors would have contributed to the failure. A table such as this would need to be incorporated into the Inference Engine, and it would be necessary for someone to establish the limits for safe operation. This is something that is best done by inspection of the start up techniques and readings from the plant instrumentation. On the assumption that Table 8.6 has been formulated by any experienced person, it would be rational to think that the likelihood of a failure occurring is greatest on Andrew’s shift.

8.7.2 Operation at High Base Load Conditions

For the early part of its life, a new plant will be on base load operation and temperatures and pressures should be reasonably steady. Superheater failures ought not to occur during this period, unless there is a serious deficiency in the design or the materials of construction. Problems might be expected if the plant is run at above the design rating, especially if the fuel grade is lower than that specified.

P91 does, in fact, present special concern in terms of it ability to reach the design life. These matters were initially highlighted in Chapter 2. They are given even more
consideration in Chapter 9, in which the implications of overestimation of the creep properties, effects of heat treatment and oxidation resistance, etc, are reviewed in terms of building up rules for an Expert System, in which the postulated root cause is a shortcoming with the material rather than with the plant.

Once a unit is fully commissioned, and the characteristics of the plant are known, a decision might be taken to run the plant at above its maximum capacity to maximise revenue. This will require slightly higher values of fuel and steam flow. Unfortunately there cannot be a direct relationship between fuel input and metal temperatures since increased steam production from the furnace will absorb much of the heat. Furthermore, the temperature rise in the furnace is the difference between the air preheat temperature and the flue gas outlet temperature. Given the fact that the air preheat temperature is typically around 300°C, the actual temperature rise will be in the 700-900°C range. Thus a 5% increase in the fuel input would only raise temperature by 50°C or less, which would have minor affect on tube temperatures.

8.7.3 Plant Cycling and P91

The general impact of plant cycling has essentially been covered in Section 8.7.1, which, as well as highlighting the way that operators can “contribute” to plant failures, showed that the build up of condensate in pendant and platen type superheaters can lead to overheating of tubes or thermal shock of headers. Temperature changes themselves, without condensation of steam will induce thermal fatigue, with heavy section components such as superheater headers, main stop valves, HP and IP turbines, and feedheaters all tending to suffer. This was one reason for introduction of P91, since its ability to withstand higher stresses permitted the use of thinner section designs. Indeed the first significant use of P91 was for replacement superheater headers, where although the steam temperatures in such plants were relatively low, the expectation was that P91 headers would be more tolerant of plant cycling than those made from T22.

The use of P91 for superheater tubes came later. As indicated in Chapter 2 it is now recognised that the resistance of P91 to oxidation in steam is below expectations. The immediate effect of a high rate of scale growth is high tube temperatures. But with thick scales there is always a propensity for such scales to delaminate. Although this can occur at any time, this is more likely to occur when the tubes are subject to temperature changes, when differential expansion between the oxide scales and the tubing may be sufficient to cause delamination.

The high rate of oxide growth is an issue for P91, but there is a suspicion that the chunks or platelets of scale which spall from this material are bigger than what would normally be expected. The risk of spallation is greater during stop-start operating, with the platelets falling down and accumulating in the bottom bends of superheaters. Steam flow will then be permanently disrupted, leading to increased tube temperatures, and, of course, even higher rates of oxidation.

It follows from this that if a failure has occurred one should investigate whether there has been a sudden increase in steam temperatures following a switch to plant
cycling after a long period of operation at high base load conditions. Note that to
detect such a change, it is necessary to be able to monitor the steam temperature
coming from individual tubes. It would be pointless to do the assessment on the
outlet steam temperature from the header. Nor would one expect to see any increase
in pressure drops across the superheater. The steam flow from the other tubes would
blanket both temperature and pressure.

Unfortunately, the physical evidence for blockage may disappear after a creep
failure occurs. The release of pressure will blow the spalled oxide out of the tubes.
Other evidence should be looked for, which includes:

- An X-ray examination of the bottom bends in other tubes
- Whether inlet HP turbine blades have suffered from erosion by spalled oxide
- Whether ultrasonic oxide surveys show random and significant variations in
  oxide thickness (c.50 microns) suggesting oxide has fallen off
- Whether tube-to-tube oxide thickness measurements and tube diameters
  show random variations

8.7.4 Fuel and Burner Changes

Flue gas temperatures can also be controlled through judicious use of the burners. If
the bottom rows of burners are fired up, whilst the top row is left off, this will
increase steam production, but because the flue gas temperature is low, the plant will
have difficulty attaining good superheater temperatures. A similar situation will
occur if it is possible to point the burners downwards.

Table 8.7: Schematic that Shows Burner Positions

<table>
<thead>
<tr>
<th>Burner Row</th>
<th>Line 1</th>
<th>Line 2</th>
<th>Line 3</th>
<th>Line 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Row (A)</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
</tr>
<tr>
<td>Middle Row (B)</td>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
</tr>
<tr>
<td>Bottom Row (C)</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
</tr>
</tbody>
</table>

The Knowledge Base would therefore need to incorporate a table such as Table 8.7
which shows schematically the positions of the burners. Having asked the ESO to
click on the burners that are operating, it could make simple statements along the
lines suggested above which would be of the type:

If more than Two_burners on Top_Row are off
Then
Superheater_Steam_Temperature is low

As indicated in Chapter 2, fuel changes can have a marked effect on superheater
temperatures. The basic cause of this is a relative change in the heat input to the
boiler or evaporator section of the furnace. Given a constant fuel energy input, if
there is a reduction in heat pick up by the evaporator, the flue gases exiting the
furnace will be hotter. The most dramatic of such fuel changes will result from a
switch from oil, or coal, to firing by natural gas. This is regarded as a reasonable
easy conversion, since an oil or coal fired furnace has to be larger than a natural gas
design of the same thermal rating. Nevertheless the superheater will tend to suffer.
Because of the low emissivity of the natural gas flames, less radiant heat reaches the
evaporator, resulting in a higher flue gas temperature. There is some compensation
for the lower amount of radiant heat, as the evaporator walls would no longer be
covered with an insulating layer of ash or slag, but then the superheater is similarly
free from deposits. The overall effect is that the superheater (i.e. the secondary
superheater) that is situated at the immediate exit of the furnace will be overheated.
Temperatures further down the flue gas duct will also be high, and borderline
materials, such as P91, may be affected.

Although in the late seventies many oil based plants were converted to coal, and,
nonetheless more recently, a few coal based plants have been converted to natural gas,
these major conversions have come to a halt. Today, the most likely change would
be in the type of coal. This would be done on environmental or economic grounds.
Where the environment was the main consideration, the change would be to a low
sulphur and chlorine coal, enabling the plant to either dispense with or bypass the
flue gas desulphurisation system. Such a reduction in sulphur content could also
imply a move to a coal with a higher melting point ash, since one of main oxides
which reduces ash melting point is that of iron, and iron is often present as pyrites.

Conversely, the switch could be to a higher ash coal, or to a coal with a lower ash
melting point, as these would be of lower cost. Checks will have been made on the
likely effects of making this change, but simple calculations may not highlight all
the implications. In general, increased slag coverage of the evaporator tubes reduces
steam raising capacity, raising flue gas temperatures and increasing the tendency
towards fireside corrosion and creep of superheaters.

It follows that in terms of If...Then rules, where that has been a fuel switch, the
basis for formulating these is not so much the absolute properties of the new coal,
but how it compares with the "design coal". In this respect, the slag property
composition correlations given in Section 2.4.4 of Chapter 2 are reasonably helpful.
Their main shortcoming is that most of the relationships are a best semi-quantitative
and are aimed more at indicating whether the evaporator tubing is likely to slag
rather than the superheaters.

Accordingly if slagging is being experienced, some simple If...Then statements can
be made:

\[
\text{If after Coal Change} \\
\text{Superheater Inlet Temperatures are Low or Steam Output is Low} \\
\text{Then} \\
\text{Superheater Slagging and Furnace Slagging is Probable}
\]
In some respects the Ultra Systems Coal Calculator, as discussed in Chapter 2, is better than these various numerical factors or indices, as it states in plain language whether the slagging behaviour and fouling factor of a coal is “Good” “Moderate” or “Bad”. These statements are given for each one of the various factors, but the Coal Calculator itself gives a weighted average of what are viewed to be the more important of these various factors. The step change can be noticed in the Coal Calculator verbal assessment, in which less than 5 is “Good”, 5-10 is “Moderate” and more than 10 is “Bad” Table 8.8 compares the various correlations.

Table 8.8 : Correlations Relating to Slag Behaviour

<table>
<thead>
<tr>
<th>Likelihood of Slag Problems</th>
<th>Slagging Index Temperature</th>
<th>MVI</th>
<th>Slagging Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe</td>
<td>Less than 1050°C</td>
<td>More than 1.11</td>
<td>More than 2.6</td>
</tr>
<tr>
<td>High</td>
<td>1050°C-1230°C</td>
<td>0.55-1.11</td>
<td>2.0-2.6</td>
</tr>
<tr>
<td>Medium</td>
<td>1230-1340°C</td>
<td>0.277-0.55</td>
<td>0.6-2.0</td>
</tr>
<tr>
<td>Low</td>
<td>More than 1340°C</td>
<td>Less than 0.277</td>
<td>Less than 0.6</td>
</tr>
</tbody>
</table>

Table 8.9: Slagging Properties of Three UK Coals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Original Coal (CEGB No 6)</th>
<th>Harworth Coal</th>
<th>High Slagging Coal (CEGB No 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base/acid Ratio</strong></td>
<td>0.21</td>
<td>0.28</td>
<td>0.87</td>
</tr>
<tr>
<td><strong>Iron Index</strong></td>
<td>0.79%</td>
<td>4.02%</td>
<td>4.02</td>
</tr>
<tr>
<td><strong>MVI</strong></td>
<td>1.08</td>
<td>1.06</td>
<td>2.52</td>
</tr>
<tr>
<td><strong>Viscosity at 1426°C</strong></td>
<td>542 Poises</td>
<td>313 Poises</td>
<td>4 Poises</td>
</tr>
<tr>
<td><strong>250 Poises Temperature</strong></td>
<td>1310°C</td>
<td>1348°C</td>
<td>977°C</td>
</tr>
<tr>
<td><strong>Fe₂O₃ +CaO</strong></td>
<td>6.5%</td>
<td>15.7%</td>
<td>37.0%</td>
</tr>
<tr>
<td><strong>Slagging Factor</strong></td>
<td>0.21%</td>
<td>0.62%</td>
<td>1.74%</td>
</tr>
<tr>
<td><strong>Coal Calculator</strong></td>
<td>7.7</td>
<td>13.1</td>
<td>40.6</td>
</tr>
<tr>
<td><strong>Coal Calculator Conclusions</strong></td>
<td>Moderate</td>
<td>Bad</td>
<td>Bad</td>
</tr>
</tbody>
</table>

In terms of three UK coals Table 8.9 shows that CEGB No 6 is reasonable good, but CEGB No 1 is terrible. The high iron content Harworth Coals put it into the high slagging class.

Correlations such as this can be incorporated into the Knowledge Base. Their main use would be to show if there had been any big changes in slagging behaviour. One
would suppose that plant management would try to use a coal that was either the same or better than for which the plant was designed.

In many cases this would be impractical and if furnace and superheater slagging is a problem, the plant management will need to look at other options. One such is through control of the furnace temperature. Fig 2.29 in Chapter 2 shows that as the viscosity of slag at 1426°C falls, it is necessary to reduce the furnace temperature in keeping with the lowered viscosity, otherwise slagging will occur. This information has therefore been transposed into a look up table which could be incorporated into the Fact Base. See Table 8.10

<table>
<thead>
<tr>
<th>Viscosity Range (Poises)</th>
<th>Below 500</th>
<th>500 to 1000</th>
<th>1000 to 2000</th>
<th>1500 to 2000</th>
<th>2000 to 2500</th>
<th>2500 to 3000</th>
<th>3000 to 3500</th>
<th>3500 to 4000</th>
<th>Above 4000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Flue Gas Temperature</td>
<td>1200°C</td>
<td>1225°C</td>
<td>1260°</td>
<td>1300°</td>
<td>1325°</td>
<td>1350°</td>
<td>1380°</td>
<td>1400°</td>
<td>1425°</td>
</tr>
</tbody>
</table>

8.7.5 Maintenance, Instrumentation and Control Systems

If equipment is not maintained it does not necessarily mean that the plant will no longer run. Smaller items of equipment such as pumps for the water treatment system can be duplicated. In the case of the more important item, which are either too big or to costly to duplicate, the equipment is expected to keep running between major overalls, and if deterioration occurs it should not prevent the plant from operating, although this might require other equipment to work harder. In terms of engineering parlance “the plant should have a lot of fat built into it”

Typical examples of normal in-service deterioration that would impact on plant performance are:

- Fouling of the economiser → reduced feed water temperatures to evaporator
- Wear of regenerative type air preheaters → increased stack losses
- Wear of the flue gas and air preheater fan → loss of draft
- Wear of coal pulverising equipment → incomplete burn-out of coal
- Tearing of expansion joint seals on furnace ductwork → increased excess air and stack losses

There are other pieces of equipment that simply stop operating, but despite this the plant can still be made to work, albeit with reduced performance. These include:

- Badly firing or unserviceable burners → bad temperature distribution
- Stuck flue gas dampers → poor furnace heat absorption
- Feedheater being bypassed → low feed water temperatures
- Unserviceable steam-air preheaters → low combustion air temperatures
- Unserviceable soot blowers → ash and slag formation on tubing

As indicated in Chapter 2, the overall effect of these is to reduce plant output, and if there is an attempt to restore output this will almost certainly increase superheater temperatures.

It is a simple matter for the Expert System to ask questions relating to these items, although in those cases, where the equipment continues to operate, it will only be possible to assess the deterioration by comparing the performance with what it was like when the plant was newly commissioned. This may in practice be difficult since the overall deterioration in the plant may make it impossible to make a valid comparison with past conditions.

In such circumstances, a calculation of the overall thermal balance for the plant will be necessary, if the piece of equipment that has caused the problem is to be properly identified. Similarly an evaluation of the effect of unserviceable equipment will be required to avoid people jumping to conclusions.

What the Expert System can do, in posing questions about the serviceability, is to state the consequences. It could then request the dates when such equipment became unserviceable, and then on the basis of this point out the knock-on effects in terms of possible failures of other equipment.

Badly functioning instrumentation and control equipment can lead to premature failures and it always vital to keep this in mind. For example, if a superheater on plant has failed and all the temperatures and pressures are at the design level, but the plant is working "better than expected", this may imply that the temperatures were being under-recorded. Some variation is to be expected, as thermocouples are not that accurate, and positioning of thermocouples is not that good. In such a case some simple checks can be made. The temperature drops from the outlet of one superheater to the inlet of another should be around 5°C, depending on how long is the line, how large is the diameter and how well insulated is the line.
8.8. Investigation at Billingsport Generating Plant

8.8.1 Preliminary Assessment of Situation Using Expert System

The Expert System begins by asking the ESO (Expert System Operator) to choose, from a list of pieces of equipment within Billingsport Generating Plant, which of these has failed. Having ascertained the failure as being that of a superheater, the Expert System will formulate the next set of questions, using an If...Then rule which will be:

\[
\text{If Failure is Superheater Then list Superheater\_Components and identify Failed\_Superheater\_Component}
\]

The list covers superheater tubes, headers, and attemperators. Since the failure was that of a tube, the Expert System now sets down the main failure mechanisms which a superheater tube could experience. These, as stated in Chapter 2, are overheating, creep, fireside corrosion, erosion, and weld failures. The Expert System would flag up descriptions of these types of failures, using Table 9.1 in Chapter 9 as a basis, then asking the ESO to highlight the relevant key words in this table.

To move this story forwards it is now necessary to add some more information to that given earlier about the Billingsport superheater failure. The new information is:

\[
\text{In this hypothetical case the visual evidence for the failure mechanism is not very good, because the tube had lost most deposits in it removal from the superheater. All that was really apparent from the visual examination was that the tube had thinned to some extent, and there was some deformation where the tube burst. The fact that the tube had lost deposits was apparent as most of the neighbouring tubes still had deposits intact. There was some evidence of thinning of these tubes, also.}
\]

The actual failure was on the high temperature length of the leading tube of a platen superheater, which was the final superheater in terms of steam temperature. The final superheater was therefore protected by the intermediate superheater and also a set of shock tubes.

\[
\text{In terms of quantitative data, the failure time was 25000 hours, and because of the data from the header thermocouples, it was known that the steam temperature from this particular group of tubes was 550°C (The header configuration was of the sub-header type).}
\]

The boiler system was of the once through type, so that the inlet steam temperature tended to vary with furnace conditions, but since the change to P91, the plant had been operating on base load for about four years.
In terms of the failure mechanism, so many key words would have to be clicked for each potential failure mechanism, that the Expert System is not able to formulate a conclusive statement. The fail safe If...Then rule in this case is therefore:

**If** Visual_Assessment mentions Overheating, or Creep, or Fireside_Corrosion, or Erosion  
**Then**  
investigate Steam_ Temperatures and Furnace_ Temperatures

The ESO would then need to enter the design conditions for the superheater. In addition, the Expert System requests information on the types of operation to which the plant might have been subjected. The Expert System asks for the dates associated with each type of operation. It also asks for details of any shutdowns, plant trips or significant load changes in the previous week. All of this information is acquired using a check list. The thinking behind this set of rules is that there might have been a change in how the plant has been operated and that this will have been the root cause of the problem.

As part of this review of plant history, the Expert System needs to ask about previous failures. As stated in Section 8.7.1, some of the most important questions relate to whether this type of failure has previously occurred. A table which would then need to be created would be integral part of the Expert System, in which the Inference Engine would have the ability to compare the type of failure and operating circumstances of the failure under investigation, with any failures have happened in the past. Table 8.11 shows the situation for Billingsport.

**Table 8.11: Tabulated History of Previous Tube Failures at Billingsport**

<table>
<thead>
<tr>
<th>Previous Occurrences</th>
<th>Failure Location</th>
<th>Operating Mode</th>
<th>Suspected Failure Mechanism</th>
<th>Confidence in Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2003</td>
<td>Tube</td>
<td>Two Shifting</td>
<td>Overheating</td>
<td>Certain</td>
</tr>
<tr>
<td>June 2004</td>
<td>Nozzles</td>
<td>Two Shifting</td>
<td>Thermal Fatigue</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Jan 2006</td>
<td>Tube</td>
<td>Base Load</td>
<td>Creep</td>
<td>Possible</td>
</tr>
</tbody>
</table>

The bottom row in red refers to the failure under investigation. The Inference Engine would look at the table to find “coincidences” between the key words between the different rows. As there are none in this case, the conclusions would be:

**If** Base_Load (*Jan 2006*) and Creep and Tube  
And  
Two_Shifting (*May 2003*) and Overheating and Tube  
are Not_Coincident  
**Then**  
Root_Cause_Failure is Likely_To_Be_Different
Note that this is the first positive conclusion that the Expert System has made

The Expert System also notes that there had been no plant trips and shut downs during the previous week and the conclusions are:

\[
\text{If Plant\_Start\_Up\_Previous\_Week is No} \\
\text{Then} \\
\text{Plant\_Start\_Up\_Previous\_Week Root Cause is improbable}
\]

A further check list, relating to plant history will reveal that the material in the superheater has been changed from P22 to P91 and that new superheater has only been subjected to base load operation. Hence the operation of these If...The rules would conclude that:

\[
\text{P91 is a Failure Factor} \\
\text{and} \\
\text{Base\_Load is a Failure Factor}
\]

Note that, these items, each of which is a factor, does not imply that they were causes of the failures. Denoting something as a factor simply means information or data relating to these two issues will play a part in the investigation. In this case, it will be necessary to use mechanical property and corrosion resistance data to help ascertain how the failure has come about. Operation at base load means that it is possible to derive useful information about metal temperatures. Hence:

\[
\text{If Base\_Load is Yes} \\
\text{Then} \\
\text{utilise Steam\_Temperatures and Steam\_Flows} \\
\text{to calculate T\_Metal\_Superheater\_Steam\_Derived}
\]

### 8.8.2 Steam Temperature Aspects at Billingsport

In a similar way the Expert System will request that both the design and operating steam temperatures, pressures and flows should be entered for all of the superheaters, including the one under investigation. A similar procedure was used in Section 6.4 in Chapter 6. Table 8.12 contains the chief results.

<table>
<thead>
<tr>
<th>Superheater</th>
<th>Design Inlet Temperature °C</th>
<th>Design Outlet Temperature °C</th>
<th>Actual Inlet Temperature °C</th>
<th>Actual Outlet Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>365°</td>
<td>420°</td>
<td>355°</td>
<td>430°</td>
</tr>
<tr>
<td>Secondary</td>
<td>415°</td>
<td>490°</td>
<td>425°</td>
<td>480°</td>
</tr>
<tr>
<td>Final</td>
<td>485°</td>
<td>545°</td>
<td>475°</td>
<td>550°</td>
</tr>
</tbody>
</table>
These figures show that, although the final superheater outlet sub-header temperature was only five degrees over the design value, the actual inlet temperature of the final superheater was 10°C, less than design. In the absence of data from steam tables, the Inference Engine could use this information in a more quantitative way, just as a human expert might. The ratio of the design and actual temperature increase, from superheater inlet to outlet, indicates that the heat transfer rates are 25% higher than design. As the Appendices dealing with heat transfer and flue gas temperatures show, this will have given a metal temperature increase over the normally expected design value of between 7.5-10.0°C. These figures result from the fact that the temperature difference between the tube and the steam is normally around 30-40°C. The only other way in which the heat transfer rates could have been as high as this is that if there had been a very large amount of flue gas recirculation taking place. However the levels of flue gas recirculation required to give this increase in the heat transfer rate would tend to depress the exit temperature of the furnace, and reduce the tendency of the furnace to slag. As will be shown this was not the case at Billingsport.

But on this basis the steam derived metal temperature would be calculated on the basis of

Outlet steam temperature is 550°C  
Normal temperature rise is 30-40°C  
Increase of normal temperature rise due to below design inlet temperature is 7.5-10°C  
Then Steam Derived Metal temperature is 587.5-600°C  
Average Steam Derived Metal Temperature 593.75° ≈ 595°C

But the easiest calculation to make would be the estimate the tube temperature using the Larson Miller parametric equation. In this case using Table 9.19 Chapter 9:

If actual_life is c.25000 hours  
Then  
T-Metal_Larson_Miller is 610°C

To summarise the situation:

Design Metal Temperature = 575-585°C  
Steam Derived Metal Temperature = up to 595°C  
Larson Miller Derived Metal Temperature = up to 610°C

Furthermore:

Design Temperature Rise: 60°C  
Actual Temperature Rise: 75°C  
Heat Input: 25% Above Design

All of these figures should be printed on the screen.
The simplistic view of these figures are that the plant derived estimates and the Larson-Miller calculations are in a fair degree of harmony, and that the failure mechanism is therefore one of creep. However the Expert System rules are designed to avoid this making this assumption, and as Table 9.16 in Chapter 9 states, the best that can be can be stated, without supporting information, is that failure by creep is possible. However, Table 9.17 in Chapter 9, also indicates that the results are close enough not to warrant laboratory investigation. The focus has to be on the plant.

The actual If...Then rules would be

\[
\text{If } T_{\text{Metal Larson Miller}} \text{ minus } T_{\text{Metal Temperature Steam Derived}} \text{ is less than } 20^\circ\text{C} \\
\text{Then} \\
\text{Creep Failure is possible}
\]

And in addition the Expert System would make the following recommendation

\[
\text{If } T_{\text{Metal Larson Miller}} \text{ minus } T_{\text{Metal Temperature Steam Derived}} \text{ is less than } 15^\circ\text{C} \\
\text{Then} \\
\text{Creep Failure is possible} \\
\text{but} \\
\text{need for Laboratory Investigation is questionable} \\
\text{and Plant Investigation is Needed}
\]

The Expert System can also state that:

\[
\text{If } T_{\text{Metal Larson Miller}} \text{ and } T_{\text{Metal Temperature Steam Derived}} \text{ are above Design Temperature is Yes} \\
\text{Then} \\
\text{investigate causes of High Superheater Temperature}
\]

Increases in superheater temperature would result from the plant working at increased output, an increase in the coal input, a reduction in steam flow, or an increase in the flue gas temperature. Of this set, the flue gas temperature increase is a secondary effect, being a symptom that something else has happened, rather than being a primary cause. It also differs from the other factors in that it needs to be calculated; all of the others can be ascertained from the operating information and compared to design values. Accordingly the Expert System would set down a table with the design values and ask the ESO to enter the relevant information. If there
was a significant difference between the design values and the operating values the Expert System would focus on this as being a possible root cause of the failure.

In this case the assumption is that there are no significant differences (i.e more than 5%) from the design values. It follows from this that Inference Engine must conclude that the flue gas temperature has increased, the If...Then rule being:

\[
\text{If significant Plant Output Change, Coal Energy Input Change, Steam Flow Change from Design}
\]

\[
\text{Then calculate Flue Gas Temperature}
\]

In this case a fairly good estimate of the flue gas temperature can be made on the basis that the heat input to the superheater is 25% higher than the design value.

Furthermore an intelligent guess can be made about the likely design temperature differences between the flue gas and the tubes on the final superheater (i.e the one which failed), which will be helpful in getting closer to the root cause. At this point in the flue heat exchanger train, the temperature will be high since the flue gas has only encountered the secondary superheater, before encountering the final superheater. On the other hand, the design flue gas temperature should not be much more than 1050°C, otherwise the final superheater would be running into serious fireside corrosion problems and a more resistant material would have been specified. (See Table 2.10 Chapter 2).

This estimate also puts the design flue gas temperature from the furnace at about 1150°C since the temperature drop over the secondary superheater will be about 100°C. This would keep the secondary superheater out of the fireside corrosion range and also free from slagging.

Furthermore on this basis the design temperature difference will be about 500°C between the tube and the flue gas. To get a 25% increase in heat input the flue gas temperature would need to go up to about 1170°C. The Inference Engine would be able to make a more accurate estimate than this rule of thumb calculation, if necessary. The important question for the Expert System is what could have given this temperature rise, and would this kind of rise have any implications for the failure mechanism.

The operation of this set of rules throws the whole emphasis of the investigation back onto the plant. Figure 8.4 in this Chapter indicated a very basic but essential approach to plant based investigations, which is to look for any changes in how the plant has been run. These changes might explain why the temperature of the flue gas was high. The shortcoming of Figure 8.4 is that it implies that one major change might have been responsible for the high temperature. If this were the case, a series of Yes or No responses to the way the plant has been operated or modified, as itemised in Figure 8.4, will lead through to the root cause. It is more often the case that the investigator or Expert System will have to try each possibility which could have led to the temperature increase.
Investigate Reasons for High Superheater Temperature

List Changes Leading to High Superheater Temperatures

Fuels
Plant Output
Staff
Maintenance

Change which led to Temperature Increase does not Cause Equipment Deficiencies

List Equipment Deficiencies Leading to High Superheater Temperatures

Furnace
Steam Raising
Air Preheat etc

Equipment Deficiency which led to Temperature Increase not Caused by Changes

Changes caused Unreliability or Unservicability of Equipment which Led to Temperature Increase

Figure 8.5
Investigative Routes for Identifying Changes That Could Have Led to Premature Superheater Tube Failure
In such a case the flow diagram shown in Figure 8.5 is rather more appropriate. The diagram shows two separate sets of investigation, one focusing on the obvious changes in operation and equipment, etc, that would have led to increases in the superheater temperature, and the other on whether there may be any problems with the plant equipment that might have led to a temperature rise. But it is also possible that the operational changes may have led to equipment unreliability. Hence at some point in the investigation, the two investigative threads may merge.

The diagram is also indicative of what occurs in many situations, whereby following an earlier failure on a piece of equipment, changes will have been made to the operating mode, materials of construction, manpower training, and the level of maintenance. The most satisfactory means of approaching this issue is for the Expert System to list all possible changes and ask the operators to highlight them. In this case all of these issues would need to be examined.

8.8.3 Billingsport Operational Changes Leading to High Flue Gas Temperatures

A key issue is the very high flue gas temperature at Billingsport, which, in the absence of previous failures caused by these problems, must, in some way, be related to operational changes. The changes, which could have led to an increase in flue gas temperatures, can be divided into primary factors such as fuels, burner design, plant output, etc. The other changes, from the design conditions, can be categorised as secondary factors and include high levels of excess air or carbon monoxide. Although these tend to be associated with high flue gas temperatures, they are symptoms rather than causes of poor furnace operation.

As would a human expert, it is best to begin with a consideration of how primary factors might have induced high flue gas temperatures. The only obvious change at Billingsport, apart from the reversion to base load operation, has been with the types of coal that have been used. The situation is as follows:

When the plant specification was laid down, it was decided to opt for a fairly standard steam temperatures and pressures. The design fuel was to be of a kind which is mined in the UK. Such a coal would be of the medium ash, high sulphur type. But during negotiations with coal suppliers, a seven year contract was agreed with an Australian coal producer, based in Hunter Valley. Coal from Hunter Valley was extremely good in some respects, as the ash and sulphur contents were low. Since the silica content of the ash was over 80%, the slag and emission problems would be minimal. But in some respects the high silica content was a drawback since it implied high degree of wear of pulverising equipment. Hence, the price was favourable, although because of the need to ship the coal from Australia the contract was of the take or pay type. To overcome some of the grinding problems,
and reduce the fuel cost still further, the coal was blended with one of the worst UK coals, CEGB No1. The ash of this coal had a haematite content of 20%, and the basicity and sulphur contents were high. Accordingly a 50% blend of the two coals was used during the first period of base load operation.

With the move to two shifting, a number of problems arose. The most important of these was with the flue gas desulphurisation plant (FGD), which had been designed for base load operation. The FGD manufacturers had pointed out that, due to oil residues from the start up burners being carried forward, the seals in the system could swell and disintegrate, if these were subject to continuous exposure. In base load operation this situation only happened only sporadically. But in two shift mode, the seals got a soaking every day.

A revamp of the FGD system was out of the question. The only solution was to bypass the flue gas system and use a low sulphur coal to meet pollution requirements. Fortunately, the Hunter Valley coal was of this type, and it was decided to use it in the unblended form. This fitted in with the contract to take all of this coal, even though the plant was only operating part time.

The change back to base load operation obviously required obtaining a new source of UK coal. This coincided with the end of the Hunter Valley contract, and it was necessary to find a substitute. Coal from the Harworth colliery was considered to be equivalent to original blend and was used for the whole of the base load period, until the failure occurred.

Clearly the change to Harworth coal could have been the root cause of the problem and the Expert System would need to evaluate the coal properties. On the basis of the coal compositions, the Inference Engine carried out the appropriate Coal Calculator type assessment. The results are shown in Table 8.13. This indicates that the coal is not very good and would be likely to cause slagging problems.

Nevertheless, although Harworth is not very good, the question that needs to be asked is how it compares with the coals that have been used previously. In making this assessment, as stated earlier, a reduced number of parameters are needed, and these are shown in Table 8.14.
Table 8.13: Coal Calculator Estimates for Harworth Coal

<table>
<thead>
<tr>
<th>ASH ANALYSIS</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>50.8</td>
</tr>
<tr>
<td>Alumina</td>
<td>26.1</td>
</tr>
<tr>
<td>Iron</td>
<td>14.5</td>
</tr>
<tr>
<td>Calcium</td>
<td>1.2</td>
</tr>
<tr>
<td>Magnesium</td>
<td>1.2</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.8</td>
</tr>
<tr>
<td>Potassium</td>
<td>3.9</td>
</tr>
<tr>
<td>Titanium</td>
<td>1.0</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.05</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.0001</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>0.3</td>
</tr>
<tr>
<td>Sulphur in coal</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Table 8.14: Comparison of Slagging and Fouling Characteristics of Coals used at Billingsport

<table>
<thead>
<tr>
<th>Factor</th>
<th>Blend</th>
<th>Hunter Valley</th>
<th>Harworth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity at 1426°C</td>
<td>179 Poises</td>
<td>5076 Poises</td>
<td>313</td>
</tr>
<tr>
<td>MVI</td>
<td>1.11 (Bad)</td>
<td>0.45 (Moderate)</td>
<td>1.06 (Bad)</td>
</tr>
<tr>
<td>Fouling Factor</td>
<td>0.17 (Moderate)</td>
<td>0.01 (Good)</td>
<td>0.22 (Moderate)</td>
</tr>
<tr>
<td>Coal Calculator Estimate</td>
<td>14.0 (Bad)</td>
<td>3.0 (Good)</td>
<td>13.1 (Moderate)</td>
</tr>
</tbody>
</table>

The Inference Engine would compare each of these values and make the appropriate comparison. To give one such example:

**If** Coal_Blend_Coal_Calculator is bad and Hunter_Valley_Coal_Calculator is good

**Then**

Hunter_Valley_Slagging compared to Coal_Blend_Slagging is Decreased or Eliminated
This would indicate that the switch over to running on Hunter Valley coal during the two shift period should have reduced or even eliminated any slagging problems. This would obviously have implications for heat absorption in the furnace and superheaters, but it is premature to go into this issue at this point. The more relevant comparison is that between the Coal Blend and Harworth Coal as these were used during base load operation.

Hence the If...The rule is:

\[
\begin{align*}
\text{If & Coal\_Blend\_Coal\_Calculator\ is\ bad} \\
\text{and} \\
\text{Harworth\_Coal\_Coal\_Calculator\ is\ bad} \\
\text{Then} \\
\text{Harworth\_Coal\_Slagging\ compared\ to\ Coal\_Blend\_Slagging\ is\ no\_change}
\end{align*}
\]

This rules out the fact that the change to Harworth Coal is not responsible for the problems.

The Expert System can however be made to ask what are the safe flue gas temperatures, using the calculation of the viscosity at 1426°C. There are a variety of ways of asking this question but to emphasise the point that the Coal Blend and Harworth are similar, this form of If...Then question is best asked in the following way:

\[
\begin{align*}
\text{If & Coal\_Blend\ Viscosity\ is\ 179\ poises\ and\ Harworth\_Coal\ Viscosity\ is\ 313\ poises} \\
\text{Then} \\
\text{effects\ on\ Flue\_Gas\_Temperature\_Viscosity\_Parameters\ are\ Unchanged}
\end{align*}
\]

Furthermore the Expert System can also state that

\[
\begin{align*}
\text{If & Harworth\_Coal\_Viscosity\ is\ below\ 500\ poises\ is\ YES} \\
\text{Then} \\
\text{Harworth\_Coal\_Flue\_Gas\_Temperature\_Limit\ is\ 1200°C}
\end{align*}
\]

This is an important finding which should be printed on the monitor and could be added onto the previous findings about flue gas temperatures:

\[
\begin{align*}
\text{Design\ Flue\ Gas\ Furnace\ Exit\ Temperature: 1150°C} \\
\text{Harworth\ Coal\ Flue\ Gas\ Temperature\ Limit: 1200°C}
\end{align*}
\]

\[
\begin{align*}
\text{Design\ Flue\ Gas\ Temperature\ at\ Inlet\ Final\ Superheater: 1050°C} \\
\text{Actual\ Flue\ Gas\ Temperature\ at\ Inlet\ Final\ Superheater: 1170°C}
\end{align*}
\]

Again without doing any calculations or measurements on the furnace, a very rough rule of thumb would be that the flue gas temperature drop across a superheater would be at least a 100°C. Hence, using the results it derived earlier, and assuming these estimates are reasonable, the Expert System can state the following:
If Final_Superheater_Inlet_Flue_Gas_Temperature is 1170°C
Then
Secondary_Superheater_Inlet_Flue_Gas_Temperature is 1270°C

It also follows that:

If Harworth_coal
   And
Secondary_Superheater_Inlet_Flue_Gas_Temperature is 1270°C
Then
Secondary_Superheater will be Slagged

The visual check will have shown that the secondary superheater was slagged and as a result, heat transfer performance would have been impaired. The Inference Engine can now compare its predictions against visual observations and make the following assessment:

If Secondary_Superheater is Slagged is Yes
Then
Harworth_Coal is Possible_Factor
but compare Coal_Blend and Hunter_Valley

The Expert System would print these conclusions on the screen. It would also seem that if Harworth Coal is being used, the secondary superheater will be slagged and a check should be made. The main points are:

**Design Flue Gas Furnace Exit Temperature:** 1150°C  
**Actual Flue Gas Furnace Exit Temperature:** 1270°C

The actual flue gas temperature of 1270°C now becomes a Goal (1270°C_Flue_Gas_Goal) in the Expert System. If the various ways that the plant can be operated do not allow the temperatures to reach this value, then they can be discounted as having a significant affect on their own. In some cases none of the possible causes of high flue gas temperature may be sufficient, but in combination they might be.

Visual observations confirmed that the secondary superheater was slagged. Furthermore as the Expert System also suggested, a check had to be made on the way that the plant had operated on other coals. The best indication would have come from the observations of the operating staff, but these have been replaced. In this situation the Expert System needed to rely on past and present operating data relating to steam temperatures.
The only valid comparison that could be made was to compare the plant performance when the unit was operating at base load using the Coal Blend mix. The data from the two shift period would be too erratic to be of much value. Hence the Expert System asked for the data to be tabulated from the two periods.

Without going into all the details again, what needs to be looked for by the Expert System is how the temperatures and steam flows compare between the time when unit was running on the Coal Blend, and when it was running on Harworth coal. Assuming the steam flows and final temperatures are similar, the most important parameters are the relative temperature increases across the secondary and final superheaters. If these were basically the same it would suggest that the secondary superheater was, indeed, heavily slagged when running on the Coal Blend.

As Table 8.15 shows, this was not the case. In fact the temperature rises when running on the Coal Blend were very similar to the design values, in contrast to the period when the unit was running on Harworth Coal.

Table 8.15: Comparison of Design Conditions for Final Superheater with Actual Conditions when Running on Coal Blend and Harworth Coals

<table>
<thead>
<tr>
<th>Coal</th>
<th>Steam Flow</th>
<th>Secondary Superheater Temperature Rise (°C)</th>
<th>Final Superheater Temperature Rise (°C)</th>
<th>Final Steam Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Blend</td>
<td>2900</td>
<td>73</td>
<td>62</td>
<td>545°C</td>
</tr>
<tr>
<td>Harworth</td>
<td>2876</td>
<td>55</td>
<td>75</td>
<td>550°C</td>
</tr>
<tr>
<td>Design Value</td>
<td>2900</td>
<td>75</td>
<td>60</td>
<td>545°C</td>
</tr>
</tbody>
</table>

On this basis the Expert System can state:

If fuel is Coal_Blend
Secondary_Superheater_Temperature_Rise is similar to Design_Secondary_Superheater_Temperature_Rise
and
Final_Superheater_Temperature_Rise is similar to Design_Final_Superheater_Temperature_Rise
and
Final Superheater_Outlet_Steam_Temperature is similar to Design_Final_Superheater_Outlet_Steam_Temperature
Then
Coal_Blend is unlikely to have caused Superheater_Slagging
The final If...Then conclusion about the coals is fairly obvious and is:

If Coal Blend and Harworth Coal have Similar Slagging properties is Yes, but Similar Slagging Effect on Superheaters is No

Then
Superheater Slagging is not caused by Harworth Coal

This too is a very important finding which needs to be printed out on the screen, and the Expert System would then print a request that other items of equipment be investigated as to how they might have affected furnace temperatures.

8.8.4 Evaluation of the Equipment as Root Cause of Superheater Failure

As was indicated in Chapter 2, a wide variety of conditions can increase flue gas temperatures. Some of these are caused by the normal wear and tear of the plant as it ages. For example air can leak into the furnace, or burners can deteriorate. If this is the case there should be a gradual deterioration over time. If normal deterioration was the cause, there ought to have been a slow increase in the superheater temperature differentials, during the second base load period, when the new P91 superheater was fitted. In making this comparison, the Expert System would need to select temperature data from the time when the plant had settled down, that is, when a previously clean furnace and superheater picks up a standard amount of ash and slag. It would be sensible to give the plant a month for this to happen.

In some these cases it is possible to make some quantitative estimate of how much flue gas temperatures will increase as a result of deterioration in performance of the equipment or its misuse. In other cases, the best that can be done is to use a version of Table 6.3.1.3 in Chapter 6, which gave a list of adjectival phrases covering how much affect various factors these might have. The list is:

None or Insignificant  ➞ Little or Small  ➞ Moderate  ➞ Strong or Severe or High

In this case there were no significant temperature changes in the superheaters over the past four years, and on this basis it is reasonable to infer that the “deterioration” took place whilst the plant was two shifting. This is not too surprising as equipment does wear out faster during two shifting. In addition, during the two shift period there were some a serious tube failure which would have led to a crash shutdown that might have caused damage to other pieces of equipment. It is also possible that some of the operating practices, which were suitable for a plant that is two shifting, such as methods to get the plant up to temperature as quickly as possible, might not be so desirable in a base load plant.

The equipment items whose deterioration, unserviceability, or malfunction which would lead to high flue gas temperatures include:
- Feedwater and economiser system
- Air preheater
- Burner distribution or positioning
- Flue gas and gas tempering systems

The Expert System would need to ask questions of the ESO about each of these.

Deterioration of the feed heating system will tend to reduce steam production, which can only be made good by firing the furnace harder. Unless there is very good control of the furnace, this will inevitably lead to higher superheater temperatures. It is reasonably easy to ascertain the state of feedheaters and economisers from the temperature and steam flows.

The ESO would be requested to fill in Table 8.16. The Knowledge Base would contain the design data by which comparisons can be made, and the Inference Engine, could if necessary, draw appropriate conclusions about whether the equipment was operating satisfactorily from the temperature rises.

### Table 8.16: Steam and Water System Evaluation

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Design Temperature Rise</th>
<th>Actual Temperature Rise</th>
<th>Operational Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet Deaerator</td>
<td>99°C</td>
<td>97°C</td>
<td>Operating</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed Heater 3</td>
<td>30°C</td>
<td>31°C</td>
<td>Operating</td>
</tr>
<tr>
<td>Feed Heater 4</td>
<td>37°C</td>
<td>41°C</td>
<td>Operating</td>
</tr>
<tr>
<td>Feed Heater 5</td>
<td>37°C</td>
<td>-1°C</td>
<td>Bypassed</td>
</tr>
<tr>
<td>Feed Heater 6</td>
<td>40°C</td>
<td>42°C</td>
<td>Operating</td>
</tr>
<tr>
<td>Feed Heater 7</td>
<td>40°C</td>
<td>42°C</td>
<td>Operating</td>
</tr>
<tr>
<td>Economiser</td>
<td>55°C</td>
<td>68°C</td>
<td>Operating</td>
</tr>
<tr>
<td>Furnace (Evaporator)</td>
<td>30°C</td>
<td>42°C</td>
<td>Operating</td>
</tr>
<tr>
<td><strong>Final Steam</strong></td>
<td><strong>368°C</strong></td>
<td><strong>361°C</strong></td>
<td><strong>Operating</strong></td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The table shows clearly that one of the feedheaters has been bypassed on the feed water side. The effect of this is that more heat must be added by the economiser and, more importantly, by the furnace. The steam temperature from the furnace must be kept high otherwise water droplets will be carried into the superheaters. With a steam pressure at the exit to the furnace of 175 bar, the saturation temperature is 355°C, hence the design figure of 368°C gives a reasonable margin.

The Inference Engine in utilising this information will be able to state a series of If...Then rules which are:
If T_Design_Rise Feed_Heater_3 is 37°C and T_Actual_Rise is -1°C,

Then

input Evaporator_Steam_Output, Evaporator_Steam_Pressure,
Evaporator_Steam_Temperature

Here again another set of inputs, in table form, would be required about the evaporator conditions, and at this point it would be useful if the Expert System stated a more general rule which would give an incentive to the ESO to input the data. This rule would be printed on the screen as follows:

If Feed Heater_5 is not_functioning

Then

Steam output may be reduced

and

(a) Steam_from_evaporator may be wet,
(b) Economiser may start to steam
(c) Heat input to furnace may have to be increased
(d) Superheater metal temperatures will rise

Table 8.17 includes the data relating to the evaporator:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Flow</td>
<td>2900 tonnes/h</td>
<td>2876 tonnes/h</td>
</tr>
<tr>
<td>Pressure</td>
<td>175</td>
<td>176</td>
</tr>
<tr>
<td>Inlet Water Temperature</td>
<td>338°C</td>
<td>319°C</td>
</tr>
<tr>
<td>Outlet Steam Temperature</td>
<td>368°C</td>
<td>361°C</td>
</tr>
</tbody>
</table>

The conclusions that the Expert System would make on from these figures is that steam output is at design. It would also be able to state, using the steam table data in the Fact Base and Inference Engine that the steam temperatures and pressures indicate that the steam was fully superheated. Furthermore, it would also be able to state, despite the earlier warnings, that the economiser was not steaming.

The more important question is whether the heat input to the furnace is sufficiently great to account for the increase in flue gas temperatures. Superficially the answer is in the affirmative, as the design temperature rise is 30°C, but the actual temperature rise was 42°C. This would seem to imply that the heat input has risen by 40%. This is where rule-of-thumb estimates can come adrift. In actual fact the difference is much less since most of the heat which is used in the furnace goes into evaporating the water. The Inference Engine should be able to take information from steam tables or appropriate programme and make the following calculations.
From the inlet and outlet temperatures and flows it would be able to state that:

\[
\text{If } \text{Design\_Enthalpy\_Rise\_Evaporator} \text{ is MJ/h 32905000 MJ/h}
\]

\[
\text{and}
\]

\[
\text{Actual\_Enthalpy\_Rise\_Evaporator} \text{ is 34319000 MJ/h}
\]

\[
\text{Then}
\]

\[
\text{Heat\_Input\_Evaporator} \text{ is Design\_Plus\_4%}
\]

\[
\text{And}
\]

\[
\text{Flue\_Gas\_Temperatures} \text{ is Design\_Plus\_4%}
\]

\[
\text{And}
\]

\[
\text{Calculated\_Flue\_Gas\_Temperature} \text{ is Design\_Plus\_50°C}
\]

The Expert System would then calculate that:

- The additional fuel input to the evaporator caused Flue Gas temperature to reach 1200°C.

- Additional fuel input was due to the malfunctioning of Feedheater 5

On this basis the Expert System would state that:

\[
\text{If Estimated\_Flue\_Gas\_Temperature} \text{ would be 1200°C}
\]

\[
\text{resulting from}
\]

\[
\text{Feedheater\_5\_Bypassed}
\]

\[
\text{Then}
\]

\[
1270°C \text{ Flue\_Gas\_Goal}
\]

\[
\text{is}
\]

\[
\text{Not\_Attained}
\]

\[
\text{but}
\]

\[
\text{Feedheater\_5\_Bypassed} \text{ was moderate _factor}
\]

*The question was why was the feedheater bypassed? The dates at which this was done give an answer. The shut down occurred about 18 months after the two shift period began, when a leak was noticed on the feed heater system with water getting up into the pipework leading from the turbine down to the feedheater. Such leaks are dangerous since the water in the feedheater is at a higher pressure than that of the steam and significant amounts of water getting into the turbine could wreck it. The view was that the temperature changes caused by the thermal cycling were inducing corrosion fatigue, a common problem induced by two shifting.*

Having come to the conclusion that the bypassing of the feedheater was only a contributory factor, the Expert System would then need to go on to investigate other possibilities.
The effect of high air preheat temperatures can be assessed by rule of thumb methods, in a similar manner to that of the fuel input, but with this the accuracy is not very high. In this case there was a slight drop from the preheater design conditions, so there was no effect.

With respect to the burner arrangement, this was as shown in Table 8.18. The burners that are on are highlighted in yellow. The only conclusions that the Expert System can draw from this would be:

\[
\text{If Burner Distribution is as Table 8.18} \\
\text{Then Heat Input is high} \\
\text{and Heat Input is Reasonably Even} \\
\text{but} \\
\text{Flue Gas Temperature will be High} \\
\text{is Little Factor in High Flue Gas Temperature}
\]

Table 8.18: Showing Burner Distribution at Billingsport with Harworth Coal Fuel

<table>
<thead>
<tr>
<th>Burner Row</th>
<th>Line 1</th>
<th>Line 2</th>
<th>Line 3</th>
<th>Line 4</th>
<th>Line 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Row (A)</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
<td>A5</td>
</tr>
<tr>
<td>Middle Row (B)</td>
<td>B1</td>
<td>B2</td>
<td>B3</td>
<td>B4</td>
<td>B5</td>
</tr>
<tr>
<td>Bottom Row (C)</td>
<td>C1</td>
<td>C2</td>
<td>C3</td>
<td>C4</td>
<td>C5</td>
</tr>
</tbody>
</table>

The remaining possibility, at Billingsport, was the operation of the furnace dampers. This led to the discovery that although the bottom furnace door was partly opened, allowing some flue gas recirculation to occur, the top damper door was permanently closed, so that cooling of the exit flue gases was not occurring. It was the latter that was the cause of the high flue gas temperatures.

In dealing with the question of the dampers in the system, the Expert System needs to take into account a number of possibilities, as detailed in Table 8.3 of this Chapter. After asking the ESO to highlight the dampers which were opened or closed, and to state whether the coal was of a slagging type, the Expert System would make the following assessment:

\[
\text{If Flue Gas Recirculation Damper Open} \\
\text{And} \\
\text{Gas Tempering Damper Closed} \\
\text{Then} \\
\text{Very High Flue Gas Temperature} \\
\text{and Damper Positioning is} \\
\text{moderate factor to high factor in causing high flue gas temperature}
\]
Furthermore since there is rough correlation between these qualitative statements, that is "Moderate"; 1225-1300 °C, and "High": 1300°C plus (see Section 8.6.3) the Expert System can make a rough estimate that the actual flue gas temperature is 1170°C. The Expert System can now endeavour to prove a Goal type rule, as follows:

\[
\text{If Estimated Flue Gas Temperature is } 1270^\circ C \\
\text{resulting from} \\
\text{If Flue Gas Recirculation Damper Open} \\
\text{And} \\
\text{Gas Tempering Damper Closed} \\
\text{And} \\
\text{Coal Type is Slagging} \\
\text{Then } 1270^\circ C \text{ Flue Gas Goal is Attained}
\]

In addition the Expert System would collate these conclusions about the causes of the high flue gas temperatures. The results of this analysis are shown in Table 8.19.

### Table 8.19: Expert System Conclusions about Equipment Causes of High Flue Gas Temperatures

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Affect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedheaters</td>
<td>Little/Moderate</td>
</tr>
<tr>
<td>Economiser</td>
<td>None</td>
</tr>
<tr>
<td>Air Preheater</td>
<td>None</td>
</tr>
<tr>
<td>Burner Distribution</td>
<td>Little</td>
</tr>
<tr>
<td>Damper Doors</td>
<td>Moderate-High</td>
</tr>
</tbody>
</table>

The overall conclusions would be printed on the screen and would be:

- Flue gas temperature at furnace outlet (based on heat transfer estimates) - 1270°C
- Flue gas temperature at furnace outlet (based on damper doors) - 1300°C
- Flue gas temperature at inlet to final superheater-1170°C
- Final superheater tube temperature (based on heat transfer) - 595°C
- Final superheater tube temperature (based on creep data) - 610°C

Given this series of temperatures the Expert System could use the fireside corrosion Table 2.10 in Chapter 2 and conclude that the risk of fireside corrosion of the final superheater was significant. On this basis the Expert System would state:

\[
\text{If Final Superheater Tube Temperature is } 595^\circ C \text{ and Flue Gas Temperature is } 1170^\circ C
\]
Then
Fireside_Corrosion is significant
at
0.22-0.44mm/year

Also:

If Fireside_Corrosion_Rate is 0.22-0.44mm/year
and
Service_Time is Four_Years
Then
Tube_Wastage is 0.88-1.76 mm

It can be shown that the tube wall on this superheater would have needed to be about 6-7 mm thick, so that the loss in section would have been in the 5-10% range. This would have raised the stress by similar level and perhaps explains the overestimate of the Larson-Miller calculation.

Hence the If...The conclusions regarding the mechanism of failure are:

If Tube_Wastage is 0.88-1.76 mm and Tube_Wall is 7 mm
Then
Fireside_Corrosion as Single_Failure_Mechanism is impossible

On the basis of the correlations, stated in Table 9.16 in Chapter 9, Section 9.4.3.4.2, which states that the degree of confidence in a creep failure mechanism is related to the degree of concurrence between the estimates of temperature based on heat transfer results and Larson-Miller estimates, the Expert System can state:

If T-Metal_Larson_Miller minus T_Metal_Temperature_Steam_Derived in range
10°C-30°C is Yes
Then
creep_failure_mechanism is possible
(n.b actual value is 15°C)

The Expert System would be able to combine these two mechanisms (if necessary by calculation) and state:

If Tube_Wastage by fireside corrosion is 5% and tube temperature is 595°C
Then
Failure_mechanism is combined creep and fireside_corrosion
and
not by creep alone (possible)
and
not by fireside corrosion alone (impossible)

The Expert System also asked whether the operators understood how the doors should be used. Most said that they did, but all of them also stated that, since the top
damper was stuck closed, it meant that they had never witnessed the effect of gas tempering on superheater operation. The Expert System then asked to the eight shift personnel and three technical staff, plus two management people to answer five questions, broadly based on Tables 2 and 3. These question were of the type:

- If the flue gas recirculation damper is closed what happens to the rate of steam production from the furnace?

- If the both dampers are open what will happen to the economiser temperature?

Not one of these people got the answers all correct, and on this basis the Expert System ran an If ...Then rule which having considered the test results concluded that training was necessary.

8.8.5 Expert System Identification of Root Causes at Billingsport

The main conclusions from the Expert System are

If Heat Transfer Rate into Final Superheater is 25% above design
    Then
        flue gas temperature at final superheater inlet is 1170°C

If Flue Gas Temperature is 1170°C and Final Superheater Tube Temperature is 595°C
    and t-Failure is 25000 hours
    Then
        probable Failure Mechanism is Creep plus Fireside Corrosion

If Flue Gas Recirculation Damper Open
    And
    Gas Tempering Damper Closed
    and operation with Harworth Coal continues
    Then
        it is certain that Final Superheater Tube Failures will continue

8.8.6 What Really Did Happen at Billingsport?

In the light of the conclusions from the Expert System, the idea about taking the P91 manufacturers to court was dropped, and the money that would have been spent on legal action was used to bring the plant up to standard. During the recommissioning the effects of operation of the doors were monitored and the results entered into the Fact Base of the Expert System.
The actual stream of events which had led up to the failure, were never discovered; the history would have exposed a string of management derived errors. But a few months later one of the better shift people ran into his predecessor in pub and between the two of them this story emerged.

When the plant was first put to work with the Coal Blend, the slagging of the furnace resulted in high superheater temperatures. The management and operators, having an understanding of the equipment, then ran the furnace with the tempering doors open but with the flue gas doors closed. This kept the heat in the furnace, and compensated for the fact that the furnace tubes were slagged.

When the plant switched to Hunter Valley coal, the furnace slagging problem disappeared. The difficulty was that too much heat was going into the furnace since Hunter Valley ash did not bind itself to the furnace tubes. It was also imperative on each start up to get the plant making steam as quickly as possible. Accordingly the damper on the gas tempering system was kept permanently closed, although the flue gas recirculation damper was exercised on each shift. At the start of each shift it was opened up once the furnace had reached its design steam output and then closed again at the end of each shift. This kept the heat in the furnace during the daily shutdown period. Unfortunately, towards the end of the two shift period the door stuck in a partially opened condition. This restricted the amount of flue gas recirculation to about 15% of the throughput.

When the original management and staff left, the new people had no knowledge of the previous history. So when the plant went back to base load operation, using Harworth coal, there was no attempt to use the doors in the correct manner. By this time too the top door had become stuck closed, due the build up of ash and slag, and lack of maintenance. The fact that both doors were immovable and it would cost a lot money was another reason for not bothering about them. Further inquiries also revealed that the effect of feed heater unserviceability on furnace performance was not understood either.

8.9 Conclusions to Chapter 8

This fictitious example of a superheater failure gives a good idea of how If...Then rules to identify the root causes of plant failures would need to be utilised. It needs to be emphasised that although the example is fictitious, as were the numerical values for superheater temperatures, etc, there was no attempt to massage the
figures. Indeed the author had hoped that the effect of bypassing of Feedheater 5 would have stronger impact on the flue gas temperatures than it did.

A good deal of use was made of rule of thumb correlations to estimate what were the flue gas temperatures. These were partly based on what were the likely temperature drops over superheaters and on what is normally considered to be good design practice. In a real Expert System much better estimates could arrived at using process flow modelling programs. This was done in the case of the heat inputs to the feed heaters where data from a program called CHEMCAD was used. Nevertheless, even given the much better estimates that such programs can offer, it is still necessary to make the connection with the root causes of the failure. So If...Then rules still need to be written to show what the quantitative data implies. Such rules would be essentially the same as those formulated in Section 8 of this Chapter.

To avoid too much tedium not every rule was stated. If this had been attempted Section 8 would have been unreadable, and would not have showed the reader how some definite and self-consistent findings emerged. But it will be apparent that the rules have to be modified to suit the technical issue being evaluated. Accordingly a major finding of Chapter 8 is that it is impossible to formulate all the rules in isolation. A full set can only be created by trying an existing set of rules on a real problem. On the other hand, efforts to devise rules by “jumping in at the deep end” with a real problem and hoping the rules will emerge does not work either.

The Expert System came up with some very definite conclusions. A very important result was that the material was not the cause of the premature failure. Another key result also went against the preconception that the slagging properties of the Harworth Coal were to blame. The operation of the If...Then rules showing that this coal was very similar to the original Coal Blend.

The Expert System showed that main root cause was closure of the gas tempering doors. Unless rectified, the problem of high flue gas temperatures, superheater slagging and premature failure of the final superheater will continue.

In this manner the Expert system was acting exactly like a group of human experts who would be able to:

- Identify the mechanism of failure of the component
- Quantify the factors which would have caused the component to fail, in terms of temperature, stress, corrosion, etc
- Decide whether or not to do an in-depth investigation
- Determine how these factors were produced through the design or operation of the equipment
- Suggest changes which significantly reduce the risks of premature failure
Chapter 9

Failure Analysis of P91 Superheaters

9.1 Introduction

Chapter 2 reviewed the main failure mechanisms in power plant superheaters, and highlighted some of the difficulties in identifying the mechanisms of failure in P91. These problems stem from the relative absence of changes in the microstructure of P91 as the material ages, and in the way in which the formation of oxide can reduce superheater life. These issues have been highlighted by the author in various conference publications and journal papers [1, 2, and 3]. Other authors have made similar comments [4, 5]. The issue in this Chapter is therefore to show how rules can be formulated in an Expert System that can be used to help identify the failure mechanisms and their root causes in failures which involve P91.

The previous Chapter, which concentrated on the plant aspects of the investigation, showed how the Expert System could use various clues to point towards the root cause of a failure, when this had originated from the way that the plant was designed, operated or maintained. These clues would include such factors as the time and location of the failure, the way in which the plant had been operated, and the interpretation of steam and water temperatures and flow rates.

In many cases a visual inspection of the failure can suggest the mechanism that will also lead onto identification of the root cause. If the conclusions of the visual inspection are in concurrence with those coming from the way that the plant is operated, etc, this would tend rule out the possibility that the material was at fault. As this is often the case, there is no need for laboratory investigations, since Management would make appropriate changes to the operation of the plant. Only when the plant itself appeared blameless or the failure was of an unusual and/or recurring type would the plant management call in the “backroom boys”.

It seems more likely that the need for deeper investigations will occur with superheaters with headers made out of P91 and tubing made out of T91. These are relatively new alloys. With this material there is a general need to build up experience. In the case of the failures involving the headers and associated components, the analysis of the situation is greatly simplified because the metal temperature is known, as this will be at the steam temperature. It would also be unusual for the header to be operating in excess of the design temperature. The investigation can concentrate on the metallurgy of the material instead of worrying about whether the header temperature has been excessive.

Turning to the investigation of tube failures in T91, it is much more difficult to ascertain the operating temperature, since the time/temperature metallurgical changes are slight. Hence much of the forensic work in identifying root causes has to rely on circumstantial evidence. This is a highly suitable problem for an expert system where each piece of circumstantial evidence can be subject to its own
If...Then rules. This section will show how some of these rules can be built up and utilised.

Section 2.3 of Chapter 2 outlined the problems associated with life estimation of P91, this survey being completed in 2002. But at the time of writing, judging from a recent conference on “Proceedings on Industry and Research Experience in the Use of P/T91 in HRSGs/Boilers” (ETD Ltd Dec 2005), there have been no breakthroughs. It is apparent that the work on life assessment has tended to be based on relatively short term tests, in which changes in the sub-optical microstructure and hardness are much more noticeable than with longer term exposures. It is going to be more difficult than some authorities think to estimate the life of components. Furthermore, a view was expressed at this conference that it was vital to get the tempering conditions right otherwise the creep strength of the P91 would be deficient. This is a new and complicating factor, impacting on tube life and also on temperature assessments. Two presentations at the Conference, including one from the author, highlighted the fact that steam side oxide formation will reduce the time to failure through its insulating effect.

Nevertheless, for the failure investigator, the fact that the most recent work on life assessment is based on short term tests may not be too much of a drawback. The type of failure that has to be investigated is usually one where a tube has failed prematurely, this resulting from the stresses being high in terms of the operating temperature. Hence, with such failures one would expect to see significant hardness and micro structural changes.

The overall intention is to create rules that not only confirm the failure mechanism but show whether the failure was caused by furnace problems or shortcomings with the materials of construction. Naturally, any supposition that the fault is with the P91 alloy will have to be supported by laboratory and background investigations. Flow charts will be used to help formulate the rules. As was shown in Chapter 7 this will require the development of a Bayesian technique to bring together what will be seen to be as rather problematic, conjectural, or circumstantial pieces of evidence.

To show how these sets of Bayesian based rules might work in practice, as was done in Chapter 8, these rules are tested by seeing how they work in investigating a reasonably complex super heater failure. The main difference is that in Chapter 8, the operation of the plant was the focus; the example in this Chapter is orientated to possible metallurgical shortcomings.

9.2 Flow Charts in Backroom Metallurgical Investigations

If it is assumed that we are investigating a creep failure in P91, the majority of such failures in superheaters will have resulted from a moderate degree of overheating, with failures occurring after some tens of thousands hours of operation. The simplistic approach to such failures is shown in Figure 9.1. This indicates that if a creep failure has occurred, and has been positively identified as such, there are likely to be only a few root causes. One possibility is that something is amiss with the furnace design or operation, leading to excessive metal temperatures. Alternative possibilities are that the alloy itself is deficient.
Figure 9.1: Simplistic approach to creep failures in superheaters

Figure 9.1 also indicates the possibility that “off-specification material” may be a possible cause of creep failure. Under this heading we can rank the question of the basic creep strength of these alloys. Although there may be some degree of overestimation of the stress rupture properties of these alloys, the fact that the design stress is a fraction of the stress rupture value, should eliminate the risk of a highly premature failure. Such failures seem only possible if the alloy has been overtempered, subject to cold working, or if there are problems with some of the key strengthening elements.

A more sophisticated approach to tube failures is shown schematically in Figure 9.2. Here the fact that excessive oxidation rates can play an important part in reducing the creep life of superheaters is emphasised. With high strength alloys, oxidation on both the steam side or on the furnace side of tubing can reduce wall thickness to a sufficient extent so as to raise stress and creep life. What is probably of greater importance in P91 is the fact that if the steam side oxidation rate is high, this will form an insulating layer raising tube temperatures and increasing creep rates. Excessive steam side oxide thicknesses can also result in oxide spalling, tube blockage and overheated tubing. Figure 9.2 also shows that poor furnace design or operation can have an influence on the oxidation rate of the metal, but only if the basic oxidation rate of the material is borderline, as is the case with P91.
Figure 9.2: Summary of Failure Mechanism and Causes of Failure on P91 Superheater Tubes
The question is where should the Expert System start its questioning and analysis procedures when there are so many options? Note that although Figure 9.2 is complex, the factors that would lead to poor furnace design and operation are not exhaustive. The following sections of this chapter show how an expert system can be constructed to first identify failure mechanisms and then highlight the root causes.

9.3 Flow Charts for P91 Metallurgical Failure Investigations

Using the flow chart shown in Figure 9.3, a set of If...Then rules can be formulated to initiate the detailed laboratory work and back-up questions that would be put to the plant operational staff and management.

![Flow Chart](image)

Figure 9.3: Failure locations in a superheater

The set of If...Then questions would be

```
If Superheater Then state_location
  Header, Tube, Attemperator.
```

```
If Tube
  Then
  state_location
  Tube_Straight_Length, Tube_Bend, Tube_Support
```
In practice the ESO (Expert System Operator) would highlight these words in sets of tables and the Expert System would respond to these. Once this had been done the Expert System would then move to the rules analysing mechanisms and root causes.

\[
\textbf{If} \ \text{Tube\_Straight\_Length} \\
\textbf{Then} \\
\text{activate Visual\_Assessment\_Rules}
\]

Following the firing of this preliminary set of rules the Expert System would then, as outlined in Chapter 7, set out the specific rules that relate to failures in each section of the superheater tube. Figure 9.4 therefore shows another flow chart, representing the evaluation process, which would lead through to the identification of the failure mechanism and then to the root cause. On the assumption that the failure is of the creep type, the findings of the laboratory work are shown to overlap with information coming from the plant, in terms of operational and design data.

Inspection of Figure 9.4 shows that although the investigation proceeds on the basis that the failure is of the creep type, the figure also implies that there is the possibility that, at the laboratory stage in the investigation it may become apparent that, for example, overheating could be a possible cause of failure. Hence, backtracking is needed, with a dotted line leading back to the box marked “Overheating Failure Appearance”. This would lead to the firing of If...Then rules relevant to this failure mechanism. Figure 9.4 also shows that once the backroom investigations have confirmed that the failure mechanism is creep, the next step would be identify the root cause.

There are only three basic root causes, the first of which results from the way the plant was designed, operated or maintained. In this case the Expert System would endeavour to find out whether these plant-type issues, knowledge of which was obtained using the If...Then rules discussed in Chapter 8, would be supported by the results of the backroom investigations. The Expert System would then conclude that some feature connected with the plant is at fault. If there was not a problem with the plant, the second set of root causes would need to be examined, which would stem from a deficiency in the material. A prime suspect would be the metallurgy of the superheater alloy, which could point to a lack of control in the heat treatment, or to a problem with the composition. However, with a new material like P91, the question must also be asked about uncertainties about the mechanical properties, which may have led the designers to expect too much of the material. The third type of failure has a mixed root cause. Here the material has problems of a fairly specific type, which only show themselves when it is subject to somewhat unusual or arduous operating conditions.
Superheater Tube Failure Preliminary Assessment

- Creep Failure Appearance
- Fireside Corrosion Appearance
- Erosive Failure Appearance
- Weld Failure
- Unknown Failure Appearance

Laboratory Assessment

Plant Information

Confirmation of Creep Failure Mechanism

Detailed Investigations to Identify Root Cause of Creep Failure

- Wholly Plant Induced Root Cause
- Wholly Metallurgical Root Cause
- Combination of Material and Plant Induced Root Cause

Figure 9.4: Flow chart for investigation of tube failures
A series of If...Then rules would be required to move the procedure on from the process of having identified the mechanism of failure, using the backroom investigations, to identifying the root cause. On the assumption that the failure is due to creep, the rules would be of the following type:

If the Backroom_Investigations confirm Creep_Failure
Then
Confirm_Agreement_With_Plant_Based_Rules
is Creep_Failure is Yes or No

If Yes Then state the probable causes of creep_failure
are Plant_Operations, Plant_Design, Plant_Maintenance

If No Then fire Creep_Failure_Causal_Rules

9.4 Assessment of Failure Mechanism

9.4.1 Visual Assessment and Formulation of Initial Hypothesis

Before the Expert System embarks on identifying the root causes, it must determine the most likely failure mechanism. The procedure by which this is done utilise the Bayesian approach discussed in Chapter 7. In this an initial assumption is made about the failure mechanism, which is largely based on the visual appearance of the failure. These visual observations cannot be conclusive, but the probability of being correct is stated in verbal terms, which are then transposed into Bayesian probabilities. This initial assumption is then tested against the metallographic and other information, which are also given Bayesian confidence levels.

To set the process of determining the failure mechanism into action, the Expert System would request the operator of the Expert System to examine Table 9.1. He or she would highlight any of the phrases in the Preliminary Visual Assessment column that best describe the appearance of the failure. These phrases are based on the descriptions of “Metallurgical Failures” described in Section 2.4 of Chapter 2. The italicised column in Table 9.1 would normally be hidden, but each of the phrases relate to a specific superheater failure mechanism.

Table 9.1 shows how various phrases in the Table might be highlighted in the course of a real investigation. In this example it is apparent that the visual clues point to more than one possible mechanism. These phrases would be automatically entered into the expert system and would then be manipulated using If...Then rules as was shown in more detail in Section 6.4 of Chapter 6.
Table 9.1: Key Phrases Describing Failure Appearance

<table>
<thead>
<tr>
<th>Preliminary Visual Assessment</th>
<th>Proposed Failure Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fissuring - Limited Bulging - Blunt Edge Crack - Oxidation</td>
<td>Creep</td>
</tr>
<tr>
<td>Fish Mouth Crack - Severe Bulging - Marked Thinning due to Bulging</td>
<td>Overheating</td>
</tr>
<tr>
<td>White Layer in Deposits - Thinning at Tube Sides - Perforation - Heavy Deposits</td>
<td>Fireside Corrosion</td>
</tr>
<tr>
<td>Wear on Tube Front - Wear at Tube Sides</td>
<td>Erosion</td>
</tr>
<tr>
<td>Fine cracking or Failure in Support Weld</td>
<td>Support Weld</td>
</tr>
<tr>
<td>Fine Circumferential Cracking at Circumferential Weld</td>
<td>Tube Weld</td>
</tr>
<tr>
<td>Cracking at Bend</td>
<td>Stress Corrosion or Fabrication Premature Failure</td>
</tr>
<tr>
<td>Cracking or Perforation with None of Above Indications</td>
<td>Unknown Type</td>
</tr>
</tbody>
</table>

The If...Then rules would rank the responses on the basis of the number of phrases that were highlighted and also on the likelihood of the occurrence of that specific mechanism. With superheater tubes there is an in-built bias towards creep. If the investigation had been on a header failure the bias would have been towards weld cracking.

The expert system would evaluate the outcome of Table 9.1 as follows:

If Creep Phrases are highlighted Then activate Visual_Assessment_Creep

If Overheating Phrases are highlighted Then activate Visual_Assessment_Overheating

If Erosion Phrases are highlighted Then activate Visual_Assessment_Erosion

The expert system would then request the investigator to examine the tube more closely and highlight which of the following applies, using the Tables, 9.2, 9.3, 9.4 and 9.5 covering respectively creep, overheating, fireside corrosion and erosion. These tables are similar to those shown in Chapter 7, Section 7.5.2. As will be apparent, although this set of Tables is mainly based on visual observations, they also include input from the way that the plant has been operated. It will be apparent that the categorisation of the visual appearance of the failure will require judgement but this should not be a problem as difference between the categories is explicit. Having been told which category best fits the Expert System would quantify the outcome in terms of Bayesian probabilistics, giving a “Probability of Reliability”.
Table 9.2: Detailed Visual Assessment Rules for Creep

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Possible fissuring associated with crack.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bulging of tube away from crack indicating general overheating.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Severe thinning of tube, greater than 25% of wall.</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Main crack longitudinal crack surrounded with fissures.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limited bulging of tube in area of cracking.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some evidence of wastage due to fireside corrosion or erosion.</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Fairly narrow main crack longitudinal crack surrounded with fissures.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack position faces hottest flue gas or radiation source.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some mild bulging of tube in area of cracking and away from this.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Significant simple oxidation, but no serious wastage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plant has reached significant proportion of over 70% of its life based on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>operating hours</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Fairly narrow main crack longitudinal crack surrounded with fissures.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crack position faces hottest flue gas or radiation source.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Some mild bulging of tube in area of cracking and away from this.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No significant oxidation or wastage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Plant close to end or beyond end of life based on LM parameter estimates</td>
</tr>
</tbody>
</table>

Similarly the ESO would be asked to use the Tables for Overheating, Fireside Corrosion, and Erosion and highlight the specific rows that best describe the appearance of the failure.

Table 9.3: Detailed Visual Assessment Rules for Overheating

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>See Creep</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Bulging of tube away from crack indicating general overheating.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Severe thinning of tube, greater than 25% of wall.</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Wide fish mouth split type failure with evidence of thick lips and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>indications from plant records of flow starvation</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Wide fish mouth split type failure with thin lips</td>
</tr>
</tbody>
</table>
Table 9.4: Detailed Visual Assessment Rules for Fireside Attack

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Deposits have produced attack but no particular characteristics, Final failure has been due to creep or overuse of soot blowers. Some ash on superheaters. Temperatures not known</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Heavy deposits of ash on front side of tube facing on coming gas flow. Considerable amounts of ash on superheater bundle. Flue gas temperatures could be high at this point. General attack associated indications of creep failure</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Heavy deposits of ash on front side of tube facing on coming gas flow. Considerable amounts of ash on superheater bundle. Deposits definitely show the white layer Flue gas temperatures and tube temperatures are high at this point. Not much attack on the front side of tubes. Attack stronger on sides of tube</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Heavy deposits of ash on front side of tube facing on coming gas flow. Considerable amounts of ash on superheater bundle. Deposits definitely show the white layer Flue gas and tube temperatures known to be high. Not much attack on the front side of tubes. Attack is on side producing “facets” on tube in cross section, leading to a wear through type hole at this point</td>
</tr>
</tbody>
</table>

Table 9.5: Detailed Visual Assessment Rules for Erosion

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Some thinning on front side of tube facing erosion source but failure was by creep</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Wear type failure possibly a combination of soot blower erosion and fireside attack</td>
</tr>
<tr>
<td>Almost Certain</td>
<td>0.90</td>
<td>Strong evidence from direction of possible erosion flow whether from soot blowers or steam blast from local failure that the failure is by wear. Need for frequent soot blowing.</td>
</tr>
<tr>
<td>Certain</td>
<td>0.99</td>
<td>Strong evidence from direction of possible erosion flow whether from soot blowers or steam blast from local failure that the failure is by wear. Need for frequent soot blowing. Temperature records suggest overuse when few deposits are present.</td>
</tr>
</tbody>
</table>
The expert system will then print out each of the failure mechanisms, stating the Bayesian probability and also the probability in words, as has been described in Chapters 6 and 7. It will now request as priority tasks, a set of background or laboratory investigations, which would be needed to confirm the failure mechanism.

9.4.2 Implications of Long and Short Term Creep Data for P91

On the assumption that the initial visual interpretation suggests that the failure is due to creep, exhibiting at least some of the creep symptoms, that is mild bulging and fissuring, the laboratory and backroom work would be set up to confirm this preliminary hypothesis. The problem with P91, as has been emphasised, is that one of the best indications that the material has been exposed to temperature for a long period, spheroidisation of carbides, is absent. There are also conflicting opinions about the correlation between the development of cavitation and how falls in hardness relate to component life.

![Figure 9.5: Recent European Creep Committee (ECCC) Stress Rupture Data for P91 [6]](image-url)

To compound these difficulties there are questions about the basic creep properties of the material. It follows that a somewhat different set of tables to those previously set up in Section 7.5 of Chapter 7, which covered “Quantifying Evidence and Symptoms in Failure Analysis” will be needed. It follows that the investigator will
need to be much more reliant than usual on the information supplied by the plant personnel. Methods to bring together these two forms evidence, using Bayes' rules need to be devised.

As discussed in Chapter 2 some of these problems about the creep strength originate from extrapolation of relatively short term tests, in which the stress level is raised to well above typical design values for the specified operating temperature. As the initial target in creep testing is intended to determine the stress level to give a life of 100000 hours, anything less than a test duration of one third of this can be considered to be an accelerated test.

Much stronger evidence has now emerged, with the publication of recent ECCC (European Collaborative Creep Committee) data sheets on P91, and Cipolla et al have reassessed the differences between the old and the new data. Figure 9.5 shows the recently published log stress/log time plot for stress rupture failure times at test temperature between 500° and 700°C [6]. Each set of coloured points correspond to a specific test temperature, and the line passing through these indicates the mean creep rupture stress, as judged by Cipolla et al.

The green lines for 500°, 550°, 600° and 650°C test temperature, which are just above the mean lines, represent the older estimates dating from 1995. At that time most of the longer term data had to be based on extrapolation. It will be seen that at the shorter times, below 10000 hours, the two sets of trend lines overlap. At longer times, above about 30000 hours, the lines begin to diverge. The more recent trend lines fall significantly below the older ones. In addition to this divergence between the old and new mean stress values, this improved method suggests that the Larson-Miller parametric approach significantly overestimates the strength values at temperatures above 550°C. Table 9.6 shows that trend in the data from the different bodies responsible for making estimates of the creep strength, with ASME overestimating the strength by about 15%.

<table>
<thead>
<tr>
<th>P91 Evaluation Method</th>
<th>500°C</th>
<th>550°C</th>
<th>600°C</th>
<th>650°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASME</td>
<td>164</td>
<td>141</td>
<td>98</td>
<td>---</td>
</tr>
<tr>
<td>VdTÜV</td>
<td>253</td>
<td>162</td>
<td>90</td>
<td>---</td>
</tr>
<tr>
<td>EN (Old EEEC)</td>
<td>258</td>
<td>166</td>
<td>94</td>
<td>48 (approx)</td>
</tr>
<tr>
<td>New EEEC</td>
<td>239</td>
<td>150</td>
<td>85</td>
<td>44</td>
</tr>
</tbody>
</table>

In practice, as Table 9.7 shows, design stresses in the ASME code are set at well below the recent 100000 hour stress rupture value. If the tube fails before 100000 hours, the implication is therefore, that either there is something badly wrong with the material, so that it is running at too high a stress level, or that the temperature is higher than expected.
Table 9.7: ASME Design Stress Values [2]

<table>
<thead>
<tr>
<th>Temperature °C.</th>
<th>Stress MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>110</td>
</tr>
<tr>
<td>525</td>
<td>103</td>
</tr>
<tr>
<td>550</td>
<td>95</td>
</tr>
<tr>
<td>575</td>
<td>87</td>
</tr>
<tr>
<td>600</td>
<td>65</td>
</tr>
<tr>
<td>625</td>
<td>45</td>
</tr>
<tr>
<td>650</td>
<td>29</td>
</tr>
</tbody>
</table>

It also follows that two sets of rules will be needed in making temperature estimates based on the Larson-Miller parameter. Set A rules are where the failure time is fairly short and Set B where the failure time is closer to the design life. For Set A the Larson-Miller constant would be 31. For Set B rules the constant should be reduced to 23.

This clearly impacts on how the failure investigator or Expert System goes about the job with the rules being:

**If** Design Life is 100000 hours and Failure Time is less than 30000 hours  
**Then** use Set A rules

**If** Design Life is 100000 hours and Failure Time is more than 30000 hours  
**Then** use Set B rules

**9.4.3 Implications for Bayesian Probabilistics**

In addition to these stress rupture effects, one would also anticipate that other changes would be subject to what might be termed Set A and Set B considerations. This seems to be born out by the results of the cavitation, hardness and precipitation effects discussed in Chapter 2 where, the more accelerated the test, the more dramatic the changes. The differences between Set A and B data and observations are probably the result of dislocation movements enhancing diffusion processes. Hence any of the phenomena, which relate to precipitation effects or vacancy aggregation, such as hardness changes or cavitation, as well some parametric calculations, will be governed by whether the failure occurred in relatively short or relatively long term. At the time of writing, since most P91 tubes have not been in service very long, and Set A rules would apply.
9.4.3.1 Cavitation

If cavitation can be detected at all in P91, it points positively towards a creep failure mechanism. However if the failure time indicates compliance with the Set B rules, the absence of cavitation would not disallow the possibility of creep. Tables 9.8 and 9.9 exemplify these differences, with Table 9.8 being quite similar to the original cavitation table 7.12 in Chapter 7, but with a slightly greater recognition that if cavities are detected at all, it is a reasonably good indication of creep. In the Set B case, as exemplified Table 9.9, because of the longer failure time, the presence of cavities is an even better indication of creep.

Table 9.8: Cavitation Rules for Short-Medium Term Failures

<table>
<thead>
<tr>
<th>Row Number</th>
<th>Cavitation Description</th>
<th>Creep Failure Indication</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cav A 1</td>
<td>No cavities detected</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>Cav A 2</td>
<td>Isolated cavities are detected. Not possible to deduce direction of maximum principle stress from damage</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>Cav A 3</td>
<td>Cavities present, often with multiple cavities on same grain boundary. A clear alignment of damaged boundaries can be seen indicating axis of principle stress</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>Cav A 4</td>
<td>Cavities have reached the micro cracking stage and are on boundaries normal to the maximum principal stress. Some boundaries have separated due to interlinkage of cavities so forming the microcracks</td>
<td>Almost Certain</td>
<td>0.9</td>
</tr>
<tr>
<td>Cav A 5</td>
<td>Cracking has reached the clearly fissured stage, whereby the micro cracks have joined together to form macrocracks</td>
<td>Certain</td>
<td>0.99</td>
</tr>
</tbody>
</table>

The way the Expert System would need to operate would be to set out the Rule A Cavitation Table and ask the investigator to highlight the row in the Table that best describes the condition of the material. The Expert System would then run an If....Then rule which would generate a verbal probability and a Bayesian probability. These would be of the form:

If Cav_A_4 Then cavity_observations indicate creep_failure is almost_certain and equivalent to Baysian_probability of 0.9
Table 9.9: Cavitation Rules for Long Term Failures

<table>
<thead>
<tr>
<th>Row Number</th>
<th>Cavitation Description</th>
<th>Creep Failure Indication</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cav B1</td>
<td>No cavities detected</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>Cav B2</td>
<td>Isolated cavities are detected, with difficulty</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>Cav B3</td>
<td>Cavities clearly present, often with multiple cavities on same grain boundary.</td>
<td>Almost Certain</td>
<td>0.9</td>
</tr>
<tr>
<td>Cav B4</td>
<td>Cracking has reached the clearly fissured stage, whereby the micro cracks have joined together to form macrocracks</td>
<td>Certain</td>
<td>0.99</td>
</tr>
</tbody>
</table>

9.4.3.2 Hardness

With respect to hardness, the picture is similar. Short term tests to failure give the largest reductions in hardness. Tables 9.10 and 9.11 set out the probability that creep has occurred using Set A and Set B rules.

Table 9.10: Hardness Changes for Short-Medium Term Failures

<table>
<thead>
<tr>
<th>Hardness (VHN)</th>
<th>Set A Rules</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Creep Failure Indication</td>
<td></td>
</tr>
<tr>
<td>&gt;230</td>
<td>Impossible</td>
<td>0.001</td>
</tr>
<tr>
<td>230-215</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>215-200</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>200-185</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>185-170</td>
<td>Almost Certain</td>
<td>0.9</td>
</tr>
<tr>
<td>&lt;170</td>
<td>Certain</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Table 9.11: Hardness Changes for Long Term Failures

<table>
<thead>
<tr>
<th>Hardness (VHN)</th>
<th>Set B Rules</th>
<th>Creep Failure Indication</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;230</td>
<td>Impossible</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>230-215</td>
<td>Improbable</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>215-200</td>
<td>Possible</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>200-190</td>
<td>Probable</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>190-180</td>
<td>Almost Certain</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>&lt;180</td>
<td>Certain</td>
<td>0.99</td>
<td></td>
</tr>
</tbody>
</table>

Here the picture is complicated by the effect of over tempering on hardness, possibly combined with high Al/N ratios, which can lead to low figures at the beginning of the service life. As discussed in the section dealing with root causes, what does seem to be clear is that either over tempering, high Al/N ratios or too high a service temperature would lead to a premature creep failure, with this resulting a low value of hardness at the failure site.

9.4.3.3 Lathe Boundary Precipitation

As indicated, microstructural changes are of limited Help, but the absence of any noticeable changes would tend to rule out creep. Hence Table 9.12 has only two rows, one indicating that creep is improbable, the other that creep is possible.

Table 9.12: Lathe Boundary Precipitation Versus Likelihood of Creep

<table>
<thead>
<tr>
<th>Precipitation at Lath Boundaries</th>
<th>Creep Failure Indication</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Apparent in TEM</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>Apparent in TEM</td>
<td>Possible</td>
<td>0.3</td>
</tr>
</tbody>
</table>

9.4.3.4 Larson-Miller Parametric Estimates

9.4.3.4.1 Larson-Miller Estimates in Validating Creep Failure Mechanism

Before reiterating whether and how the Larson-Miller parametric estimates need to be modified to cover short or long term failures, their primary use in P91 failure investigations would be to give support to the temperature estimates which are made by the plant personnel and heat transfer specialists. The parametric estimates can also be used to give support to the validation of the failure mechanism. Table 7.14 in Chapter 7, which correlated the parametric estimate of the failure time with the actual failure time, showed how this might be done.
Table 9.13: Relationship Between Failure Time and the Likelihood of a Premature Creep Failure

<table>
<thead>
<tr>
<th>Failure Time as Fraction of Time to Failure at Design Conditions</th>
<th>Premature Failure due Creep Mechanism</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;10%</td>
<td>Certain</td>
<td>0.99</td>
</tr>
<tr>
<td>10-25%</td>
<td>Almost Certain</td>
<td>0.9</td>
</tr>
<tr>
<td>25-50%</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>50-90%</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>90-120%</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>&gt;120%</td>
<td>Impossible</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Here, it should be noted that a parametric estimate will always give a higher metal temperature than the design. This is simply because, at the design stress, the material should last for hundred of thousands of hours, and when premature failures occur they are measured in tens of thousands of hours. It follows from this that there is an inbuilt bias in the parametric estimates. Furthermore there is always likely to be some corrosion which will raise the stress level, with the stress level continually increasing over the life of the component.

On this basis we can take the thinking behind Table 7.14 Chapter 6 and suggest that providing there has been no wastage, the shorter the time to failure, the more likely it is that the tube has failed by creep. Table 9.13 shown above is derived from this earlier table. The key word in the Table 9.13 is “premature”. A tube could have failed by creep at all of the times given in the table. A failure occurring at 300000 hours, which would correspond to the life of the tube at the design conditions, can hardly be described as “premature”!

9.4.3.4.2 Larson-Miller Estimates to Verify Plant Data and Further Support Creep Failure Mechanism

Because P91 works close to its limits, the header of P91 superheater would have been well instrumented, so that the steam temperature would be recorded at a number of points along its length. In such cases, a rule of thumb estimate would be that the peak metal temperature of a tube would be about 30-40 °C above the steam temperature. Where these measurements can also be combined with heat transfer calculation it is then possible to estimate peak metal temperatures somewhat more closely, of course. In the case of P91, allowance must be made for the insulating effect of the steam side oxide and the gradual build up in temperature which occurs over the life of the superheater.

In these circumstances, where with best efforts, the plant derived thermocouple data and heat transfer calculations can only give an estimate, there are two ways in which the Larson-Miller calculations can be of help. As stated in the opening paragraph, their most important use is to give support to the plant derived temperature
estimates. That is, if the Larson-Miller and plant derived temperature estimates are in reasonable accord, one can then be more certain of the reliability of the plant information, and if the temperature is higher than design, it points to a fault in the plant. But in this case the main conclusion is that if the two sets of temperature estimates are in accord, this is strong evidence for creep failure.

It follows that at least two sets of probabilistic tables are needed, the first relating to the degree of concurrence between the temperature estimates, and the second one, which covers how well this temperature and time evidence supports the creep failure mechanism. (More sets of tables will be needed, taking into account the change in Larson-Miller parameter, depending on whether the failure is short or long term)

When the header is equipped with local thermocouples there can be more confidence that the Larson-Miller calculations and the plant data support each another. Table 9.14 shows the situation.

Table 9.14: Degree of Compliance Between L-M Parametric Estimates and Plant Derived Data Where Local Header Temperatures are Known

<table>
<thead>
<tr>
<th>Temperature Discrepancy L-M Value minus Plant Value</th>
<th>Amount of Compliance Between Values</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>More than +50°</td>
<td>More than -50°</td>
<td>Impossible</td>
</tr>
<tr>
<td>+50° to +40°</td>
<td>-50° to -40°</td>
<td>Improbable</td>
</tr>
<tr>
<td>+40° to +30°</td>
<td>-40° to -30°</td>
<td>Possible</td>
</tr>
<tr>
<td>+30° to +10°</td>
<td>-30° to +20°</td>
<td>Probable</td>
</tr>
<tr>
<td>+20° to +10°</td>
<td>-15° to -5°</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>Less than +10°</td>
<td>Less than -5°</td>
<td>Certain</td>
</tr>
</tbody>
</table>

Turning now to the actual use of the parametric calculations to give support to the view that the failure was via a creep mechanism, Table 9.14 showed that this is only really possible when the temperature estimates can be considered to be reliable. Hence, the efforts, previously described, to confirm the results of the parametric calculations. The problem is that the time to failure is extremely sensitive to temperature. In such a situation, the best that can be done is to state that even when there is good support for the estimated temperatures, the conclusions are not particularly reliable; hence the support for the creep mechanism is not strong.

With this in mind, the following Table 9.15, based on Table 9.14, can be constructed. It will be seen that the table only contains two rows. Here the intention is to prevent rather inconclusive evidence having an untoward effect on the operation of the Bayesian equations. For similar reasons, if it is only possible to make use the outlet steam temperature, as exemplified in Table 9.14, here too the Expert System would only make use of the bottom two rows. The respective probabilities for a creep failure mechanism would be “possible” and “probable”.
Table 9.15: Larson-Miller Parametric Estimates and Support for Creep Failure Mechanism

<table>
<thead>
<tr>
<th>Temperature Discrepancy</th>
<th>Likelihood of a Creep Mechanism</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-M Value minus Plant Value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+30° to +10°</td>
<td>-15° to -5°</td>
<td>Possible</td>
</tr>
<tr>
<td>Less than +10°</td>
<td>Less than -5°</td>
<td>Probable</td>
</tr>
</tbody>
</table>

It is of course disappointing that the calculations based on the Larson-Miller parameter, cannot give very good support to a creep failure mechanism. But it must be kept in mind that normally plant operators would not be looking into the causes of failures in such detail.

9.4.3.4.3 Larson-Miller Estimates to Highlight Other Failure Mechanisms and Causes

The previous section showed the tentative nature of the conclusions that can be made about the reliability of temperatures derived from the Larson-Miller and plant derived calculations, and whether they can give support to a creep failure mechanism. The findings were that the agreement between the two sets of temperature data has to be very good, before even tentative conclusions can be drawn.

What is the situation, if there is a wide discrepancy between the Larson-Miller and plant estimates? Can this tell us anything? If the estimates using the plant data are higher than the parametric estimates, this would be very odd, especially as the superheater has failed prematurely. Assuming that the correct tube material had been used in the superheater, it would be necessary to recheck the plant derived calculations. Ideally the Expert System could assist with this, indicating likely furnace and flue gas temperatures and querying the results whenever they appeared to be abnormal.

The more interesting situation occurs when the parametric calculations suggest that the superheater metal temperature has been much higher than would be expected from the plant calculations. The first possibility would be that the failure was occurring because of metal wastage, leading to an increase in stress and premature failure because of this. The probable causes of this would be fireside corrosion, erosion corrosion or localised cracking from stress corrosion or weld problems. If there were no significant indications of these mechanisms, the conclusion would have to be that there is some deficiency in the material. The third possibility, the effects of oxidation, results from the insulating properties of the oxide, and its tendency to spall off and block tubing.
Figure 9.6: Flow Chart Showing Use of Larson – Miller Calculations

Figure 9.6 is a flow chart which can be used as a guide to help formulate the If...Then questions that are needed to deal with the situation where the parametric temperature calculations and plant derived estimates are out of line. The If...Then rules for these steps are somewhat trivial but the more important issue is what levels
of temperature difference might be considered to be significant. In a sense the outcome of these particular rules are the obverse of those which were discussed in the previous sections. In that case the intention was to get support for a “normal creep failure” mechanism resulting from the effects of high temperature. Accordingly, the closer the two estimates were to one another, the more confidence there is that the failure is of a normal type.

In the present case, the wider the difference between these two estimates, the greater the likelihood that this failure is unusual. Hence a set of If...Then rules are needed which will spark off investigations into whether the material is deficient or whether the Expert System should backtrack to investigate other failure mechanisms. Where backtracking still indicates no other mechanism but creep, it becomes even more important to make these more detailed investigations. It follows that the If...Then rules are beginning to show how cost effective the investigations will be.

The form of the If...Then rule is therefore:

\[
\text{If } T_{\text{Metal \_ Larson \_ Miller \_ Derived}} \text{ is more than } 30^\circ \text{ C than } T_{\text{Metal \_ Steam \_ derived}} \text{ Then the significance is high and investigate P91 \_ Root \_ Cause}
\]

Sets of rules of this type can be devised, providing an appropriate correspondence can be made between the temperature difference, its significance and the need for further investigation. Table 9.16 sets out these relationships, using the phrases given in Sections 6.3.13 and 6.3.1.7 of Chapter 6, in which the use of Semantic Glossaries in formulating expert system rules was discussed.

**Table 9.16: Relationship Between Temperature Differences, their Significance and Need for Further Investigation**

<table>
<thead>
<tr>
<th>Temperature Discrepancy</th>
<th>Significance</th>
<th>Requirement for Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-M Value minus Plant Value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>More than +30°</td>
<td>High</td>
<td>Imperative</td>
</tr>
<tr>
<td>+30° to +15°</td>
<td>Moderate</td>
<td>Desirable</td>
</tr>
<tr>
<td>+15° to +10°</td>
<td>Little</td>
<td>Questionable</td>
</tr>
<tr>
<td>Less than +10°C</td>
<td>Insignificant</td>
<td>Unnecessary</td>
</tr>
</tbody>
</table>

**9.4.3.4.4 Larson Miller Estimates of Failure Time-Temperature Relationships**

As noted previously, an underlying issue in failure investigation relates to the difference in behaviour of P91 in short and long term tests, which seems to account for differences in the value of the Larson-Miller constant quoted by different workers. It follows that in making life assessment of components that have got close to, or exceeded their normal service life, without any significant indications of creep, a value of around 23 should be used. This figure, as discussed in Chapter 2 is significantly less than the mid-thirties values, derived from short terms tests, which
were quoted by Japanese workers. More recently, for short term accelerated values, practical tests on a trial superheater header, suggest a Larson-Miller value of 31 seems appropriate [7].

Table 9.17: Effect of Changes in Larson-Miller Parameter on Estimated Long Term Temperature Capability Based on Failure at 10000 Hours at 650°C at Stress of 65 MPa

<table>
<thead>
<tr>
<th>Failure Time in Hours</th>
<th>LM Constant@23 (Parameter =24921)</th>
<th>LM Constant@31 (Parameter =32305)</th>
<th>LM Constant @35 (Parameter =35997)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10000</td>
<td>650°C</td>
<td>650°C</td>
<td>650°C</td>
</tr>
<tr>
<td>25000</td>
<td>636°C</td>
<td>639°C</td>
<td>641°C</td>
</tr>
<tr>
<td>50000</td>
<td>626°C</td>
<td>631°C</td>
<td>633°C</td>
</tr>
<tr>
<td>75000</td>
<td>621°C</td>
<td>627°C</td>
<td>629°C</td>
</tr>
<tr>
<td>100000</td>
<td>617°C</td>
<td>624°C</td>
<td>627°C</td>
</tr>
<tr>
<td>225000</td>
<td>605°C</td>
<td>615°C</td>
<td>619°C</td>
</tr>
<tr>
<td>300000</td>
<td>602°C</td>
<td>612°C</td>
<td>616°C</td>
</tr>
<tr>
<td>500000</td>
<td>595°C</td>
<td>607°C</td>
<td>611°C</td>
</tr>
</tbody>
</table>

Table 9.17 indicates how higher values for the constant could lead to an overestimation of the long term temperature capability of P91 by 10-15°C and has been one cause of the overestimation of creep strength. But Table 9.17 also shows that quite small increases in temperature have a very detrimental effect on tube

Table 9.18: Relationship Between Failure Temperatures and Design Temperatures for a Failure Time of 25000 hours

<table>
<thead>
<tr>
<th>Design Temperature for 300000 hour Life</th>
<th>Estimated Failure Temperature P=31 at 25000 hours</th>
<th>Estimated Failure Temperature P=23 at 25000 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>650°</td>
<td>678°</td>
<td>686°</td>
</tr>
<tr>
<td>625°</td>
<td>652°</td>
<td>660°</td>
</tr>
<tr>
<td>600°</td>
<td>627°</td>
<td>634°</td>
</tr>
<tr>
<td>575°</td>
<td>601°</td>
<td>608°</td>
</tr>
<tr>
<td>550°</td>
<td>575°</td>
<td>582°</td>
</tr>
<tr>
<td>525°</td>
<td>549°</td>
<td>556°</td>
</tr>
<tr>
<td>500°</td>
<td>524°</td>
<td>530°</td>
</tr>
</tbody>
</table>
Table 9.19: Relationship Between Failure Temperatures and Design Temperatures for a Failure Time of 75000 hours

<table>
<thead>
<tr>
<th>Design Temperature for 300000 hour Life</th>
<th>Estimated Failure Temperature P=31 at 75000 hours</th>
<th>Estimated Failure Temperature P=23 at 75000 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>650°</td>
<td>665°</td>
<td>670°</td>
</tr>
<tr>
<td>625°</td>
<td>640°</td>
<td>644°</td>
</tr>
<tr>
<td>600°</td>
<td>615°</td>
<td>619°</td>
</tr>
<tr>
<td>575°</td>
<td>589°</td>
<td>593°</td>
</tr>
<tr>
<td>550°</td>
<td>564°</td>
<td>568°</td>
</tr>
<tr>
<td>525°</td>
<td>538°</td>
<td>542°</td>
</tr>
<tr>
<td>500°</td>
<td>513°</td>
<td>517°</td>
</tr>
</tbody>
</table>

This issue of the marked effect that metal temperatures have on failure times is given further emphasis in Tables 9.18 and 9.19, where the nominal tube life is set at 100000 hours, giving a safe design life of about 300000 hours, and where the design temperature varies from 500° to 650°C. Note that a temperature increase of about 25-35°C over design values will give a failure time in the vicinity of 25000 hours. If the temperature increase is somewhat less, at 15°C to 20°C, the tube would have still failed prematurely at something in the vicinity of 75000 hours.

9.4.3.5 Oxide Thickness

Time dependant, rules could be set up which would use the thickness of steam side oxide to indicate over-temperature operation and therefore the possibility that a creep failure may have occurred. However, because oxide growth in P91 is sensitive to alloy content, and the gradual build up of temperature as a result of oxide growth under conditions of heat transfer, and the possibility of oxide spallation, the results cannot be considered to be highly accurate.

Table 9.20: Oxide Thickness Versus Likelihood of Creep

<table>
<thead>
<tr>
<th>Oxide Thickness</th>
<th>Creep Failure Indication</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 25 μm</td>
<td>Impossible</td>
<td>0.001</td>
</tr>
<tr>
<td>25-50 μm</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>50-75 μm</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>75-150 μm</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>&gt; 150 μm</td>
<td>Almost Certain</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 9.20 sets out how oxide thickness might correlate with the likelihood of creep for short-medium term failures. Note that unlike cavitation and changes in hardness, a thick oxide only tends to indicate that the tubing has been running at high
temperature, and does not directly indicate that creep is the failure mechanism. High tube temperature would also increase the risk of failure by fireside corrosion or overheating.

9.5 Application of Bayesian Rules in Identifying Failure Mechanisms

9.5.1 Use of Japanese Superheater Failure as a Practical Example

As described in Section 7.5.3.2 in Chapter 7, on the basis of the investigations to determine a failure mechanism, a table can be drawn up which incorporates \( P(F) \) and \( P(E|F) \) which will show the value of \( P(F|E) \) derived from these two functions. To reiterate, in this case, \( P(F) \) is the Bayesian assessment or probability that, on the basis of the visual assessment and plant based information, the failure mechanism is that of creep. The function \( P(E|F) \) is how well the individual laboratory observations and correlations support the creep mechanism hypothesis. The final function \( P(F|E) \) indicates how confident we can be, combining the initial visual assessment and the conclusions from the laboratory work, that the failure mechanism is that of creep.

To show how a Bayesian approach might be used in identifying the root cause of a failure it is best to use an example, and this will be done in the following sections of this chapter. The example comes from a recent Japanese paper, which was published in Materials at High Temperature [8]. For our purposes, the important part of the paper was the background information relating to the circumstances of the failure and the examination of the tube. In this case a P91 superheater tube began to fail after about six years in service, showing signs of bulging of the tubing. Subsequent laboratory work showed the tubes to be heavily oxidised and the material had suffered a severe drop in hardness. The tubes, apparently, were not subject to fireside attack or erosion, and although the oxide was extremely thick and had begun to crack, there was no evidence of tube blockage because of oxide spalling. Unfortunately only limited information was available about the plant itself, but from its Japanese location, and the fact that plant was commissioned quite recently, the assumption is that the plant was of the supercritical type with steam temperature and pressures around 580-590°C and 300 bar. On the basis of what was not stated in the paper, it is reasonable to conjecture that the steam temperature rise across the superheater was close to normal, and may even have been less. This would have resulted in slightly higher flue gas temperatures than normal. These conjectural statements are italicised in the section below relating to “Circumstances of Failure”
The main factors and assumptions used in identifying creep as the failure mechanism are:

**Superheater Design Factors:**

Outlet Steam Temperature and Pressure - 580°C and 280 bar
Estimated Design Metal Temperature - Outlet Steam Temperature + 40°C
Estimated Flue Gas Temperature - 1000°C
Superheater Life - 100000 hours
Corrosion Allowance - 3 mm
Fuel - Low Chorine Coal

**Circumstances Relating to Failure:**

Failure Time - 40000 Hours (i.e six years of normal service)
Plant Operation - Base Load
Superheater Inlet Temperature - At design or “slightly higher”
Superheater Outlet Temperature - At design or “slightly lower”
Flue Gas Temperatures - Not immediately known but higher than normal
Steam Flow Rate - At design

It would also be reasonable to suppose that the superheater tubes were checked every two or three years and that it is only on this last occasion was the bulging detected.

### 9.5.2 Bayesian Procedure to Identify Failure Mechanism

The first step in the Bayesian assessment is to determine $P(F)$, which is the level of certainty that the mechanism of failure is that of creep, this being based on a preliminary visual assessment. Table 9.21 shows the relevant section of the Table used to assess whether a creep failure had occurred. It will be apparent that because the tube had not actually cracked, and because (apparently) there was no indication that the steam temperatures had been excessive, a creep mechanism was only “possible”, corresponding to a $P(F)$ of 0.3.

**Table 9.21: Section of Bayesian Table Containing Visual Rules for Assessing whether the Failure Mechanism was due to Creep**

<table>
<thead>
<tr>
<th>Category</th>
<th>Probability of Reliability</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>0.30</td>
<td>Bulging or swelling of tube up to about 15% increase in diameter. Any thinning of tube is fairly limited and uniform, and corresponds to the general swelling.</td>
</tr>
<tr>
<td>Probable</td>
<td>0.60</td>
<td>Main crack longitudinal crack surrounded with fissures. Bulging of tube in area of crack. Some evidence of wastage due to fireside corrosion or erosion. Alternatively indications from severity of bulging and more open crack an overheating failure</td>
</tr>
</tbody>
</table>
Because the visual assessment was so tentative, with a creep mechanism being only “possible”, it is necessary to back up this initial judgement with the laboratory work. In this respect the facts that we have to go on are:

**Big drop in hardness**
**Significant tube swelling**
**Oxide growth in excess of 200 microns**
**Tube failure in 40000 hours**

Although the hardness changes and amount of tube swelling were not quantified, the statements about these in the paper are so definite, that it would be reasonable to postulate that hardness fell to at least 190 VHN and that the tube swelling was in the 5-10% range. On this basis we can make use of the various Bayesian tables that have been formulated in this work to give the Bayesian probability $P(E|F)$ for how these phenomena would give support to a creep mechanism. Hence the respective Bayesian probabilities are, for hardness 0.6, and for tube swelling 0.6. In terms of quantified data, the photomicrographs in the Japanese paper show that the oxide thickness to be in excess of 200 microns, giving a $P(E|F)$ of 0.9. Furthermore, as noted, the tube was coming to the end of its life after a period of 40000 hours. On the basis that the design life was 100000 hours, the mean time failure time would have been 300000 hours. Hence the failure had occurred after just 13% of the expected life of the tube. This corresponds to a $P(E|F)$ which is also 0.9. These results are summarised in Table 9.22.

**Table 9.22: Bayesian Probabilities for how Laboratory Work Supports a Creep Failure Mechanism**

| Laboratory Based Creep Mechanism Indication | Bayesian Table Used | Verbal Assessment of Support for Creep | Bayesian Probability $P(E|F)$ |
|-------------------------------------------|---------------------|--------------------------------------|-----------------------------|
| Hardness Drop                             | Table 9.10          | Probable                             | 0.6                         |
| Tube Swelling                             | Table 7.15          | Probable                             | 0.6                         |
| Oxide Growth                              | Table 9.21          | Almost Certain                       | 0.9                         |
| Failure Time                              | Table 9.13          | Almost Certain                       | 0.9                         |

Theses figures can now be used in the Bayes’ equation as described in Chapter 7, which is:

$$P(F|E) = \left[ P(E|F).P(F) \right] / \left[ P(E|F).P(F) + [1-P(E|F)].[1-P(F)] \right]$$
Table 9.23 shows the results of these calculations for each of the laboratory investigations. The average of these values is 0.59, which would suggest that combination of these visual and laboratory based observations suggests that a creep failure mechanism is extremely close to being probable. There are, however, four pieces of evidence that are being used in this case. None of these can be regarded as critical in the identification of creep mechanism and used to improve the value of \( P(\mathbf{F} | \mathbf{E}) \). Only cavitation observations and Larson-Miller calculations (when there is an accurate knowledge of temperature) are of this type. Fortunately, because there is a reasonable amount of evidence it is possible to use the “Evidence Volume Factor” to enhance \( P(\mathbf{F} | \mathbf{E}) \), as described in Chapter 7. Since there are four pieces of evidence the Evidence Volume Factor is 0.9 raising \( P(\mathbf{F} | \mathbf{E}) \) to 0.65, that is well within the “probable” range.

| Laboratory Based Creep Mechanism Indication | Verbal Assessment Level | Laboratory Based Probability \( P(\mathbf{E} | \mathbf{F}) \) | Visual Evidence for Creep Mechanism \( P(\mathbf{F}) \) | Failure Supported by Evidence \( P(\mathbf{F} | \mathbf{E}) \) |
|---------------------------------------------|------------------------|-----------------|-----------------|-----------------------------|
| Hardness Drop                               | Probable               | 0.6             | 0.3             | 0.39                        |
| Tube Swelling                               | Probable               | 0.6             | 0.3             | 0.39                        |
| Oxide Growth                                | Probable               | 0.9             | 0.3             | 0.79                        |
| Failure Time                                | Almost Certain         | 0.9             | 0.3             | 0.79                        |

Average \( P(\mathbf{F} | \mathbf{E}) = 0.59 \)

To distinguish this particular value of \( P(\mathbf{F} | \mathbf{E}) \) from others it is given the subscript “creep mechanism”. Hence \( P(\mathbf{F} | \mathbf{E})_{\text{Creep Mechanism}} \) is 0.65, as determined above.

### 9.6 Application of Bayesian Analysis to Identify Root Cause of Japanese Superheater Failure

There is a major difficulty for the author in formulating this section, which has the key job of showing how Bayesian probabilities can be used in conjunction with If...Then rules to determine the root causes of this particular failure. One obvious problem is that much of the information is missing. Nevertheless, as pointed out in Chapter 3, such a situation is not untypical and, just as human expert would be expected to “get on with the job” so must an expert system. Hence the Expert System has been given the capability to construct rules to bypass any gaps in the information given to it.
A more important difficulty is conceptual. One aim of this section is to show how backtracking might work in an Expert System. The problem with this, in going through the possible materials-derived root causes, is that this can engender repetition, which the author and the reader will be anxious to avoid. What should be kept in mind is that all of the conclusions that are reached in each section can be transformed into Bayesian probabilities. Indeed, this is done in the final section of this Chapter.

The development of a Bayesian approach for the manipulation of this type of evidence is one of the key aspects of this Thesis. In line with this, each Section shows how the implications of any data (not the data itself) are transformed into Bayesian probabilities, in which the evidence relating to a possible cause is quantified and can be used in the Bayes equation.

9.6.1 Preliminary Steps to Authorise In-Depth Investigation

This section details the procedure whereby a Bayesian approach is used to identify the root causes of creep failure, basing this on the example from the Japanese paper. This part of the thesis therefore contrasts with the identification of plant based root causes discussed in Chapter 8, where only If...Then verbally based rules were used.

A preliminary step, in having established that the failure mechanism was that of creep, is that there must be some attempt to determine the tube temperature and it is reasonable to use a Larson-Miller calculation to do this. Note that this will be an average temperature. As shown in Chapter 2 tube temperatures tend to increase over time due to deterioration in the plant.

However on the basis of a mean life of 300000 hours at 620°C the Expert System would do a calculation and conclude that the average temperature over the life of tube had been 652°C.

Three If....The rules, stated more fully than usual, related to this would be

\[
\text{If Outlet Steam Temperature is 580°C Then add 40°C to Outlet Steam Temperature for Design Metal Temperature = 620°C}
\]

\[
\text{If Time Failure Ratio is less than 1 Then use C value of 31 in LM equation}
\]

\[
\text{If Superheater Maximum Life is 300000 hours at 620°C Then calculate Failure Temperature for 40000 hours = 641°C}
\]

As stated earlier, because of the inability to estimate the tube temperature from metallurgical changes in P91, there can be no direct confirmation of this figure. It would be apparent however from the temperature rise across the superheater, which is slightly less than normal, and the fact that the outlet steam temperature is also slightly below design, that it would be unlikely that more detailed heat transfer
calculations would be in disagreement with the parametric estimate. This begins to point to some unusual reasons for the failure.

As an aside, this author makes the point that one possible reason why the Japanese paper was silent on the issue of plant conditions was partly the difficulty in making estimates about tube temperatures, given the uncertainties about the parametric calculation, and also because of the difficulties in estimating the final temperature if there was a gradual increase in tube temperature over the superheater life.

A more important reason is perhaps, that a natural human reaction is for materials personnel to have initially suggested that the cause of the failure was a mismanaged plant, with the superheater being driven harder than it should. This would undoubtedly engender some controversy, but if it turned out that the plant had after all been run well, it is not surprising that a paper, written by metallurgists, would not go into aspects of plant operation, after their initial suggestions had been refuted.

The Larson-Miller calculation showed that, compared to the design estimates, the temperature would have been at least 32°C higher. Table 9.14, which shows the degree of compliance between the plant derived estimates of temperatures and those from the Larson-Miller calculations, shows that it is “improbable” that the two temperatures were in agreement. However, given the possibility that the superheater temperature rise was lower than design, the probability of compliance may be even worse.

As Table 9.16 shows, this information can be used by the Expert System to call for a more in-depth laboratory examination, to identify the causes of failure. The form of the rules is:

\[
\text{If } T_{\text{Metal}\_\text{Larson}\_\text{Miller\_Derived}} \text{ is more than } 30^\circ \text{C than } T_{\text{Metal}\_\text{Steam\_derived}} \text{ Then the significance is high and investigate P91 \_Root\_Cause}
\]

The possible reasons for the premature failure are as follows:

- Creep was not the failure mechanism
- Average metal temperatures were higher than the estimates
- Short term temperature excursion at some point in plant life
- Design stresses being too high in view of recent data
- Insulating affect of steam side oxide combined with high heat transfer rates
- Low creep properties due to composition or heat treatment
- Unknown cause

Some of these can be discounted as a result of the metallurgical examination. The Bayesian analysis gave good support to the initial view that the mechanism of
failure as being one of creep. In terms of short term temperature excursions, there was no mention of this in the Japanese paper, so this has to be discounted. There is some evidence, however, from the Larson-Miller calculations, that the metal temperature over the life of the tube has been too high. The problem here, as was stated earlier, is that a parametric calculation, involving a premature failure will always result in the estimated temperature being higher than the design value. The challenge to the Expert System is to devise rules that either confirm that the temperature was excessive, or to show that the parametric indications were misleading, because the stresses were too high or the material was defective because of composition and heat treatment.

9.6.2 Design Stress Issues

The recent publication by the ECCC of the results of further long term creep tests on P91 have shown that in the 575-625°C temperature range there has been some overestimation of the creep properties, as shown by Table 9.24. The question for the Expert System is whether excessive stress has been a significant issue in the present case? This requires a quick method to ascertain how increases in stress affect life.

Table 9.24: Comparison of Older ASME and Recent ECCC 100000 Hour Stress Rupture Data

<table>
<thead>
<tr>
<th>Temperature °C.</th>
<th>ASME MPa</th>
<th>ECCC MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>550</td>
<td>141</td>
<td>150</td>
</tr>
<tr>
<td>575</td>
<td>130</td>
<td>116</td>
</tr>
<tr>
<td>600</td>
<td>98</td>
<td>85</td>
</tr>
<tr>
<td>625</td>
<td>67</td>
<td>62</td>
</tr>
<tr>
<td>650</td>
<td>43</td>
<td>44</td>
</tr>
</tbody>
</table>

Figure 9.7: Fifth Power Relationship Between Failure Stress and Time to Failure

Theoretically for long term creep, where dislocation climb is the governing factor, the time to failure is inversely proportional to the fourth power of the design stress[9]. This approach has been used by the author to estimate the development
potential of austenitic materials or superheater tubing [9]. But, in this case, the power factor is closer to five, as shown by Figure 9.7.

In Figure 9.8 the time to failure at 10000, 300000, 1000000 and 2000000 hours, is compensated by multiplying these times by the “stress ratio” raised to the power five. The stress ratio is the creep rupture stress at the failure time, divided by the stress to give failure at 100000 hours, Hence

\[
\text{Stress Compensated Failure Time} = T_F \left(\frac{\sigma_F}{\sigma_{100000}}\right)^5
\]

Where:

- \(T_F\) = Failure time
- \(\sigma_F\) = Creep rupture stress at failure time
- \(\sigma_{100000}\) = Creep rupture strength at 100000 hours

If the relationship between failure times and the fifth power of the stress had been exact, the values on the “Y” axis of the graph would have been all equal to 1000000 hours. In practice they are not, probably due to various precipitates coming into action, and to over ageing of these, as the service time accumulates. However, the fifth power relationship does enable some useful rules of thumb to be formulated in estimating the effects of over stressing or of possible weakness on the part of the material.

From Table 9.24 one would estimate the ECCC and ASME stress rupture values, at 620°C, to be approximately 65 and 70 MPa respectively. The ratio of these is 0.929.

The Expert System would investigate the significance of this with the following set of rules:

- **If** Japanese plant **constructed before** 2001 **Then**
  ASME design code was used

- **If** ASME stress rupture value (70MPa) at design temperature (620°C) **is higher than**
  ECCC stress rupture value (65MPa)
  **Then**
  use fifth _ power rule to estimate effect on life

If the design life was 100000 hours, the fifth power relationship shows that the theoretical life to failure would be 750000 hours. This follows from the fact that the design stress is 0.67 of the failure stress at the design time. But taking into account the uncertainties in long term prediction, and that the value of the power tends to drop as the times to failure increase, a safer round number would be 500000 hours.

The ratio of the ECCC and ASME values is 0.929. This fraction raised to the fifth power, is 0.692. On the basis that the absolute tube life at a stress of 70 MPa was supposed to be 500000 hours, it follows that the life would drop to 350000 hours, in the light of the recent data on the long term creep strength. In other words, since the
actual life was 40000 hours, the higher stress level had very little effect. Table 9.25 summarises the significant of a reduction in the life due to operation at too high a stress value.

Table 9.25: Relationship between Reduction in Failure Times and whether Over Stressing was a Likely Root Cause

<table>
<thead>
<tr>
<th>Ratio of Calculated Time Due to Excessive Stress v. Actual Time to Failure</th>
<th>Probability in Excessive Stress Having Led to Premature Creep Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1.1</td>
<td>Certain</td>
</tr>
<tr>
<td>1.1-1.5</td>
<td>Almost Certain</td>
</tr>
<tr>
<td>1.5-2.0</td>
<td>Probable</td>
</tr>
<tr>
<td>2.0-3.0</td>
<td>Possible</td>
</tr>
<tr>
<td>3.0-5.0</td>
<td>Improbable</td>
</tr>
<tr>
<td>&gt;5.0</td>
<td>Impossible</td>
</tr>
</tbody>
</table>

Accordingly, the final If...Then rule in this set would be

If calculated_time_to_failure is 350000 hours and actual_time_to_failure is 40000 hours
Then ratio is 8.75 and effect of higher stress is impossible
And back track to other root_cause

9.6.3 Annealing and Tempering Treatments

The properties of P91 steels are dependant on the formation of a martensitic structure which is both stabilised and strengthened by the presence of precipitates of the MX type as described in the following section. The basic martensitic structure is produced by cooling the alloy from the austenitic phase field. Because of the high level of ferrite forming elements in this material, this restricts the size of the field and the annealing range. As well as producing the austenitic structure required, this austenitising treatment dissolves many of the precipitates and can be also be regarded, as a form of solution treatment [4,10].

Too high an austenitising temperature will lead to the formation of delta ferrite, but this will probably require temperatures in excess of 1175°C to induce this. Annealing below the temperature, under a 1000°C will result in an incomplete austenite formation, in which either ferrite will form, or any untransformed martensite that remains will be highly tempered. Such a microstructure would be similar to that produced in the heat affected zone of P91 welds.
On the assumption that either of these possibilities have occurred, that is the alloy has been austenitised either well above or well below the normal range of about 1040°-1070°C, and then normalised in the correct manner, the alloys will have a hardness significantly below expectations, at entry to service. If nevertheless, the material was allowed to go into service one would expect the time to failure to be quite short. In the case of a treatment in excess of 1175°C, this would be due to the presence of delta ferrite. With the alloy that had not been fully austenitised, the properties of this material would be similar to that of Type IV HAZ material which is well known to have poor creep properties. With both sets of material it is also likely that the non-standard microstructure would be preserved, even after long exposure to service. In addition the cooler section of the tube, close to the inlet would have definitely preserved this out-of-specification microstructure.

Table 9.26: Showing Likely Relationship between As-Tempered Hardness and Probability of this Having led to Premature Creep Failure

<table>
<thead>
<tr>
<th>As Received Hardness VHN</th>
<th>Probability of Low Hardness Having Caused a premature Creep Failure</th>
<th>Bayesian Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;220</td>
<td>Impossible</td>
<td>0.001</td>
</tr>
<tr>
<td>220-205</td>
<td>Improbable</td>
<td>0.05</td>
</tr>
<tr>
<td>205-185</td>
<td>Possible</td>
<td>0.3</td>
</tr>
<tr>
<td>185-170</td>
<td>Probable</td>
<td>0.6</td>
</tr>
<tr>
<td>≤170</td>
<td>Almost Certain</td>
<td>0.9</td>
</tr>
</tbody>
</table>

It would be unlikely that the austenitising treatment would be so bad as to cause such serious metallurgical problems, but as a check a set of If...Then rules can be devised to eliminate this possible factor. Much more likely, as a cause of premature creep failure, would be over tempering, especially as there is a wide range of opinions on what is the best hardness. The lowest value known for a normal material is that quoted by Masuyama is where a start value of about 210VHN was quoted [7, 11]. This appears to be about the lowest acceptable limit, since Brett has investigated this in the context of the aluminium and nitrogen contents, as discussed in Section 6.4, in which the aluminium reacts with nitrogen precluding the formation of MX. Similar metallurgical effects would also stem from over tempering in which the MX phase will tend to overage, along with other strengthening precipitates [4,11].

Brett’s results also show that at as-received hardness below 210-200 VHN the creep rate at 600°C and 155 MPa increases very rapidly. It would seem therefore that if the hardness is much above this figure, the creep properties would be adequate. Hence chances of premature creep failures occurring above 220 HVN can be considered to be virtually impossible. One other factor that can be adduced in drawing up Table 9.26 is that extreme over tempering will also tend to destroy the martensitic structure, with the properties tending to approach that of a simple P9 type material, which has only about 60% of the creep strength of P91. The hardness of this alloy
would be around 170 VHN, so that this helps to give a value for the “Certain” category.

In carrying out these hardness tests these need to be taken from a portion of the tube well away from the failure region and ideally not exposed to direct heating from the furnace. They are therefore in a different category from the hardness tests used to help determine that the mechanism of failure was that of creep.

In this case the Japanese paper only indicated that there was severe hardness drop which was set at 190 VHN. This would tend to imply that the initial hardness was over 220 VHN at the very least, suggesting that initial hardness was not a very strong reason for the premature failure.

If, however the hardness had been low the Expert System would need to call for three separate lines of action. These would be to ask for records of tempering treatment to assess whether the temperature was too high. It would also ask for the composition to assess whether the high aluminium/low nitrogen was the cause of the low hardness. The Expert System would countenance caution in the use and interpretation of these figures. With respect to the tempering records, a company that permitted a material with such a low hardness to reach the fabricator might be also one that was not averse to manipulating the figures. And with respect to composition, it is difficult to determine very low levels of elements, especially gaseous ones, so these figures too may not be fully reliable. The best approach would be to carry out a full annealing tempering treatment at standard conditions. If the alloy was of an acceptable hardness, at around 230 VHN the tempering treatment would be at fault. If the hardness was lower, it would tend to point to composition problem.

9.6.4 Alloy Composition and Effects of Strengthening Precipitates

As discussed in the literature survey in Chapter 2, precipitate strengthening is the critical factor in helping to stabilise the martensitic structure and giving high creep strength. The consensus is now that, in P91 steels, the most important precipitates are those of the MX type, which have the composition (Nb,V)(N,C). There are two forms, both showing low growth during long term creep. The niobium rich variety of the MX phase is relatively insoluble, even when the material at solution treatment (i.e. annealing) temperatures. In contrast, the vanadium rich form of MX goes into solution during the annealing treatment precipitates during tempering. The other precipitates which form in P91, (Cr,Fe,Mo)\textsubscript{23}C\textsubscript{6}, and Laves Phase, (Fe,Cr)\textsubscript{2}Mo both tend to grow in service and add little to the long term creep strength.

If MX is to form, free nitrogen is necessary, and this requires the aluminium to be kept at a low level, as this will react with the nitrogen during the tempering treatment. This is now recognised to be highly critical. Because of this, in the efforts to improve the strength of this type of alloy, aluminium levels are being kept to below 0.002%. 
Figure 9.8: Effect of Aluminium and Nitrogen Levels on Creep Strength [Ref 12]

Figure 9.8 shows the effect of nitrogen and aluminium on the creep strength of P91 steels [12]. It will be apparent that an alloy with 0.03% aluminium and 0.05% nitrogen will have a creep strength of about 84 MPa, quite close to the recent ECCC determinations for P91, whereby the mean stress rupture value at 600°C is given as 85 MPa (See Table 25). From this one can then formulate a similar procedure to that described in Section 9.6.2 of this chapter, whereby the effects of stress on life were calculated.

**Table 9.27: Effect of High Aluminium and Low Nitrogen Contents in Reducing Creep Strength of P91 Steels**

<table>
<thead>
<tr>
<th>Aluminium %</th>
<th>Nitrogen %</th>
<th>Failure Stress MPa</th>
<th>Ratio to 84 MPa</th>
<th>Estimated Time To Failure</th>
<th>Ratio to Failure Time</th>
<th>Probability Of Causing Creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.045</td>
<td>0.05</td>
<td>80</td>
<td>0.952</td>
<td>352000</td>
<td>8.8</td>
<td>Impossible</td>
</tr>
<tr>
<td>0.045</td>
<td>0.03</td>
<td>57</td>
<td>0.679</td>
<td>72000</td>
<td>1.8</td>
<td>Probable</td>
</tr>
<tr>
<td>0.03</td>
<td>0.05</td>
<td>84</td>
<td>1.000</td>
<td>500000</td>
<td>12.5</td>
<td>Impossible</td>
</tr>
<tr>
<td>0.03</td>
<td>0.03</td>
<td>64</td>
<td>0.762</td>
<td>128000</td>
<td>3.2</td>
<td>Improbable</td>
</tr>
<tr>
<td>0.01</td>
<td>0.03</td>
<td>75</td>
<td>0.892</td>
<td>284000</td>
<td>7.1</td>
<td>Impossible</td>
</tr>
<tr>
<td>0.005</td>
<td>0.03</td>
<td>78</td>
<td>0.928</td>
<td>345000</td>
<td>8.6</td>
<td>Impossible</td>
</tr>
</tbody>
</table>

If this figure for the 0.03 Al/0.05N steel is taken as the standard, that is the failure stress in 100000 hours is 84 MPa, the “Fifth Power of Stress-500000 Hour” rule (formulated in Section 9.6.2) can be used to estimate the reduction in life caused by inferior mechanical properties due to high aluminium, and low nitrogen levels. Table 9.27 is based on this, and shows that the creep life can suffer significantly. However, even when the alloy is just outside of its composition range (See Table 28) that is 0.045Al/0.03 N, the calculated time to failure is 72000 hours, making the ratio of failure time to the actual time of failure 1.8.
Using Table 9.28, on the assumption that this alloy was just on the composition limits, the chances that the composition was responsible for a creep failure mechanism can be stated as being “probable”. This sounds quite serious, until it is realised that “probable” only corresponds to a Bayesian probability of 0.6. As will be shown later the implications of this only become really significant when the initial diagnosis itself has a high probability.

### Table 9.28: Composition Range for P91 Steels

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Nb</th>
<th>N</th>
<th>Al</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.08</td>
<td>0.3</td>
<td>--</td>
<td>--</td>
<td>0.2</td>
<td>8.00</td>
<td>0.85</td>
<td>0.18</td>
<td>0.06</td>
<td>0.030</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Max</td>
<td>0.12</td>
<td>0.6</td>
<td>0.02</td>
<td>0.01</td>
<td>0.5</td>
<td>9.50</td>
<td>1.05</td>
<td>0.25</td>
<td>0.10</td>
<td>0.07</td>
<td>0.04</td>
<td>0.40</td>
</tr>
</tbody>
</table>

#### 9.6.5 Steam Side Oxidation Induced Failures

As was discussed in Sections 9.3.3.7 and 9.3.3.8 in Chapter 2, the formation of an oxide scale on the steam side of a superheater tube will raise the superheater tube temperature [13]. This will reduce tube life and, as the previous discussion in this chapter has shown, even a relatively small rise in temperature can have a dramatic effect on tube life.

![Figure 9.9: Relationship Between Heat Transfer Rate and Oxide Thickness in Increasing Superheater Tube Temperature](image-url)
The rise in temperature is proportional to the oxide thickness and the heat transfer rate. Figure 9.9 shows the effect for P91 type materials [10,14]. In the Japanese case the oxide thickness is known, but the rate of heat transfer is not. This figure was not revealed by the authors of the Japanese paper, either because it is considered to be commercially confidential, or because it was too difficult to determine. As discussed in Chapter 3, in such circumstances, where some vital information is missing, it behoves a human expert, or an Expert System, to be able to resort to a Plan B. On of the purposes of having a Plan B, is that if the resulting conclusions do support the original suppositions about the root cause, the arguments for following through with the more complex and time consuming work investigations become stronger.

The purpose of this particular approach is therefore, to come up with a set of semi-quantitative rules of thumb which bring together the chances of creep failure, oxide thickness and heat transfer rate. In a well developed Expert System the heat transfer rate could be calculated from the steam flow etc. But even where this figure was available it would be necessary to come up with rules of thumb of this type.

In this case the problem is made difficult as we need to make a reasonable guess at the heat transfer rate. Appendix 3 indicates how superheater heat transfer rates tend to increase with superheater pressure. Since these calculations are somewhat dependant on steam flow, tube diameters and steam temperatures, they are only a rough guide. Nevertheless they are extremely useful in carrying the argument forward about whether the combination of high heat transfer rate and high rate of scale growth was the root cause of creep failure. Table 9.29 based on Appendix 3, shows how pressure will affect heat transfer rates.

<table>
<thead>
<tr>
<th>Steam Pressure (bar)</th>
<th>Superheater Heat Transfer Rate (kW.m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 50</td>
<td>20</td>
</tr>
<tr>
<td>50-100</td>
<td>30</td>
</tr>
<tr>
<td>100-200</td>
<td>60</td>
</tr>
<tr>
<td>More than 200</td>
<td>90</td>
</tr>
</tbody>
</table>

Using a Bayesian approach in the identifying the root cause of the failure, the first issue to determine the value of $P(F)$ _Heat Transfer/Oxidation_, this being a "combination root cause" which could conceivably have caused the temperature to increase and induce a subsequent creep failure. At this point it is worth emphasising that although it may seem obvious that the failure mechanism is actually that of creep, until the Expert System had come to this conclusion this fact was not known. For example, if the fuel had been of an aggressive type, the increase in metal temperature could have led to fireside attack. But there was no evidence of this. To give another example, the formation of a thick oxide could have led to an overheating failure (perhaps by the oxide spalling off and blocking the tube), but again there was no evidence of this.
Having identified that the Bayesian probability $P(F | E)_{\text{Creep Mechanism}}$ for the failure was 0.65, it seems reasonable to equate this value to that of $P(F)_{\text{Heat Transfer/Oxidation}}$. This seems to be similar to the way in which people think, in that having established the mechanism by which the tube has failed is by creep, the initial assumption is that the probabilistic values that can be assigned to the proven mechanism and the possible root cause is likely to be similar. That is:

**Posterior Probability Mechanism $\approx$ Conditional Probability of Root Cause**

In this case:

$$P(F | E)_{\text{Creep Mechanism}} \approx P(F)_{\text{Heat Transfer/Oxidation}} = 0.65$$

The next step in the investigation is to show that there is good support for this idea in the evidence. For this the value of $P(E | F)_{\text{Heat Transfer/Oxidation}}$ needs to be ascertained. These values can then be put into the Bayes' equation in as previously shown.

---

**Fig 9.10: Venn Diagram Showing Relationship between Creep Mechanism and the Heat Transfer/Oxide Thickness Combination.**

Another way to think about the relationship between the two probabilities, $P(F | E)_{\text{Creep Mechanism}}$ and $P(F)_{\text{Heat Transfer/Oxidation}}$, is in terms of a Venn diagram, as shown in Figure 9.10. Here to show that the probabilities both have a value of 0.65, accordingly they are given the same areas. Furthermore, in this analogy, $P(E | F)_{\text{Heat Transfer/Oxidation}}$, which is the posterior probability, is represented by the overlap between the two areas. But the closeness between the two areas represents the strength of evidence, $P(E | F)_{\text{Heat Transfer/Oxidation}}$. As the value of $P(E | F)_{\text{Heat}}$
Transfer/Oxidation increases, the areas begin to overlap. When there is complete overlap it becomes certain that this particular root cause supports the original hypothesis.

Figure 9.9 shows that the bigger the combination of heat transfer rate and oxide thickness the greater the temperature rise. Figure 9.9 can therefore be used to formulate a look up table, in which these values can be used to formulate values for $P(E|F)_{\text{Heat Transfer/Oxidation}}$. The table is formulated, course, taking into consideration how the life of P91 is related to temperature. The results are shown in Table 9.30.

Table 9.30: Bayesian Probabilities for Relationship between Temperature Rise due to Oxide Thickness and Transfer and Affect on Tube Life

| Temperature Rise Over Design | Will Cause Premature Creep Failure | $P(E|F)_{\text{Heat Transfer/Oxidation}}$ | Heat Transfer Rate |
|------------------------------|-----------------------------------|----------------------------------------|------------------|
|                              |                                   |                                        | 25 kW.m$^{-2}$   | 50 kW.m$^{-2}$ | 75 kW.m$^{-2}$ | 100 kW.m$^{-2}$ | 125 kW.m$^{-2}$ |
| 0-5°C                        | Impossible                        | 0.001                                  | < 80 µm         | < 40 µm      | < 30 µm      | < 20 µm      | < 15 µm     |
| 5-10°C                       | Improbable                        | 0.05                                   | 80-150 µm       | 40-80 µm    | 30-50 µm    | 20-40 µm    | 15-30 µm    |
| 10-15°C                      | Possible                          | 0.3                                    | 150-240 µm      | 80-120 µm   | 50-80 µm    | 40-60 µm    | 30-50 µm    |
| 15-25°C                      | Probable                          | 0.6                                    | 240-400 µm      | 120-200 µm  | 80-130 µm   | 60-90 µm    | 50-80 µm    |
| 25-35°C                      | Almost Certain                    | 0.9                                    | 400-600 µm      | 200-300 µm  | 130-200 µm  | 90-140 µm   | 80-125 µm   |
| >35°C                        | Certain                           | 0.99                                   | >600 µm         | >300 µm     | >200 µm     | >140 µm     | >125 µm     |

For the case under discussion the oxide thickness is in excess of 200 microns and the estimated heat transfer rate was 90 kW.m$^{-2}$. From Table 9.30 these values suggest that it is "Certain" that they will be the root cause of creep failure, if creep is the mechanism.

The numerical value of $P(E|F)_{\text{Heat Transfer/Oxidation}}$ corresponding to "certain" is 0.99, a very high value. Inspection of Table 9.31 shows that this largely stems from the effect of the oxide thickness. The Bayesian calculation to determine $P(F|E)_{\text{Heat Transfer/Oxidation}}$ is obtained from the usual expression:

$$P(F|E) = \frac{[P(E|F).P(F)]}{P(E|F).P(F) + [1-P(E|F)].[1-P(F)]]}$$

Where:

$P(F)_{\text{Heat Transfer/Oxidation}} = 0.65$

$P(E|F)_{\text{Heat Transfer/Oxidation}} = 0.99$

That is $[0.99 \times 0.65] / [(0.99 \times 0.65) + (1-0.99) \times (1-0.65)]$

Using these values $P(F|E)_{\text{Heat Transfer/Oxidation}} = 0.995$
In verbal terms this makes it "Certain" that not only did the tube fail by creep, but this was brought about by the combination of the growth of a very thick oxide and a rather high heat transfer coefficient. It can also be shown that even if the oxide scale fell below 200 microns, and the heat transfer rate dropped to 75 kW.m\(^{-2}\) the value of \(P(\text{F} | \text{E})\) would still be quite high, at 0.944. This in part results from the fact that the Bayesian probability for the tube having failed by a creep mechanism was 0.65.

9.7 End Result of Bayesian Identification of Metallurgical Root Cause.

As was stated at the start of Section 9.6 in using a Bayesian approach to deal with each possible metallurgical root cause of failure, the intention was to use each possible root cause to show the thinking behind the use of Bayesian analysis. But only the final sub-section 9.6.4, which covered oxidation/heat transfer as a possible mechanism, showed the complete development of these ideas. Having shown this, it is now possible to go back and apply the complete process to each of the failure mechanisms.

As was shown in Section 9.6.4, the original probabilistic value which was obtained in the determination of the mechanism of creep, is then used in as the numerical value of \(P(\text{F})\) as being the prior probability that a specific failure mechanism could conceivably have caused the failure. This is equivalent to an investigator saying "Well we have a pretty good what is the mechanism of failure. Let us now go through each potential cause of such a failure and assess whether such a cause could in fact give rise to such a failure".

Clearly the stronger the initial assessment of the failure mechanism, and the stronger the evidence that a particular cause will have led to this type of failure, the more likely it is that the supposed root cause is the actual cause. It also follows if the confidence in the initial assessment about the failure mechanism is weak, then the confidence in the evidence for supposed root cause will have to be extremely strong if this is judged to be the actual cause of the failure.

An example of such might have been one where it was judged "improbable" that creep was the failure mechanism, That is in Bayesian probabilistics the prior probability \(P(\text{F})\) was 0.05. (Maybe, in this case wastage by fireside erosion was much more likely to have caused failure). In contrast the oxidation and heat transfer evidence relating to this creep failure is assessed to be certain, giving \(P(\text{E} | \text{F})\) a value of 0.99. In this case the posterior probability would be 0.839, that is in verbal terms, a likelihood of "probable". However if the oxidation thickness and heat transfer rate had dropped to "almost certain" category \(P(\text{E} | \text{F})\) is down to 0.9, then the posterior probability \(P(\text{F} | \text{E})\) would have fallen to 0.321. In verbal terms this is just into the "possible" category.

This procedure therefore, of using the Bayesian posterior probability of the failure mechanism as being equivalent to the prior probability of a particular cause seems to work well in simulating human thought processes. Note that a further advantage of this approach is that since \(P(\text{F} | \text{E})\) for the creep mechanism is given a number, this
is a real advantage compared to stating the probability of creep in verbal terms, where in probabilistics there is a big jump between such adjectival statements as “possible”, probable, and “almost certain” (i.e. 0.3, 0.6 and 0.9 respectively).

Table 9.31 has been formulated on the basis that \( P(F) \) is equal to 0.65 for the four different root causes under review. The results show that it is “impossible” for the failure to have been caused by too high a stress. In this case \( P(F|E)_{\text{Stress}} \) for this particular failure cause is only 0.0018. On the other hand it is certain that the combination of a thick oxide and a high stress would have been a “certain” cause of the failure, since as calculated above \( P(F|E)_{\text{Heat Transfer/Oxidation}} \) is 0.995. The two other potential causes, over tempering, and a high aluminium to nitrogen ratio are significantly less probable.

### Table 9.31: Bayesian Assessment of Metallurgical Failure Causes

| Potential Root Cause          | Creep Failure Probability And \( P(F) \) for Root Cause | Verbal Assessment of Bayesian Probability of Root Cause \( P(E|F) \) | Bayesian Probability that Root Cause led to Creep Failure \( P(F|E) \) | Verbal Assessment that Root Cause led to Creep Failure |
|------------------------------|--------------------------------------------------------|------------------------------------------------|-------------------------------------------------|-----------------------------------------------------|
| Excessive Design Stress      | 0.65                                                   | Impossible (0.001)                               | 0.0018                                          | Impossible                                          |
| Over Tempering               | 0.65                                                   | Possible (0.3)                                   | 0.443                                           | Possible                                            |
| Al/Ni Ratio                  | 0.65                                                   | Probable (0.6)                                   | 0.736                                           | Probable                                            |
| Oxidation and High Heat Transfer Combination | 0.65                                                   | Certain (0.99)                                   | 0.994                                           | Certain                                             |

The Expert System can contain rules which would carry out the Bayesian calculations and then set out the results in the form of Table 9.31. It would examine the results and state that the most likely cause of failure was a combination of high rates of heat transfer and, at the planned operating temperature, an oxidation resistance which was not adequate for the conditions.

### 9.8 Conclusions to Chapter 9

There is clearly not much point in subjecting everything to a probabilistic analysis of the Bayesian type but it is obviously valuable when various pieces of complex evidence, as occurs in metallurgical investigations, have got to be combined to come to a conclusion. To derive Bayesian probabilities often requires the construction of tables of various types, which can be tedious but once formulated are simple to operate.
The key stages in utilising a Bayesian approach in failure investigations of superheater tubing are:

- Use a Bayesian approach to decide on the mechanism of failure using an initial visual assessment plus some fairly routine metallographic and parametric estimates to either support or contradict this initial assessment.

- If the failure cause appears to be temperature related, estimate the metal temperatures based on steam flow and heating rates, etc, and compare this with the estimates derived from metallurgical observations.

- If the plant estimates are similar to the metallurgical estimates, the root cause is likely to be due to some feature of plant operation and this needs to be investigated (Bayesian type rules are probably not required in such a case).

- If the plant estimates are below the metallurgical estimates this suggests that there is some deficiency in the superheater material and this needs to be investigated.

- The likelihood that the various potential metallurgical root causes having caused the identified failure mechanism is assessed using a set of Bayesian probabilities, which are based, as far as possible on quantitative data.

References


2. T91/T91 Hand book c/o Vallorec and Mannesmann 1999


7. Masuyama, F. "Integrity and Assessment of P91 Components" in Proceedings on Industry and Research Experience in the Use of P/T91 in HRSGs/Boilers in ETD Ltd Seminar, Dec 2005


14. Von Husemann, R. Werkstoffe "Gebrauchseigenschaften für Überhitzer- und-Zwischen- überhitzer in Kraftwerken mit erhöhten Dampfparametern" (VGB 9/99) and 146-149 (VGB 10/99) VGB KraftwerksTechnik 1999
Chapter 10

Discussion

10.1 Introduction

This Chapter brings together the main findings of this work, showing that it has achieved its original aims as set out in Chapter 1. The incentive for initiating this work is worth restating, which is "organisations do not have memory" and the ability of an organisation to respond to events depends upon the experience and aptitudes of its employees. As a result of the constant restructuring of the power industry there is a shortage of expertise and there are few signs of a revival. Hence, the motivation to develop an "Expert System for the Investigation of Power Plant Failures" exists. The conclusion of this thesis is that such a development is indeed possible, and that an expert system of this type could be used to supplement or replace much of the human expertise that is required in failure investigation.

The approach that has been used in this thesis has been to examine the construction of expert systems from the point of view of the Technical or Domain Expert, rather than the Knowledge Engineer. As a result, methods have been developed for producing expert system rules which are of general application, leading to more streamlined and cost-effective procedures.

When the work started, four basic issues were identified that needed to be tackled. These were:

- To provide a procedure to break down complex ideas into quite simple statements, which then contain this information in a highly condensed form
- To marshal raw data and information from the literature, contacts, and personal experience, to enable expert system rules to be formulated, each of which encapsulates specific pieces of information.
- To group these rules, so that they cover relevant aspects of power plant management, design, operation, fabrication, and materials of construction, with the aim of using them to identify failure mechanisms and root causes.
- To devise a method of being able to put together the conclusions from sets of rules, when the evidence is weak, and is of disparate types coming from different sources.
These points are covered in Section 10.2 of this Chapter. But other issues have emerged in the course of the work, which should be of value to people wishing to make use of this thesis to:

- Formulate their own fully developed expert system
- Stimulate interest in expert systems through advanced teaching courses, intended to deal with the specific issues of building expert systems, rather than discussing matters in general terms.
- Utilise the methods of rule formation that have been demonstrated, particularly those relating to combining evidence.

The work which relates to these three points are covered in Sections 10.3 to 10.6.

10.2 Results of the Thesis

10.2.1 Procedures for Writing If...Then Rules

Each If...Then rule is intended to compress some highly detailed information in the form of a simple logic expression of the type If A Then B. Examples of such rules were given early on in the Thesis in Chapters 4 and 5, but the methods of constructing such rules were outlined in Chapter 6. Section 6.1 of that Chapter gave an example of rule formation based on the use of the Larson-Miller parameter, in which the key factors need to be incorporated into the If...Then expression. It was emphasised that was only a preliminary step to breaking down or deconstructing these rules into statements that could be incorporated into an expert system computer program.

It was shown that logic expressions of this type have to incorporate the words “If” and “Then”, but other words are also required to enable the Inference Engine to carry out the necessary evaluation of the input or make calculations. Hence words such as “Yes”, “No” and “Calculate” are also necessary.

The technical expert who writes the rules needs to make them in what might be described as a pre-digested form. These rules will be passed onto the Knowledge Engineer, who would be responsible for breaking these pre-digested rules into components which are in the form of extremely simple logic statements or operating procedures, which can be incorporated into the Expert System. The technique of producing pre-digested statements seems essential, if only to avoid the technical expert getting bogged down on what is a mechanical task, best left to specialists. Furthermore it is also important that rules be formulated in such a way that others can read If...Then rules with relative ease and assess their validity. Section 6.4 gave a fuller account of the processes needed to write machine readable rules.

The A’s and B’s, in the If...Then rules need to be replaced with words, or more usually sets of words if the rules are to be of any practical use. This leads to a glossary of terms, which then splits into series of sub-glossaries. A major innovation
was the Semantic Glossary, aspects of which are covered in Section 6.3 of Chapter 6. Here adjectival and adverbial words and phrases are used to modify the two valued Yes/No logic. The most important of these is the group of adjectives which qualify the reliability of conclusions. These are:

Impossible → Improbable → Possible → Probable

Almost Certain → Certain

Because these particular words and phrases are used so much it was necessary to give each of them quantitative levels of probabilities. This quantification is an aid to technical experts to ensure consistency in use, but as Section 10.2.4 in the present Chapter shows, this is a vital step to translating the results of Bayesian calculations back into ordinary language.

10.2.2 Ability to Marshal Data

Chapters 6, 7, 8 and 9 all relate to the way in which data and information are manipulated. The literature survey, in one sense, is the source of this data, but it is really just a formal account of the information known to the author and the author's views on materials, plant design and plant operations. Where the literature survey is most useful is that it documents quantitative data and includes complex equations, which the author could not hold in his head, except in the most general way. This type of numerical information would need to be stored in the Fact Base of the Expert System.

As indicated, the basis for the literature survey came from the experience of the author in failure investigation, power station design, high temperature steels, heat transfer, slagging properties of coals, and practical experience with plant operation. Some of this knowledge has come from "the literature", of course, but much has come from visits to various power stations in connection with the problems of two shift operation of power plant. The author has also been greatly helped through the connection with ETD Ltd who had a strong interest in P91. Other metallurgists would have a similar background although the focus of their activities might be different....only a few of the author's peers know much about heat transfer.

The main problem with the literature survey was in translating information into the kind of semi-quantitative statements that a technical expert would use in expressing the amount of confidence that he or she would have in their conclusions. It is apparent that this does require judgement and experience, but in most cases this judgement and experience really comes from having had to consider these issues previously. This background was helpful in developing methods that used the adjectival rules for Bayesian based procedures for utilising and combining evidence.

An Expert System is likely to have more appeal to potential users if it deals with new technical problems, and incorporates rules which cover this situation. Here the technical expert will have to evaluate the existing information and create a new set of heuristic judgements in the first place, before turning these into If...Then rules. Failure investigations of P91 fall into this category. The material is unusual by the
standards of most superheater steels, and is being used in borderline situations where it is arguable whether or not the alloy is good enough for the duty. Hence much of the focus of this thesis was in the development of rules to cover potential failures in P91, but the underlying aim was to bring out the fact that in developing an expert system, if the system is to be attractive to consumers, it must show them something new. Obviously in formulating new rules about new situations, the expert will have to be able to justify his or her views, and this can be quite an arcane procedure.

The best example of how careful one must be in formulating heuristic rules relates to the change in the Larson-Miller values for P91 with stress levels and failure times. Essentially there were two problems, both of which were fully discussed in Sections 9.4.2 and 9.4.3.4 in Chapter 9. The initial question was whether the use of over optimistic stress rupture data, which was being used when these alloys were first put into service, would result in premature failures. Thankfully this appears to be unlikely. The second issue was what Larson-Miller constant should be used when estimating service temperatures of failed components. Should this be the old, higher values in the 30-40 range, or the newer values which were closer to 20? Eventually the view was taken that the old value was best, since premature failures represent a type of accelerated test.

This issue of which Larson-Miller constant to use is important in trying to estimate tube temperatures, since a significant discrepancy between that and those derived from heat transfer considerations could indicate that the material was deficient. This is an onerous job, but it is one of critical importance. Once the rules associated with this have been derived and put into the Fact Base, the Inference Engine will do the necessary calculations and decide whether plant operations or shortcomings with the alloy are to blame.

10.2.3 Rule Grouping and Detailed Rule Formulation

Rule grouping is essential in expert systems since each rule needs to be placed in an appropriate shell. But as Chapters 5 and 6 showed, there is a direct benefit to the technical expert in arranging the rules in this way, and this is best done by using flow charts to set up the overall structure and then by utilising this to build up the rules in a set of modules.

Section 6.4 of Chapter 6 entitled “More Detailed Analysis of Rule Build Up and Use” showed how the principles behind the flow chart idea could be used to build up the rules in modules, each module culminating in a goal. The rules in Section 6.4 were written around a situation where there was a need to identify the failure mechanism as being one of creep, and then to decide on whether a plant based or a laboratory investigation was needed.

This particular set of rules were written out in some detail, at a level at which would allow them to be manipulated by the Expert System. Some of the rules were intended for the Fact Base, others were required by the Inference Engine. The surprising feature was that more than one hundred rules were required even for this straightforward example. As might be expected, the later rules, in particular those
involving calculations by the Inference Engine, required other rules from the Fact Base to decide on which particular set of data would be needed. The later rules therefore were becoming intractable. The solution to this was to itemise the rules by giving them numbers, which made the later rules much more readable.

10.2.4 Bringing Together Conclusions

The biggest innovation in the Thesis was to utilise Bayesian rules in a form which apparently has not been used before. Essentially the approach used was to postulate, from an initial evaluation of the problem (for example a possible creep failure) a level of probability of this being correct, and then to use Bayesian rules to bring in the supporting evidence. The background to this is described in Chapter 7, and the procedure was applied to the Japanese superheater problem in Chapter 9.

The merit of this approach is that it is close to the way that people operate when thinking rationally about the possibility of various events, in which an initial hypothesis is framed and then evidence is adduced to support this hypothesis. The examples given, detail how one relates quantitative Bayesian probabilities to adjectival or adverbial statements about the strength of the evidence. These adjectival and adverbial expressions were originally formulated to get over the Yes/No aspects of If...Then logic statements, but it was a surprise to find that they could be quantified relatively easily and consistently.

The Bayesian procedure was a major step forward, in that it allowed single pieces of evidence to be quantified, and showed how much support each of the pieces of evidence could give to an initial hypothesis. This still left the problem of formulating a method by which pieces of evidence could be added together. This is obviously a key issue, as the more evidence there is, the stronger is the belief in the hypothesis.

Several approaches were examined. Simply adding the Bayesian probabilities for each piece of supporting evidence will quickly result in overwhelming support for any reasonable hypothesis. This did not work very well even when so-called “weighting factors” were used. These were intended to show how well even good observations, or data, support a specific mechanism or root cause. Such an example might be spheroidisation in which even a highly spheroidised structure would not necessarily be good evidence to support the view that failure was by a creep mechanism. So this approach was discounted.

The process of simple averaging the individual Bayesian probabilities did not work very well either. The basic cause of this is that although one might start with very strong evidence, as more pieces of weaker evidence accumulate the whole case becomes less strong. Such a phenomenon does happen in real life. If the central argument, however strong, is surrounded by a mass of much weaker conjectures, it becomes difficult to “see the wood for the trees”.

Nevertheless, there needed to be a procedure which takes into account the volume of evidence. This was achieved through the use of an “evidence volume factor”. Here the number of pieces of evidence was raised to the power of 0.95, to give an
evidence volume factor". The effect of this was to increase the average $P(F | E)$ when the number of pieces of evidences was more than two. This technique, developed in the concluding section of Chapter 7, was used with considerable success in Chapter 9 to identify the failure mechanism in the Japanese superheater tube.

10.3 Technical Experts and the Knowledge Engineer

One of the questions that was asked earlier on in this work by one of the reviewers was "What is a superheater?" More recently the question was posed as to why only one pump had been put in a schematic diagram of the steam and water flows in a power plant. Both questions epitomise the problems that a technical expert might have with a Knowledge Engineer. First and foremost, as was conceived, right at the start of the work, it would be very difficult for a sensible dialogue to occur between the Knowledge Engineer and the technical expert without the former having a reasonable understanding of the subject. Parts of the literature survey in the Thesis were incorporated solely to ensure that all readers would be able to glean a basic understanding of what is going on in a power plant. This kind of information was of no value to the author, as a technical expert. But something like this would be needed to enable the Knowledge Engineer to begin work.

This leads to the second question, about the number of pumps required to pump water in into a boiler. This impacts on the level of detail that is needed to enable a Knowledge Engineer to start work. The author is fully confident that the description he has given about the steam plant, about the superheaters, about the materials and how they degrade is more than enough for the Knowledge Engineer to start work. What would necessary, when broadening the expert system to cover, for example, turbines and condensers, is for the technical expert to write up a straightforward account of how this type of equipment works and how it might fail.

10.4 The Story Line Approach to Rule Formulation

It became apparent at an early stage that the process of writing rules is conceptually difficult. Where does one start? A suggestion which was made early on was to assume that for example a creep failure had been "proved". That is that the evidence points to a creep failure. This was helpful in some respects in that it does stimulate one into setting down, in the simplest possible way, the If...Then rules, for example, which link cavitation to creep. But the feeling was, that this was in a sense was a kind of circular argument, as cavitation is synonymous with creep. Furthermore, this kind of statement, to any experienced person, is so true that it is not worth saying. But, however demoralising, one does have to go through this process to become familiar with rule formulation.

Hence, in the author's opinion simply working backwards from a statement that "creep has occurred" is not that helpful in building up an expert system. The "Story Line" approach is it is felt, is more constructive and certainly better for maintaining interest. The idea of a story line is to determine what needs to be done in the course of a reasonably complex failure investigation. The failure can be one on which the expert has previously worked. Alternatively, it can be one, which although fictitious,
has been synthesised from situations of which the investigator is aware. This approach can also be used to examine situations where the investigation went astray.

In the Thesis itself, two such story lines were given. The first, in Chapter 8, covered a completely made up situation in which a superheater had failed, apparently because of a change in the type of fuel. A series of If...Then rules, which were of the verbal type, were used to show that the failure had in fact resulted from poor operation of the furnace by untrained staff. This exemplified the approach that would be needed in a plant based failure. The second example was given in Chapter 9. This was largely based on a real superheater failure of a Japanese power plant, in which tubes had swollen after some years of service. Here a more sophisticated approach was used, in which Bayesian concepts were used to identify the failure mechanism and then to identify the root cause. This was shown to be due to the formation a thick steam side oxide layer, which under conditions of high heat transfer, led to the tube running at an excessive temperature.

With these two examples, some of the rules that had already been previously formulated were applied to the failures in question. But it was found that new rules were required as it became apparent that certain things had been taken for granted. In this way the story line approach is extremely useful. However, it is essential to have a reasonably good understanding of the basics of expert systems, and in particular the methods of writing relevant If...The rules beforehand.

10. 5 Viability of Such an Expert System

Much of the discussion in Chapter 3 concerned the shortcomings of printed material, in the shape of handbooks and text books and indicated why it is that such material is little used by experts. The main reason, of course, is that experts, by definition, have extremely good memories for this sort of technical information, and once such information has been used a few times, there is no need to go back to the book.

The ability of people to remember facts is a real threat to the viability of any type of expert system. Here the term "viability" is used in the literal sense, in that if the system does not offer something new each time it is used it will die. It will be left to gather dust, only to be switched on to impress the occasional visitor.

It has become apparent to the author that if the expert system simply consists of "rules of thumb" the viability of the system will always be a threat. A rule of thumb might be the "fact" that a 20°C increase in the metal temperature will halve the life of tube. People have an amazing ability to remember this type of information. What people are unable to do is to remember vast amounts of hard data. Neither have people the ability to do calculations with the accuracy and speed which is demanded of modern technology. This latter point is worth emphasis. Even in conventional failure investigation, a point will come where figures are needed, either to support the qualitative technical arguments that have been put forward, or to justify some change in the equipment or method of operation. It is here where a good expert system has a real advantage over people. Its Knowledge Base can store data, and contain look up tables and equations, and its Inference Engine can carry out highly complex calculations, taking micro seconds instead of days or weeks.
Several examples of this were shown in this Thesis. In Chapter 8 the data from steam tables was utilised to work out what was the additional fuel input which resulted from the by-passing of a feed heater. This data was taken from CHEMCAD, a process flow analysis programme which the author has used. With respect to the metallurgical investigations, the data relating to mechanical properties, such as design stress, creep strength, Larson-Miller parameters are information which can be incorporated into the Knowledge Base.

There is, of course, no reason why the expert in a given field should not create his or her own expressions of this type. The author himself effectively had to do this when having to calculate the effect of the growth of steam side oxide on metal temperatures and tube life. This required the construction of a complex spreadsheet, which took into account the gradual build up of the metal temperature as the oxide grew in thickness.

This capability will make such an Expert System attractive, increasing the chances of its continued use. What else would help? A valid criticism which could be made is that the information in the expert system is "too general", and not geared to what is happening on a specific power plant. Clearly the program can contain the relevant materials property data, but a more pressing objection relates to the heat transfer aspects of power plant operations. What can be done here?

In setting up the expert system for a given power plant the minimum input would be basic information about the various heat exchangers, turbines, fans etc. The data would include design flows, temperatures, and pressures. There would be no reason why operational data could not be fed into the system when this was of good quality; that is when the plant was operating under base load conditions, at close to the design parameters. A somewhat more sophisticated data set, based on heat exchanger surfaces and mass flows, could be used to estimate heat transfer rates and metal temperatures. Clearly furnace exit temperatures could also be estimated.

### 10.6 Streamlining Expert System Development

The fact that it has taken nine chapters, plus a series of appendices and papers shows the conceptual difficulties in developing this type of expert system. But now that the problems have been overcome, the ideas that have been set down can now be used by others to streamline the development of this type of expert system. Will this be an improvement over the conventional rate of production of two rules a day, which typically result from the dialogue between the technical expert and the Knowledge Engineer? Here we are thinking about reasonably complex rules which the Knowledge Engineer should be able to break down into more programmable statements. Note that the conventional rate equates to one rule per person per day!

The real savings would come if the Expert System was expanded to cover all potential failures in power plant. These would include turbines, water treatment, coal milling, SOx and NOx removal, alternators, control systems etc, each of which requires specialised knowledge from an expert in the field. Each of these technical
experts would need to formulate sets of If...Then rules in the pre-digested form for manipulation by the Knowledge Engineer.

Let us suppose therefore that we have an expert who is willing to incorporate his knowledge of steam turbine failures into this type of expert system. His overall task then becomes one of compressing his knowledge into If...Then rules. The first step is therefore for him to understand how expert systems are configured, that is the concept of the Knowledge Base, the Inference Engine etc, and the flow chart structure. Much of the content of Chapters 4 and 5 can be used for this purpose. The second step is to get the turbine expert to write some If...Then rules to become familiar with the technique. This initial part would take less than a week.

At the same time, a Knowledge Engineer, who would be responsible for developing the expert system shell, would need to be given some basic training on how a power station is designed and operated. The opening part of Chapter 2 would be sufficient for this. There would be little point in teaching him very much about materials. What he or she does need to know are what are the failure mechanisms in individual turbine components. This is needed to enable appropriate flow charts to be formulated. Here again the charts devised for superheaters can be used as examples, but the initial construction of the charts would need to be done by the technical expert.

It essential for the Knowledge Engineer to have properly assimilated an understanding about power plants and turbines, even though this training is very basic. It would greatly help if the Knowledge Engineer was shown around a couple of power plants. In this way he or she would get a better idea of types of equipment that can fail, and the types of operations to which power plants are subjected. Given this background, there is much less chance that when drawing up the basic outline of the expert system, that key items will be overlooked. The main technical task of the Knowledge Engineer would be to choose an appropriate Expert System shell and formulate a protocol that would make interaction with the shell user-friendly. This process is estimated to take 21 days in all. Table 10.1 shows a likely schedule and it will be seen that spread across each power station speciality, it averages about 2-3 days for each of these.

<table>
<thead>
<tr>
<th>Knowledge Engineer Training and Preliminary Activities</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aim of Expert System and Procedures</td>
<td>1</td>
</tr>
<tr>
<td>Power Station Background</td>
<td>3</td>
</tr>
<tr>
<td>Visit to Power Station</td>
<td>2</td>
</tr>
<tr>
<td>Training in Bayesian Logic</td>
<td>3</td>
</tr>
<tr>
<td>Choice of Shell</td>
<td>3</td>
</tr>
<tr>
<td>Formulation of Protocol</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>15</strong></td>
</tr>
</tbody>
</table>
It therefore needs to be emphasised that the Knowledge Engineer would be interacting with more than one specialist, each one of whom would be going through the same procedures as the turbine expert. The turbine expert would need to compile the flow charts, and also need to state what were the main turbine components and failure mechanisms. The technical expert would then need to consider how such failure mechanisms can be identified, and how it would be possible to incorporate this type of information into If...Then questions.

The technical expert would be advised, initially, to limit the type of If...Then rules to the adjectival and adverbial rule types discussed in Chapters 6, as it is best to think about the reliability of evidence or conclusions using something akin to his or her way of speaking and writing. Even this procedure requires much judgement, and he would need to get used to using the Semantic Glossary to ensure consistency. The compilation of this initial list of questions would require a glossary to be formulated, but some of it would be in existence already. One of the jobs of the Knowledge Engineer would be to circulate periodic updates of the glossary.

It should take two to three days to produce a set of rules that could be used to identify just one major turbine failure mechanism and how it can be differentiated from other failure modes. At this point the turbine expert should get the draft of the rules assessed by the Knowledge Engineer. The prime aim of this evaluation is for the Knowledge Expert to assess whether each rule contains the information that would permit the Expert System to run, and ascertain whether the sequence of rules is reasonable. The Knowledge Engineer should not expect rules to be broken down into their component parts. This would be his task. If too much is asked of the technical expert in this respect, the risks of demotivation will be very high. The technical expert is there to supply technical information, in a pre-digested form rather than one which is fully digested.

The Knowledge Engineer, having evaluated this initial attempt, should bring to the attention of the technical expert, any misunderstandings about the methods of rule formulation. At the same time the Knowledge Engineer should take each of the pre-digested rules, and break them down into their fully digested condition. The technical expert should examine these to try to assess if anything has been left out or added. This two-way interaction should take about 5 days. If both sides are getting it right, the technical expert can then work on other failure modes or root causes, passing the rules up to the Knowledge Engineer who then breaks them down as appropriate. Once this initial part of the learning curve is over, it should be possible for both parties to tackle each individual failure mode in about 3 days.

Having completed a few sets of If...The rules relating to failure mechanisms, it may well be worth the technical expert moving on to the storyline approach to assess how easily these rules might be used in practice. It is almost certain that new issues (and corresponding rules) will emerge from the exposition of the storylines. Judging from the experience of the author, four to five days will be required for each storyline. The aim should be to create at least three separate storylines and out of each 5-10 new rules should emerge.
The individual If...Then rules which may need to be formulated, when various types of evidence become available, will probably have to be brought together in support of a specific hypothesis. Making a convincing case, either for a specific failure mechanism, or for a root cause, requires a much deeper consideration about how to bring together supporting pieces of evidence. In this respect some training in the use of Bayesian logic will be needed for both the Knowledge Engineer and the technical expert. This will take up to about a week. Formulation of this type of rule is not easy. There are several stages including:

- Determining what is going to be \( P(E|F) \) (that is the probability with which the evidence is normally associated with a specific failure mechanism).

- Deciding, in verbal terms, what is the reliability of the evidence and then transposing these into Bayesian probabilities.

- Giving appropriate weight to the pieces of evidence so that they can be summed up to come to a consensus about the mechanism or cause of the failure.

Such training in Bayesian logic can take up to two to three weeks. Trial calculations by the technical expert should have as end product about 10-20 reasonably complex rules. The Knowledge Engineer, however, should be able to transpose these rules in two to three days.

Assuming that the turbine is subject to five failure modes, viz, vibration, thermal fatigue, stress corrosion, blade erosion, rubbing and bearing problems, the turbine expert will need to have spent the following amounts of time:

<table>
<thead>
<tr>
<th>Technical Expert Task</th>
<th>Days</th>
<th>No of Main Rules Produced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic training</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Production of preliminary set of rules</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Checking with Knowledge Engineer</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Production of remaining five sets</td>
<td>15</td>
<td>150</td>
</tr>
<tr>
<td>Production of three story lines and rules</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>Training in Bayesian Logic</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Production of One Set of Bayesian Rules</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>70</strong></td>
<td><strong>230</strong></td>
</tr>
</tbody>
</table>

The rule production has increased to three per day, which is a 50% improvement over the standard rate for a technical expert. But most of the improvements in productivity are from the Knowledge Engineer. A big saving comes from the fact that the specialised training required by the Knowledge Engineer about power plants and Bayesian rules is the same no matter what the specific area. Hence most of the
time of the Knowledge Engineer, apart from the initial 5 day interaction with the turbine expert, would be spend on recasting the turbine failure rules into a form that the expert system can utilise. This would be around 15 days for five sets. Of course this leaves out system debugging and testing, but these problems are common to any programming development. If another 5 days are added on to cover part of the training requirements, the total time spent is about 25 days. Adding together these 25 days, plus the 70 days of the turbine expert, this makes 105 days, which gives about 2.4 rules per manday.

10.7 Implications for the Use of P91 in Superheaters

A topic underlying the work was the question, which is exercising the minds of plant designers, operators and metallurgists, is how useful is P91 (and even more so P92) as a superheater material. Even at the start of the work there were some question about P91, but the main concern at that time was the Type IV cracking issue, where possible weakness in the HAZ could lead to premature creep failure. Although this is still an important point, the more pressing issue appears to be the effects of the high rate of steam side oxidation on superheater tube life. Under conditions of high rates of heat transfer, tube wall temperatures are increased to the point where failure because of creep or fireside attack could occur. A spreadsheet model was developed in the course of this work to show the effects of the gradual build up of oxide, at varying rates of heat transfer.

In the course of examining this issue, which required heat transfer calculations to be made, the author became aware of the fact that as steam pressures increase, heat transfer rates are tending to go up as well, which tied in with some comments various people have made. Accordingly, the effects of oxide growth are likely to be much more serious than in the past. A "known unknown" is whether or not an increase in the tube temperature increases, as a result of the oxide formation, will increase the oxide growth rate. If this did happen, the increase in tube temperatures would increase much more rapidly than simple calculation would predict. Spreadsheet calculations suggested that if this effect were to occur, it becomes significant at heat transfer rates in excess of 75kW.m⁻².

The other, generally expressed concern dating from the late nineties was a possible overestimation of the creep strength of P91. Recent data does suggest that there has indeed been some overestimation, stemming in part from the use of unrealistically high Larson-Miller constants. Fortunately, the downgrading of the strength should not have serious implications for equipment life, since the design codes contain such a high safety factor.

10.8 Predicting the Effect of Oxide Growth on Tube Temperatures and Life

The spreadsheet oxidation model is attracting the attention of the author’s former colleagues at ETD Ltd and may be offered commercially.

The model can also be used to predict the effect of temperature in accelerating the rate of oxide growth. As noted the question is still open of whether an increase in the tube temperature does lead to an acceleration in the rate of oxide growth. The
practical difficulties and costs in determining whether this is an affect are high, and there is a natural reluctance to embark on such experiments, although the author is trying to get organisations to run such a project.

10.9 Stimulation of Clearer Thinking

As far as the author is concerned, a benefit in developing the ideas in the Thesis, is that he is much more self-aware about what is going on when he thinks about how evidence is used to support conclusions. A feature in most people’s thinking is that they have to form a hypothesis first, before looking for supporting evidence. There seems to be no real alternative, despite the fact that on occasion one may be barking up the wrong tree. The benefit of having formulated the adjectival and probabilistic approach in If...Then questions is that the author feels that he now thinks about the quality of evidence in a more consistent and stricter manner. It is moot point whether this type of approach to evaluating evidence should be taught as a specific subject in science courses. The awakening interest in Bayesian theory suggests that this will be necessary.
Chapter 11

Conclusions and Further Work

The main intention of this Thesis was to show how an expert system intended to assist with failure analysis would need to be built up. In carrying out this process the author took the view that it should be done by examining the fundamental issues in constructing such a system. The approach that has been used was to break down the thought processes which are needed to solve typical problems, showing how the steps that a human expert or group of experts might take can be simulated by a machine.

The Thesis was written around superheater failures as superheaters are susceptible to a failure by a number of mechanisms, and, in addition, each of these mechanisms can result from a variety of causes. Some of these would result from shortcomings of the plant or its operation, others stem from problems with the material.

The main conclusions are as follows:

1. Chapter 2 showed that the information for a knowledge based system can be obtained using a standard literature survey, providing that this is critiqued and modified by persons who have experience in applying the relevant information to actual power plant failures.

2. Chapters 3 to 5 showed the importance of establishing flow charts to help begin the formulation of If...Then rules and setting out the rules in a logical sequence.

3. Chapter 6 showed that a glossary of terms is required which can be incorporated into If...Then rules to represent objects in the rules in a consistent manner.

4. Chapter 6 also showed that the glossary needs to incorporate adjectival and adverbial phrases to enable the user to state and assess the reliability of information in the If...Then rules in a qualitative but consistent manner.

5. Chapter 7 showed how these adjectival and adverbial expressions can be transposed into Bayesian probabilities, so as to quantify how evidence supports conclusions relating to failure mechanisms and root causes.

6. Chapters 8 and 9 indicated that in developing an Expert System, it is extremely helpful that once an initial set of rules is built up, these should be tested against real plant failures. Such failures can be based on real events or alternatively be based upon fictitious but realistic plant and equipment failures.
7. In addition, Chapters 8 and 9 confirmed the views expressed in Chapter 3 that a viable expert system needs to contain complex numerical information in the form of databases, spreadsheets and equations, if such an expert system is to be a viable commercial product which will be bought and used by power plant organisations.

To formulate the ideas that are required to develop this type of expert system and then test them, much of the work focused on P91 steel. This is a superheater material which has only recently been introduced. As with many such materials, its deficiencies are only now becoming recognised as in-service experience accumulates. P91 is a martensitic alloy, which relies on a tempering treatment to form a set of strengthening precipitates. These, in combination with a dislocation subcell network, give it good creep strength. Accordingly, P91 is rather different to the older low alloy steels, in which much of the strengthening precipitation occurs in service. P91 is intended for operation at temperatures at which oxidation is becoming serious, but because of the need to form a sizeable austenitic phase field for heat treatment purposes, the level of chromium is quite constrained. Hence the resistance to attack by dry air is good, but it has become all too apparent that this is not the case when P91 is exposed to superheated steam. The peculiarities of P91 have forced the author to think more deeply about how to formulate the rules that are needed to determine mechanisms and causes of failures.

The intention is now to give more exposure to the ideas behind the Thesis and seek funding for a fully developed Expert System. The motivation behind this is the continued importance of high temperature materials in the power plant sector. As the author himself has repeatedly argued over the past five years, fossil fuel plant will play a critical part in ensuring the reliability of the electricity supply, when more of the power is coming from wind and solar sources. Conventional generating plant will have to cycle much more, and in these circumstances plant life will be rapidly consumed. This has to be set against a backdrop of a much reduced supply of experienced metallurgists and engineers from the Universities. In these circumstances an Expert System would be of considerable help to the overworked and technically extended individuals who continue to work at the vital job of ensuring that electricity is there when we need it.

F. Starr : March 2007

Acknowledgements

Naturally I accept complete responsibility for all the statements made in this Thesis, and affirm that this is all my own work, but I would like to thank the following:

Dr R. Walker:

I would like to thank first Dr Robert Walker, who not only suggested that I should embark on a Thesis, but did the necessary groundwork to enable me to get the
support from the University. I also thank Dr Walker, as a lecturer at Battersea College of Technology, for sparking off my interest in the subject of corrosion in general and oxidation in particular, which has then formed the underpinning of my subsequent career. If I may also add at this point, another lecturer, also from the Battersea years, who was instrumental in forming my attitudes. This was Dr Hornsby-Smith who taught me the rudiments of heat transfer and combustion science, which is a vital aspect of failure analysis in high temperature energy conversion equipment, and I would be grateful if my thanks could be relayed to him.

Prof JE. Castle:

I thank Prof. Jim Castle, who supported with enthusiasm, from the start, the idea of working on a Thesis on Expert Systems, something about which I offered up as a possibility after some early discussions with Dr Shibli of ETD Ltd. Both Robert and Jim have taken the time to go through what I have been offering up and made specific and well founded suggestions about keeping on track.

Prof J. Watts

I thank Prof. John Watt for formally taking over the reins from Jim, but continuing to trust that the direction of the work was satisfactory and leaving the guidance with Robert and Jim.

Dr A. Shibli and other Colleagues at ETD Ltd

Dr Shibli started up ETD Ltd in 1999 and I was his first (part time) employee. Dr Shibli can not have known too much about me at that stage, but he thought that I would be useful in helping to put together a report for EPRI and other organisations on the Two Shifting of Power Plant. I was with ETD until 2004 when I joined the Institute for Energy of European Commission on what was then a one year contract.

Working with Dr Shibli gave me an opportunity to formalise my knowledge of power plant design and operation, but he also brought to my attention a new material P91 which was then starting to be extensively used in power plant superheaters. It was Dr Shibli, also, who suggested the need for a user friendly Expert System for power plant personnel and management.

I would also like to thank Drs A. Fleming, J. Gostling and A. Bissell at ETD who supplied valuable background on superheater materials and power plant operation.

My Wife and Family

The combination of holding down a “part time” job and trying to write a Thesis was always a problem in terms of family responsibilities. This became even more difficult when I moved to the Netherlands for my “one year” contract, which eventually was extended to almost four years. My intention to visit home one every three weeks vanished with the need to spend my weekends on the Thesis. I now get home about once every two months. I thank for their support during this difficult
period when most husbands and fathers would be winding-down and spending more rather than less time with their loved ones.
APPENDICES
APPENDIX 1

Methods of Estimating Furnace Outlet, Flue Gas and Superheater Temperatures

The furnace outlet temperature is also that of the flue gas inlet temperature to the superheaters. This is an important parameter as it tends to determine the flue gas conditions all the way through the train of superheaters, reheaters and economisers. However, as with all of these calculations the outlet temperature is governed by the energy which is put into the furnace in the shape fuel and preheated air, and the abstraction or loss of energy in evaporating boiler water in the furnace tubes, or in having to heat up any air which has leaked into the furnace. When attempting to determine whether there is a design fault leading to the overheating of superheaters, or whether it is due to some operational factor, the initial calculations should be carried out using the design parameters for the furnace and superheaters.

Table 1 outlines the procedure whereby the heat input into (enthalpy rise) the furnace, resulting from the combustion of a given mass of fuel per hour, is calculated first of all. The levels of C, H and S in fuel govern the enthalpy rise in the furnace, but the proportion of these elements also dictate the quantity of air needed for complete combustion, that is the stochiometric quantity of air. The stochiometric combustion air figure is also needed to work out the mass of excess air going through the furnace, which has a very strong influence on the furnace outlet temperature.

The air to the burners will be preheated and this too adds to the enthalpy going into the furnace, and if recirculation of flue gas is used this will also add to the heat input.

From this is taken the heat (enthalpy drop) used for evaporation of the water in the boiler or evaporator section of the furnace. The net enthalpy increase appears as the increase in temperature from entrance to exit of the furnace. For this latter part of the calculation we need the composition, mass and specific heat of the individual products of combustion, including ash. This calculation will probably give a slight overestimate of the temperature rise as neither the effects of heat losses from the furnace nor "dissociation" are allowed for. There will also be, especially in older furnaces, a reduction in temperature due to the need to heat up air that has leaked into the furnace. Any unburnt carbon will need to be accounted for.

The flue gas temperature at the exit or entrance to each bank of superheaters, reheaters etc can be determined in a similar way as shown in Table 2. The superheater calculations are based on the fact that the amount of heat abstracted from flue gases, as they pass over the superheater, is equal to the amount of heat taken up by the steam. The latter value can be obtained from steam tables. Once again, providing that the composition of flue gases is known, the enthalpy decrease in the flue gases can be translated into a temperature drop. Under design conditions the attemperator should not be operating, so that the overall or average flue gas temperature drop should be very accurate.
The average metal temperature, at any point in the superheater, will be governed by the steam temperature, pressure and flow rate at that point, these factors determining the heat transfer coefficients and rates. Obviously when a failure occurs the interest will be in the likely heat transfer rates at the point of failure and in what might be occurring in nearby tubes. The biggest uncertainty is likely to be in the steam temperature. If the flow is truly counterflow, the steam temperature rise is likely to be reasonably constant through the superheater. Metal temperatures will show a similar trend. If the superheater is of the parallel flow type the aim of the designer will have been to try to obtain a uniform metal temperature all along the superheater, this avoiding the need for sophisticated alloys. In practice, the tube lengths in most sections of superheaters are of the cross flow type and the temperature rise across each length of tube will be reasonably uniform, and this needs to be taken account in estimating metal temperatures.
Table 1: Sequence for Estimating Flue Gas Temperatures from Furnace

<table>
<thead>
<tr>
<th>Section of Furnace</th>
<th>Input Data</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Estimated Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporator or Boiler</td>
<td>Water Flow</td>
<td>Evaporator enthalpy increase</td>
<td>Furnace Enthalpy Drop Due to Evaporation</td>
<td>Net Temperature Rise</td>
<td>Furnace Outlet Temperature</td>
</tr>
<tr>
<td></td>
<td>Temperature Rise</td>
<td></td>
<td></td>
<td></td>
<td>Or</td>
</tr>
<tr>
<td></td>
<td>Fuel Flow</td>
<td></td>
<td>Furnace Enthalpy Rise due to Combustion</td>
<td>Specific heats of gases and slags</td>
<td>Flue Gas Inlet Temperature</td>
</tr>
<tr>
<td></td>
<td>Unburnt Fuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel Calorific Value</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Furnace</td>
<td>Fuel Water Content</td>
<td>Slag and Unburnt Fuel In Furnace Atmosphere</td>
<td></td>
<td>Net Enthalpy of Furnace Atmosphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel Ash Content</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel C,H,O,N,S,Cl</td>
<td>Stochiometric Air Requirement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Excess Combustion Air at Burners</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Air Leakage into Furnace</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Flue Gas Recirculation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combustion Air Inlet Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated Air Leakage Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recirculated Flue Gas Temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Section of Furnace</td>
<td>Input Data</td>
<td>Step 1</td>
<td>Step 2</td>
<td>Estimated Temperature</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>------------</td>
<td>--------</td>
<td>--------</td>
<td>-----------------------</td>
<td></td>
</tr>
<tr>
<td>Superheater 2</td>
<td>Superheater Steam Flow</td>
<td>Enthalpy Increase In Steam</td>
<td>Enthalpy Drop of Inlet Superheater 2 Flue Gas Products</td>
<td>Flue Gas Outlet Superheater Temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Superheater Temperature Rise</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated Flue Gas Side Inlet Temp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated Gas Composition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Estimated slag and unburnt fuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Specific heats of gases and slags</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 2

Spreadsheet for Predicting Oxidation Growth Rate and Effect on Tube Temperatures and Life

The spreadsheet that was developed to assess the effect of oxide scale growth is based on the assumption

- The rate of scale growth is parabolic,
- The rate of increase of oxide doubles for a given temperature rise
- That if there is an increase in the rate of oxidation due to temperature, this is determined by the temperature at the metal-to-oxide interface
- The tube life can be calculated using the Larson-Miller parameter
- The tube life is significantly longer than the design life of the superheater

The basic idea is that as the oxide increases in thickness the tube temperature will gradually increase. The increase in tube temperature will then reduce the tube life. In this situation it is a fairly simple matter to calculate how much life has been used in every thousand hours of service. This loss of life is summed up over a period of a year's operation. Note that within a relatively short time because the oxide grows parabolically, the rate of oxidation slows and hence the increase in tube temperature slows. In this scenario there is no acceleration of the rate of oxide growth due to the temperature increase of the tube.

Where there is an acceleration, the procedure at the end of each thousand hours, is the use the new tube temperature as a basis for working out the increased rate of oxidation. This is a slightly difficult procedure, as the existing oxide will have slowed the rate of oxidation. The procedure, which was adapted to overcome this problem, was to work out how long it would have taken the oxide to grow, if the "start temperature" had not been 600°C but had been the higher temperature, due to the insulating affect of the oxide. Once this figure was obtained it is fairly easy to calculate what will be the new thickness after another 1000 hours of exposure.

The spreadsheet is intended to carry out a number of different calculations, the main one are:

- Calculation of oxide thickness after every thousand hour exposure -- Column B
- Effect of oxide growth on tube temperatures --------------------------Column C
- Percentage of life used due to creep ----------------------------- Column V

In making these calculations some basic information needed to be entered. The key parameters are the parabolic rate constant at 600°C, the parabolic rate constant for oxidation growth, the mean tube life at the design stress and temperature, the Larson Miller Constant, and the temperature gradient through the oxide at the specified heat transfer rate. With respect to the parabolic rate constant the assumption is that the growth rate is in fact parabolic, that is, the thickness of the oxide is proportional to the square root of time. However the effect of other growth rate functions can easily
be checked, by changing the power coefficient which is used in columns G, J, M and N.

This data is required when there is no acceleration in the rate of oxidation due to the temperature increase in the tube. However, in the spreadsheet the assumption has been made that the rate of growth of the oxide doubles for every 30°C of temperature increase, as shown in Column Q. From this value and the parabolic rate constant at 600°C it is possible to calculate the acceleration at any other temperature, which is displayed in Column E.

To avoid having two spreadsheets, the effect of no acceleration can be shown by changing the values in Column Q to 10000, which implies that the rate of acceleration only doubles after a temperature rise of 10000°C.
APPENDIX 3

Trends in Heat Transfer Rates in Superheaters and Implications for Tube Wall Temperature Estimates

Flow velocities in superheater tubes have remained fairly constant between 10 and 20 metres per second over the years, despite changes in operating pressure. Below these velocities steam side heat transfer rates fall with the risk of tube temperatures becoming excessive. Above these velocities pressure drops become excessive, reducing steam turbines power output and station efficiency.

Increased operating pressures and plant outputs will lead, however, to the need to increase heat transfer rates if the physical size of superheaters is to be kept roughly constant. The increased pressure will increase the density of the steam flowing through the tubes, and therefore the mass flow. In addition the specific heat of steam tends to increase with pressure, for example, the specific heat increases by almost 50% from 50 bar pressure to 300 bar. Other things being equal it can be seen that the amount of heat needed to be put into a given length of tube, in going from 50 bar to 300 bar pressure would increase by almost nine times.

Fortunately, the higher rates of mass flow also permit designers to put the heat in more effectively, since the steam side heat transfer coefficient also rises with increased pressure. The rate of heat input is then governed by temperature difference between the inside surface of the superheater tube and the bulk steam temperature at the point of the tube. This temperature difference is usually taken to be about 30°C. This figure, multiplied by the heat transfer coefficient will give the rate of heat input.

Since P91 tends to be used in higher pressure systems the rates of heat transfer used in P91 superheaters will therefore tend to be significantly higher than in older designs. Because of the higher rates of heat transfer, the insulating effect of steam side oxide scales will be much more significant than in older, lower pressure designs.

No rates of heat transfer are available in the literature and it is necessary to calculate these using the standard heat transfer equation for flow in tubes. This is

\[
h = 0.0023 \cdot C_T \cdot C_L \cdot (\lambda/d) \cdot Re^{0.8} \cdot Pr^{0.4}
\]

\(h\) = Heat transfer coefficient (kW.m\(^{-2}\).K\(^{-1}\))
\(\lambda\) = Thermal conductivity of steam kW.m\(^{-1}\).K\(^{-1}\)
\(d\) = Tube diameter (m)
\(C_T\) = Coefficient dependant on wall to tube temperature difference (taken as 1 in this case)
\(C_L\) = Coefficient dependant on tube length (taken as 1 in this case)
\(Re\) = Reynolds number
Pr = Prandl number

Both the Reynolds number and Prandl number are dimensionless. The Reynolds number is very important in governing the heat transfer rate, it changing radically with pressure, as the Reynolds number is a function which includes the density, kinematic viscosity, flow velocity and tube diameter. The Prandl number is close to unity for all conditions and is given by a function which incorporates thermal conductivity, specific heat, and absolute viscosity.

The basic data for these calculations for various pressures at a temperature of 560°C, as representative of modern power plant are shown in Table 1. They were obtained from a commercially available programme used for process flow modelling in steam and chemical plants called CHEMCAD.

### Table 1: Properties of Steam at Various Pressures at 560°C

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Density (kg.m⁻³)</th>
<th>Absolute Viscosity</th>
<th>Kinematic Viscosity</th>
<th>Specific Heat kJ.kg⁻¹</th>
<th>Thermal Conductivity kW.m⁻¹.K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2602</td>
<td>0.00003097</td>
<td>0.000119</td>
<td>2.164</td>
<td>7.45E-05</td>
</tr>
<tr>
<td>25</td>
<td>6.599</td>
<td>0.00003097</td>
<td>4.69E-06</td>
<td>2.226</td>
<td>7.62E-05</td>
</tr>
<tr>
<td>50</td>
<td>13.4</td>
<td>0.00003139</td>
<td>2.34E-06</td>
<td>2.296</td>
<td>0.000078</td>
</tr>
<tr>
<td>100</td>
<td>27.69</td>
<td>0.00003191</td>
<td>1.15E-06</td>
<td>2.454</td>
<td>8.18E-05</td>
</tr>
<tr>
<td>200</td>
<td>59.45</td>
<td>0.00003329</td>
<td>6.6E-07</td>
<td>2.845</td>
<td>9.06E-05</td>
</tr>
<tr>
<td>250</td>
<td>77.25</td>
<td>0.00003421</td>
<td>4.43E-07</td>
<td>3.083</td>
<td>9.58E-05</td>
</tr>
<tr>
<td>300</td>
<td>96.54</td>
<td>0.00003533</td>
<td>3.66E-07</td>
<td>3.353</td>
<td>0.000102</td>
</tr>
</tbody>
</table>

Table 2 shows the results of these calculations at various pressures for steam flows of 10 metres per second through a pipe whose interior diameter is 3 centimetres, again at a temperature of 560°C. The rates of heat flow are also shown based on a 30°C temperature difference between the tube wall and the bulk steam temperature. Note how the heat flow rates are very strongly dependant on the pressure.

### Table 2 : Heat Transfer Coefficients and Rates for 30°C Temperature Difference for Steam Flows at Various Pressures at 560°C through 0.03m (ID) tube at 10 m.s⁻¹

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Reynolds Number</th>
<th>Re⁰·³</th>
<th>Prandl Number</th>
<th>Pr⁰·⁴</th>
<th>Heat Transfer Coefficient kW.m⁻².K⁻¹</th>
<th>Heat Transfer Rate kW.m⁻²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2521</td>
<td>526</td>
<td>0.8995</td>
<td>0.9585</td>
<td>0.03</td>
<td>0.9</td>
</tr>
<tr>
<td>25</td>
<td>63923</td>
<td>6990</td>
<td>0.9048</td>
<td>0.9608</td>
<td>0.39</td>
<td>11.8</td>
</tr>
<tr>
<td>50</td>
<td>128066</td>
<td>12188</td>
<td>0.9242</td>
<td>0.9689</td>
<td>0.71</td>
<td>21.2</td>
</tr>
<tr>
<td>100</td>
<td>260326</td>
<td>21498</td>
<td>0.9575</td>
<td>0.9828</td>
<td>1.33</td>
<td>39.8</td>
</tr>
<tr>
<td>200</td>
<td>535746</td>
<td>38297</td>
<td>1.0455</td>
<td>1.0180</td>
<td>2.71</td>
<td>81.2</td>
</tr>
<tr>
<td>250</td>
<td>677433</td>
<td>46205</td>
<td>1.1001</td>
<td>1.0392</td>
<td>3.53</td>
<td>105.8</td>
</tr>
<tr>
<td>300</td>
<td>819757</td>
<td>53820</td>
<td>1.1662</td>
<td>1.0634</td>
<td>4.46</td>
<td>133.7</td>
</tr>
</tbody>
</table>
Since the mass flow of steam is roughly proportional to pressure more heat energy is required as pressure increases, to give a satisfactory increase in tube temperature from the inlet to outlet of a tube. Hence the heat transfer coefficient must also increase. It can be shown that at low and medium pressures the rates of heat transfer calculated above are more than adequate to produce a satisfactory temperature increase. However at the higher pressures it is not possible to get a satisfactory temperature rise, and the heat transfer rates need to go up by about 10% over the values stated in Table 2. This can only be obtained by increasing the temperature difference between the tube wall and the bulk steam temperature by a similar level.

The calculations are illustrative only as they neglect the difficulties in getting the heat into the tube from the flue gases. This too is limited by basis heat transfer parameters which are governed by the flue gas temperature, flue gas flow rate and how much radiation is received by the tube from primary radiation from hot particulates in the flues gas or secondary radiation from the tube walls. These parameters are fixed to a large extent. The calculations also assume that amount of heating that a tube receives is uniform all the way round the circumference. In practice almost 50% of a tube will be shielded by neighbouring or by being located close to a wall.

However the calculations do show that as steam pressures have increased heat transfer rates will tend to increase too and hence the impact of insulating layers become more significant, in disrupting heat flows and raising tube temperatures.

On the basis of these calculations, etc, plus a general awareness of how steam temperatures and pressures influence, and recommendations in various boiler codes, in the absence of detailed calculations about tube wall temperatures, the tube wall temperature, used for design purposes, is approximately:

Normal steam outlet temperature from superheater +40°C

This figure can then be put into Larson-Miller calculations, in which the assumption is that for a life of a 100000 hours, which includes a large safety factor. Because of this large safety factor, the tube would actually have a life of around 300000 hours at the design stress and temperature. This approach gets over the problem that experts may not always have access to either the original stress rupture data that were used to compile the codes, or in some cases the design stresses themselves.
APPENDIX 4

Design Stresses for P91

The maximum allowable stresses for P91 from the ASME Section II Code Part D are given in Table I, with the values converted to SI units. Since the temperatures were originally in degrees Fahrenheit, they cannot easily be compared with European data.

Hence these figures were first put on an Excel spreadsheet and graph and then the corresponding values were interpolated for every 25°C at temperatures above 500°C. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>Temperature °C.</th>
<th>Stress MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>38</td>
<td>147</td>
</tr>
<tr>
<td>93</td>
<td>147</td>
</tr>
<tr>
<td>149</td>
<td>146</td>
</tr>
<tr>
<td>204</td>
<td>146</td>
</tr>
<tr>
<td>260</td>
<td>146</td>
</tr>
<tr>
<td>316</td>
<td>143</td>
</tr>
<tr>
<td>343</td>
<td>141</td>
</tr>
<tr>
<td>371</td>
<td>138</td>
</tr>
<tr>
<td>399</td>
<td>134</td>
</tr>
<tr>
<td>427</td>
<td>129</td>
</tr>
<tr>
<td>454</td>
<td>123</td>
</tr>
<tr>
<td>482</td>
<td>115</td>
</tr>
<tr>
<td>510</td>
<td>107</td>
</tr>
<tr>
<td>538</td>
<td>99</td>
</tr>
<tr>
<td>566</td>
<td>89</td>
</tr>
<tr>
<td>593</td>
<td>71</td>
</tr>
<tr>
<td>621</td>
<td>48</td>
</tr>
<tr>
<td>649</td>
<td>30</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature °C.</th>
<th>Stress MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>110</td>
</tr>
<tr>
<td>525</td>
<td>103</td>
</tr>
<tr>
<td>550</td>
<td>87</td>
</tr>
<tr>
<td>575</td>
<td>95</td>
</tr>
<tr>
<td>600</td>
<td>65</td>
</tr>
<tr>
<td>625</td>
<td>45</td>
</tr>
<tr>
<td>650</td>
<td>29</td>
</tr>
</tbody>
</table>
APPENDIX 5

Notes of Visits to Drakelow and High Marnham

24th Feb 2003

Drakelow

The supercritical units have spiral water walls which extend all the way up the furnace. The upper section of the furnace can be regarded as a primary superheater of the radiant type. This design has given problems even during load changes as well as startup since the transition between higher density water-substance and steam-substance changes, so that there is a high risk of overheating and tube leaks.

The situation cannot be helped by the fact that the furnace is coal fired.

Not sure about burner position. No steam by pass.

The subcritical, drum type unit also suffered from tube leaks. One had stopped operation of the furnace the morning of the visit. It was clear that none of these leaks ever sees a laboratory for examination.

Furnace tube failures seemed more common than superheater failures on both units. Second stage pendant superheater configuration on supercritical unit apparently had, from the diagram, extra passes at front

It was confirmed that feedheaters could be by passed if the leakage was high enough, as this could lead to water getting back into the turbines. This is despite the fact that the feedheaters were of the vertical type and were positioned on the floor about 10-15 metres below the turbines.

No flue gas recirculation on either boilers. This seems to be unusual on CEGB plants although this is definitely in place at Littlebrook, an oil fired station.

High Marnham

These were relatively early fairly small coal fired 200 MW units which were thought to be highly suitable for two shifting. The plant now “double two shifts and more”. Can be brought on line after burners being lit from a hot start after about 45minutes. Matching steam turbine temperatures. The use of four separate recirculation pumps obviated the flow reversal problem which tends to occur on natural circulation boilers. Hence the risks of thermal stress, due to differential expansion were eliminated.

No bypass was available or really needed on this plant as the furnace consists of two separate cells with a water wall division through the furnace box. The ducting from each of the cells goes into quite separate arrangements fro the superheater and reheater trains. This means that the reheater is not likely to be overheated during
startup as is common on single cell systems. Even so when the reheater does
eventually start to take steam flow and be heated, the sudden temperature changes
lead to spallation of oxide, leading to erosion of the reheate turbine blades (See
below).

Steam soot blowing is done every 24 hours, but it should be noted that the plant is
two shifting. The superheater soot blowers consist of long tubes which are poked
into the side of the ducting so that the cross through the spaces between the sets of
pendant tubes and also the “U” shaped gap in the centre of the pendants. The soot
blowers rotate as they move across the duct, blasting steam out sideways from a
nozzle. As the same method was used each time this meant hat parts of the
superheater never got cleaned. A new system is used so that the angle of the nozzle
is changed before the soot blower starts its cross motion.

Windage heating due to churning of the steam is a problem on the back end blades
of the LP turbine during startup, because of the reduced flow. This is prevented by
water injection into the inlet of the LP turbine.

The two cell system is used on other plants, but in the cases mentioned the
superheaters and reheaters were in a common duct. In this situation, all that can be
done to protect the reheaters is to change the burner angle. In some of the two cell
plants the water wall was used for superheating. This appeared to give most troubles
during startup, presumably die to water logging, as it was stated that on later units
the steam direction had been changed and the drainage improved.

The burners on each of the cells were of the corner type, which by firing tangentially
they are intended to produce a fireball in the centre (I wonder what happens if one
burner fails?)

Playing about with the secondary air had helped reduce NOx at High Marnham and
had reduced the amount of furnace wall corrosion. At West Burton the conversion
had been more complete and furnace wall corrosion had been eliminated completely.
The attack mechanism was described as oxidising reducing. The downside of the
conversion was that the changes in the secondary (and presumably tertiary) air had
led to the flames lifting so that the superheaters tended to run hotter.

The feedheaters on this plant have one very large feed pump, which is electrically
powered using a submersible motor, rather than a boiler feed pump. On other plants
a series of feed pumps is used for each feedheater. Pump cost is increased but the
cost of the pressure vessels is lower and presumably the risk of corrosion fatigue
will be reduced.

Only two double flow LP turbines are used. These are supplemented by an
additional combined IP/LP rotor, in which somehow part of the steam is taken out of
the end stage of the IP rotor section and then directed back into LP rotors (so there
are effectively five LP rotors).
The erosion on the blades of the LP turbine is on the back and this was on the outer

The erosion on the blades of the LP turbine is on the back and this was on the outer

The erosion on the blades of the LP turbine is on the back and this was on the outer
PAPERS AND PRESENTATIONS
Baltica V Conference:
Hotel Haikko Manor, Porvoo, Finland, June 2000

Expert System for Failure Analysis
in
High Temperature Plant

F. Starr A. Shibli JE. Castle and R. Walker
Expert System for Failure Analysis in High Temperature Plant
F. Starr, A. Shibli JE. Castle and RW. Walker Baltica V Conference
Espoo, Finland June 20001

1. Abstract

The issues involved in the formulation of an Expert System for the analysis of failures in high temperature sections of generating plant are discussed. Initial work shows that, using creep failures as an example, it is possible to draw up a set of heuristic rules, which encapsulate the expertise of failure analysis specialists. Examples of such are given.

This procedure has shown that there is no single foolproof way of characterising a creep failure, and the evidence must come from a number of different sources. Furthermore, some of the older techniques of assessing whether creep has occurred may not be applicable to the modern martensitic and austenitic superheater alloys, and new approaches may be desirable.

1. Introduction

Work is currently in progress to analyse the issues in the development of an expert or knowledge based system for failure analysis of high temperature components in steam power plant. The aim is to progress towards a user friendly knowledge based program, which will be of value to operational management on power stations, and to technical personnel in failure analysis laboratories.

The principal motivation for this effort has come from the realisation that, in the UK in particular, the loss of experienced personnel from power stations and in centralised laboratories has had serious implications for rapid and effective failure analysis. Therefore the question of how to supplement non-expert human capabilities is both critical and topical.

The Expert System must simulate, as far as possible, a real flesh and blood human being, one capable of “discussing” the salient aspects of failures with both power plant management and laboratory based materials scientists. Hence it must work on two quite different levels.

Power plant management will have a limited knowledge of materials science. Nor will management have access to sophisticated analytical techniques. They will know, however, or think they know, a great deal about the operation and history of their plant. But above all else, the concern of management is to ascertain, as quickly as possible, why a failure has occurred and how to avoid it in future.

In answering the needs of power station operators, laboratory based failure analysis personnel have a somewhat different remit. They have to identify the mechanism of failure, reasonably quickly, and need to ascertain the likely history of the component as well as possible. In so doing, a failure analysis specialist will have access to many different methods of examining materials. Nevertheless these methods must be used
cost effectively, and the Expert System can help in this, and in the interpretation of visual observations and quantitative data.

In the setting up and examination of the underlying philosophy of an Expert System for Failure Analysis, it is necessary to choose concrete and well documented examples upon which one can formulate **RULES**. The procedure by which this is done may seem tedious, but it is vital to get this right at the start. It enables the identification of failures to be made with greater certainty. Just as important, when new information is incorporated into the System, perhaps by others than the original group, the method of writing the **RULES** etc, is properly understood.

The example or paradigm chosen, for this initial exercise, is that of simple creep in superheater and reheater tubing. This is deceptively straightforward issue. Nevertheless it has already begun to expose some questions relating to the interpretation of such failures, particularly with respect to some of the modern alloys such as the T91, T92 and modified Type 300 stainless steels. It is considered that some of the points raised are worth putting before this Conference, as well as outlining how the Expert System is being set up.

### 2. Expert System Benefits

What are the benefits of an Expert System for Failure Analysis? Providing that it is updated frequently the system should:

- Permit Technical Plant Management, and Material Investigators, to make quick, but reliable assessments of failures and to take rapid remedial action.

- Enable Senior Management to assess the benefits of a full laboratory based metallurgical investigation and, if necessary, challenge any conclusions that are offered.

- Minimise the need for specialised materials and engineering knowledge.

- Enable experiences to be shared with other users of the Expert System, via the Internet.

- Minimise space requirements for the storage of technical information.

- Enable, using lap top computers, in-situ comparisons to be made of actual plant failures against photographs and drawings in the Expert System database.

- Permit the Expert System to be used as a **Training Aid** by academia at postgraduate level on materials and engineering courses, or by the Power Industry itself.

- Help moves towards a **Common Standard** for the interpretation of failure mechanisms and remedial work.
It may also be remarked, in passing, that in the present culture in which “someone must be to blame” therefore “someone must pay” the existence of a fully approved Expert System should greatly reduce the need for long drawn out litigation.

2. Expert System Types

There may be confusion in what is meant by an Expert System. This has arisen, in part, from the interest in Artificial Intelligence, and the rapid development of computer based information retrieval and manipulation systems.

Data retrieval systems are the most common and can be of various degrees of sophistication. An example of such is that of the “Petten Databank” which includes quantitative information relating to creep crack growth.

Hypertext, which can provide useful backup to an Expert System in terms of the written word, is a method of searching the literature, picking out key words and phrases. Roberge has advocated the use of hypertext packages to process corrosion information to improve coating selection. Hence hypertext can help support, or indeed contradict assertions made by the Expert System and provide the basis for additional sets of questions. It is intended to incorporate this capability in a future phase of the research.

For the interpretation of complex masses of data, neural networks are beginning to be used. One definition of these comes from the paper by Silverman, who indicates that:

“A Neural Network is a computational system which can learn patterns of behaviour between input and output information, in the absence of a specific model”

Such networks are at present best used as genuine research tools where complex amounts of semi-reliable data need to be correlated. For example, it should be possible to use neural networks to correlate the effect of trace elements against creep ductility, and creep strength.

In the future, however, one could envisage a neural network being used in conjunction with the Expert System. Providing that there are many users of an Expert System for power plant component problems, it should be possible to record anomalous failures along with the vagaries of plant performance and the detailed design of components. This would suggest that an Expert System should have some means of down loading “inexplicable occurrences” into a data bank, for future evaluation. Again this brings the Expert System closer to how a real human being operates.

This is for the more distant future, when a neural network could be made part of the Expert System package, along with databanks and hypertext links. Expert systems, per se, seek to do a rather different job, enabling relatively untrained personnel to carry out complicated and time consuming tasks with confidence. Such a system is that of HIDA-KBS. When fully developed, this will make it possible for the
ordinary mechanical engineer or materials scientist to calculate crack propagation rates under creep-fatigue conditions in pipework and nozzles.

To summarise, these various computer based programmes, sometimes viewed as Expert Systems, are used by different personnel. Quite specific types of question are required, as inputs, if the various programmes are to work. Conversely as outputs, they give distinct types of answer. These differences can best be illustrated in the forms of a simple table.

<table>
<thead>
<tr>
<th>Programme Type</th>
<th>Operator/User</th>
<th>Quality of Question</th>
<th>Quality of Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Retrieval</td>
<td>Middle Management or Technical Staff</td>
<td>Precise for Forecasting</td>
<td>Arithmetically Reliable Only</td>
</tr>
<tr>
<td>Hypertext</td>
<td>Expertly Trained Personnel</td>
<td>General Information</td>
<td>Fuzzy but Intelligible</td>
</tr>
<tr>
<td>Neural Network</td>
<td>Experienced R&amp;D Staff</td>
<td>For Concept Development and Pattern Learning</td>
<td>Precise but Initially Unintelligible</td>
</tr>
<tr>
<td>Expert System</td>
<td>Technicians</td>
<td>Precise for Required Action</td>
<td>Reliable but Unintelligible</td>
</tr>
</tbody>
</table>

The suggestion that Expert Systems give “Reliable but Unintelligible” answers may be regarded as controversial. The aim of an Expert System is to replace with a human expert in favour an operator or user who has lower levels of training or more generalised experience. It follows that the reasoning behind some of the responses, provided by the Expert System, can be unintelligible, initially at least. It is at this point access to a data retrieval system, or a hypertext program, may be vital to give the necessary back up and confidence in the use of an Expert System.

The same problem, of course, can occur when one human being deals with another. If there is an obvious lack of understanding or belief by the non-expert, it behoves the expert to call upon previous experience, relevant literature, or other authorities in the field, if he or she is to get his or her arguments accepted.

4. RULES and GOALS in the Development of an Expert System

Most knowledge based systems work towards a defined GOAL. This is the final conclusion or “bottom line” after all our exertions. In this simple example about creep in superheaters we adopt this approach and define the GOAL using the statement:

**Failure_Mechanism is Creep_Failure**

In making this statement we have made use of another feature in the encapsulation of knowledge for the Expert System. We have defined the phrases “Failure_Mechanism” and “Creep_Failure” as OBJECTS. The SHELL, that is the empty computer program which we use to undertake to draw inferences from the expert knowledge, working with the INPUT information, will use OBJECTS to search its data fields and hence generate OUTPUT. OBJECT, INPUT, and OUTPUT relate to short factual statements, numeric values, or images.
By means of this symbolism we can begin to build up a set of knowledge statements which represent the expertise which we wish to embody in the system. These statements are called RULES. RULES in our case consist of “if”.....“then” statements. To identify words which belong together in a particular OBJECT, INPUT or OUTPUT phrase, the words are linked by a hyphen-like symbol “−”, as in the phrase Failure_Mechanism

In this paper we write the RULES in bold lettering, centred in the text, so that they are easily recognised. Thus the RULES are readily available for verification and agreement by experts in the field of high temperature materials.

We will now review some of the issues relating to the identification of creep and see how they can be expressed in the form of RULES.

Most graduates before they encounter creep in the (real) world of high temperature engineering accept the simple picture that failure by creep is intergranular, and that this is a very positive indication.

For example, in the book by Reed-Hill, a hypothetical diagram shows that after a very short time, circa 10 hours, the failure changes from one of transcrystalline cracking to one of the intergranular type.

Thus, if this were a sufficient indication, we would write:

If Failure is Intergranular
then Failure_Mechanism is Creep_Failure

and we would have achieved the GOAL.

Such an indication taken on its own is misleading because intergranular failure is not sufficient evidence on its own.

Hence further indications are needed. This can be done by firing other RULES, which would either support or contradict the hypothesis that the failure was due to creep. Some of these RULES would stem from microstructural observations, others would rely on the estimated or measured temperature of the superheater, still others would come from the performance and history of similar units, etc.

Accordingly, for a temperature limiting RULE, in conjunction with the intergranular evidence, we could write:

If Pipe_Temperature is greater than Allowable_Temperature_Limit (INPUT value)
and Failure is Intergranular
then Failure_Mechanism is Creep_Failure

To reach the GOAL by this apparently simple route we need to give a value to two objects, Pipe_Temperature and Allowable_Temperature_Limit. We would therefore need to INPUT a value for the Pipe_Temperature and automatically consult a database for the Allowable_Temperature_Limit for that particular material and stress value. The Allowable Temperature limit would be found from the database using another RULE with the Stress_Level as an INPUT:

If Stress_Level is (INPUT value)
then Allowable_Temperature_Limit is yyyy°C (OUTPUT value)
Note that the pipe material need not be entered, since in practice, something so fundamental would have been asked for by the Expert System at an early stage. The stress level itself and the time of exposure could also have been entered much earlier on.

Many other indications will be necessary to support the view that the material has been exposed to high temperature and failed by creep. Some of these clues are visual. Assuming that the failure has occurred in a superheater tube there should be a fine network of longitudinal cracks in the vicinity of the main crack. This knowledge could be expressed by the RULE:

\[
\text{Fine\_Network\_Of\_Longitudinal\_Cracks is yes} \\
\text{then Failure\_Mechanism is Creep\_Failure}
\]

Here it is worth noting that the OBJECT ‘Fine\_Network\_Of\_Longitudinal\_Cracks’ is an example of heuristic knowledge, and like so many others in failure analysis, is derived from agreed good practice. In short, the observation that whether or not a pipe has a network of longitudinal cracks is something an expert would need to ascertain. Hence this OBJECT is incorporated into the Expert System and requires an INPUT to be the form of “yes”, “no”, or “don’t know”. This type of heuristic knowledge can only come from experts in high temperature failure analysis, and it is the assembly and use of such rules that gives the Expert System its power and its interviewing skills.

Visual observations, like this, of failed equipment, are vital to the plant operator, since he may not have time to carry out much more than a cursory inspection before getting a plant back into operation. He would be foolhardy, however, to conclude that the failure was due to creep, just on the basis of fissuring. He would look for other evidence, for example, the amount of swelling of the superheater pipework. The Expert System would therefore, for this type of observation, offer an estimate of the probability that the failure had occurred by creep, using a RULE of the type:

\[
\text{If Pipe\_Diameter is Swollen} \\
\text{then Failure\_Mechanism is Creep\_Failure \{30\%\}}
\]

This particular RULE shows that it can be unwise to rely on visual indications only. It also introduces an estimate of the probability that a given outcome has been identified. Such probabilities taken together enable a consensus to be reached on the basis of firing a large number of RULES.

At the microstructural level we can also use probability rules. Accelerated oxidation is often associated with creep and we can use a probability RULE of the type

\[
\text{Is Oxide\_Thickness greater than Normal\_Oxide\_Thickness (yes)} \\
\text{if Oxide\_Thickness is yes and} \\
\text{Failure is Intergranular} \\
\text{then Failure\_Mechanism is Creep\_Failure \{25\%\}}
\]

If this stage is reached, measurements of the oxide thickness may give some idea of the temperature history of the pipe. Such a procedure has been used to estimate crack propagation rates in bolts in air. Unfortunately it is not normally possible to do this with superheater pipework, since fireside deposits corrode the external surfaces. However a semi-quantitative approach can be used using steam side measurements to make an assessment of
the temperature profile in the vicinity of the failure. This assessment cannot be made highly accurate since the oxide scales on low alloy steels can be laminated, indicating that the rate of growth is only quasi-parabolic.

One approach, utilises measurements of steam side oxide thickness from the unheated inlet section of the failed tube and compares this with a point P, close to the failure.

Let us assume that, for example, the steam inlet temperature to the superheater is 470°C and the oxide thickness is 10 microns in this region. Let us also assume that the oxide thickness at point P is 80 microns. The first statement that the Expert System would need to make is:

Oxide_Thickness_Measurements is Steam_Side is yes

This prevents the Expert System using air derived oxidation data.

We can now make the following assertion:

If Baseline_Inlet_Temperature is Steam_Inlet_Temperature (470°C) and Baseline_Inlet_Temperature_Oxide_Thickness is 10 microns then Baseline_Oxide_Thickness corresponds to Steam_Inlet_Temperature (470°C)

The Expert System would now be able to make a rough estimate of the temperature at point P. This is done by using a “rule of thumb” which states that for a low alloy steel, the oxide thickness will double for every 35°C increase in temperature. This rule of thumb, although crude, is another example of a heuristic. It something accepted by experts in failure analysis. Hence the follow-on assertion is:

If Point_P_Oxide_Thickness is 80 microns then Point_P_Temperature is Baseline_Inlet_Temperature + (Point_P_Oxide_Thickness/Baseline_Oxide_Thickness)*35/2

or: Point_P_Temperature is 470° + (80/10)*35/2

The outcome of this application of a RULE in the form of a short calculation is that the value of the OBJECT, Point_P_Temperature, has been set to the value 610°C. The system is always trying to set a value for all the OBJECTS which it has identified in the rule set that it has assembled as being in some way relevant to achieving the GOAL.

The validity of this approach could be checked by the Expert System from a lookup table or graph of steam side oxidation rates, if they were available. This would add extra confidence to the assessment of temperature. For the Plant Operator it would be also important to measure the oxide thickness at the tube outlet. If this was in keeping with that expected, for the design outlet temperature, the result would indicate that the failure was due to some local overheating of the tube, rather than reduced steam flow due to bad design or the accumulation of scale in the superheater tube bend. The logic within the Expert System could be made to highlight this possibility and suggest additional lines of inquiry.

Examples of several RULES have now been created. Some relate to the question of temperature, others to a more direct assessment as to whether creep has occurred. None are sufficient on their own but taken together form a body of knowledge building up to a likelihood that failure was by creep. All of these could be given weightings or probabilities.
The GOAL that failure had occurred by creep would be reached when the overall or totalled probability reached 100%.

5. Issues in the Formulation of Heuristic RULES for Creep Failure

The approach to RULE formulation has been outlined above, but clearly the cognoscenti would regard the examples given as being trivial. The intention, in this section, is to show how the assessment by the Expert System can be deepened and its conclusions made more reliable. It can take on the interpretation of other modes of material degradation. However once one departs from the more trivial and well known criteria for assessing whether failure by creep has occurred, the conclusions become more contentious. Some of these issues are highlighted below.

The metallographic observations of cracks need to be supplemented with other data. In the case of the carbon-manganese and low alloy Cr-Mo steels, spheroidisation of the alloy carbides will have, in general, taken place. These changes affect the pearlite within the steel and are visible with the optical microscope. Coarsening and the increased dispersion of sub-optical carbides will also occur and can be detected through hardness changes. These changes in hardness can be complex being affected by the silicon content of the steel, stress induced effects, and by surface decarburisation. More fundamentally, the problem with attempting to estimate the temperature history from spheroidisation, oxidation and hardness changes is that it can be difficult to decide whether these are due to a long period at a slightly higher temperature than design, or a short period at a much higher temperature. This can be an important question to the operator of the plant.

Turning now to the question of intergranular cracking as a basis for the identification of creep, it can be argued that this, as a criterion, is much more restricted than commonly supposed. This stems from the fact that modern power plant steels range from the simple ferritic-pearlitic carbon steels, through to slightly higher alloyed materials which contain bainite to a greater or lesser extent, to the modern 9-12 Cr fully martensitic alloys. As mentioned above, we can also expect to see in future, the reintroduction of austenitic alloys.

The modern approach is to look for other microstructural indications, foremost among which would be the appearance of cavities in areas contiguous with the failure, or in nearby pipework that is showing signs of swelling. This can be applied quantitatively to estimate future the life of a component, most notably through the use of the $A^*$ method, which essentially assumes that a cavitated region unloads its stress onto the surrounding area.

Cavity counting eliminates the problem that, in practice, it can be difficult to identify grain boundary cracking, since such surfaces may be oxidised and decarburised, leading to specimen preparation problems. It also begins to overcome the conceptual difficulty as to when to begin to describe a failure has having been due to creep. One of the authors of this paper investigated a failure of 2.25Cr-1Mo tubing in a fired heater, which had failed in less than 4000 hours, but showed all the symptoms of classical creep failure of swelling, multiple fissuring, and indications of intergranular cracking.

Conversely Greenwell and Beech noted that the Grade 91 steels failed by transgranular cracking below 10000 hours. Similarly the Ashby map for Type AISI 316 shows that the switch-over, from transgranular to intergranular cracking, begins to occur after around 100 days of testing at 697°C and 100 MPa stress but is not fully complete until many years have passed. In contradiction to all of this, Strang and Vodarek reported that the "sigmoidal drop" in creep properties in the 12CrMoVNB steels, after medium term exposures ranging
from 8000-25000 hours, was associated with an increase in creep ductility and a change from intergranular to transgranular cracking. This of course is a cast material for turbine rotors, but the Expert System will eventually need to encompass this type of equipment.

The appearance of cavities can be used as an indication that creep is responsible for the failure, but still needs to be supplemented by other methods. Of these the use of thin foil or replica techniques to determine sub grain structures and precipitation is beginning to emerge, particularly as applied to the martensitic pipe steels. Of these the work of Mayer et al is very interesting, since these workers showed how, under the influence of creep stress, the sub grain structure in a 10 Cr martensitic alloy changes from a lenticular type structure to one which is much less oriented.

6. Discussion

The aim of this account has been to highlight some of the issues in constructing an Expert System for identifying creep failures in superheater and reheater tubes. Clearly a simplistic approach is unsatisfactory, so that the Expert System will need to encompass a wide variety of different materials, each of which will have their own characteristics. Furthermore, if creep is to be identified as being the cause of failure, we have the situation in which there is no such thing as a fingerprint or DNA sample, which on its own can convict.

Essentially all evidence for creep is circumstantial. From various observations it is possible to make inferences, which collectively point to a particular failure mechanism. It is worth noting that Dobrzanski and Hernas, whilst not using an expert system in the quantification of creep damage, used a variety of different approaches to estimate residual life. These included the spheroidisation of the ferrite-bainite structure, the change in sub-microscopic carbides from M₇C to M₂₃C₆ and eventually to MeC, as well as the evolution and growth of cavities into microcracks and macro cracks.

Normally given the conjectural state of the evidence, and need for a quick answer, other inputs will be needed from plant records and statements of operating personnel. This is particularly the case with what the authors refer to as a “Level 1 Analysis” in which no metallography of any sort is carried out. Essentially all the evidence is derived from plant records, anecdotal history, and the visual appearance of the failure. Although this may appear unsatisfactory to the metallurgical fraternity, it may be the most appropriate approach at the time, and in the short term at least, will be highly cost effective.

7. Conclusions

- The fundamental issues that underlie the development of an Expert System for Failure Analysis of High Temperature Plant are under review.

- The initial approach is to use the various modes of degradation of superheater materials associated with creep failures to create a set of heuristic RULES that will be utilised by the Expert System shell.
• The paper has shown that in the identification of creep failures, evidence must be marshalled from different sources, each item being given due weighting.

• The paper has outlined how heuristic RULEs are formulated, so that they can be transposed into the SHELL of the Expert System.

• Newer methods of assessing whether failure has occurred by creep will be needed for the more modern martensitic and austenitic superheater alloys.

References

1. PH.Winston "Artificial Intelligence"Addison-Wesley 1993


3. PR.Roberge ‘Transforming Computerised Information for its Integration into a Hyper Tutorial Environment pp 3404-3411 NACE 12th International Corrosion Congress. NACE 1993


8. LH.Toft and RA.Marden ‘The Structure and Properties of 1% Cr-0.5% Mo Steel after Service in CEGB Power Stations’ pp 276 Structural Processes in Creep ISI 1961


Presentation to Surrey University Engineering Faculty
Guildford Feb 2002

Development of an Expert System for Power Plant Failure Analysis

F. Starr
Development of an Expert System for Power Plant Failure Analysis

F. Starr

Presentation to Surrey University Engineering Faculty

21st Feb 2002
An Expert System for Power Plant Failure Analysis

*Should*

Diagnose using evidence from plant operational procedures, visual clues and laboratory examinations, the failure mechanism

Identify positively and objectively the root cause of the failure

Be relevant to the needs and requirements of:
HOW DO DIAGNOSTIC TYPE
EXPERT SYSTEMS
OPERATE?

Operational Staff
Plant Management
Headquarters, Design Office and Regulatory Personnel
What Makes an Expert?

- Deeply Knowledgeable
- Practical Experience
- Questions
- Listens
- No Fuss
- Predicts Future Correctly
- Learns
- Forgets Nothing
- Solves Problems
- Has New Insights
- Highlights True Causes
- Remembers How He Reached a Conclusion
Power Plant Equipment Failure Expert

- Has up-to-date knowledge of power plant and failure mechanisms.
- Talks to operators on their own terms
- Begins to diagnose origin and mechanism of failure from initial discussions
- Targets likely causes of failure and arranges investigations accordingly
- Weighs the evidence and provides a solution

- Explains underlying causes of failure
- Predicts likely reoccurrence of problem
- Learns from this particular experience
Expert System Features

- User interface is intelligible to plant operators and laboratory technicians

- A search tree is that is limited and directed

- Evidence for and against failure mechanism is weighed objectively

- Contains deep knowledge to explain failure causes and predict equipment life#

- Learns intelligently from this and related experiences
Rule Based Systems (1)

Questions are asked to elicit FACTS. This leads onto further questions and eventually onto identification of failure mechanism via the FACT BASE and INFERENC ENGINE

FACTS are produced by operating Rules of two types:

*Forward Chaining:*

- If pipe is swollen_and_fissured
- Then probability of creep_failure is 70%

*Backward Chaining*

- Probability of creep_failure is 70%
- If pipe is swollen_and_fissured

Knowledge of word “creep” or its implications is not required

You need to know about “creep” to use the rule
Issues in the Identification of Creep as the Failure Mechanism in a P91 Superheater Tube

And

Identification of the Root Causes of the Failure
Why Use a P91 Failure as an Example?

- It is critical to the development of modern power plant
- The microstructure is different to most other superheater steels
- Heat treatment and composition are critical
- The oxidation resistance is close to the limit
- Papers on P91 attract attention and comment
Premature Failure

- Off-Specification Material
- High Creep Rates
- Excessive Metal Temperatures
- Poor Furnace Design or Operation
Why Did the Superheater Tube Really Fail?

- Low Cr Content
- High Fireside Oxidation Rates
- Low Si Content
- High Steam Side Oxidation Rates
- Loss of Wall Section
- Premature Failure
- Excessive Stresses
- High Creep Rates
- Overestimation of Creep Properties
- Non-Optimum Strengthening
- Delta Ferrite Formation
- Poor Heat Treatment
- Tube Blockage
- Poor Furnace Design or Operation
More Complex Explanation of Failure Cause

- Low Cr Content
- High Steam Side Oxidation Rates
- Loss of Wall Section
- Low Si Content
- High Fireside Oxidation Rates
- Excessive Metal Temperatures
- Excessive Stresses
- Tube Blockage
- High Creep Rates

Premature Failure
Effect of Oxide Formation on Superheater Temperature and Tube Life
Laboratory and Plant Based Procedures to Determine Root Cause of Creep Failure of P91

1. Remove Material from Affected and Unaffected Tubes for Examination and Testing
2. Determine Conclusively that Tube has Failed by Creep
3. Begin Aging Tests on Representative Samples
4. Assess Whether High or Low Heat Transfer Rate
   - Assess Through-Wall Gradient
   - Assess Steam Inlet and Outlet Temperatures to Pendant
   - Refer to Flue Gas Temperatures and other Plant Data
5. Assess Whether Creep is Due to Steam Starvation
   - Look for Spalled Oxide in Tubes
   - Assess Steam Inlet and Outlet Temperatures
6. Assess Whether Creep is Due to Excessive Oxidation Rate
7. Utilise Ageing Data to Obtain Better Temperature Estimates
8. Begin Steam Oxidation Tests on Representative Samples
9. FINAL DECISION ON ROOT CAUSE
Formulating check lists and IF THEN rules for the identification of failure mechanisms and root causes by power plant personnel at "Levels 1 and 2"

What did a macro view of a cross section through the failure show?

a. Limited amount of thinning and deformation close to failure
b. Highly thinned and deformed
c. Fissuring near fracture
d. No fissuring near fracture

e. Little steam side oxidation (<0.25 mm)
f. Severe steam side oxidation (>0.5 mm)
g. Evidence of steam side oxide spalling

h. Deposition of salts or similar material

Click on as many as appropriate
Level 1

Failure Mechanism Identification

1. Type of Plant
2. Type of Equipment that has failed
3. Type of Superheater that has failed
4. Type of Material
5. General Location of Failure
6. Position of Failure on Tube Circumference
7. Position Relative to Furnace Walls
8. External Appearance of Failure
9. Internal Appearance of Failure
10. Appearance of Adjacent Tubing
11. How is Plant being Operated?
12. Recent changes in Boiler Fuel?
13. How Old is Equipment?
Application of If–Then Rules to Superheater Failures

Now_testing_failure_mechanisms_of_superheater_heater_and_reheater_tubes

Rank possible superheater failure mechanisms

- Overheating
  - Creep
- Weldment failure
- Fireside corrosion
  - Thermal fatigue
  - External erosion
  - Internal erosion
  - Steamside corrosion

Overheating Failure

If 6a,8a and 8c Then overheating_is_possible and check_on_supporting_evidence

If not Then check on rules_for_creep

Creep Failure
If 8a, 8c and 8f Then creep is possible and check_on_supporting_evidence

↓

If in_addition 9b and 10c and 10d Then creep is possible

↓

If in_addition 11a Then is creep is probable main_failure_mechanism and ask if operator requires estimate of tube operating temperature

If calculation is required Then input necessary data in accompanying table
Level 1 and 2 Flow Chart

Level 1 (Plant Maintenance Personnel)

1. Collect Basic Information about Plant Design and Operation

2. Designate Equipment that has Failed
   (Pendant Superheater)

3. Itemise Visual Clues on Failure

4. Use If-Then Rules to Show Failure Mechanism was Probably Creep
Level 2 (Plant Management)

- Collect Information about Location, Ownership and Equipment
- Use If-Then Rules in Laboratory Investigation to Establish Creep as Failure Mechanism
- Collect Detailed Information on Plant Operations
- State Changes to Operating Procedures
- State Equipment Items not Functioning (Feed heater)
- State Consequences of Feed Heater Not Functioning

**Use If-Then Rules to Show**

*Root Cause was Feed Heater being Bypassed*
The End
Potential Problems in the Identification of the Root Cause of Superheater Tube Failures in 9Cr Martensitic Alloys:

F. Starr, J. Castle and R. Walker
Potential problems in the identification of the root cause of superheater tube failures in 9Cr martensitic alloys

Fred Starr*, J. Castleb and R. Walkerb
*aEuropean Technology Development Ltd, Ashtead Surrey KT21 2HR
bSchool of Engineering University of Surrey, Guildford GU2 7XH, UK
*To whom Correspondence should be addressed.

The metallurgy and levels of protective elements in the new P91 and P92 martensitic alloys are quite different to older ferrite pearlite and ferrite bainite steels. This is likely to give problems in the positive identification of failure mechanisms and assessment of the life of superheater tubing. Techniques such as spheroidisation and oxide thickness to assess metal temperatures, or hardness testing and cavitation to estimate the level of creep damage cannot be used with these materials, or are likely to give ambiguous results. These issues are discussed in the paper and were explored in depth in part of a project at the University of Surrey to develop "If-Then" rules for an expert system for power plant failure analysis.

The main aim of the proposed expert system is to identify the root causes of such failures in superheater tubing and will encapsulate current knowledge about superheater problems in the form of "If-Then" rules. Root causes of creep failures include furnace design and operation, overestimation of alloy creep properties, inadequate heat treatment and a non-optimum content of strengthening elements.

A characteristic of these alloys is that oxidation on the steam side of the tubing can induce premature failures due to the insulating effect of the oxide scales raising tube temperatures. In addition, scale spallation could also increase tube temperatures, as spallation debris may collect in the bottom of tubes, blocking steam flow. Attention is drawn to a potential "runaway affect" in which the tube temperature and rate of oxidation increase with time as the oxide builds up. The root cause of this could either be excessive rates of heat transfer or could be due inadequate oxidation resistance caused by low levels of protective elements. Methods of identifying which of these is the root cause are discussed.

Keywords: expert systems, Superheaters, 9 Cr martensitic steels, creep, oxidation, life prediction

1. INTRODUCTION

Advances in the output and efficiency of power stations have greatly depended on the development of materials for superheaters. Such materials must have a creep strength of about 100 MPa for at least 100,000 hours at the design metal temperature. This is typically around 600°C in a modern coal fired power plant, where steam temperatures are in the range 540°-580°C. Efficiencies are now in the region of 45% and the output per unit is between 500-1000 MW. This is a considerable advance over the 1960s when the best plants were achieving 35%. Nevertheless most of the improvement over the past forty years has come from better design of equipment, rather than from new high temperature alloys. Only over the past ten years have designers begun to turn to better materials to improve plant efficiency and make plant more capable of meeting "two shifting" requirements. But these new materials are beginning to cause problems with life prediction and failure analysis as highlighted at a recent conference on these subjects [1].

Along with technical advances in power generation there have been significant changes in structure of the industry, which has had implications for failure analysis of power plant equipment. These changes have been at their most intense in the UK, where the amount of power produced from coal fired stations fell by a quarter over the period 1970–2000. Of greater significance has been the reduction in number of plants (because of the huge increases in power outputs from individual units), along with changes in the pattern of ownership. Whereas there were around 200 plants in the sixties, all owned by the then Central Electricity Generating Board (CEGB), there are now just 10–15 coal fired steam plants run by about 6–8 independent companies.

Given that peak demand in the UK is in the region of 55–60 GW, this means that each unit produces a very large proportion of the nation's power. Reliability is vital, which requires skilled manpower and management judgement of the highest order. Unfortunately the small size of each organisation and small number of plants which each owns is not really compatible with having large experienced teams of people working in the failure analysis area. In this context there has been the rise of the litigation culture, in which failure of a power plant at a critical time could lead to long and complex court
actions to determine what was the root cause of the failure. Was it due to the materials, design, or mistakes by the operators? A whole panoply of experts from various disciplines could be needed, few of whom would be completely objective or able to comprehend the full picture. There is clearly a need to develop techniques that can assist technical specialists who undertake failure investigations. This paper relates to such a development, that is the formulation of an ‘expert system’ for failure analysis of power plant components.

What is an expert system, and what is it intended to do? It is a system that uses artificial intelligence to replace human experts or to augment their expertise. The aim is to encapsulate human expertise in sets of “If-Then” type rules, to assess whether the facts about something which has occurred, or is about to occur, will lead to a certain conclusion [2,3]. For example the long term exposure of carbon steels, at temperatures in the 450°-650°C range, will lead to spheroidisation, whereby iron carbide lamellae, in pearlitic colonies, eventually coalesce to form small spheroids of cementite [4]. Hence in failure analysis spheroidisation can be used to indicate that a tube made of carbon-manganese steel has been running at temperature. Accordingly an “If-Then” rule on spheroidisation would be:

If carbon_manganese_steel is highly_spheroidised Then carbon_manganese_steel has been above 500°C for long_periods

“If-Then” rules of this type, each of which represents a nugget of expertise, are incorporated into an “Inference Engine”, within the expert system, see Figure 1. To activate the system, information about the type of equipment that has failed, the failure location, metallography of the failure, temperatures and pressures, etc, are entered into the “Fact Base” via a conventional PC keyboard. The Inference Engine then puts the facts into the relevant “If-Then” rules, and in so doing, draws inferences or conclusions from these. Any quantitative calculations, such as estimated times to failure, would be done using sub-routines. A key requirement is that the Inference Engine should be able to put together individual conclusions from each of the “If-Then” rules, so as to come to an overall view about the failure mechanisms, and, more importantly, the root causes of such failures.

Work at the University of Surrey has concentrated on the technique of rule formulation and the issues that relate to the marshalling of individual conclusions from each “If-Then” rule. An important aim of the work is to show that a complex expert system can be built up by experienced engineering staff with the minimal involvement of computer specialists such as “knowledge engineers”. This is being done by focusing on a piece of plant equipment and a material of construction that can suffer failures from a variety of different mechanisms. This procedure is vital in exposing the difficulties in constructing an expert system of some real depth, complexity, and use.

A piece of equipment that has the characteristics of being likely to fail through a variety of mechanisms, because of wide variations in the types of operation and design, is the superheater section on a power plant. What, however, should be the superheater alloy around which the expert system should be formulated?

As mentioned earlier, over the past few years some new materials have been introduced into power plants, particularly in equipment running at high temperature, such as superheaters, reheaters and turbines. One of the most important classes is that of the 9% chromium martensitic steels. The issues involved in investigating failures, of such alloys, gives some real point to the development of an expert system. With P91 in particular, which was the first of the new grade of alloys to be used, there is now a strong commercial interest in the accurate diagnosis of the root causes of P91 and T91 (i.e. materials for headers and tubes respectively) superheater failures, since problems are emerging with superheaters built using these alloys. Some failures may well be due to shortcomings with P91/T91, but others, as will be seen, are due a combination of factors, including the alloy itself, the design of the furnace and its operation. Hence even before the expert system is in operation, “If-Then” rule formulation has resulted in new insights into the problems of failure diagnosis.

Since its introduction in the early nineties, first as P91 for headers, efforts have been made to improve on P91. The alloy closest to production is P92, which contains tungsten as well as molybdenum for solid-solution strengthening, the alloy alloy also having a tighter specification of the precipitate strengthening elements. It will be seen that these 9Cr martensitic steels have a metallurgy that is quite different to older alloys such as the carbon-manganese grades and T22 grade (2.25Cr–1Mo steels).

One test of a good expert system is that it should be capable of covering a wide variety of alloy types, some of which will exhibit unusual characteristics compared to more common materials. The older class of alloys have either ferrite-pearlite or ferrite-bainite microstructures whereby, after long term exposure to temperature, the optically visible carbides spheroidise and the sub-microscopic carbides coarsen. Optical and scanning electron microscopy can then be used to help estimate temperature and the remaining life of components. These observations can be supplemented by measurement of the hardness and oxide thickness [4]. On the contrary, a review of the literature on P91 and related alloys indicates that the situation is not so simple, as will be shown later in this paper.

Premature failures of superheaters can be a consequence from the workings of apparently unrelated other sections of a power plant [5]. Some failures can be due to management decisions on how the plant should be operated. In this type of scenario, unless changes are made, it is likely that premature failures of superheaters will continue. Hence, just as a human expert would need a working knowledge of power plant layout and operational procedures to be able to investigate failures, an expert system must also have similar ability. Accordingly

---

**Figure 1** Operation of an expert system.
The basic principle behind the design of fossil fuel steam plants is that coal, oil or gas is burnt to produce steam at high pressure and temperature. The steam is used to drive a set of turbines, which in turn, drive a generator. The steam used in modern units is turned directly into steam, using the heat from the burning fuel. The steam is then heated further, to about 540–600°C in a set of heat exchangers (superheaters), using the heat in the flue gas (i.e. combustion gases from the furnace), which are located in the flue gas duct.

As the steam progresses through the turbines, doing work and giving up energy, its pressure and temperature drops, until eventually the temperature of the steam is quite close to ambient. The steam, now at a pressure well below that of the atmosphere, is condensed. The condensed steam forms water of high purity, which is pumped back to the boiler. Once a plant is operating, only a relatively small amount of "treated" water is needed for "boiler make up" to take care of any losses.

Steam production and its use is actually more complex than this simple account, and a detailed knowledge of the steam system, flue gas and combustion air preheating systems is essential if root causes of superheater problems are to be identified. In practice there are three sets of turbines; the HP (High Pressure), IP (Intermediate Pressure) and LP (Low Pressure) turbine sets. After the steam has gone through the HP turbine it is passed back through a further set of heat exchangers (reheaters), rather similar to the superheaters, where the steam is brought back to around 560°C, see Figure 2. The reheated steam is then used to drive the IP turbine before going on to the LP turbines, of which there are a set of three, and the condenser.

It will also be seen from Figure 2 that the water from the condenser is preheated before it enters the boilers, using feed heaters and an economiser. Feedheaters take "bled steam" from the turbines at various points along their length, which is used to preheat the "boiler feed water". The economiser, where fitted, uses some of the heat in the flue gas system to heat the water up even further. These measures improve plant efficiency considerably. After leaving the economiser the flue gas can still be at 300–400°C and the heat in this is used to preheat the combustion air to the furnace.

Any deterioration in the performance of heat exchangers used to preheat the boiler feed water or combustion air will have an adverse effect on the superheaters. For example, if a feed heater was to fail through fatigue and had to be bypassed, the water entering the boiler would be cooler than usual. To maintain steam production the furnace would need to be fired harder and this would tend to raise flue gas temperatures and superheater temperatures.

Why is the production of superheated steam at high temperature so essential to plant efficiency? The simple response is that as the Carnot cycle indicates, a high inlet temperature into the steam turbine is needed if a significant proportion of the heat in the steam is to be converted into work. To answer this more fully requires a somewhat deeper understanding of steam plant thermodynamics [8]. Essentially the expansion of steam through a turbine causes the steam temperature to drop, as heat is converted into work. Hence the work done is a function of the difference in temperature between that of the steam as it enters the turbine and that of the steam as it leaves the back end of turbine. It follows that if the plant is to take full advantage of a high steam temperature, the pressure must also be high.

Because of the properties of steam, it can be shown on thermodynamic grounds that pressure needs to increase exponentially with temperature. Figure 3 shows this relationship, plotting pressure against temperature for steam plants built between the 1920s and the modern day. In fact steam pressures have risen even more rapidly than might be expected from a thermodynamic analysis, which focused solely on the benefits that superheaters bring [9]. This resulted from the introduction of reheating during the late thirties, which required plants to work at even higher pressures to get adequate expansion through each set of turbines.
Potential problems in the identification of the root cause: F. Starr, J. Castle and R. Walker

3. SUPERHEATER DESIGNS AND MATERIALS

Superheaters are essentially tubular type heat exchangers in which high pressure steam on the inside of the tubes is heated by the flue gases exiting the furnace. The tubes (approximately 50 in each section of the superheater), run between larger diameter pipes (headers), which conduct the steam into and out of the tubing.

Superheater tubes are around 50 mm diameter and have a wall thickness of about 5 mm. Superheater headers, are 0.5–1.0 m across and although the outlet header runs at a lower temperature than the tube, it has a much thicker wall. Figure 4 shows convective and pendant type superheaters. Note that with the pendant type that although the bending stresses due to the weight of the tubes are absent, this type of design is likely to trap condensed steam during weekend shutdown periods. During restarts, the carryover of relatively cool condensate will result in quenching and thermal stress of the hot outlet header.

The need for both pressures and temperatures to increase, at the same time, has had a major impact on superheater materials. There as been a progressive evolution starting from carbon steels in the 1920s through to Cr-Mo and Cr-Mo-V in the middle decades of the 20th century. During the 1960s there were efforts to push steam temperatures up to 565°C and even higher. This necessitated the use of austenitic stainless steels, such as Type 316 stainless, as these were the only steels that had satisfactory creep strength and could withstand attack from the flue gases. A major drawback of the austenitics was the tendency to thermal fatigue. The relative susceptibility to thermal fatigue of superheater alloys is given in Table 1, using data from [10], and is best categorised by the “Merit Order Parameter R” which is given by:

$$R = k \cdot \sigma_y \cdot E^{-1}$$

where $k =$ thermal conductivity, $\sigma_y =$ yield strength at temperature, $\alpha =$ coefficient of thermal expansion and $E =$ Young’s modulus using the units shown in Table 1[10].

As can be seen the $R$ value of Type 316 is very low. De-rating was necessary in some 'advanced' plants utilising austenitics. Because of this experience, steam temperatures settled back to 540°C for almost twenty years, and the two ferritic materials which came into use for superheater construction were “T22” (Fe-2.25Cr-1Mo) and “X20” (Fe-12-1Mo-0.3V) steels.

Table 2 indicates that T22 is well below the criteria of 100 MPa stress rupture strength, even at steam temperatures in the mid-500°C range, this leading to thick walled headers and tubes, which give problems with thermal stress. Alloy X20 has reasonable strength and a sufficient level of chromium to give reasonable resistance to corrosion in most circumstances. The main difficulties are with welding. Being a highly alloyed martensitic steel, cracking is likely during welding, and the material has a tendency to stress corrode.

The need to increase thermal efficiency led during the 1990’s to martensitic alloys of the P91 and P92 type. These permit steam temperatures to be raised to about 560°–600°C. The composition of these alloys is shown in Table 3.

The chromium levels are held down to the 8–9.5% range to permit the introduction of higher levels of ferrite-forming elements to enhance creep strength, at some sacrifice to oxidation resistance. Alloy P91 is now quite established, the first superheater headers having gone into service in the early nineties. Nevertheless due to lack of experience with this material the estimated creep stresses for this alloy vary quite markedly between the different standard authorities as Table 4 shows [13]. Alloy P92 is still in the process of being introduced, and long term creep rupture strengths are still under consideration.

4. ROOT CAUSES OF SUPERHEATER TUBE FAILURE

The sections of a superheater which are liable to fail by creep, are the tube bank itself, wherein the steam is heated, the main outlet header and, where they are fitted, sub headers. The majority of creep failures in P91 superheater tubing will have resulted from a moderate degree of overheating, with failures occurring after some tens of thousands hours of operation. The simplistic approach to such failures is shown in Figure 5. This indicates that if a creep failure has occurred, and has been positively identified as such, there are likely to be only a few root causes. One possibility is with furnace design or operation, leading to excessive metal temperatures. An alternative is that the alloy itself is responsible. The creep strength may be, for a variety of reasons, somewhat lower than anticipated, or that corrosion on the flue gas or the steam side of the tubing, has led to excessive thinning, raising the stress level.

Figure 5, although indicating possible causes of a creep failure, is not really satisfactory as these are not root causes. It offers no suggestions as to what should be done to avoid premature failures in future. For example the superheater tubing might be failing due to excessive metal temperatures This could be traced back to high flue gas temperatures, suggesting that there was problem with the furnace design or its operation. A good expert system would activate sets of “If-Then” rules, based on the implications of steam and flue gas temperatures, water and steam flows, and energy inputs and outputs to and from the furnace. The output from these rules would point to root causes such as those detailed below [4,14,15,16]:

- Operation of furnace at design limit or higher
- Bad flue gas distribution
- Bad burner set up
- Air in-leakage in the furnace
- Furnace wall slagging
- Fouling of economiser or air heater
- Switch to natural gas from coal or oil firing
Potential problems in the identification of the root cause: F. Starr, J. Castle and R. Walker

### Table 1: Physical properties and merit order resistance for superheater steels.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Conductivity (WmK⁻¹)</th>
<th>Coefficient of thermal expansion (10⁶K⁻¹)</th>
<th>Young’s modulus (GPa)</th>
<th>Yield strength at temperature</th>
<th>Merit order R</th>
</tr>
</thead>
<tbody>
<tr>
<td>T22</td>
<td>33</td>
<td>14.6</td>
<td>167</td>
<td>175MPa@500°C</td>
<td>2300</td>
</tr>
<tr>
<td>X20</td>
<td>26</td>
<td>12.3</td>
<td>198</td>
<td>250MPa@550°C</td>
<td>2700</td>
</tr>
<tr>
<td>Type 316</td>
<td>22.5</td>
<td>18.0</td>
<td>150</td>
<td>98MPa@600°C</td>
<td>800</td>
</tr>
<tr>
<td>P91</td>
<td>30</td>
<td>12.7</td>
<td>175</td>
<td>220(Min)MPa@600°C</td>
<td>3000</td>
</tr>
<tr>
<td>P92</td>
<td>-27</td>
<td>-12</td>
<td>-180</td>
<td>-300MPa@600°C</td>
<td>-3750</td>
</tr>
</tbody>
</table>

### Table 2: 100,000 hour rupture strengths in MPa for older superheater alloys [11]

<table>
<thead>
<tr>
<th>Material</th>
<th>500°C</th>
<th>550°C</th>
<th>600°C</th>
<th>650°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T22</td>
<td>135</td>
<td>68</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>X20</td>
<td>235</td>
<td>128</td>
<td>59</td>
<td>23</td>
</tr>
<tr>
<td>Type 316</td>
<td>-</td>
<td>175</td>
<td>120</td>
<td>69</td>
</tr>
</tbody>
</table>

### Table 3: Composition of P91 and P92 [12 and 13]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Element %</th>
<th>C</th>
<th>Mn</th>
<th>B</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>W</th>
<th>Nb</th>
<th>N</th>
<th>Al</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>P91</td>
<td>Min</td>
<td>0.08</td>
<td>0.3</td>
<td>-</td>
<td>0.2</td>
<td>8.00</td>
<td>0.85</td>
<td>0.18</td>
<td>-</td>
<td>0.06</td>
<td>0.030</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Max</td>
<td>0.12</td>
<td>0.6</td>
<td>-</td>
<td>0.5</td>
<td>9.50</td>
<td>1.05</td>
<td>0.25</td>
<td>-</td>
<td>0.10</td>
<td>0.07</td>
<td>0.04</td>
<td>0.40</td>
</tr>
<tr>
<td>P92</td>
<td>(approx)</td>
<td>0.07</td>
<td>0.45</td>
<td>0.004</td>
<td>0.06</td>
<td>9.0</td>
<td>0.5</td>
<td>0.2</td>
<td>1.8</td>
<td>0.05</td>
<td>0.06</td>
<td>&lt;0.02</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4: 100,000 hour creep rupture strengths in MPa for P91 according to ASME, VdTÜV and EN evaluations [13]

<table>
<thead>
<tr>
<th>P91 Evaluation Method</th>
<th>500°C</th>
<th>550°C</th>
<th>600°C</th>
<th>650°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASME</td>
<td>164</td>
<td>141</td>
<td>98</td>
<td>---</td>
</tr>
<tr>
<td>VdTÜV</td>
<td>253</td>
<td>162</td>
<td>90</td>
<td>---</td>
</tr>
<tr>
<td>EN</td>
<td>258</td>
<td>166</td>
<td>94</td>
<td>48 (approx)</td>
</tr>
</tbody>
</table>

This paper concentrates on metallurgical root causes of premature failures. Hence Figure 6, which shows the potential effects of root causes in more detail, excludes the list of furnace-derived root causes detailed above.

The yellow and blue boxes in Figure 6 indicate, respectively, the various factors that could have lead to poor creep or poor oxidation resistance. Oxidation, as shown in this diagram, suggests that it has an indirect effect, in thinning the tubing, so raising stresses. This is more usually a problem originating from excessive rates of attack from the fireside of superheater tubing. Ennis and Quadakkers [17] have drawn attention to this potential shortcoming of P92, as it is intended for use at temperatures higher than those of P91.

www.scilet.com
Potential problems in the identification of the root cause: F. Starr, J. Castle and R. Walker

peratures in excess of 600°C, where oxidation rates of this alloy are quite high.

Identification of root causes is made more difficult if the tube forms a relatively thick oxide layer on the steam side of the tubing, as is the case with both P91 and P92. As the oxide on the inside of the tube builds up, it acts as an insulating barrier to the heat being transmitted through the tube walls, thereby raising the tube temperature [18,19]. The magnitude of the temperature rise is proportional to the heat transfer rate in superheaters, the oxide thickness, oxide conductivity, porosity and adherence. Data for heat transfer rates is difficult to obtain but French [18] shows a graph with rates varying from 19 to 63 kW.m⁻² and Husemann [19] quotes 50–75kWm⁻². It should be noted that this is the 'steam' side heat transfer rate, which is significantly higher than that on the 'flue' gas side, the increase resulting from the difference between the inside and outside diameters of the superheater tubing.

Figure 7, based largely on the paper by Husemann [19], shows that, in the absence of heat transfer, or the formation of a thick oxide, a superheater tube, running at a constant metal temperature of 600°C, would use up about 1.6% of its life over a year. However at a heat transfer rate of 50kWm⁻², the build up of the oxide scale gradually raises the tube temperature by about 17°C over a year. This progressive increase in temperature reduces tube life by about 4%.

These particular calculations assumed that the oxide growth was determined by the original metal temperature, that is 600°C. Here the hypothesis is that oxide growth rate is determined by the Arrhenius relationship between the molecules of steam and metal ions, which arrive at the outer surface of the oxide. But it would seem equally probable that the rate of diffusion of ionic or molecular species through the oxide scale is the rate determining step. If this is the case, as the oxide thickens up, the average temperature of the oxide will increase, with the rates of diffusion also increasing. This will lead to the 'runaway effect' at high rates of heat transfer, whereby the formation of oxide will lead high metal temperatures and hence high higher rates of oxidation.

Figure 8 shows the runaway phenomena schematically in which an interactive cycle builds up between metal temperatures and oxide growth. Excessive rates of oxidation will also lead to scale spallation, which in the past has been a considerable problem. Oxide debris can collect in the bottom bends of superheater tubing, restricting steam flow and raising metal temperatures. Here again there is the prospect of a runaway effect, as the increased metal temperature will accelerate oxidation rates.

The present authors have developed a spreadsheet model to quantify the magnitude of runaway oxidation and its impact on the creep life of superheater tubes. In working out the final thickness of an oxide layer after an exposure of one year, it takes into account the following factors. Typical values for each of these are shown:

- Oxide thickness temperature Gradient (12.5°/100μm @ 50kW/m²) [19]
- Basic oxide growth rate (125μm/year @600°C) [20,21]
- Temperature acceleration (Doubles for every 30°C increase) [20,21]
- Initial tube temperature (600°C)

The oxide thickness calculation was performed in 1000 hour steps, with the temperature increase induced in the tube at the end of each step being used calculate the increased oxidation rate in the ensuing step. The effect of these step changes in temperature on tube life usage was calculated using a Larson–Miller parameter approach for the effect of each 1000 hour exposure at the different temperatures (see Section 6.1). To determine the actual value of the parameter it is necessary to make an estimate of the absolute life at the design temperature and to decide on the value of the Larson–Miller constant. As will be discussed later, there is a measure of disagreement about this last figure. Note that the absolute life is much higher than the design life as normally understood. Actual values used in the current version of the spreadsheet are

- Larson Miller constant: 31
- Absolute life: 500,000 hours at 600°C

In Figure 9, the dashed curves show the magnitude of the runaway effect at a heat transfer rate of 75 kW.m⁻², indicating that the effect increases the tube temperature by about 9°C after 8000 hours, with the build up due to the oxidation rate being fixed at the 600°C level. Tube life suffers, runaway raising the life usage from 6.32% to 8.95%, as shown by the solid curves. Note that the runaway affect on temperature does not become really apparent until several thousands of hours have elapsed. However the runaway effect becomes far more marked if the oxidation resistance decreases, especially when com-
Potential problems in the identification of the root cause: F. Starr, J. Castle and R. Walker

Prominent features of the investigations include:

- The exposure time of the failed tube using a Larson-Miller or similar life/stress/temperature extrapolation technique.
- Steam side oxide thickness
- Spheroidisation of pearlitic and bainitic carbides using optical microscopy.
- Levels of grain boundary cavitation
- Coarsening of sub-optical carbides and interparticle distances using SEM observations
- Drop in hardness caused by carbide coarsening

Spheroidisation is at best only semi-quantitative, but is useful in failure diagnosis of the lower alloy steels, as it can show the extent of overheating of neighbouring tubes. It has the advantage that it is a non-destructive test that uses surface replication. As Figure 10 shows, for the pearlitic-containing steels such as T11 (Fe-1.25Cr-0.5Mo) the changes are very apparent [4]. Unfortunately, with the martensitic steels, there are no real changes in the optical microstructure over the life of the material. Figure 11 shows that after long term exposure of P91 and P92, the microstructure of these has a distinct martensitic appearance [25,26]. Ennis [26] has suggested that the lathes of martensite lose their body-centred-tetragonal structure and revert to the body-centred structure of true ferrite, there being no real changes in the microstructure while this happens.

The other techniques mentioned also suffer from the weighted average temperature effects, but are normally used in the direct assessment of component life. For this specific purpose cavitation is probably the best method for life assessment of the low alloy steels. Unfortunately with P91 it is extremely difficult to detect cavitation until the material is very close to the end of its life [25]. Measurement of interparticle distances and carbide coarsening with the martensitics requires the use of TEM of thin foil specimens with these alloys, as according to Ennis et al., [27] the particle size is 100–200 μm. This would preclude using the conventional electron probe to detect changes in carbide composition.

6. SHORTCOMINGS OF QUANTITATIVE TECHNIQUES FOR ESTIMATING TEMPERATURES IN P91 AND P92 SUPERHEATER TUBING, AND RELATED MATTERS

6.1 Parametric methods

During the initial period when a new superheater alloy is being introduced, the stresses for a the design life of 100,000 or 225,000 hours, need to be extrapolated from tests which are of much shorter duration. Accordingly, some tests are accelerated by running them at higher temperatures, with the results being extrapolated back to longer times at lower temperatures, using a Larson-Miller or some other extrapolation technique. The alternative is to extrapolate plots of log stress against log time. The main difficulty with log stress/log time extrapolations is that at long times, the curves bend downwards in a manner that is difficult to predict. In addition, data are only collected at specific temperatures, typically every 50°C; the consequence is that the stresses at other temperatures need to be interpolated, which again causes uncertainties.

As can be seen from Table 4 which shows estimated creep stresses, the approaches being used by National and International testing authorities give rather different values. As creep life is inversely proportional to the third or fourth power of the stress level at longer times, even a
Potential problems in the identification of the root cause: F. Starr, J. Castle and R. Walker

Figure 10 Effect of exposure to temperature on pearlitic structure (left) of T11 steel leading to spheroidised structure (right) x300 [4].

Figure 11 Appearance of P91 (left) and P92 (right) creep test specimens at end of creep rupture testing. Note absence of cavities and maintenance of martensitic structure [25,26].

10% overestimate in the design stress could lead to superheater failing in less than three quarters of the expected time. These problems are quite distinct from any particular shortcomings of a given alloy batch, and seem to have been first highlighted by Franklin and Henry in 1994 [28].

In addition although specific data are not available it is almost certain that the presence of high levels of aluminium, particularly when nitrogen levels are low, will have an adverse effect on creep strength as shown in Figure 12. Here the aluminium is removing nitrogen from solution in the alloy, preventing the formation of vanadium carbo-nitrides which pin dislocations and sub grain boundaries [29].

Brett [30] has suggested that the reaction of aluminium and nitrogen will occur during tempering treatment, which these alloys receive after air hardening, particularly if the materials are overtempered. In such cases the hardness is likely to be lower than expected.

Simple rules, which could be utilised by an expert system, covering these possible root causes of premature failure might be:

- If aluminium content is above 0.02% and the Al/N ratio is more than 2 Then the creep strength is almost certainly reduced by 15%
- If Al/N ratio is more than 2 Then check as_received_hardness and tempering_treatments

Similar rules have been devised covering the likely effect of chromium, molybdenum, vanadium and nickel on creep strength.

Extrapolation of creep rupture data is always needed in assessing the degree of overheating that has

![Graph showing calculated effect of aluminium and nitrogen on creep strength of a 9 Cr steel [29].](image-url)
occurred, since the stress levels used in plant equipment design can only be validated with creep tests lasting for many decades. The most common extrapolation technique is that of Larson-Miller, where there is specific "parameter" for each stress level, given by the equation:

\[ P = T(C + \log t) \]

where \( P \) = parameter, \( T = \) temperature in Kelvin, \( C = \) constant which modifies the impact of the time of exposure, and \( t = \) time in hours to failure.

The \( C \) term does not change with stress, but a reasonably accurate value is needed to assess the amount of overheating.

There is some debate about the relevant \( C \) value for P91. The preliminary extrapolations appear to have originated from the use of a value of \( C \) of around 35 [31]. More recently, Kimura et al. [32] indicate up to 20000 hours that a parameter value of 38 is appropriate, but at longer times they suggest that a value of 20 gives a better fit. Cerjak et al. [33] also have stated that the Larson Miller constant for long term tests is far too high. For a P91 alloy, these authors derive a best fit value of 31 for short term tests, but for longer term tests at lower stresses, they suggest that 22 is more appropriate. For the complete range of high and lower stresses they quote a "polynomial derived value" of 23.9 [33]. Similar observations about the stress dependence have been made elsewhere [34,35].

To take a practical example, if we assume that the design metal temperature is 600°C, values from a brochure, dating from 1989 [36], (which might well have been used by designers for much of the nineties) indicates that the design stress for 100,000 hours exposure is 65.5 MPa. The actual time to failure at this stress level and temperature cannot be reliably predicted, but would be the order of 40 years of continuous operation. But what would be the estimated temperature of the superheater if the failure had occurred in 50, 75 or 100 thousand hours?

Fortunately, using the design stress of 65.5MPa we can in principle use a Larson–Miller based calculation, in conjunction with Figure 13, as this shows that at a temperature of 650°C the failure time is 10000 hours [37].

Table 6 shows the temperatures that would correspond to failure times of 50, 75 and 100 thousand hours using \( C \) values of 23 and 35 respectively. The temperatures for failure times of 225,000 hours and 500,000 hours are also given.

Compared with design metal temperature of 600°C, these estimates, which suggest that the metal (for failure at 50000 hours) had been running at between 21° to 29°C above design, seem reasonable. To give this type of increase one would anticipate that outlet steam temperature would be higher than design, this resulting from excessive flue gas temperatures, or low steam flows. Other potential causes of high metal temperatures would be the formation of a thick oxide scale, especially if the heat transfer rate was high. An expert system would need to marshal these various observations to determine whether or not they supported the estimates made using the parametric methods.

If there was no or little evidence for furnace or plant equipment problems, there is the possibility that the creep strength of an alloy had been overestimated, leading to an incorrect judgement of tube temperature. As noted, this is always a possibility with a newly introduced material, such as P91. Hence in such cases the declared creep properties need examination. Even where there are clear indications that a superheater tube is running above the design temperature, it is worth, after taking the likely metal temperature into consideration, considering whether the material is failing at below the times predicted.

A suggested way of dealing with this is to add 35°C onto the outlet steam temperature and carry the following set of rules.

If creep_failure_calc_time_(LM31) is premature Then run Larson-Miller_Parameter_test (LM23) and record creep_failure_calc_time_(LM23)

If creep_failure_calc_time_(LM23) is +/-10% of actual_time_to_failure Then creep_strength_overestimation is almost certain premature_failure root_cause and consult_manufacturer

If creep_failure_calc_time_(LM23) is less 90% of actual_time_to_failure Then check effect of alloy_composition and heat_treatment

6.2 Oxide thickness

Measurement of the steam-side oxide thickness, often using non-destructive ultrasonic techniques on the tubing itself, is used to assess the average operating temperature of the superheater tubes of the low alloy steels of the T22 type [4,38]. The problems in applying this to the 9Cr martensitic types are illustrated in Figure 14 showing oxidation rates in steam at 650°C. Between about 9 and 11% chromium the resistance to oxidation increases quite dramatically. These figures were replotted from a presentation by Scarlin [39] which suggests that over the allowable range of chromium contents for P91 (i.e. 8.0–9.5%) the oxidation rate drops by about 40%, with most of the
Potential problems in the identification of the root cause: F. Starr, J. Castle and R. Walker

Figure 14 Effect of chromium contents on oxidation rates of P92 and developmental alloys containing cobalt in steam at 650°C after 2650 hour exposure.

Figure 15 showing the one-hour exposure. Developmental alloys containing cobalt in steam at 650°C after 2650 hour exposure. Figure 15 showing the one-hour exposure. Developmental alloys containing cobalt in steam at 650°C after 2650 hour exposure.

Because of the marked effect of chromium it would be difficult to use oxide thickness as a reliable technique for temperature estimation. It is also known that variations in the levels of silicon, and possibly manganese and nitrogen, may impact on oxidation resistance. In this respect it is worth noting that oxidation resistance has become of pressing concern with the P92 alloy, as chromium levels in this material have been held to around 9%, and silicon and manganese levels have also been restricted. Hence caution is needed in using oxidation data because of the scatter from the effects of second-order elements. At best, oxide thickness can be used as a semi-quantitative method of estimating temperature. However, assuming that all the tubes in a given section of a superheater were from the same batch, the technique could be used to determine whether there were tube-to-tube differences, this pointing to variations in steam or flue gas flow, or local tube blockages.

At this stage only tentative “If-Then” rules can be written to take into account the effect of composition on the oxidation rate. Within the specified compositions for P91 there is no definite point at which the levels of chromium and silicon will give good protection. For this, chromium levels would need to be in excess of 10.5%. It can be stated with confidence that if the chromium content is below 9% the steam side oxidation rate will be high and overheating and tube blockages are to be expected.

An appropriate “If-Then” rule would be:

If chromium is less than 9% Then oxide build up possible root_cause of premature_crep_fail

The corollary to such a rule follows from the fact that below a chromium content of below 9% chromium, the oxidation rate is unaffected by composition and would be:

If the chromium is less than 9% Then if heat_transfer_coefficient is known it will be possible to estimate average_metal_temperature

This rule would also apply to unheated sections of the superheater tube close to the headers, and in consequence oxide thickness could be used (providing the chromium content were below 9%) to estimate outlet steam temperatures, in the absence of any direct measurements.

Figure 16, which used results taken from a paper by Tamura et al. [41] on the oxidation of various grades of NF616 (i.e. P92 type alloy) at 650°C in steam, suggests that there is also no definite point at which the level of silicon becomes protective. Schlitz et al. [42] consider that silicon, rather than forming a protective sublayer slows down the loss of chromium and may help in repassivation once oxide cracking and spalling occurs. Here again only a rather negative rule can be formulated. This could be of the form that:

If silicon_content is below 0.15% Then high_rates of oxidation in steam are possible

Where there is argument about the extent that oxidation may have contributed to a premature creep failure it would be necessary to subject the material to an accelerated oxidation test in steam. Following discussion with Dr J. Quadakkers at FA Jülich, it is tentatively suggested that this should be done in a steam-argon mixture at 650°C for 150 hours using polished specimens.

6.3 Hardness testing

Hardness testing can also, in principle, be used to detect overheating, although there are practical problems in the application of this even with well understood materials. Fleming [43] has commented that there is much scatter with in-situ hardness testing. Furthermore a serious problem is that the pre-service hardness figures are not always available and can be distorted by stress relief of weldments, etc. The outcome is more certain when evaluating the life of steam turbine rotors, where due to the fall in steam temperature, there is a drop in hardness along the rotor from the inlet section to the outlet. This obviates tempering induced effects.

With the older alloys, precipitate coarsening and the consequential easier movement of dislocations causes the
controlled, and are stress-as well as temperature-drop in hardness. Such sub-optical changes are diffusion-dependent. Bhadeshia phenomenon as the results on a 12Cr martensitic show occurs, reducing hardness, but in addition recrystallisation problems this causes for life assessment for the lower alloy steels. With P91 and P92 alloys, precipitate coarsening also occurs, reducing hardness, but in addition recrystallisation of the martensitic structure reduces the barriers to dislocation movement. Stress as well as temperature, in a similar manner to the low alloy steels, also appears to accelerate these changes in P91. Hence hardness changes are more enhanced in the gauge length of the specimens, where the stress is therefore higher than in the specimen heads. Orlová et al. [45] found that in P91 the hardness in the specimen heads dropped fairly quickly to 230 VHN from the original value of 237 VHN, after which there was little further fall. This may be a general phenomenon as the results on a 12Cr martensitic show the same head/gauge effects [46]. The Orlová results showed that in a creep test at 600°C, which lasted some 16,000 hours at a stress of 110 MPa, the hardness in the gauge length fell to about 190 VHN. This gives a drop of about 20%, which roughly corresponds to a fall of 25% reported by Bianchi et al. in similar tests [47].

The experiments of Ishii et al. [48] on a martensitic forging with a chromium content of 10% have taken the hardness aspect much further. They found that as the failure time increases from about 3000 to about 28,000 hours, the fall-off in hardness was not so marked. These results led to an equation that relates the hardness ratio (the ratio between the hardness as a result of creep divided by the hardness after tempering) to the creep life, as shown in Figure 17. For this purpose, complex functions which include the initial hardness, plus the stress and temperature dependence need to be taken into account. Similarly, the same type of parametric equations could be developed for P91 and P92.

Unfortunately the creep tests used by all of these authors, even those of Ishii et al., [48] are of the accelerated type, compared to typical plant exposures. It is therefore not clear how much the hardness will fall in a very long term test. The question is whether, at stress values used for design purposes, these alloys will behave like the material in the head or in the gauge length of a laboratory specimen.

7. DISCUSSION

7.1 Diagnosis of root causes of superheater failures

There are clearly a number of potential problems in the identification of the root cause of creep failures in superheater tubes. The basic aim of such an investigation would be to decide whether the problems originated from the design or operation of the plant or whether it was caused by the composition of the tube material. Some of the difficulties stem from the uncertainty in estimating the metal temperature, since an excessive temperature might point towards a design problem. Unfortunately none of the usual methods based on parametric calculations, oxide thickness, hardness or cavitation provides a reliable figure with P91. A recent paper by Seliger and Gampe [49] broadly supports this conclusion [49].

In these circumstances it will be necessary to use temperature estimates based on heat transfer in the furnace and superheaters. Such calculations would be essential, of course, where there has been a change in the fuel or in the operation of the plant, particularly if flue gas or steam temperatures have increased. However superheaters may have been running hot since commissioning, due to unwarranted design assumptions or departure from recommended operating procedures. The calculations would need to be based on the heat inputs into the various heat exchangers in the flue gas train, that is the primary, secondary and tertiary superheaters, reheater units and economisers. This would be reasonably easy to perform, using the water and steam throughputs, temperatures and pressures.

Where the heat transfer rates and superheater tube temperatures appear excessive, this might point to unduly high flue gas temperatures or flow rates. Again plant-based calculations, and where feasible, measurements, would be needed. High flue gas temperature would indicate a possible root cause, examples of such being furnace slagging, high levels of excess air, too much flue gas recirculation, over-firing etc. Flue gas temperatures would need to be calculated from the amount of fuel being burnt, the level of combustion air and the heat abstracted in the furnace to evaporate water. Rates of flue gas flow would be calculated from the flue gas composition and knowledge of the fuel input and composition.

Given these data it would then be possible to make a considered estimate of peak tube temperatures and heat transfer rates, taking into account the position of the failed tube in the superheater bank. The main shortcoming would be that these estimates would give average values. Ideally they would need to be combined with direct measurements of the outlet temperature of the steam in the failed tube, or failing this, estimates based on the thickness of steam-side oxide. As was indicated in Section 6.2 this only seems possible if the chromium content of the alloy is below 9%, when the oxide thickness would give a reasonably reliable value. The best that can be claimed for changes in hardness is that they will give an estimate of the tube-to-tube temperatures.

If the tube has failed by creep, but the heat transfer investigations and other indications suggest that there has been little or no overheating, the implication would be that the creep strength of the material is insufficiently high. This might be caused by the heat treatment, which may be reflected in the original hardness value. Compositional effects may also impact on the 'as heat-
Potential problems in the identification of the root cause: F. Starr, J. Castle and R. Walker

The effects of high levels of aluminium on creep properties, although prescribing the appropriate amounts of vanadium, carbon, and molybdenum is also important. However it does seem possible, that even when the alloys are made exactly to specification, the properties of P91 may have been overestimated, due to the difficulties in the extrapolation of data from accelerated stress rupture tests.

The efforts to develop "If-Then" rules of high reliability, for failure analysis, have highlighted the possibility of "runaway oxidation" in superheater tubes when the steam-side oxidation resistance is relatively high. The hypothesis is that, as the metal and the oxide temperature build up, as a result of the growth of an insulating oxide, the oxide growth rate increases, thereby pushing up temperatures still further. Section 4 discussed this matter in detail with calculations based on the oxidation rate of P91, indicating that even without runaway oxidation, the formation of a steam-side oxide would have a marked effect on superheater temperatures and life. Here it should be noted that the oxidation resistance of P92 is only about half that of P91, because its composition has been optimised towards maximising creep strength. Here chromium and silicon have been held down to suppress the formation of delta ferrite at austenitising temperatures, as the levels of other ferrite-stabilising elements have been increased. In particular, tungsten has been added to give improved solid-solution strengthening although some researchers consider that this element is detrimental to oxidation resistance. In summary, there are potential problems with the 9Cr martensitics, especially when the chromium content is below 9% and the heat transfer rate is high, that is above 50kWm⁻².

Thick oxide scales can also cause overheating if they spall off, the debris collecting as a mass in bends of the headers or superheaters, blocking steam flow and raising the temperatures of partially blocked tubes. This is most likely to happen after a shutdown to room temperature. Hence an expert system should be capable of making use of changes in steam pressures and temperatures after a restart, via appropriate "If-Then" rules, which might point towards possible blockages.

7.2 Implications for the formulation of an expert system for failure analysis

The basic aim of this project is to show how a failure analysis type 'expert system' can be assembled by using information derived from the literature or from personal contacts. To reiterate, this has been done by carefully evaluating all potential materials of construction, failure mechanisms and causes of such failures in a power plant superheater.

This gave a failure analysis problem of sufficient complexity highlighting the parameters that need to be taken into account in devising an expert system of this type. It is clear that the techniques in formulating this expert system can also be applied to other engineering problems. Such problems often require trial-and-error solutions. It is worth noting that metallurgical engineering greatly depends on the application of such heuristic rules. Perhaps the most important, are those used to formulate safety factors in engineering design, based on experience.

It has not been possible here to cover all aspects of an expert system or indeed go beyond dealing with one type of failure (creep), one class of material (the Cr-marten-
sitic alloys) and one section of the superheater (the tubing). A good knowledge of the metallurgy of these materials and of plant operation is needed to determine, with confidence, why a superheater bank has failed prematurely.

One important finding is that, as suggested by Parsaye and Chignell [2], it is possible for people with little or no experience of expert systems to put together the rules which form the inference engine (See Figure 1). It is generally held that the creation of "If-Then" rules should be by a "Knowledge Engineer". A major task for the Knowledge Engineer is to interview the "Domain Expert" i.e. person the who has an in-depth knowledge of the technology under review. The dialogue that develops is then used to create a "Knowledge Base". The knowledge base encapsulates the know-how of the Domain Expert into sets of "If-Then" rules in a form that the Inference Engine can manipulate. Clearly this may be a cumbersome procedure which could break down when the solution to an engineering problem needs expertise from many sources.

The authors have shown is that it is possible to dispense with the knowledge engineer, instead relying on just a few people with appropriate experience, provided that they have some awareness of expert system construction. In this respect, although only a few examples of "If-Then" rules have been described, it has required much background work to postulate and then validate them. In short, it would seem to be easier to train experts in the techniques of formulating expert systems, than to appoint the services of a Knowledge Engineer.

8. CONCLUSIONS

The development an expert system for the failure analysis of superheater systems in power plant has highlighted a number of aspects relating to the use of P91/P92 martensitic steels for superheater tubing. These are:

- Reliable techniques are not available for estimating tube temperatures.
- Indirect methods will need to be used, based on steam and flue gas side heat transfer calculations.
- Oxide formation on the steam side of superheater tubing could lead to a foreshortening of tube life of P91/P92 materials due to the relatively high oxidation rate of these alloys.
- There is the possibility of runaway oxidation at high heat transfer rates.
- Use of high values of the Larson–Miller constant for parametric extrapolations of the creep stress will lead to overestimation of operating temperatures of failed P91 tubing and may have led to an overestimation of the alloy capabilities.

The work has also shown that the formulation of rules, in expert systems, can largely be done by the experts themselves without the intercession of knowledge engineers.

ACKNOWLEDGEMENTS

The authors would like to thank Mr A. Fleming of European Technology Development Ltd and Drs P. Ennis and J.A. Quadakkers of FA Jülich for their assistance and suggestions. However the views expressed in this paper
are those of the authors and not necessarily those of those above, nor of European Technology Development Ltd, nor of the University of Surrey.

REFERENCES


[10] I. Davidson, Fig. 16, Steam Temperature Control by Excess Air, In: "Steam: Its


[12] Franklin, C.J. and Henry, C., Material Developments and Require-


[20] Ennis, P.J., Photomicrographs of P92 Stress Rupture Specimens at 650°C/820MPa/13000h exposure and consequent discussions


[25] I. Davidson, Fig. 16, Steam Temperature Control by Excess Air, In: "Steam: Its


[27] Frankin, C.J. and Henry, C., Material Developments and Require-


[29] Folydina, V., Kubon, Z., Jakobov, A. and Vodla, V., Development of Advanced High Chromium Ferritic Steels, pp. 73–92. Micro-


[35] Ennis, P.J., Photomicrographs of P92 Stress Rupture Specimens at 650°C/820MPa/13000h exposure and consequent discussions


[37] Frankin, C.J. and Henry, C., Material Developments and Require-


[45] Ennis, P.J., Photomicrographs of P92 Stress Rupture Specimens at 650°C/820MPa/13000h exposure and consequent discussions
Potential problems in the identification of the root cause: F. Starr, J. Castle and R. Walker


Root Cause Identification of Superheater Tube Failures in 9 Cr Martensitic Alloys

F. Starr, J. Castle and R. Walker
Formulation of If-Then Rules in an expert system for the identification of the root cause of failures in superheaters have helped highlight a number of potential difficulties in determining the root cause of premature creep failures in P91 superheater tubing.

Creep failures can occur through shortcomings in the materials of construction, general overheating due to furnace and plant induced problems, and also local overheating caused by poor distribution of steam or flue gas flow. With older ferritic-pearlitic alloys it is possible to use spheroidisation, and measurements of oxide thickness, hardness, etc, to help differentiate between these “root causes” of failures. The newer 9Cr alloys have a martensitic structure that does not change significantly at the optical scale whilst undergoing creep, and oxide growth is highly dependant on small changes in composition.

It is shown that steam side oxidation of these alloys could induce premature failures due to the insulating effect of the oxide scales, which cause tube temperatures to rise. Attention is drawn to a potential “runaway effect” in which the tube temperature and rate of oxidation increase with time as the oxide builds up on the tube walls.

1. Introduction

Over the past ten years designers have turned to better materials to improve plant efficiency and make plant more capable of meeting “two shifting” requirements. But these new materials are beginning to cause problems with life prediction and failure analysis, as highlighted at a recent conference on these subjects [1].

In this context there has been the rise of the litigation culture, in which failure of a power plant at a critical time could lead to long and complex court actions to determine what was the root cause of the failure. Was it due to the materials, the design, or mistakes by the operators? A whole panoply of experts from various disciplines could be needed, few of whom would be completely objective or able to comprehend the full picture. There is a need to develop techniques that can assist technical specialists who undertake failure investigations. One such technique is to use an expert system to help with failure investigations. This paper derives from work to formulate an expert system to assist with the investigation of P91 superheater failures. However the main thrust of this paper is to show how this work
has led to a consideration of how steam side oxide formation in P91 (and P92) alloys could lead to premature creep failures.

What is an expert system, and what is it intended to do? The short answer is that it is a system that uses artificial intelligence to replace human experts or to augment their expertise. The aim is to encapsulate human expertise in sets of **If -Then** type rules, to assess whether the facts about something, which has occurred, will lead to a certain conclusion

The work at the University of Surrey has concentrated on the technique of rule formulation and the issues that relate to the marshalling of individual conclusions from each If-then rule. An important aim of the work is to show that a complex expert system can be built up by experienced engineering staff with the minimal involvement of computer specialists such as “knowledge engineers”. This is being done by focusing on a piece of equipment and a material of construction that can suffer failures from a variety of different mechanisms. This procedure is vital in exposing the difficulties in constructing an expert system of some real depth, complexity, and use.

A piece of equipment that has the characteristics of being likely to fail through a variety of mechanisms, because of wide variations in the types of operation and design and materials of construction is the power plant superheater. Currently one of the most important materials used in superheaters are the 9% chromium martensitic steels. The issues involved in investigating failures of such alloys gives some real point to the development of an expert system.

### 2. Background to P91

In P91 chromium levels are held down to the 8-9.5% range to permit the introduction of higher levels of ferrite forming elements to enhance creep strength, at some sacrifice to oxidation resistance. P91 is now quite an established, the first superheater headers having gone into service in the early nineties. Nevertheless due to lack of experience with this material, the estimated creep stresses for this alloy vary quite markedly between the different standard authorities, as Table 1 shows [2].

<table>
<thead>
<tr>
<th>P91 Evaluation Method</th>
<th>500°C</th>
<th>550°C</th>
<th>600°C</th>
<th>650°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASME</td>
<td>164</td>
<td>141</td>
<td>98</td>
<td>---</td>
</tr>
<tr>
<td>VdTÜV</td>
<td>253</td>
<td>162</td>
<td>90</td>
<td>---</td>
</tr>
<tr>
<td>EN</td>
<td>258</td>
<td>166</td>
<td>94</td>
<td>48 (approx)</td>
</tr>
</tbody>
</table>

The majority of creep failures in P91 superheater tubing will have resulted from a moderate degree of overheating, with failures occurring after some tens of thousands hours of operation. When a creep failure has occurred, a simplistic approach is to think that there are likely to be only a few root causes. Something might be amiss with the furnace design or operation, leading to excessive metal temperatures. The
alloy itself is deficient. In this case the creep strength may be somewhat lower than anticipated, or corrosion on the flue gas or the steam side of the tubing, has led to excessive thinning, raising the stress level.

Hence, as well as focusing on the material, a good expert system would activate sets of If-Then rules, based on steam and flue gas temperatures, water and steam flows, and energy inputs and outputs to and from the furnace. This would enable the expert system user to assess whether the root cause was due to plant, or operating derived, problems of the following type.

- Operation of furnace at design limit or higher
- Bad flue gas distribution
- Bad burner set up
- Air in-leakage in the furnace
- Furnace wall slagging
- Fouling of economiser or air heater
- Switch to natural gas from coal or oil firing
- Switch to low NOx burners
- Excessive air to fuel ratio
- Need to by-pass feedwater heater
- Continuing low steam flow
- Weather factors

3. Estimating Temperature of Failed Tubing

Many creep failures in superheater tubing result from some deficiency in the operation of the furnace or from a starvation in the steam flow. In determining the actual cause it is helpful to establish the temperature gradient along the failed tube and the temperature in neighbouring tubes. This would suggest whether just the one, failed tube, was suffering from a blockage, or whether there was a general problem of overheated tubes. Estimating temperature is reasonably straightforward with the lower alloy steels, the main techniques being:

- Use of the exposure time of the failed tube using a Larson-Miller or other Life/Stress/Temperature extrapolation technique
- Steam side oxide thickness
- Spheroidisation of pearlitic and bainitic carbides using optical microscopy
- Levels of grain boundary cavitation
- Coarsening of sub-optical carbides and interparticle distances using SEM observations
- Drop in hardness caused by carbide coarsening

The first approach to estimating tube temperatures would be based on the failure time using a Larson-Millar parametric method. But the spread in estimated creep
properties, shown in Table 1, indicates that there may be problems with this method. In this respect a paper in *Materials at High Temperature (MAHT)* by the present authors highlights the considerable range in the values for the Larson-Miller constant ranging from 38 to 20, which greatly influences temperature estimates [3].

In the *MAHT* paper the authors have also shown that the classical microstructural methods for estimating temperature or remaining creep life are problematic [3]. Spheroidisation does not occur in martensitic alloys of the P91 type, and with other methods there is a considerable spread in the data, for example hardness changes. In addition these microstructural changes are strongly influenced by the level of stresses as well as the operating temperature.

4. Problems in Using Oxide Thickness to Determine Tube Temperatures

A common technique of estimating temperatures is to use steam side oxide thickness. The attraction of this is that it can be done in-situ using ultrasonic techniques. The problems in applying this to the 9Cr martensitic types are illustrated in Figure 1. This shows the one-year metal loss rate using data from a paper by Ennis and Quadakkers. Note the dramatic increase in oxidation resistance as the chromium level changes from 9 to 10.5% [4].

![Figure 1](image)

**Figure 1** Effect of chromium content on oxidation rates at 600° and 650° in steam

Because of the marked effect of chromium it would be difficult to use oxide thickness as a reliable technique for temperature estimation. It is also known that variations in the levels of silicon, and possibly manganese and nitrogen, will also influence oxidation resistance. Hence caution is needed in using oxidation data because of the scatter from the effects of second order elements.

At this stage only tentative If-Then rules can be written to take into account the effect of composition on the oxidation rate. Within the specified compositions for P91 there is no definite point at which the levels of chromium and silicon will give good protection. For this chromium levels would need to be in excess of 10.5%. What can be stated quite definitely is that if the chromium content is below 9% the
steam side oxidation rate will be high and overheating and tube blockages are to be expected.

The corollary is that below a chromium content of below 9% chromium the oxidation rate is unaffected by composition and can be used to estimate tube or header temperatures. The appropriate If–Then rule would be:

If the chromium is less than 9% Then if heat transfer coefficient is known it will be possible to estimate average metal temperature

Figure 2, which used results taken from a paper by Tamura et al on the oxidation of various grades of NF616 (i.e. P92 type alloy) at 650°C in steam, suggests that there is also no definite point at which the level of silicon becomes protective [5]. Schütze et al consider that silicon, rather than forming a protective sublayer slows down the loss of chromium and may help in repassivation once oxide cracking and spalling occurs [6]. The If-The rule in this case could be:

If silicon content is below 0.15% Then high rates of oxidation in steam are possible

Where there is argument about how much oxidation may have contributed to a premature creep failure it would be necessary to subject the material to an accelerated oxidation test in steam.

![Figure 2: Effect of Si content on oxidation of NF616 alloys at 650°C for 1000 hours in steam](image)

4. Effects of Oxide Scale Build Up on Tube Temperatures

Identification of root causes is made more difficult if the tubing forms a relatively thick oxide layer on the steam side of the tubing, as is the case with both P91 and
P92. As the oxide on the inside of the tube builds up, it acts as an insulating barrier to the heat being transmitted through the tube walls, thereby raising the tube temperature. The magnitude of the temperature rise is proportional to the heat transfer rate in superheaters, the oxide thickness, porosity and adherence and inversely proportional to the conductivity of the oxide. Data for heat transfer rates is difficult to obtain but French indicates a range varying from 19-63 kW.m$^{-2}$ and Husemann quotes 50-75 kW.m$^{-2}$ [7,8]. It should be noted that this is the steam side heat transfer rate, which is significantly higher than that on the flue gas side, the increase resulting from the difference between the inside and outside diameters of the superheater tubing.

Figure 3, based on largely on the paper by Husemann, shows that, in the absence of heat transfer, or the formation of a thick oxide, a superheater tube, running at a constant metal temperature of 600°C, would use up about 1.6% of its life over a year. However at a heat transfer rate of 50 kW per sq metre, the build up of the oxide scale gradually raises the tube temperature by about 17°C over a year. This progressive increase in temperature reduces tube life by about 4%.

![Figure 3: Effect of oxide build up on tube temperatures and life at 50 kW.m$^{-2}$](image)

These particular calculations assumed that the oxide growth was determined by the original metal temperature, that is 600°C. The hypothesis is that oxide growth rate is determined by the rate of reaction between molecules of steam and metal ions, which arrive at the outer surface of the oxide. But it would seem that it is just as likely that it is the rate of diffusion of ionic or molecular species through the oxide scale which is the rate determining step. As the oxide thickens up, the average temperature of the oxide will increase, with the rates of diffusion also increasing. It will lead to the “runaway effect” at high rates of heat transfer, whereby the formation of oxide will lead high metal temperatures and hence high higher rates of oxidation and so forth.
Fig 4: Development of runaway oxidation whereby either poor furnace design or excessive oxidation rates can result in high creep rates.

The oxide thickness calculation was done in 1000 hour steps, with the temperature increase induced in the tube at the end of each step being used to calculate the increased oxidation rate in the ensuing step. The effect of these step changes in temperature on tube life usage was calculated using a Larson Miller parameter approach for the effect of each 1000 hour exposure at the different temperatures. Note that the absolute life is much higher than the design life as normally understood. Actual values used in the current version of the spreadsheet are:

- Larson Miller Constant: 31
- Absolute Life: 500000 hours at 600°C

Figure 5: Tube temperatures and life fractions with and without acceleration of oxide growth at 75kW.m⁻²
In Figure 5, the dashed curves show the magnitude of the runaway effect at a heat transfer rate of 75 kW.m$^{-2}$, indicating that runaway increases the tube temperature by about 9°C after 8000 hours, over the build up due to the oxidation rate being fixed at the 600°C level. Tube life suffers, runaway raising the life usage from 6.32% to 8.95%, as shown by the solid curves. Note that the runaway affect on temperature does not become really apparent until several thousands of hours have elapsed.

An appropriate If-Then rule would be:

**If** chromium is less than 9% **Then** oxide build up possible root cause of premature creep failure

However the runaway effect becomes far more marked if the oxidation resistance decreases, especially when combined with high rates of heat transfer. Table 2 summarises these effects at heat transfer rates of 50, 62.5 and 75kW.m$^{-2}$ and with oxidation rates higher and lower than those quoted above. For comparison figures for the “no acceleration-no runaway effect” are also included in brackets at the 100% level.

<table>
<thead>
<tr>
<th>Oxidation Rate Compared to Standard at 600°C</th>
<th>Life Fraction Usage at Heat Transfer Rate of 50kW.m$^{-2}$</th>
<th>Life Fraction Usage at Heat Transfer Rate of 62.5kW.m$^{-2}$</th>
<th>Life Fraction Usage at Heat Transfer Rate of 75kW.m$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>75%</td>
<td>3.25%</td>
<td>4.00%</td>
<td>5.05%</td>
</tr>
<tr>
<td>100%</td>
<td>4.31% (4.03)</td>
<td>5.99% (5.15)</td>
<td>8.94% (6.32)</td>
</tr>
<tr>
<td>125%</td>
<td>5.99%</td>
<td>10.55%</td>
<td>21.64%</td>
</tr>
</tbody>
</table>

7. Discussion

There are clearly a number of potential problems in the identification of the root cause of creep failures in superheater tubes. The basic aim of such an investigation would be to decide whether the problems originated from the design or operation of the plant or whether it was caused by deficiencies in the tube material. Some of the difficulties stem from the uncertainty in estimating the metal temperature, since an excessive temperature might point towards a design problem. Unfortunately none of the usual methods based on parametric calculations, oxide thickness, hardness or cavitation provides a reliable figure with P91. A recent paper by P. Seliger and Gampe broadly supports this conclusion [9].

In these circumstances it will be necessary to use temperature estimates based on heat transfer in the furnace and superheaters. And where heat transfer rates and superheater tube temperatures appeared to be excessive, this might point to unduly high flue gas temperatures or flow rates. Again plant based calculations, and where feasible, measurements, would be needed. High flue gas temperature would indicate...
a possible root cause, examples of such being furnace slagging, high levels of excess air, too much flue gas recirculation, over-firing etc. Flue gas temperatures would need to be calculated from the amount of fuel being burnt, the level of combustion air and the heat abstracted in the furnace to evaporate water. Rates of flue gas flow would be calculated from the flue gas composition and knowledge of the fuel input and composition.

Given this data it would then be possible to make a considered estimate of peak tube temperatures and heat transfer rates, taking into account the position of the failed tube in the superheater bank. The main shortcoming would be that these estimates would give average values. Ideally they would need to be combined with direct measurements of the outlet temperature of the steam in the failed tube, or failing this estimates based on the thickness of steam side oxide. This only seems possible if the chromium content of the alloy is below 9%, when the oxide thickness should give a reasonably reliable value. The best that can be said for changes in hardness is that they will give an idea of the tube-to-tube temperatures.

The efforts to develop If-Then rules of high reliability, for failure analysis, have highlighted the possibility of “runaway oxidation” in superheater tubes when the steam side oxidation resistance is relatively high. The hypothesis is that, as the metal and the oxide temperature builds up, as a result of the growth of an insulating oxide, the oxide growth rate increases, thereby pushing up temperatures still further. But even without runaway oxidation, the formation of a steam side oxide would have a marked effect on superheater temperatures and life. Here it should be noted that the oxidation resistance of P92 is only about half that of P91, because its composition has been geared towards maximising creep strength. In summary, there are potential problem with the 9Cr martensitics, especially when the chromium content is below 9% and the heat transfer rate is high, that is above 50kW.m⁻²

Thick oxide scales can also cause overheating if they spall off, the debris collecting as a mass in the bends or the headers of the superheaters, blocking steam flow and raising the temperatures of partially blocked tubes. This is most likely to happen after a shutdown to room temperature.

8. Conclusions

The development an expert system for the failure analysis of superheater systems in power plant has highlighted a number of issues relating to the use of P91 martensitic steels for superheater tubing. These are:

- Reliable techniques are not available for estimating tube temperatures. Larson-Miller based calculations are suspect.

- Indirect methods will need to be used based on steam and flue gas side heat transfer calculations.

- Oxide formation on the steam side of superheater tubing could lead to a foreshortening of tube life of P91/P92 materials due to the relatively high oxidation rate of these alloys.
• There is the possibility of runaway oxidation at high heat transfer rates.

• The work has also shown that the formulation of rules, in expert systems, can largely be done by the experts themselves without the intercession of knowledge engineers.

Acknowledgements

The authors would like to thank Mr A. Fleming of European Technology Development Ltd and Drs P. Ennis and JA. Quadakkers of FA Jülich for their assistance and suggestions. However the views expressed in this paper are those of the authors and not necessarily those of the aforesaid individuals nor of European Technology Development Ltd, nor of the University of Surrey.

References


2. Table 6.17 p28 in the T91/P91 Hand book c/o Vallorec and Mannesmann 1999


6. Schütze, M. Renusch, D. Schorr, M. “Parameters Determining the Breakaway Oxidation Behaviour of Ferritic-Martensitic 9Cr Steels in H2O Environments” Corrosion Engineering Science and Technology (to be published)

7. French, DN. Sections on Effects of ID Scale in “Metallurgical Failures in Fossil Fired Boilers” Wiley 1982