Submission of Published Works for the Award of the Degree of Doctor of Philosophy

Eur Ing A W E Henham BSc(Eng) CEng FIMechE FInstE MRAeS

Department of Mechanical Engineering
University of Surrey
Guildford
Surrey  GU2 5XH
UK

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Department of Mechanical Engineering, University of Surrey

INTRODUCTORY STATEMENT

The research described in the published work submitted has been carried out entirely during the author's period of employment in the University of Surrey. The work on which the publications are based was conducted either in the University or on site in the course of contracts placed with the University by industry and the public sector. None of this work has been submitted for any other qualification.

The papers are divided into two main groups. The linking theme is the efficient use of energy with which is associated the optimisation of processes in industry and transport, utilization of alternatives to fossil fuels and systems and education for the management of energy in industry and the public sector.

Energy and Engines for Transport and Stationary Power

This section begins with an invited review paper, including a literature survey, concerning the sources, effects and control of atmospheric pollution (1). This is mainly concerned with that pollution resulting from combustion of fossil fuels in power plant for both stationary and transport applications, a topic which has come into much greater prominence in recent times than at the time this was written.

Also dealing with both transport and stationary power installations is an invited paper published by the Institute of Energy examining the analysis of dual purpose energy systems (2). This is particularly concerned with increasing the proportion of the input energy utilized in the production of power and heat transfer. It relates the thermodynamic considerations of the First and Second Laws to specific applications in automotive compound cycles, combined heat and power plant (based on a project supervised by the author in the frozen food industry) and engine-driven heat pumps.
Two papers, one published in Beyond the Energy Crisis and the other in Resources and Conservation look at the total energy requirements for the automobile including both capital and running components (3,4). This work was carried out in collaboration with a part-time MSc course student whose dissertation was supervised by the author. The papers analyse the manufacturing energy requirements for cars of various types and the effect of changes in materials and design on both this and the energy used in propulsion. The author was invited to be a member of the Energy Committee of the Institution of Mechanical Engineers which was set up to produce an Energy Policy Statement for the United Kingdom. He was responsible for researching energy utilization in transport and contributing a section on that subject to the detailed papers supporting the policy statement (5) and for presenting this to a meeting held at the Institution. Material from this, also drawing on the discussion at the seminar, was included in a centrally edited publication which members, including the author, presented to a meeting of Institution members and others and which was then submitted to the Department of Energy (6). The whole of this statement is included as, although the author contributed the material on transport, the document was the result of a corporate activity.

Work on the development of engine combustion systems was begun in the Department of Mechanical Engineering by the author in 1978 with a feasibility study, not published or included here, into possible future configurations of fuel air mixture production and combustion chamber design to minimise exhaust emissions and fuel consumption. The main options in the spark-ignition field were stratified-charge and lean-burn. The former had been extensively studied in the USA and, to some extent, in France and other European countries. Little appeared to be published on the subject of homogeneous, lean-burn operation and it was thought appropriate to look into the factors affecting the operation of engines using this approach. Combustion chamber design, particularly as it affects in-cylinder turbulence, was identified in a paper (published by the Institute of Energy) as a key parameter. Turbulence was established as enabling steady combustion to be established over a wider range of air:fuel ratios than is possible in a quiescent chamber (7). When the work was broadened to include the combustion of oxygenate fuels it was also found that these further extended the range of equivalence ratios possible, lowering considerably the lean limit of reliable combustion, reported in a paper in Energy from Biomass (8). This work was undertaken on two four-stroke, single-cylinder engines with modified cylinder heads in the author's laboratory. One was a single-chamber engine having a flat cylinder head with a specially designed, offset recessed piston to create turbulence and the other
a divided head engine based on a pre-chamber diesel with lowered compression ratio. A University of Surrey report describes this work and gives a comparison of the characteristics of the two types of combustion chamber when compared with a disk-shaped quiescent chamber (9). Computer modelling work, some of which forms part of a PhD degree thesis supervised by the author, provided additional understanding of the processes involved by enabling estimates to be made of the flame speed and of the fuel burning rate. This aspect of the research programme is described in papers in the *International Journal of Vehicle Design* (10) and in *Energy from Biomass* (8).

Following this work and study of the requirements of several countries, consideration was given to the prospects for the wider use of alcohol fuels derived from biomass. These appeared to be especially important for future progress in the developing world where imported petroleum demanded precious foreign currency at the, then, high international oil price. In many of these countries agricultural land was abundant and there was surplus rural labour so that the cultivation of crops for biomass energy was potentially beneficial in social terms. The most widely used type of engine in the rural situation in such countries is the small, single or twin cylinder diesel engine of a few kilowatt rated power. These are employed for pumping, small-scale power generation, milling and grinding crops. Related units are used in driving light vehicles. The diesel has advantages in its higher compression ratio but, more particularly, in its high part-load efficiency. Little work had been published in the field of diesels using alternative fuels produced by distillation of biomass and so this was selected as an appropriate field for further investigation. The possible approaches to this are summarised in an invited paper for the *International Journal of Ambient Energy* (11). After consideration of these methods, an SERC grant was obtained and a modified single-cylinder, four-stroke, direct-injection diesel engine was installed in the laboratory in place of one of the spark-ignition engines mentioned above. The modifications included a new combustion system incorporating combustion initiation aided by a high-frequency, repeated high-energy spark. In view of the low calorific value of alcohol fuels a separate, larger capacity, pump replaced the standard, fixed-timing version. The replacement incorporated an indexing drive system to enable injection timing to be investigated as a variable. The equipment and some early results are described in papers in *Proceedings* published by the Institute of Energy (12), in *Biomass for Energy and Industry* (13), and in *Renewable Energy Sources for the 21st Century* (14). As the work continued it was found that there was a considerable range over which the engine would operate and that the injection and ignition timing could be optimised to give an overall thermal efficiency on ethanol (potentially the most widely available liquid fuel from biomass) comparable with that on gas oil.
Combustion analysis continued alongside the investigation of fuel consumption to try to establish what were the factors inside the combustion chamber which led to optimum operating conditions. This led to conclusions that the engine operated either like a lean-burn spark-ignition engine with early injection or as a stratified-charge engine when injection was nearer top dead centre. These investigations led to the realisation that a much simpler spark-assistance system than that developed for the experimental rig would suffice in practice and that this could be made from widely available automotive parts. Stages in the development of the optimised engine combustion system and the results obtained from it are described in papers in the Proceedings of the VIII International Symposium on Alcohol Fuels, Tokyo (15), the International Journal of Vehicle Design (16) and the Proceedings of the Institution of Mechanical Engineers (17). An extension of this optimisation process, showing that methanol as well as ethanol gives performance equal to gas oil, is published in Proceedings by the Institute of Energy (18). A review of all the work undertaken for the SERC project was requested for a meeting between industry and universities and polytechnics to be published in the Proceedings of the Institution of Mechanical Engineers (19).

Alongside this the author was asked to act as an adviser to the Universiti Teknologi Malaysia (UTM) and, as part of this British Council project, became involved in collaboration in a project on the combustion of palm oil in diesel engines. The arrangements included visits by the author to UTM and to the Palm Oil Research Institute Malaysia with which it was involved. Co-supervision was provided for a junior member of staff at UTM who was able to spend a short time at Surrey to help him establish his programme and to learn laboratory and modelling techniques. As a result of this collaboration two joint papers were published, one in Proceedings by the Institute of Energy (20) and the other in Biomass for Energy and Industry (21).

A paper describing the various projects in alternative fuels for diesel engines has been published in Proceedings of the Institution of Mechanical Engineers (22). In conjunction with this work on a wide range of fuels, the author was invited to contribute a paper to a United Nations Seminar on small scale power generation. This concerned choice of fuels for this purpose especially for the developing countries (23) and the author was also invited to act as technical editor for the seminar proceedings.

In addition to the papers listed the author has given seminars on the topics of Alternative Fuels for Engines and of Transport Energy in England (University of Sussex), Italy (Politecnico di Torino and Istituto Motori, Napoli), Thailand (Asian
Institute of Technology) and Malaysia (Universiti Teknologi Malaysia) and on Pollution Control in Spark-ignition Engines (at UMIST). In addition to the research degree supervision mentioned above, the author has supervised a PhD concerning the vehicle energy implications of road junction design and co-supervised an MPhil on the analysis of a novel engine design. He has also acted as a consultant for industrial clients and a report illustrating this kind of activity is included in the Appendix (24). Some other projects (eg for BOC, Grand Metropolitan Innovation Centre and Johnson Matthey) were of a confidential nature and are not included. He was an External Examiner at Brunel University for an MPhil degree concerned with alternative fuels for engines.
Energy Engineering, Management and Education

As a Lecturer in Thermodynamics the author had been involved in the analysis of energy-efficient processes and cycles in the regular undergraduate teaching programme. He became responsible for the setting up and direction of a Master's degree course in Energy Engineering, sub-titled the Utilization, Optimization and Management of Energy. The first intake of this course was in 1978 and its, mostly mature, students have been drawn from many industries and the public sector and there have been students from 25 countries in Europe, Africa, Asia and Central and South America. In the course of this 45 individual study projects on a wide range of energy engineering, planning and management topics have been supervised by the author. This course has resulted in a wide range of contacts with industry and the public sector in the UK and overseas. Short courses in specific areas of energy engineering and management have been run for industry, government and a professional institution, in the UK and in Portugal. In addition to the papers listed in this presentation of work, many seminars in this field have been given in England, Scotland, Malaysia, Singapore and Thailand. In the same subject area the author has acted as External Examiner for the BEng and BEng Honours Degree in Energy Engineering at Napier Polytechnic of Edinburgh and for a PhD thesis in the University of Wales and has been a member of validation committees for CNAA BEng degrees at Napier and Kingston Polytechnics.

A series of papers have been given on the philosophy and practice of the provision of educational and advisory services in energy engineering and management. The first of these was published in *Energy Use Futures* (25) following presentation of a paper at the 2nd International Conference on Energy Use Management in Los Angeles. The author has been involved with the Energy Management movement in the UK at national level, in particular as a Member of the National Energy Management Advisory Committee and Chairman of its Education Sub-Committee and at local level as Founder-Chairman of the Guildford Energy Management Group (and of its successor, the Thameswey Group). In this connection he was asked by the Department of Energy to give a paper to the National Energy Management Conference (26). The European Society for Engineering Education (SEFI) arranged the 2nd World Congress in Continuing Engineering Education and a paper considering the continuing education opportunities and the University of Surrey experience in this was presented at this and published in the *Proceedings* (27). In the following year the Curriculum Development Group of SEFI arranged an International Seminar on Energy Studies and the author was invited to contribute a more detailed paper to this, subsequently
published in a *SEFI Proceedings* volume (28). The specific aspects of university-
industry co-operation, vital to the concept of the Surrey MSc in Energy Engineering,
were covered in another SEFI Conference and its *Proceedings* (29). Experience with
the design, management and delivery of short courses for industry and the public
sector has been described in a paper for the Institute of Energy Conference in Industrial
Energy Management (30). The author has served as an invited member on the
Education Sub-Committee of the Watt Committee on Energy and on the Energy
Committee of the Institution of Mechanical Engineers.

The author's involvement with energy engineering and management in industry has not
been restricted to the educational aspects. Consultancy and contract research work has
been undertaken for a number of companies. In addition many postgraduate student
projects and case studies have given the opportunity to become involved in a wide
variety of energy applications in commercial and industrial buildings, processes,
hospitals, public buildings and defence establishments. Some of these engineering
applications of energy efficiency analysis have been described in papers at conferences
and in subsequently published proceedings. The European Conference in the
Economics and Management of Energy in Industry (held in Portugal) the author
presented a paper, subsequently published in *Energy Economics and Management in
Industry* (31), and chaired a session on Energy-Intensive Industry. A paper for a
Conference in Bilbao described the co-operative aspects of the links between the
University and industry in a range of projects also published in the Conference Volume
(32).

A contract to examine the feasibility of utilizing steam generated from hospital waste on
a year-round basis was undertaken by the author for a district health authority with
additional support by the Department of Health. This involved investigation of
historic data and of current operation, a continuous trial and energy and economic
analysis of possible plant configurations. The work was reported, with the
permission of the sponsor, to the Institute of Energy's Applied Energy Research
Conference in Wales and published in *Applied Energy Research* (33) and, in detail, in
the full report to the sponsor in the Appendix (40).

The author was awarded a contract to investigate various aspects of energy use in the
printing and publishing industry. Some of the projects described as case studies in the
publications mentioned above derived from this work which was done in conjunction
with Anco Engineers Inc of Los Angeles. Energy surveys were made of a number of
printing and book production plants and a paper mill and detailed studies of steam
production and distribution made. As a result a number of modifications to existing processes and practices were proposed and some of these were installed by the client. The reports on these projects, which are in the Appendix, were distributed only within the company concerned (34, 35, 36, 37, 38). A similar analysis was done for a company manufacturing secondary cells (mainly lead-acid) in which there were unusual processes requiring special consideration (39).

Energy and the Environment

In the work on energy from hospital waste disposal, efficiency in the printing industry and in the secondary cell production plant there were serious environmental restrictions to be considered alongside, and sometimes conflicting with, energy efficiency. This is a continuing theme through the work presented on both engines and energy engineering. Indeed, now that the successful operation of diesel engines on low-cetane fuels has been established, that work is continuing with more emphasis on the environmental aspects. The current political interest in such matters as the greenhouse effect, atmospheric lead, the ozone layer, safety of nuclear power plant and the disposal of its waste has raised public awareness of the potential damage caused by energy conversion processes. In its wake this has brought about a re-emphasis on the efficient use of all energy forms which is the basis of the work reported in this collection of papers.

AWEH
23 November 1990
Publications, Conference Papers and Reports

A W E Henham

Energy and Engines for Transport and Stationary Power

1. Henham, A W E
Atmospheric Pollution: sources, effects and controls. 

2. Henham, A W E
Dual purpose energy systems - analysis and applications. 

3. Henham, A W E & Jacobson, M A I

4. Henham, A W E & Jacobson, M A I

5. Henham, A W E

6. Henham, A W E


9. Henham, A W E & Johns, R A


20. Henham, A W E, Mukti, M Afifi b Abdul & Aziz, Azhar A

21. Henham, A W E, Mukti, M Afifi b Abdul & Aziz, Azhar A

22. Henham, A W E & Johns, R A

23. Henham, A W E
Contract and Consultancy Report

24. Henham, A W E & Johns, R A
Energy Engineering, Management and Education

25. Henham, A W E

26. Henham, A W E

27. Henham, A W E

28. Henham, A W E

29. Henham, A W E

30. Henham, A W E & Johns, R A

31. Henham, A W E

32. Henham, A W E

33. Henham, A.W.E. & Johns, R.A
Contract and Consultancy Reports

34. Henham, A W E  

35. Henham, A W E  
BPCC Energy Management Programme, Boiler and steam plant project appraisal, *(8 pp.)* 1982.

36. Henham, A W E  

37. Henham, A W E  

38. Henham, A W E  

39. Henham, A W E  

40. Henham, A W E & Johns, R A  
Feasibility study - combined heat and power from waste incineration at East Surrey Hospital, *(60 pp.)* 1989.

AWEH  
23 November 1990
Atmospheric Pollution: sources, effects and controls

A W E Henham

Presented at the Conference on Urban Development, Environment and Pollution, European Conservation year at Guildford 1970
ATMOSPHERIC POLLUTION - Sources, Effects and Control

A W E HENHAM

1.0 ATMOSPHERIC POLLUTION - INTRODUCTION

Before examining the causes, effects and cures of air pollution we must pause for a moment to decide what we shall regard as pollution. The easiest solution to this problem would be to define "clean air" as 78.09% Nitrogen, 20.95% Oxygen, 0.93% Argon, 0.03% Carbon Dioxide with small quantities of Hydrogen, Helium, Neon and other inert gases and a variable quantity of water vapour depending on the local humidity. Whether such standard reference clean air is actually to be found in natural surroundings on the Earth's surface is another question. As an example it is said that in early tests GM laboratories put air through five stages of filtration before supplying it to engines used for emissions research. Perhaps it is easier to identify the unpleasant, the harmful, substances and to say that clean air is air from which these are absent, Carbon Monoxide, Aldehydes, Oxides of Nitrogen, for example. Many such substances, at large in the air we breathe, have not been listed. One authority says that 70% of urban air contaminants have not yet been identified. For the time being, however, this approach will suffice: find the substance causing damage or loss of amenity, trace its life history, discover its source, either eliminate its formation or, at least, prevent its escape into the air.

President Nixon (1), in a recent statement on pollution control said, "...no longer is it enough to conserve what we have; we must restore what we have lost." In the air, though, this may not be desirable! John Evelyn in the mid 17th Century wrote about, "The Inconvenience of the Aer and Smoak of London," saying that the city "resembled the face rather of Mount Aetna, the Court of Vulcan, Stromboli, or the subjects of Hell than an Assembly of Rational Creatures and the Imperial Seat of our Incomparable Monarch." Neither had matters improved 150 years later when Shelley (2) wrote, "Hell is a city much like London - A populous and smoky city." This one pollutant, smoke, has abated in the intervening years and for the first time in 250 years it has been considered worthwhile to clean up the stonework of St Paul's Cathedral. The thick,
yellow, London smogs of only a few years ago are no longer with us. So why all the fuss?

Basically the desire for cleaner air now stems from the need to reduce the harmful, though mostly invisible and in some cases odourless, contaminants. Attention was focussed sharply onto this problem by events in one or two trigger points, predominantly in the Los Angeles Basin. Here is a region bounded by mountains and the sea, forming an extremely localised atmosphere, movement of which is often severely restricted additionally by a temperature inversion layer in the atmosphere. Into this stagnant volume of air are discharged the products of an increasing population, developing industry and a rapidly expanding motor vehicle population which trebled in the 24 years from its 1940 level of 1.2 million. These influences, combined with the effect of strong sunlight on the polluted air, aggravated the situation to the point where some smog was experienced on about two-thirds of the days in each year.

These conditions are not experienced in the same combination in all parts of the world but they have attracted attention to the possible results of rapid growth in population, industrial and automobile density in limited areas of urban communities.
2.0 COMPONENTS AND THEIR SOURCES

The pollution of the air arising from man-made devices is most easily divided into:
(a) products of production of specific substances in chemical and industrial plant and
(b) products of the combustion of fossil fuels.

It is only the second category with which this paper is concerned since other contributors will deal with the former.

Combustion takes place for various purposes:
- Domestic heating,
- Heating large premises,
- Heat supply for industrial processes,
- Destruction of refuse,
- Steam raising for industrial purposes,
- Steam raising for electrical power generating plant,
- Part of the gas turbine cycle for power supply and aircraft propulsion,
- Internal combustion engines for industrial and electrical power,
- Rail and road transport and small mobile plant.

2.1 Fuels and Combustion

In order to investigate the substances produced by these varied devices it is necessary to examine the fuels used and the way in which fuel is introduced, mixed with air, ignited and the products exhausted since all these aspects control the composition of the final products. Fossil fuels essentially contain various compounds of carbon and hydrogen but will include other natural substances, the presence of which may be either unnecessary to the combustion process (e.g., water) or undesirable (e.g., sulphur). Deliberate additives may be included for the benefit of the plant which is running on the fuel (e.g., Tetraethyl Lead, Pb(C₂H₅)₄ in gasoline).

2.11 Continuous Combustion

The chemical composition of coal varies considerably from one source to another but the analysis of one type in use in the electricity generating industry is (by mass):
C: 62.1 %, H: 3.9 %, O: 5 %, N: 1 %, S: 1.5 %, water: 12.5 %, ash:14 % (3).

This coal, used in a power station boiler, would be pulverised, mixed with air and burned in a large furnace lined with tubes through which steam passes. Since more air than the minimum necessary (stoichiometric) quantity is supplied complete combustion should occur and oxygen will be present in the flue gas as well as carbon dioxide and
water vapour, the two normal and not undesirable products of combustion of any hydrocarbon fuel.

The main products of combustion would be approximately as follows:
CO$_2$: 13.05 %, H$_2$O: 6.7 %, N$_2$: 75.6 %, O$_2$: 4.56 %, SO$_2$: 0.11 %.
Additionally there will be small traces of oxides of nitrogen (700 ppm), CO (17 ppm) and some conversion of SO$_2$ to SO$_3$ giving about 12 ppm. The flue gas will also contain suspended particles, especially of ash.

Fuel oil, used in almost identical plants, will contain a different proportion of carbon to hydrogen, some sulphur and a very small amount of ash. A typical composition may be:
C: 84.9 %, H: 11 %, O: 1 %, S: 2%, water: 0.05 %, ash: 0.05 % (3).

The products of combustion (with the much smaller excess air quantity used) could give an analysis:
CO$_2$: 13.5 %, H$_2$O: 10.6 %, N$_2$: 74.8 %, O$_2$: 1.0 %, SO$_2$: 0.1 % and smaller amounts (as for coal) of NO$_X$: 1000 ppm, CO: 8 ppm, SO$_3$: 12 ppm, unburned hydrocarbons: 32 ppm, particulate matter: very small amount.

It is a feature of continuous combustion under properly controlled conditions that the CO and HC production is very small. The main pollutants produced by such plant are smoke (suspension of unburned carbon, mainly), resulting from cooling of the flame in localised regions, and sulphur dioxide.

In the gas turbine fuel is also burned continuously but under very different conditions. Here the amount of excess air is very high (eg 400 %) and CO and HC form a very small part of the exhaust. Smoke will form in areas of local fuel surplus and remain unreacted because of the addition of cooler air later in the combustion chamber. An aircraft gas turbine (jet) engine may have this exhaust analysis: (take off conditions after idle):
CO$_2$: 2.7 %, H$_2$O: 2.7 %, N$_2$: 78 %, O$_2$: 16.6 %, HC: 5 ppm, CO: 7 ppm, NO$_X$: 110 ppm, particulates: 0.007 kg/kg fuel.

While these figures seem low in the problem substances, it must be remembered that the gas turbine handles vast quantities of air. It has been estimated that the arrival of a Boeing 707 at an airport deposits about 11 kg of carbon monoxide, 5 kg of oxides of nitrogen and 2 kg of hydrocarbons as well as pure carbon particles (about 11 kg).
is thought that for a busy airport this could in one day equal the production of these pollutants from all other sources in the city (4,5,6).

Stationary gas turbines run on heavier oil and produce ash and sulphur dioxide in addition.

2.12 Combustion in the Compression-Ignition Engine
In the compression-ignition or Diesel engine air is compressed in the cylinder to a high temperature and pressure and fuel injected, igniting by contact with the very hot air and metal surfaces. More than the minimum quantity of air required may be taken into the cylinder since the air:fuel ratio need be right only in the flame region. Carbon monoxide concentration should, therefore, be very low. Products of combustion depend on the quality of fuel used - large, stationary power plant burns fuel oil similar to that used by large steam turbine plant, while road transport and light power plant applications use derv or gas oil which is lighter than this and contains less sulphur. Smoke is produced only on high load engine settings when the fuelling rate is high and CO also appears in small quantities in these conditions. At three-quarters full-load the products may typically contain: CO: 0.18 %, HC: 90 ppm, 850 ppm NOx and some particulates (7).

2.13 Combustion in the Spark-Ignition Engine
In the spark-ignition engine, fitted to the typical motor car, air and fuel are mixed in the carburettor, distributed and the fuel further evaporated in the manifold, taken into the cylinders, compressed and then ignited by means of a spark. In practice for most conditions (including idle, acceleration and the beginning of deceleration) more fuel than the stoichiometric proportion is used. Using a simple chemical balance the result of burning a mixture 10 % rich in fuel would appear to be:
CO₂: 11.1 %, CO: 2.5 %, H₂O: 13.9 %, N₂: 72.5 %.

A phenomenon known as chemical equilibrium intervenes, however. At high temperatures some compounds partially dissociate and other compounds may be formed. The proportions of these substances can be calculated using the thermodynamic properties. At a temperature 3000 K and pressure 55 bar the above products would become:
CO₂: 8 %, CO: 5 %, H₂O: 13 %, N₂: 70.1 %, H₂: 1.2 %, H: 0.25 %, OH: 1.4 %, O₂: 0.4 %, O: 0.1 %, NO: 0.65 %.
NO appears as a result of the presence of nitrogen and oxygen at high temperature and pressure. The substances formed under these circumstances might be expected to revert to their original forms when the conditions change. The rate at which reactions take place is also governed by the laws of chemical processes and the return of NO to its elements is a slow rate process when the residence time in the exhaust system is considered. A considerable quantity remains in frozen equilibrium. The resulting exhaust from an automobile engine running 10% fuel rich may be: CO\textsubscript{2}: 10.2 %, CO: 3.4 %, H\textsubscript{2}O: 15.2 %, N\textsubscript{2}: 71.4 %, HC: 450 ppm, NO\textsubscript{X}: 180 ppm. In addition lead compounds will be present because of the use of lead alkyls as combustion control additives.

2.2 Evaporative and Crankcase Emissions

In addition to the exhaust the effects of other sources of pollution must be considered in the case of the spark-ignition engine. Some hydrocarbon/air mixture escapes into the crankcase past the piston during the compression process and has, in the past, been exhausted into the atmosphere. Gasoline is necessarily a volatile fuel and some components inevitably escape from the fuel tank vent and carburettor float chamber.

Approximate proportions of the total hydrocarbon emission are:

- crankcase: 20 %
- tank and carburettor: 15 %
- exhaust: 65 %

Note: In general the stationary type of plant works at reasonably constant conditions, whereas transport applications require satisfactory operation at a wide range of loads, possibly with widely and rapidly varying power and speed demands, and with ambient temperatures, pressures and humidity at any value encountered in the range of activity. Combustion products are, therefore, much less consistent in transport power plants than in stationary ones.
3.0 QUANTITY AND DISTRIBUTION

Estimates of the quantity of various contaminants present in the atmosphere vary wildly. With regard to health, what is important is the amount present at the level at which people live. Considerable work has been done by health authorities and research bodies in the USA and Europe to determine the amount of these substances in the air we breathe and how this varies during the day and the seasons of the year and possible correlation with the activity of various sources. Carbon monoxide levels of 100 ppm have been measured occasionally in London streets (9) while lower peaks are recorded in Paris (10) and in the USA (11). The proportion of pollutants retained in a local area depends on the natural ventilation, consequently wind direction and speed, building height and density all play a part in this.

Myers (12) has estimated the quantities of various pollutants emitted annually in the belt 30 ° to 60 ° N latitude, which is thought to contain about 10^{21} g of air:

<table>
<thead>
<tr>
<th>Substance</th>
<th>Natural events</th>
<th>Man-caused events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g</td>
<td>g</td>
</tr>
<tr>
<td>particulates</td>
<td>1.0 x 10^{14}</td>
<td>1.0 x 10^{14}</td>
</tr>
<tr>
<td>carbon monoxide</td>
<td>0.2 x 10^{14}</td>
<td>2.0 x 10^{14}</td>
</tr>
<tr>
<td>carbon dioxide</td>
<td>2.0 x 10^{17}</td>
<td>2.0 x 10^{16}</td>
</tr>
<tr>
<td>lead</td>
<td>negligible</td>
<td>leaded fuel 2.0 x 10^{11}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>storage battery 4.0 x 10^{11}</td>
</tr>
</tbody>
</table>

Nitrogen oxides are produced by nature at a rate about four times that by man-caused events but it must be remembered that nature tends to produce its airborne emissions over a large part of the land mass, much of which is uninhabited, but man-caused events take place by their very nature in small highly populated areas. Sulphur dioxide is largely man's responsibility but only forms a small part of the total sulphur present.
It has been estimated (13) that in Britain in 1967 output of various substances attributable to vehicle emissions were as follows (compared with estimated annual totals):

<table>
<thead>
<tr>
<th>Substance</th>
<th>gasoline vehicles</th>
<th>diesel vehicles</th>
<th>all sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>$5.7 \times 10^{12}$</td>
<td>$0.086 \times 10^{12}$</td>
<td>$12 \times 10^{12}$</td>
</tr>
<tr>
<td>HC</td>
<td>$0.28 \times 10^{12}$</td>
<td>$0.017 \times 10^{12}$</td>
<td></td>
</tr>
<tr>
<td>NO$_x$</td>
<td>$0.19 \times 10^{12}$</td>
<td>$0.053 \times 10^{12}$</td>
<td></td>
</tr>
<tr>
<td>SO$_2$</td>
<td>$0.02 \times 10^{12}$</td>
<td>$0.034 \times 10^{12}$</td>
<td>$6.3 \times 10^{12}$</td>
</tr>
</tbody>
</table>

Again it must be remembered that only about 1% of the surface considered contains urban settlement and that most man-caused pollution takes place in these small areas where, for example, CO levels can be 25 times those in the country. Not all the emission remains local, however, and wind conditions do share it out to the extent that otherwise 'clear' areas of the South coast of England and parts of Scandinavia experience loss of visibility owing to air flow from industrial areas of continental Europe. Dispersion is necessary to avoid intense local ground level pollution and can be encouraged by such measures as the use of tall chimneys (eg power station chimneys 180 m to 200 m high giving efflux velocities of over 20 m/s) (14).
4.0 THE EFFECTS OF AIR POLLUTION

The effects of air pollution are many and varied. Each contaminant has its own effects some of which may simply add to the effect of other constituents, while others have a synergistic effect, the result of combining the two substances giving a result far exceeding, or even quite different from, that of either by itself. The effects about which we are most sensitive are, of course, the short-term ones- those we can see, smell or otherwise experience at the time of exposure. An exhaustive list would be impossible in this context and only the more widespread and apparently important will be discussed here (15).

4.1 Carbon Dioxide

Not normally regarded as undesirable, since it occurs naturally in large quantity and is inert, CO\(_2\) does absorb longer wave length infra-red radiation from the earth's surface during its cooling down periods. A considerable increase in the proportion of CO\(_2\), as the balance between combustion of fuels and the amount of plant life present changes, may be sufficient to raise the earth's temperature by a few degrees with sequential ecological changes. This "greenhouse effect" is of dubious significance because of other balancing changes. The most catastrophic result of this, if unmoderated, could be a considerable rise in sea level through melting in the polar ice regions.

4.2 Carbon Monoxide

Also colourless and odourless, CO is far from harmless. Taken into the lungs it combines with haemoglobin to form carboxy-haemoglobin which it does in preference to the normal combination with oxygen by a factor of about 200:1 and in addition depletes the proper use of that oxygen which does combine. Progressive effects with increasing concentrations are noted from impairment of visual perception and the performance of fine tasks (a particular hazard in the traffic situation) to headache, nausea and ultimately (in very large concentrations) death.

4.3 Hydrocarbons

The individual effect of the various members of the hydrocarbon family is not proved to be serious. Some substances have been shown to produce carcinogenic reactions in animals (notably 3:4 benzpyrene) but direct correlation between this and lung cancer has not been established. The levels of concentration in air are so small and the records
of exposure of particular subjects are impossible to trace. The importance of hydrocarbons would seem to lie in their synergistic effects to some extent with CO and more importantly in some locations in the formation of photochemical smog.

4.4 Oxides of Nitrogen

Nitrogen dioxide is itself a highly toxic gas, small quantities of which can be extremely harmful to lung tissue, but the effect of nitric oxide does not appear, by itself, to be significant. That oxides of nitrogen have been brought into the list of major contaminants is largely due to the part played in the synthesis of the "Los Angeles photochemical smog". NO2, subject to sunlight, releases atomic oxygen which is free to combine with the molecular oxygen to produce ozone.

The existence of ozone, together with hydrocarbons, produces free radicals which further react with hydrocarbons to form peroxyacylnitrates (PAN) Fig A. These with ozone and aldehydes cause reduction in visibility, eye irritations, odour and damage to organic substances. Until recently the atmosphere of most cities has been so smoke laden that the necessary sunlight for these reactions has not been available but the effect may now become more widespread. Sunshine levels in this country do not seem likely to put our towns on this particular danger list.

4.5 Sulphur Dioxide

SO2 is converted in the atmosphere to sulphuric acid with obvious effect on plant life. SO3 also forms sulphuric acid (by directly combining with moisture).

4.6 Particulates

Various sizes and substances are involved in the particulate pollution in the atmosphere. Some settle, combining their effect with the large amount of natural dustfall, others remain for very long period in suspension. Carbon, tarry substances and mineral compounds have the effect of reducing visibility and of long-term discolouration of our surroundings, both plant life and buildings. Small particulates are not filtered out during their passage through the outer regions of the respiratory system (as are the larger ones) and so they do reach the lungs.

The human body works to an equilibrium between the lead intake and output. Lead taken in from food and water is treated differently from that inhaled. Lead from the
atmosphere (and more significantly from local and voluntary air pollution, i.e. smoking) is absorbed more readily into the blood stream. Industrial regulations limit exposure to 200 μg/ m³ and there is no record of general air levels remotely approaching this.
5.0 CONTROL OF POLLUTION

In order to control pollution, the standards of air quality at which the area in question is aiming must be clearly specified. The next step is to relate this to the acceptable quantity of a particular constituent each source of each type is to be allowed to emit. This already difficult step is made more so by the problems of acquiring accurate statistical data about the range of operating conditions, time spent at each of them, deterioration of control methods with use, future increase in numbers of sources, rate of dispersion into surrounding areas, life history of conversion to other more or less reactive substances and the many other factors involved.

The political issue is, of course, the balance between desired improvements in air quality and the cost to the community and the individual of effecting them. The law of diminishing returns works here and the more severe emission reduction requirements become, the more rapid becomes the rise in the cost of the measures. Associated with this is the decision to control existing contributors or only new installations. Sources with low life expectancy (like the motor car with its infamous built-in obsolescence - and even in future the "throw-away car") may safely be left to eliminate themselves over the planned period of control. High capital investment industrial and power-generating plant may need to be dealt with before this.

5.1 Industrial and Domestic Emission Control

The domestic combustion of sulphur-bearing coal created a large spread of small, inefficient and uncontrolled sources of smoke and SO₂. Local regulations have in many places counteracted this situation by the creation of "smokeless zones". It has been said that the smoke produced by industry also had been halved in the 10 years following the Clean Air Act of 1956. The increasing installation of central heating tends to increase the proportion of properly controlled sources especially since the use of gas and oil as fuels is often associated with this change of system.

Ash and SO₂ are the most important pollutants arising from many large installations and plant to reduce these may be installed as part of new equipment or even added to existing plant though with great difficulty and expense. Such equipment is sometimes able to produce by-products such as sulphuric acid (16) or ammonium sulphate. Since the initial cost is high (e.g. £3 x 10⁶ for a 100 MW station) some possibility of recovering this by the sale of products is an advantage.
Difficulties of combustion systems working at increasing temperatures in larger plant are expected to be reduced by the introduction of new techniques such as the fluidised-bed furnace.

5.2 Aircraft Emission Control

The large volume of fluid passing through a modern jet or turbofan engine presents a serious problem in that the proportion of pollutants must be maintained at a very low limit if the mass produced is to be reasonable. Film of the Concorde taking off from London Airport for the first time revealed a very black exhaust trail indeed, suggesting that the new generation of aircraft may be worse than the old. Fortunately for all of us, the manufacturers are not unaware of this and later Concorde engines will be of considerably different design to bring them within the very stringent limits laid down by the aircraft designers (4 HSU) (17,18). In aircraft engines the visible smoke is the pollution aspect requiring most careful attention. What seems to be its magnitude by a merely visual check is often misleading since the appearance depends on the plume diameter as well as the density and closely sited sets of engines, such as those in the example mentioned, look worse than they are. The higher combustion chamber pressures necessary for economic flight bring about problems of fuel air mixing leading to a reduction in combustion efficiency (as opposed to thermodynamic efficiency) which is only in recent developments being overcome by new designs of annular chamber and fuel sprayer. Increased combustion efficiency brings double benefits in aircraft, where fuel which would be wasted has not only to be paid for but lifted off the ground with energy which could be used to lift a fare-paying passenger.

5.3 AUTOMOTIVE EMISSION CONTROL

The C-I and S-I engines used require such different treatment that they must be considered separately and forms of control legislation throughout the world recognize this fact. There is a considerable quantity of literature published on various specific methods of control. References 19, 20 and 21 contain detailed reports on these.

5.31 The Compression-Ignition Engine

Present plans for control are based mainly on the reduction or effective elimination of smoke. This is only produced during overfuelling to meet high-load conditions or through bad adjustment or lack of maintenance. The formerly common practice of truck drivers' using the starting enrichment control to cope with overloads has been
thwarted by positioning the starting mixture control so that it can only be used for starting. Careful maintenance and checks can reduce the possibility of smoke emission considerably. The problem of high load operation still exists, however, and it would appear that the only solution to this is to insist on an engine of adequate power for the gross vehicle weight in the gradient and speed conditions to be encountered. Only a sufficiently large engine will provide adequate hill-climbing performance without smoke unless the penalty of obstructing the highway with painfully slow transport vehicles is to be tolerated. Happily the small (and relatively cheap application cost) turbo-charger may be used to raise engine power without vehicle size increase.

5.32 The Spark-Ignition Engine

Often indicted as the villain of the air pollution story, the engine fitted to the large majority of private cars was certainly a major contributor to the Los Angeles crisis. There must be, if control is to be effective, consideration of all the sources of emission: exhaust, crankcase and evaporation, although only the first need be considered if carbon monoxide is the only problem.

The simplest of all control devices is the installation of piping and valves to connect the crankcase to the air intake for the recycling of blow-by gases (fig.B). US regulations have asked for this since 1963 and European countries are following this lead.

Fuel tank and float chamber evaporative losses present a more complex problem since air must enter the tank while vapour must be retained. The use of activated charcoal to store vapour, which is released to the engine air intake at suitable points in the operating range, appears to be the most popular method so far (fig C). Another method uses the crankcase as a storage reservoir. In the USA legislation becomes effective this year to control evaporative emissions, but the complexity and cost would not be justified, in view of the limited importance of hydrocarbon emissions, in this country.

Exhaust gas remains as the main component of automobile emission and the most varied in content. Any control procedure applied to a vehicle normally affects only one part of the operating range. In order to establish the significant parts of the range for overall air pollution, it is necessary to investigate the pattern of traffic in the urban situation. A driving cycle, known as the "seven mode cycle", was drawn up as the original basis of evaluation in California. A vehicle can be made to run through this cycle of idle, accelerate, cruise and decelerate conditions on a chassis dynamometer and
a continuous record of its emissions recorded. A weighted average of the concentrations of CO, HC and NOₓ can be compared with legal maxima. This method is cumbersome, requires expert staff, complex analysis, recording and computing equipment. A similar but simpler cycle has been drawn up by ECE (Fig D) as an attempt to represent the European situation and to avoid conflicting demands on manufacturers supplying various markets. Each car supplied has to be built not for minimum emissions in its lifetime but to beat the regulations imposed by the government of the country to which it is exported. Continuous analysis has been giving way gradually to the bag method in which gas from all the modes is collected in an enormous PVC bag and the homogeneous mixture sampled at the end of the test. Early regulations limiting percentages of the pollutants are also being superseded by limits on mass/test or mass/km which discourage the practise of increasing the flow of air merely to dilute the same mass of pollutant or of increasing the engine size (possibly increasing the mass while reducing the %).

How is control effected once the limits have been set? There are probably as many answers to this as there are motor manufacturers, if not more (fig E). The answer is also dependent on whether it is required to control CO, HC, NOₓ and particulates or only one or two of these. There seems to be a tendency to legislate against more of these constituents than air quality requirements demand, but that is a political rather than a technical decision.

To reduce CO and hydrocarbons the basic answer is to encourage the combustion to complete itself by providing the right amount of oxygen at the right time and at the right temperature and at the right place. Most economically this would be achieved inside the engine cylinder where the expanding gases do useful work. The magnitude of the problem becomes more evident when it is realised that the cylinder has to be filled and emptied 25 times a second even at the moderate speeds of the European cycle. Early attempts were made to cure rather than prevent by fitting a catalytic converter to the exhaust pipe. The problems of catalyst poisoning by lead, initial and running costs and frequency of replacement have encouraged the industry to search for more permanent and, if possible, cheaper solutions. The injection of air into the exhaust ports while the combustible elements of the exhaust are still hot enough to react with it is the most commonly use of these. Sometimes this is combined (and in future may be increasingly so) with a specially designed reaction chamber replacing the orthodox manifold (fig F & G). Experiments have shown that this will meet U.S. goals for 1980.
Where some hydrocarbons remain after the processes described it is necessary to look into the combustion chamber design itself for remedy. Here any thin layer of gas is subject to cooling by the cooled metal surfaces of the engine, a phenomenon known as "quenching". (fig H). Opening out the chamber shape, changing the stroke:bore ratio and compression ratio may all be involved which, in turn, leads to retooling engine production lines.

Careful design of the interaction between fuel supply, mixture temperature, spark advance, throttle angle (and rate of change) with changes in engine speed and load can make a substantial reduction in pollutant concentration. Maintenance will need to be of a higher order to keep these designed settings effective throughout the vehicle life. Table Z shows the combinations of measures taken by various manufacturers and one of these, aimed at reducing air density variations is illustrated (fig J).

It has been argued that a simple idle setting check on CO could be provided easily at a large number of stations and that this in itself would make an appreciable contributions to air cleanliness in cities where so much time is spent in this engine mode. In Sweden, where such a test was recently instituted, a large number of cars tested were well outside the generous limits allowed.

Nitrogen oxides constitute a quite different topic since, unhappily, they tend to increase as carbon monoxide decreases. Attempts at improving the situation centre on reduction of the peak cycle temperature by addition of inert gas (especially re-cycled exhaust gas since an adequate supply is available) (23).

Yet another aspect is the removal of particulates, notably lead. Cyclone separators could be a method of doing this, involving more weight, cost and complexity in the exhaust system. Whether air-borne lead is a sufficiently significant pollutant to justify this, or the even more drastic solution of removing lead from the fuel, is highly debatable. Emotion appears to be winning over evidence at present and legislation is under way in some countries. In fact, recent experiments show that engines running on lead-free fuel burn out valves so rapidly that pollution from this cause exceeds prescribed limits within (say) 16 000 km (24).

5.4 Alternative Power Devices

Why bother about the gasoline engine anyway when there are steam engines, Stirling cycle engines and electric cars? Probably the simplest answer is that we have become
so used to the reliability, convenience, performance, economy, rapid starting, light weight and relatively easy maintenance of the device that we are unwilling to exchange it for one that may possess some but certainly not all of its virtues.

One alternative fuel, requiring only moderate design changes to the S.-I. engine, is liquefied petroleum gas, which gives very clean combustion not needing lead additives to control it (25).

Of the alternative thermodynamic cycles, the Rankine vapour power cycle has greater complexity, poor start-up and high weight which are also features of the Stirling cycle. Additionally the vapour power cycle has safety hazards associated with the high pressure of the working fluid, which would probably not be steam because of the high freezing point of water.

Electric cars fall into two categories: those using storage batteries and those using fuel cells. Storage batteries are heavy and of very limited range implying the concept of changing cars at city boundaries and removing the door-to-door concept unless quick-change charged units were available at frequent points - itself a land use problem. The fuel cell theoretically offers a good solution. It is a prime mover, whereas the generation of electrical power for the storage battery creates its own pollution, and it converts fuel and air completely to CO$_2$ and H$_2$O but it suffers from a size and control problem. New technology may develop to meet this criticism but as yet no commercially viable plant is running on the impure fuels accepted by the internal-combustion engine (26).

For certain specialised types of vehicle the hybrid concept appears promising. The vehicle is driven by electric motors but carries a gas turbine or diesel prime mover to charge the batteries. This engine can be smaller than that required for direct power and works at constant speed and under controlled conditions at which pollution is low. It could be switched off altogether in tunnels and busy city centres. An experimental diesel-electric bus reported on recently (27) has a 115 kW output motor but carries only a 48kW diesel engine which is never called upon to work in the black smoke region. Electrical generation is also available (free) from regenerative braking.

For the high capital cost, long life bus always working in urban areas this may be an important development. For the multi-purpose, frequently-replaced, lightweight passenger car a viable alternative has yet to be found. At the present pace of
development in engine pollution control the standards which a competitor would need to achieve are being put further out of reach.

Above all the matter must be kept in perspective, appropriate data on production, dispersion and harmful effects of pollution being collected and related, before extreme measures are imposed. There is no record of carbon monoxide in London's streets having killed anyone whereas the effluent from the motor car's predecessor, the horse, is reported to have caused the death of hundreds each year!
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Combustion Process at High Temperatures

Hydrocarbons

\[ \text{ND} \] \rightarrow \text{O}_2

\[ \text{ND}_2 \] \rightarrow \text{O} (+ \text{NO})

\[ \text{O}_2 \] \rightarrow \text{O}_3

Free Radicals

Peroxyacylnitrates (PAN)

Fig A  Simplified diagram showing stages in formation of peroxyacylnitrates
Fig B A typical crankcase ventilation system

Fig C Simplified diagram of evaporation control system
Fig D Driving cycles for automobile emissions tests
Fig E  Control of S-I Engine Exhaust Emissions
Fig F  Exhaust manifold
reactor chamber

Fig G  Air injection reactor system
Fig H  Automobile engine combustion chamber showing quenching

Fig J  Heated air inlet system - supplies air at approximately constant temperature to carburettor, enabling more consistent air fuel mixture to be formed
Table 2  Typical modifications and additions incorporated in production engines to meet current US Federal and California State emission control requirements

<table>
<thead>
<tr>
<th>Air injection reactor system</th>
<th>Controlled combustion system</th>
<th>Cleaner air system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air pump, diverter valve, check valve</td>
<td>Calibrated carburettor Idle speed</td>
<td>Modified inlet manifold Idle speed</td>
</tr>
<tr>
<td>Calibrated carburettor Idle speed and mixture</td>
<td>Retracting throttle stop</td>
<td>Retracting throttle stop</td>
</tr>
<tr>
<td>-</td>
<td>Heated air supply Throttle closure damper</td>
<td>Heated air supply</td>
</tr>
<tr>
<td>Modified ignition centrifugal advance</td>
<td>Ported ignition vacuum advance</td>
<td>Reduced ignition tolerances</td>
</tr>
<tr>
<td>Transmission control of ignition timing</td>
<td>Transmission control of ignition timing</td>
<td>Solenoid idle retard</td>
</tr>
<tr>
<td>Temperature override</td>
<td>Temperature override</td>
<td>-</td>
</tr>
</tbody>
</table>

Positive crankcase ventilation
Evaporative emission control system
More stringent maintenance schedule
Dual purpose energy systems - analysis and applications

A W E Henham
Dual-purpose energy systems are designed to use primary energy resources in a more efficient way to produce a given mixture of different forms of energy to meet a demand. Analysis of such a system must demonstrate a clear advantage in order to justify the additional complexity, usually greater capital cost and, in some cases, organisational and marketing difficulties in handling the energy products.

Critical technical examination of these energy systems rests upon the Second Law of Thermodynamics. The trade-off between first cost increase and fuel cost savings, however, depends also upon economic analysis which involves time-variable coefficients dependent upon a large number of financial, legal and political factors.

The approach of the thermodynamic analysis involves the separation of losses into those of which further use may be made (exergy) and those which are not recoverable.

Irreversibility through large temperature differences is noted as one cause of loss in traditional plant which dual systems can minimise.

Examples of applications are given from compound plant gas and steam turbine cycles; combined heat and power steam plant; Rankine bottoming cycles and compound cycles for diesel engines; and the engine-driven heat pump.
INTRODUCTION

The analysis of dual purpose energy systems in the real world has to be made on many bases - economic, political, environmental as well as thermodynamic. Yet the laws of thermodynamics indicate the potential success of any proposed system which can then be examined from the other points of view.

THERMODYNAMICS OF DUAL PURPOSE SYSTEMS

The justification for the additional complexity of a dual purpose system has to be the more effective use of a primary energy resource to satisfy given demands for energy transfer as work or heat. The use of an energy resource in conversion processes degrades the source and produces energy transfers in the required forms. The object of the system is to convert into useful output the largest possible proportion of the energy potential of the source.

The First Law of Thermodynamics, of course, only requires energy inputs and outputs from a cyclic system to add algebraically to zero.

\[ \Sigma Q_A - \Sigma W_C = 0 \quad (i) \]

where 'inward' heat transfer and 'outward' work transfer are regarded as positive.

It is the Second Law of Thermodynamics which indicates the limitations on the relationships between these energy transfers. The maximum ideal work output when an engine works between two regions of constant temperature (fig.2) is given by Carnot's well known relationship:

\[ W_{\text{net}} \downarrow (1 - \frac{T_{\text{LOWER}}}{T_{\text{UPPER}}}) \cdot Q_{\text{UPPER}} \quad (ii) \]

i.e. efficiency, \( n \triangleq 1 - \frac{T_{\text{LOWER}}}{T_{\text{UPPER}}} \)
This is significant when looking at the potential output of a system since it encompasses the concept that, while all work transfer can theoretically be converted to heat transfer without loss, the converse has a built in maximum rate of exchange. The process of conversion in a real engine is accompanied by an increase in 'entropy' in the universe since the entropy change in the upper temperature region is $-\frac{Q_{\text{UPPER}}}{T_{\text{UPPER}}}$, that in the lower temperature region $+\frac{Q_{\text{LOWER}}}{T_{\text{LOWER}}}$ (which will be arithmetically larger in real plant) and that in the cyclic operation, zero.

$$\Delta S_{\text{UNIVERSE}} = \frac{Q_{\text{LOWER}}}{T_{\text{LOWER}}} - \frac{Q_{\text{UPPER}}}{T_{\text{UPPER}}}$$ (iii)

A quantity of substance at a temperature and pressure above ambient will have potential for work transfer comprising two elements, illustrated in fig.3.

a) that which can be created by allowing the fluid to expand to ambient pressure, and
b) that which can be obtained by operating a cycle having Carnot efficiency between the substance temperature and ambient temperature.

A system at rest at ambient pressure and temperature has no further capacity for doing work in the absence of chemical and gravitational change.

The maximum work obtainable under these conditions from an amount of substance at temperature $T_1$ and pressure $p_1$ in surroundings at $T_0$ and $p_0$ can be derived by considering the two processes (each of which may be regarded as reversible) shown in fig.3:

1 $\to$ 2 isentropic expansion
and 2 $\to$ 0 isothermal cooling

In a real situation, any process involved which is less than ideal or in which the energy transfers go to waste is diminishing the efficiency of the whole operation.
The work in the example given may be calculated as follows:

\[ \dot{Q}_2 - \dot{W}_2 = U_2 - U_1 \]  
(from 1st Law) \hfill (iv)

\[ \dot{Q}_2 = 0 \]  
(isentropic process)

\[ -\dot{W}_2 = U_2 - U_1 \] \hfill (v)

\[ \dot{Q}_0 - \dot{W}_0 = (U_0 - U_2) \] \hfill (vi)

\[ \dot{Q}_0 = T_0 (S_0 - S_2) \]

\[ -\dot{W}_0 = U_0 - U_2 - T_0 (S_0 - S_2) \] \hfill (vii)

Total work from (v) and (vii)

\[ \dot{W}_2 + \dot{W}_0 = (U_1 - U_0) + T_0 (S_0 - S_1) \] \hfill (viii)

since \[ S_1 = S_2, \]

During this process work, \[ p_0(V_0 - V_1), \] has been done on the surroundings but this is not useful work as it is only the result of expansion in system volume.

The total possible useful work is then given by

\[ W_u \doteqdot (U_1 - U_0) - T_0 (S_1 - S_0) + p_0(V_1 - V_0) \] \hfill (ix)

Similarly for a stream of fluid at \( T_1, p_1 \) etc entering a device under steady-flow conditions, the total possible useful work is given by

\[ W_u \doteqdot (H_1 - H_0) - T_0 (S_1 - S_0) \] \hfill (x)

Any kinetic and/or potential energy possessed by the stream at 1 may be added since all this is theoretically convertible to output mechanical work.
The quantities on the r.h.s. of (ix) and (x) represent the 'available energy' under each set of circumstances described.

Since most real plant can be considered steady-flow the value given by (x) is of more interest. At state 1 the availability, B, is said to be given by

\[ B_1 = H_1 - T_0 S_1 \]  

(xi)

to which must be added kinetic and potential energy terms (if any) to give, for unit mass,

\[ b_1 = h_1 - T_0 s_1 + \frac{c_i^2}{2} + gz_i \]  

(xii)

In the case of turbomachinery, the boundary of the device is regarded as adiabatic and, ideally, the process is reversible and, hence, isentropic. In real plant irreversibility leads to an increase in entropy (fig.4) \( s_2 - s'_2 \).

Conventionally, the isentropic efficiency of the process 12 is given as

\[ \eta_{isen} = \frac{\Delta h}{\Delta h'} \]

since this is the proportion of work from an ideal expansion actually realised. The implication is that the energy represented by the area 2abcd2' is lost whereas only that represented by abcd is not available.

The availability criterion would compare \( \Delta h \) with the change in availability:

\[
\frac{\Delta h}{\Delta b} = \frac{h_2-h_1}{(h_2-T_0s_2)-(h_1-T_0s_1)} = \frac{h_2-h_1}{(h_2-h_1)-T_0(s_2-s_1)} = 1 - \frac{(h_2-h_1)}{T_0(s_2-s_1)}
\]  

(xiii)
Although the work from the process is less than in the ideal case the fluid at exit has a higher enthalpy. A further stage of expansion, therefore, would begin at a higher enthalpy; alternatively a heat exchanger could obtain a greater energy recovery from the exhaust than in the case of an ideal turbine.

APPLICATION TO DUAL PURPOSE SYSTEMS

It is for similar purposes that such a concept is of special value in the analysis of a dual purpose energy system where, by definition, there is more than one useful process involved. Thus, a higher energy of a working fluid at exit from one device may indicate a less efficient primary cycle but it enhances the prospects for a secondary device whether for work or heat transfer. The most obvious, and currently widely publicised, application is the combined heat and power steam plant. By using a higher exit temperature (at least for part of the flow of working fluid) the possibilities of meeting the industrial and/or residential demand for both forms of energy can be provided. The primary cycle is less efficient but the somewhat higher grade energy rejected to the low temperature region is made useful to a greater extent.

In the following examples various aspects of the thermodynamics of dual purpose systems will be illustrated.

Compound cycle power plant

Equation (ii) showed the advantage of using the greatest possible temperature range when producing power from a given energy flow rate at high temperature. The temperatures involved in the efficiency equation are those in the working fluid which may differ considerably from those of the source and sink. The loss of availability caused by the difference between source and working fluid temperatures is not, of course, recoverable.

This problem is especially difficult in steam power plant where the maximum temperature of the steam cycle is limited to about 540°C. This is because of the properties at elevated temperatures of the steel used in steam
generators, pipes and fittings, the size of which is such that exotic materials are not practicable. Gas turbines, where the combustion chamber contains the working fluid itself, do not have such a severe limit. A large amount of excess air is used which gives a temperature, in that small part of the plant subject to it, which can be accepted using more exotic materials for the turbine blades. In reciprocating engines, with air fuel ratios around stoichiometric, the even higher temperatures alternate with low temperatures in the same space as the cycle of operations proceeds through induction, compression, expansion and exhaust.

Examples of plant using this principle are found in both static and transport applications.

Gas turbine/steam turbine compound cycle.

Figure 5 shows a plant in which the high temperatures of combustion are utilised effectively in a gas turbine, the exhaust gases from which pass through a steam generator when the temperature differences between products of combustion and steam are much smaller than in steam only plant. An installation of the type illustrated (1) can be shown to produce 47% of the input energy as useful output compared with 40% from the typical 'straight' steam cycle. Figure 6 shows the comparative energy flows for this type of cycle compared with those for a conventional steam plant. The flows are divided into that part of the energy which is available for further use (exergy) and that which is not (anenergy). Further flexibility in output, at the expense of efficiency, can be obtained by supplementary firing in the steam generator, since large excess air amounts allow this. In this plant the power from the gas turbine represents over 60% of the total shaft output. Other plants (2,3) emphasise the steam component with additional firing of steam generators as the standard mode of operation. Here the gas turbine power represents as little as 15% of the total.

In both types of plant it is possible to utilise peak temperatures in the gas turbine of the order 1000°C while having temperatures on the gas side of the steam generator only slightly above the steam cycle maxima.
Automotive compound cycles

Similar reasoning lies behind two automotive developments involving compression-ignition engines. In the so called Rankine-bottoming cycle the gases from the vehicle's main engine are fed into a vapour generator (4). The layout, illustrated in fig. 7 offers increases in efficiency of up to 17.5%, the turbine providing typically 15% of the power.

The second family of cycles (5) is based upon extensions of the turbocharging principle where the turbine provides an additional shaft power output as well as the compressor power. One possible configuration is shown in fig.8. In this the engine supercharger is shaft driven through gears while the exhaust turbine contributes to the engine power output through a continuously variable transmission. Although only at test bed stage it is expected that up to 20% better efficiencies may be available in heavy vehicle operation using this type of engine.

Combined heat and power plant (steam)

In the traditional steam plant designed to provide shaft output only it has been seen (fig.6) that a large proportion of the energy supplied is rejected in the condenser. However only 2% of this quantity is lost exergy since the remainder is energy at the conditions of the surroundings. It is this fact which makes impossible the use of unmodified power station plant for CHP. Usually a temperature well above ambient is required, even for space heating applications, as allowance must be made for losses in the supply pipes. For industrial process heating the temperature depends upon the process requirement and this will determine the pressure at which steam is to be extracted. A simplified energy flow diagram (fig.9) compares, for a typical situation, CHP with a straightforward power plant and separate heating system.

Plant configurations depend upon the process or heating system temperature, the ratio of heating:shaft power and the variation of this ratio required. The worst case is for space heating where there is no load in the summer months, the best for an integrated plant where the requirements
for shaft power and for process steam are directly related to production rates. [Analysis of different CHP configurations based on various prime movers is in reference (6).] In the latter case it is possible to use the back pressure turbine in which the process load replaces the condenser, although working at higher temperature than the condenser in a straight power plant. An example of this with which the author was involved was for a frozen food plant (7). In this a new refrigeration compressor was required and new heating output for cooking purposes. The usual solution was an electrically driven compressor and a low pressure boiler. Instead a higher pressure boiler was installed supplying a steam turbine to drive the compressor directly, the exhaust from which was used to supply the cooking processes (fig.10). Both loads are directly related to output, efficiency is improved and the electricity maximum demand is not increased.

Engine driven heat pump.

The principles of the heat pump are well known. It takes energy from a low grade source, i.e. at, or even below, ambient temperature, and upgrades it for a heating purpose adding energy by means of a compressor. This has mostly been for space or water heating purposes but recently industrial demonstration projects have been undertaken. Such a heat pump becomes an example of dual energy system when it is engine driven as opposed to electrically driven. In this configuration the inevitable heat transfers involved in converting energy in the prime mover are available to the user of the heat pump (8) (figs.11,12). They can be used to upgrade the heating effect of the heat pump cycle itself or as a supply for a separate purpose (e.g. domestic hot water where the main heat pump provides space heating).

The ideal coefficient of performance of a heat pump cycle is given by

\[ \text{COP}_{hp} \geq \frac{T_U}{T_U - T_L} \]  

(xiv)

This relates only to the cycle of the working fluid within the pump. It can be seen that irreversible heat transfer across boundaries where there are large temperature differences will have considerable effect here since \( T_U - T_L \) is small. To account for the differences between types of
complete plant according to prime mover other performance indicators are sometimes used (given different names by various analysts):

The actual coefficient of performance (COP)

\[
\text{COP} = \frac{\text{heat transfer from heat pump cycle}}{\text{power input to compressor}}
\]

Performance effectiveness ratio (PER)

\[
\text{PER} = \frac{\text{useful heat transfer from whole plant}}{\text{energy input at plant boundary}}
\]

Coefficient of fuel utilisation (CFU)

\[
\text{CFU} = \frac{\text{useful heat transfer from whole plant}}{\text{primary energy resource depleted}}
\]

Naturally one has to be careful when drawing general conclusions in circumstances where electricity is available from hydro or nuclear sources. It could be argued then that the use of gas to obtain improvements in these indicators provides only nominal advantages while depleting reserves of a premium resource.

CONCLUSIONS

System analysis can be made using simple energy flows to examine the possible development of a situation for more effective use of the primary energy resource by a dual-purpose system.

To be certain of the potential, however, analysis based on the Second Law is essential since the useful components of energy flow (exergy) are indicated more clearly by this.

The importance of an economic appraisal of the increased capital cost in comparison with the reduced running costs over the lifetime should be realised. Attempts to quantify this assessment have been made by Myron Tribus and his colleagues at MIT (9,10). This approach, sometimes referred to as thermoeconomic analysis, requires extensive knowledge of the relative costs of plant. Whereas the running costs, particularly those for fuels, are fairly easily determined within reasonable accuracy, capital costs of any new projects are much more difficult to predict with certainty.
REFERENCES


2. Bruckner, H. and Wittchrow, E., Combined steam/gas turbine cycles - their effect on steam generator design and operation, Energie und Technik, 24, No 5, pp 147-152, 1972 (translation)


Fig. 1. Cycle diagram with arrows for $Q_A$, $Q_B$, $W_X$, and $W_Y$.

Fig. 2. Engine diagram with arrows for $T_{UPPER}$, $Q_{UPPER}$, and $Q_{LOWER}$.

Fig. 3. Concept of available energy diagram with points $T_0$, $S_0$, $P_0$, and $V_0$. 

Fig. 3. CONCEPT OF AVAILABLE ENERGY
Fig. 4. EFFECT OF IRREVERSIBILITY

(a) Steam power plant with reheat
(b) Combined gas and steam turbine power plant

Fig. 5 COMPARISON OF PLANT DIAGRAMS FOR SIMPLE AND COMPOUND POWER PLANTS
Fig. 6. COMPARISON OF EXERGY DIAGRAMS FOR SIMPLE AND COMPOUND POWER PLANTS
Fig. 7(a). DIESEL ENGINE WITH ORGANIC RANKINE BOTTOMING CYCLE

Fig. 7(b) DIESEL ENGINE WITH ORGANIC RANKINE BOTTOMING CYCLE
Fig. 8. DIFFERENTIAL COMPOUND ENGINE
BV bypass valve; BS boost sensor; C compressor; CC charge cooler; E semiaadiabatic engine; ECG epicyclic gear train; FP fuel pump; PT power turbine; TC torque converter; VN variable turbine nozzles; TSS output torque and speed sensor; \( N_e \) engine speed; \( N_{os} \) output shaft speed; \( N_{pc} \) planet carrier speed; MP microprocessor.
Input signals: 1 torque transducer; 2 speed transducer; 3 boost transducer
Output signals: 4 bypass valve control; 5 CVT control; 6 nozzle control

(a) Combined heat and power  (b) Separate heat and power
Fig. 9. COMPARISON OF SCHEMES FOR SUPPLY OF HEAT AND POWER
(a) Combined heat and power

(b) Separate boiler and electric motor drive

Fig. 10. COMPARISON OF SCHEMES FOR FROZEN FOOD PLANT

SANKEY DIAGRAMS
Fig. 11. ENGINE DRIVEN HEAT PUMP

Fig. 12. SANKEY DIAGRAM FOR ENGINE-DRIVEN HEAT PUMP
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Energy requirements for the motor car - analysis and opportunities for conservation

A W E Henham & M A I Jacobson

ENERGY REQUIREMENTS FOR THE MOTOR CAR
- ANALYSIS AND OPPORTUNITIES
FOR CONSERVATION

A. Henham* and M. Jacobson**

*Energy Engineering, University of Surrey, Guildford, Surrey GU2 5XH, UK
**Chief Engineer, Automobile Association, Fanum House, Basingstoke, Hants RG21 2EA, UK

ABSTRACT

This paper examines the means by which energy consumption figures have been assessed for personal means of transport. The running energy component, reckoned as the primary energy content of the fuel used is discussed first. Some reasons for the wide variations noted in on-the-road fuel consumption are expounded. Similarly the estimates of capital energy requirement, especially in the processes of automobile production, cover a large range. From an analysis of contributing processes and an observation of differing practices in the various vehicle-making centres in many parts of the world, broad conclusions are drawn as to the most promising areas for energy conservation measures.

KEYWORDS

Energy requirements; personal transport; automobile fuel economy; manufacturing process energy; energy conservation.

1.0 INTRODUCTION

In an attempt to examine the total energy consumption attributable to the automobile in the U.S.A. in 1970 Hirst and Herendeen examined manufacturing energy use, previously not given much attention, as well as running energy. Their findings, based on earlier work by Berry and Fels and by Herendeen stated that $9.4 \times 10^{15} \text{J}$ were used directly in fuel and $5.8 \times 10^{15} \text{J}$ in manufacturing, distributing and maintaining vehicles, refining fuels and providing roads. Combined these consumptions were quoted as $10.5 \text{MJ/vehicle km}$. To estimate the equivalent figures a decade later and for the European situation with special emphasis on the U.K., requires a close examination of the way in which fuel consumption and manufacturing energy use are assessed. The reliability of figures for fuel consumption on a national scale is good and can with some accuracy be applied to individual vehicles. Vehicle manufacturing energy is much more difficult to assess accurately since the path back through all the processes is a tortuous one and the forms in which energy is used are various.

2.0 ON-THE-ROAD FUEL CONSUMPTION

It is the direct consumption of gasoline (or diesel fuel) which is the most obvious energy demand of the private motor vehicle. Figures are readily
available for the annual quantity of fuel supplied and, assuming stocks held by suppliers and in vehicle tanks to vary little at the end of successive years, this is equated to the fuel consumed. Somewhat less definite is the data on distance covered by the total car population, or the breakdown into types of journey, driving methods, traffic conditions and other variables. Taking figures from UK official sources the annual distances covered by various vehicle types are shown in table 1.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>*Cars &amp; + taxis</td>
<td>67.7</td>
<td>115.2</td>
<td>161.9</td>
<td>193.3</td>
<td>218.6</td>
</tr>
<tr>
<td>*motor cycles</td>
<td>9.9</td>
<td>6.6</td>
<td>4.2</td>
<td>5.1</td>
<td>6.7</td>
</tr>
<tr>
<td>+buses &amp; + coaches</td>
<td>4.0</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>3.7</td>
</tr>
<tr>
<td>*light vans</td>
<td>14.6</td>
<td>17.9</td>
<td>19.0</td>
<td>21.1</td>
<td>22.2</td>
</tr>
<tr>
<td>+other goods vehicles</td>
<td>15.5</td>
<td>18.1</td>
<td>19.4</td>
<td>19.8</td>
<td>21.4</td>
</tr>
</tbody>
</table>

*mainly using gasoline +mainly using diesel fuel

Table 1: Distance covered by vehicle types in U.K.

World transport statistics show that the percentage increase in distance travelled by car passengers in the UK has been exceeded in the period 1966-77 by many other countries although only the USA and West Germany show higher actual distances in 1977. Dramatic increases in Japan (256%) and Yugoslavia (533%) are probably equalled by Comecon countries for which the classification of vehicles may not be comparable. Estimated annual distance by each vehicle in the U.K. was 15 200 km in 1978.

More significant in terms of fuel consumption is the congestion which is reflected in the number of vehicles/km road space, shown for 1976, 1977 or 1978 (according to available data) in table 2.

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>VEHICLES/km</th>
<th>ROAD</th>
<th>DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>82</td>
<td>1977</td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>64</td>
<td>1977</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>62</td>
<td>1977</td>
<td></td>
</tr>
<tr>
<td>W. Germany</td>
<td>118</td>
<td>1977</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td>149</td>
<td>1977</td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>122</td>
<td>1976</td>
<td></td>
</tr>
<tr>
<td>United Kingdom</td>
<td>122</td>
<td>1978</td>
<td></td>
</tr>
<tr>
<td>EEC overall</td>
<td>96</td>
<td>1977</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>72</td>
<td>1976</td>
<td></td>
</tr>
<tr>
<td>U.S.A.</td>
<td>58</td>
<td>1976</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Comparison of road congestion
2.2 Comparison of Test procedures

In tabulating performance figures for comparison between vehicles a completely representative road fuel consumption is the most difficult to define. Maximum speed, time from 0 to 100 km/h, turning circle diameter will all be found by independent testers to be the same within a very small tolerance.

2.2.1 Official figures

The official answer has been to adapt for this purpose urban test cycles originally developed for the definition of exhaust emissions. Such cycles, originating in California, are now stipulated in many separate countries and by the E.E.C. It is this last, known as ECE15, which is adopted by the UK government as a basis for its urban fuel consumption figure published by the Department of Energy alongside that at two constant speeds.

A problem for the manufacturer is the sometimes conflicting demands of authorities in all the markets in which one vehicle type is sold. The different patterns of use evident in these markets precludes any realistic common test procedure.

![Graph](image)

**Fig. 1 TYPICAL U.K. PRICE OF PREMIUM GASOLINE**

Although reasonably constant when compared with incomes and other costs the apparent increase in fuel costs illustrated in fig. 1 has encouraged buyers of cars to consider economy data more carefully. The requirement from 1978, to post 'official' figures on new cars for sale in the UK is designed to help in this consideration since a list of comparative values for all other cars has to be provided too. Such figures are only for one sample vehicle of each class (used for at least 3000 km) and so a customer's expectations may not be fulfilled by another sample. The constant speed values may be measured on track or dynamometer whereas the urban cycle must be on a dynamometer. Manufacturers conduct the tests with the Department of Energy having the right to witness.
2.2.2 Dynanometer testing

Variations in results between laboratories testing the same vehicle on the same cycle occur for many reasons some of which are listed:

(a) smoothness of control in following speed-time graph varies between drivers,
(b) gear change effects on manual vehicles cannot be the same for all drivers,
(c) exact setting of absorption in comparison with road load can vary,
(d) dynanometer maintenance and calibration,
(e) cooling air direction and flowrate affects air inlet and lubricating oil temperatures,
(f) fuel metering accuracy (especially at low rates on idling and retardation) can vary,
(g) diameter and type of rollers (which affects distortion of tyre compared with road surface) range from 0.2 to 0.5 m diameter for double rollers to even larger sizes for single rollers,
(h) dynamic alignment on large single rollers creates 'uphill' or 'downhill' effects,
(i) vehicle mass affects true consumption but dynamometer inertia only alters in 9 distinct steps (in some cases as large as 20%).

2.2.3 On-the-road testing

A test procedure developed by one of the authors (MJ) aims to provide a more realistic figure than the dynamometer results of 2.2.2. After a check of all recommended settings on a standard vehicle as sold to the public, a fuel flow meter is installed using the positive displacement principle in conjunction with a Hall effect proximity transducer. Special procedures have been developed for all types of fuel system including fuel injection. A standard test procedure for 1000 miles (1600 km) is strictly followed including four distinctly different driving modes shown in table 3 with results for four typical cars.

2.2.4 Single indication of fuel economy

Existing recommendations are given by various bodies, combining separate figures into an overall value.

Vehicles not capable of 130 km/h

\[
\text{CMCC (Common Market Constructors Committee): } 0.5 \text{ (urban cycle)} + 0.5 \text{ (steady 90 km/h)}
\]

\[
\text{SMMT (Society of Motor Manufacturers + Traders): } 0.5 \text{ (urban cycle)} + 0.5 \text{ (steady 90 km/h)}
\]

Vehicles capable of 130 km/h

\[
\text{CMCC: } \frac{(\text{urban cycle}) + (90 \text{ km/h}) + (120 \text{ km/h})}{3}
\]

\[
\text{SMMT: } 0.4 \text{ (urban cycle)} + 0.5 (90 \text{ km/h}) + 0.1 (120 \text{ km/h})
\]

\[
\text{VW: } 0.5 \text{ (urban cycle)} + 0.25 (90 \text{ km/h}) + 0.25 (120 \text{ km/h})
\]

By comparison the A.A. figure shown in table 3 is the unweighted mean of the four test modes and has been found to correlate well with the fuel consumption of a full 1600 km road test. Drivers affect the consumption heavily in certain modes and hardly at all in others. It has been found in this programme that drivers trained for this purpose rarely produce differences of more than 2% in their results for a given car and can reproduce their own values within a smaller tolerance. Attempts have been made by various workers to explore the effects of deliberately different driving methods, the difference between 'aggressive'
and 'normal' generally being greater than that between 'normal' and 'gentle'. Figures quoted are: (+21%, -15%); (+28%, -13%); (+45%, -15%); (+30%, -30%).

Widely differing results obtained by different motoring journals on road tests of the same vehicle have often been noted even when the same example has been submitted for test in each case.

<table>
<thead>
<tr>
<th>MODE</th>
<th>DESCRIPTION</th>
<th>DRIVING STYLE</th>
<th>FUEL ECONOMY/litre/100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SUBURBAN COLD START, REVERSE, 4.8 km, CIRCUIT, HALTS, JUNCTIONS, CRUISE, REPEAT WARM</td>
<td>GENTLE to BRISK</td>
<td>7.85 7.06 10.46 13.45</td>
</tr>
<tr>
<td>2 A + R</td>
<td>ROADS COLD START, REVERSE, 16 km SINGLE CARRIAGE-WAY A ROADS, LANES, TOWN, VILLAGE, REPEAT WARM</td>
<td>BRISK</td>
<td>6.31 5.77 8.25 10.27</td>
</tr>
<tr>
<td>3 QUIET</td>
<td>RURAL ROUTE AS 2 BUT MAX. SPEED LIMIT 64 km/h &amp; LOWER ACCELERATION</td>
<td>GENTLE</td>
<td>5.46 5.14 7.24 6.85</td>
</tr>
<tr>
<td>4 MOTOR-WAY</td>
<td>CONSTANT LEGAL LIMIT (112km/h) OR 85% MAX. SPEED IF LOWER (107 km/h) (96 km/h)</td>
<td>---</td>
<td>8.13 6.81 9.66 10.27</td>
</tr>
</tbody>
</table>

Table 3: AA Fuel consumption programme

2.3 Effect of Operating Variables

Examination of the wide range of variables which have an effect on fuel consumption points to means of energy conservation by improved driving methods, road planning and traffic management.

2.3.1 Actual rate of progress

Experiments were conducted on a number of cars and fuel consumptions plotted against actual rate of progress (rather than cruising speed). A family of plots for different driving methods (fig.2) indicates clearly some important factors and comparison of vehicles by drawing curves on the same axes indicates the range in which each has better economy.
2.3.2 Type of service - a regional phenomenon

A fleet of 1800 similar vehicles operated by the A.A. is driven by 2200 drivers. Each van is based in one of the regions of the UK and all cover about the same distance annually. Thus a useful statistical survey is possible. Results comparing the actual annual mean consumption with that predicted from short tests described in 2.2.3 and shown in table A give good correlation.

<table>
<thead>
<tr>
<th>REGION</th>
<th>HOURLY DISTANCE</th>
<th>ROAD TYPE</th>
<th>FUEL CONSUMPTION l/100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km</td>
<td></td>
<td>actual</td>
</tr>
<tr>
<td>NORTHAMPTON</td>
<td>80-88</td>
<td>MOTORWAY</td>
<td>10.8</td>
</tr>
<tr>
<td>WEST &amp; WALES</td>
<td>26-37</td>
<td>CROSS-COUNTRY</td>
<td>10.5</td>
</tr>
<tr>
<td>CAMBRIDGE</td>
<td>77-88</td>
<td>TRUNK, FLAT</td>
<td>10.7</td>
</tr>
<tr>
<td>SCOTLAND &amp;</td>
<td>26-36</td>
<td>MOSTLY CROSS-COUNTRY</td>
<td>10.9</td>
</tr>
<tr>
<td>NORTH IRELAND</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NORTH</td>
<td>21-32</td>
<td>TRUNK, URBAN</td>
<td>12.8</td>
</tr>
<tr>
<td>MIDLANDS</td>
<td>21-29</td>
<td>URBAN, MOTORWAY</td>
<td>14.1</td>
</tr>
<tr>
<td>SOUTH EAST</td>
<td>21-34</td>
<td>CROSS-COUNTRY, URBAN</td>
<td>12.6</td>
</tr>
<tr>
<td>GREATER LONDON</td>
<td>19-29</td>
<td>URBAN, SUBURBAN</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Table 4 : REGIONAL COMPARISON OF FLEET VEHICLES

2.3.3 Traffic conditions

Data from the tests described in 2.3.1 and 2.3.2 show that, for a given vehicle, urban fuel consumption is lower in free flow situations and that, for
traversing a given road distance the higher the average speed the lower the fuel consumption. This accords well with data from Australia\(^5\),\(^6\) and U.S.A.\(^7\). Externally imposed speed limits are seen to have an adverse effect by encouraging 'bunching' of dissimilar vehicles, each of which has a different optimum speed.

2.3.4 Other factors
Fuel consumption is also seen to depend upon other operating factors including:

- a) cold start, choke operation, manual or automatic. Steady running consumption rate was reached in experiments 4-15 minutes after cold start according to weather conditions;
- b) driving style of the individual driver (attitude, state of mind, fatigue);
- c) terrain, choice of road for given journey (types of road, congestion, hills, corners);
- d) time of day or night (traffic conditions);
- e) weather (especially wind but also snow and rain);
- f) unusual road conditions (holiday time congestion, road works, special events)
- g) vehicle maintenance (e.g. braking system, ignition and carburation settings).

2.4 Effect of design
Factors inherent in the vehicle are linked with those in 2.3. since each car is designed with a certain range of operation in mind. Results of the type shown in fig.2 have been obtained for a large number of cars and comparison made based on a number of design variables.

2.4.1 Vehicle Mass
Seen by the authors as the most significant design factor the vehicle mass has the strong correlation with fuel consumption which would be expected from theory wherever hill climbing and acceleration is involved. Over 100 different vehicles were tested to produce the relationships shown in table 5.

<table>
<thead>
<tr>
<th>MODE OF TRAVEL</th>
<th>FUEL CONSUMPTION</th>
<th>TOLERANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>litre/100 km</td>
<td>%</td>
</tr>
<tr>
<td>1 URBAN, CONGESTED</td>
<td>0.62 + 9.3 m</td>
<td>8</td>
</tr>
<tr>
<td>2 CROSS-COUNTRY</td>
<td>1.01 + 6.9 m</td>
<td>10</td>
</tr>
<tr>
<td>3 RURAL, LEISURELY</td>
<td>1.44 + 5.7 m</td>
<td>8</td>
</tr>
<tr>
<td>4 MOTORWAY</td>
<td>3.9 + 5.1 m</td>
<td>6</td>
</tr>
</tbody>
</table>

where m = vehicle mass/tonne

TABLE 5: FUEL CONSUMPTION RELATED TO MASS

Automatic transmissions were seen to add, on average, 13% in mode 1, 10% in mode 2, 10% in mode 3 and very little in mode 4. Sports cars show poor performance in mode 1 for which their engine curves and gears are inappropriate.
Opportunities for reduction in mass include:

a) reduction in thickness of metal using new alloys;
b) replacement of steel and cast iron by light alloys;
c) replacement of metals by plastics;
d) reduction in thickness of glass;
e) mass-conscious structural design.

2.4.2 Engine capacity

It is not clear that the relationship claimed in some quarters between engine swept volume and fuel consumption is valid for European cars. Larger engines are mostly associated with heavy cars. A plot of the results from the same 100 cars against the ECE15 fuel consumption shows a range of ±30% for each of the major European engine sizes 1.3, 1.5 and 2.0 litres and, thus, a considerable overlap between these sizes. Indeed the same vehicle with two sizes of engine often gives better economy overall with the larger engine.

2.4.3 Aerodynamics

Most significant in high speed operation the drag depends at a given speed on \( C_d A \) (the product of drag coefficient and frontal area). The value of \( A \) depends on the style of car, and reduction is limited by ease of access. Care must be exercised in drag reduction as it is sometimes accompanied by increased sensitivity to cross winds.

2.4.4 Engine design

One of the most profound effects on fuel consumption has heen that of emission control legislation since this has resulted in lower compression ratio, use of unleaded fuel and moving carburation and ignition from optimum economy settings.

Other features relating to economy include:

(a) degree of turbulence affecting cyclic variation;
(b) compression ratio (and its production variation between cylinders);
(c) combustion chamber surface: volume ratio;
(d) manifold design;
(e) thermal loading (new materials allow higher loading);
(f) improved carburation;
(g) turbocharging;
(h) microprocessor engine management giving optimum ignition and air: fuel ratio at all running conditions.

Because of production lead time there is a long delay before many of these changes can be introduced.

2.4.5 Other design factors

a) Gearing determines the ability of the engine to operate at its most efficient at any road speed and load. A large range of operation can only be covered appropriately by a wide range of ratios. A fifth gear or overdrive extends the economic range but other means such as new automatic transmissions without the energy losses of most existing types are anticipated.

b) Cooling system, air intake and manifolding design all affect warm-up time (mentioned in 2.3.4). Continuous fan drives are energy wasting at high speed as well as in the warm up period.
Advantages of the diesel engine at part-load are not available at full load but a comparison based on required mix of use will show whether a worthwhile gain is demonstrated and figure 3 compares the two engine types for a typical vehicle.

Component efficiency and ancillary loads are significant and a Sankey diagram illustrating some typical losses is shown in fig.4.
e) Tyre design provides little scope for significant improvement since most European cars have radial tyres. Correct pressures are required for maximum economy and safety.

f) Front-wheel drive with transverse engine shows 15-20% reduction in transmission loss over hypoid rear axle drive for much of the operating range.

g) Improved roadholding reduces necessity for fuel-expensive speed changes on corners and bends.

All the above may involve a price penalty which must be traded off against reduced running costs over anticipated life.

3.0 MANUFACTURING ENERGY REQUIREMENT

There is a natural reticence on the part of manufacturers to reveal the data necessary for the composition of an overall energy input figure for the construction of a typical car. Personal observation of the procedures employed in a wide range of works in many countries have been combined with published analyses of energy required for individual operations (such as steel, casting iron, manufacturing glass) and studies of the proportions of each material or product in each vehicle.

Figures published by the Japanese Institute of Energy Economics claim a fall from 13.65 GJ/vehicle in 1973 to 10.8 GJ/vehicle in 1978. In comparison General Motors claims that for U.S.A. and Canada energy/vehicle fell from 40.32 GJ in 1972 to 31.44 GJ in 1978. This is for a vehicle mass 1.8 times that of the Japanese model. Energy per unit mass is lower in the Japanese case but, as only the energy used 'in-house' is included, there are differences in the proportion actually made by the car maker. British manufacturers building cars comparable to the Japanese in size claim figures of 22 to 30 GJ/vehicle.

3.1 Materials, components and manufacture

Looking at the major material, steel, representing half the mass/car in sheet alone, variations in-process depending on the age of plant are wide. Table 6 shows comparisons based on the most economical country, Japan in 1973 as 100.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>126</td>
<td>115</td>
<td>103</td>
<td>100</td>
<td>96</td>
</tr>
<tr>
<td>U.K.</td>
<td>173</td>
<td>163</td>
<td>153</td>
<td>140</td>
<td>144</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>163</td>
<td>140</td>
<td>143</td>
<td>135</td>
<td>137</td>
</tr>
<tr>
<td>W. Germany</td>
<td>140</td>
<td>129</td>
<td>121</td>
<td>116</td>
<td>117</td>
</tr>
</tbody>
</table>

TABLE 6 : Relative energy use for steel production

Economies are produced by the use of continuous hot casting and by energy recovery from blast furnaces.

For the glass industry the overall figures need to be modified for the product used in cars. Some extra energy is used in the toughening process but the distribution of products is less dispersed than for building glass. Calculations suggest that 29.5 GJ/t is an appropriate figure giving 1.15 GJ/vehicle for windows and 0.18 GJ for light units.

Similar detailed analysis has been made for the production of automotive parts from zinc and aluminium alloys, plastics and rubber. In the case of plastics the basic feedstock is itself an energy source and must be included in the true energy cost.
The materials used in vehicles vary in energy use and the proportion of each varies considerably. A typical breakdown of proportions of seven types and energy/unit mass (from 100 to 170 GJ/t) has been used in producing figures used later of 118 GJ/t. One of the problems with aluminium products is that primary energy requirement depends heavily on the source of the necessary electricity. Often aluminium plant is located by hydroelectric power stations and the ratio of thermal/electric energy cannot be applied.

Table 7 presents a summary of the authors' analyses of material energy requirements for three typical cars.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>MASS/VEHICLE</th>
<th>GROSS ENERGY/VEHICLE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>US</td>
<td>EURO COMPACT</td>
</tr>
<tr>
<td>SHEET STEEL</td>
<td>680</td>
<td>550</td>
</tr>
<tr>
<td>OTHER STEEL</td>
<td>252</td>
<td>227</td>
</tr>
<tr>
<td>CAST IRON</td>
<td>285</td>
<td>131</td>
</tr>
<tr>
<td>ALUMINIUM(ALLOYS)</td>
<td>52</td>
<td>15</td>
</tr>
<tr>
<td>LEAD</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>ZINC(+ALLOYS)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>COPPER(+ALLOYS)</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>GLASS</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>RUBBER</td>
<td>65</td>
<td>55</td>
</tr>
<tr>
<td>PLASTICS</td>
<td>72</td>
<td>44</td>
</tr>
<tr>
<td>PAINT</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>PAPER, CLOTH, BOARD</td>
<td>51</td>
<td>15</td>
</tr>
<tr>
<td>TOTAL MATERIALS</td>
<td>1563</td>
<td>1112</td>
</tr>
<tr>
<td>MANUFACTURE</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SUPPLIERS' ENERGY</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GRAND TOTAL</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

TABLE 7: VEHICLE ENERGY REQUIREMENT ANALYSIS

It is believed that comparable totals for Japanese cars equivalent to the European Medium and Small types would be 56 and 39.6 GJ respectively. The VW figure for materials for a 1977 Golf was 49.4 GJ. Added to the tabulated materials figures are those for the automobile factory itself. The estimates shown exceed those in US and Australian reports which often consider only energy purchased as such by the manufacturer. It is considered that, in the U.K., between 32 and 45 GJ/car are required as gross thermal energy. In addition energy use for components and suppliers is taken as equal to that of the Manufacturer in the typical European production pattern.
3.2 Economy measures in production
The major scope for energy conservation in materials and processes is in the following areas:-

- a) reduction of mass of material;
- b) simplification of components;
- c) compactness of production plant avoiding movement of sub-assemblies between sites;
- d) double shift use of production facilities;
- e) reduction of manual labour content;
- f) improved factory insulation, door design to reduce heating requirements;
- g) new steel-making methods;
- h) heat recovery from process;
- i) training employees to save energy.

4.0 CONCLUSION
The energy use of a vehicle comprises the two important areas of manufacture gross energy requirement and energy supplied during use (mainly for fuel). A summary of these findings compared with other workers are shown in table 8.

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy/Vehicle (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Watson¹</td>
</tr>
<tr>
<td>Car &amp; Component Manufacture</td>
<td>36</td>
</tr>
<tr>
<td>Spares and repairs</td>
<td>22.5*</td>
</tr>
<tr>
<td>fuel and oil</td>
<td>482</td>
</tr>
<tr>
<td>garage trade</td>
<td>10</td>
</tr>
<tr>
<td>roads, etc.</td>
<td>10</td>
</tr>
<tr>
<td>TOTAL</td>
<td>560.5</td>
</tr>
</tbody>
</table>

TABLE 8

The authors' value of running energy use as 62% of the total energy requirement compares with others of 87.5% (Watson¹¹), 90.3% (SMMT¹²) and 76.8% (Hirst¹).

ACKNOWLEDGEMENT
The authors are grateful to the Committee and Directorate of the Automobile Association under whose auspices the collection of data by road testing and the visits to industrial sites were carried out and to members of staff who assisted in the gathering and processing of information. The analysis was originally carried out in connection with a Master of Science dissertation at the University of Surrey.
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2. Berry, R.S. and Fels, M.F., The Production and Consumption of Automobiles, Chemistry Department, University of Chicago, July 1972.


5. Kent, J. and Mudford, N.M., Sydney Driving Patterns, ER 26, University of Sydney, May 1978.


The motor car -
energy demands and potential for conservation

A W E Henham & M A I Jacobson
THE MOTOR CAR — ENERGY DEMANDS AND POTENTIAL FOR CONSERVATION

ALEX. HENHAM
University of Surrey, Guildford, Surrey GU2 5XH (U.K.)

and MARCUS JACOBSON
Automobile Association, Basingstoke, Hants RG21 2EA (U.K.)

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ABSTRACT

The energy consumption resulting from the use of personal transport has been estimated by various means. The major component of this energy use is that required to run the vehicle during its lifetime. Some reasons for the wide variation in on-the-road fuel consumption are indicated and suggestions for the selection and operation of vehicles for minimum fuel use given. Similarly the smaller, but still important capital energy requirement is analysed by consideration of the many processes contributing to the completed car. Automotive manufacturing energy estimates cover a wide range and the reasons for this are discussed. Observations are based on plants in many countries across the world. The paper summarises the promising areas for energy conservation in production.

INTRODUCTION

In an attempt to examine the total energy consumption attributable to the automobile in the United States in 1970 Hirst and Herendeen [1] examined manufacturing energy use, previously not given much attention, as well as running energy. Their findings, based on earlier work by Berry and Fels [2] and by Herendeen [3] stated that $9.4 \times 10^{15}$ J were used directly in fuel and $5.8 \times 10^{15}$ J in manufacturing, distributing and maintaining vehicles, refining fuels and providing roads. Combined these consumptions were quoted as 10.5 MJ per vehicle \cdot km. To estimate the equivalent figures a decade later and for the European situation with special emphasis on the United Kingdom requires a close examination of the way in which fuel consumption and manufacturing energy use are assessed. The reliability of figures for fuel consumption on a national scale is good and can with some accuracy be applied to individual vehicles. Vehicle manufacturing energy is much more difficult to assess accurately since the path back through all the processes is a tortuous one and the forms in which energy is used are various.
ON-THE-ROAD FUEL CONSUMPTION

It is the direct consumption of gasoline (or diesel fuel) which is the most obvious energy demand of the private motor vehicle. Figures are readily available for the annual quantity of fuel supplied and, assuming stocks held by suppliers and in vehicle tanks to vary little at the end of successive years, this is equated to the fuel consumed. Somewhat less definite is the data on distance covered by the total car population, or the breakdown into types of journey, driving methods, traffic conditions and other variables. Taking figures from U.K. official sources the annual distances covered by various vehicle types are shown in Table 1.

TABLE 1
Distance covered by vehicle types in the U.K.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars* and taxis**</td>
<td>67.7</td>
<td>115.2</td>
<td>161.9</td>
<td>193.3</td>
<td>229.8</td>
</tr>
<tr>
<td>Motor cycles*</td>
<td>9.9</td>
<td>6.6</td>
<td>4.2</td>
<td>5.1</td>
<td>7.7</td>
</tr>
<tr>
<td>Buses** and coaches**</td>
<td>4.0</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>3.7</td>
</tr>
<tr>
<td>Light vans*</td>
<td>14.6</td>
<td>17.9</td>
<td>19.0</td>
<td>21.1</td>
<td>22.6</td>
</tr>
<tr>
<td>Other goods vehicles**</td>
<td>15.5</td>
<td>18.1</td>
<td>19.4</td>
<td>19.8</td>
<td>21.4</td>
</tr>
</tbody>
</table>

* Mainly using gasoline.
** Mainly using diesel fuel.

TABLE 2
Comparison of road congestion

<table>
<thead>
<tr>
<th>Country</th>
<th>Vehicle/km road</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>82</td>
<td>1977</td>
</tr>
<tr>
<td>Denmark</td>
<td>64</td>
<td>1977</td>
</tr>
<tr>
<td>France</td>
<td>62</td>
<td>1977</td>
</tr>
<tr>
<td>W. Germany</td>
<td>118</td>
<td>1977</td>
</tr>
<tr>
<td>Italy</td>
<td>149</td>
<td>1977</td>
</tr>
<tr>
<td>Netherlands</td>
<td>122</td>
<td>1976</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>122</td>
<td>1978</td>
</tr>
<tr>
<td>E.E.C. overall</td>
<td>96</td>
<td>1977</td>
</tr>
<tr>
<td>Japan</td>
<td>72</td>
<td>1976</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>58</td>
<td>1976</td>
</tr>
</tbody>
</table>
World transport statistics show that the percentage increase in distance travelled by car passengers in the U.K. has been exceeded in the period 1966—77 by many other countries although only the U.S.A. and West Germany show higher actual distances in 1977. Dramatic increases in Japan (256%) and Yugoslavia (533%) are probably equalled by Comecon countries for which the classification of vehicles may not be comparable. Estimated annual distance by each vehicle in the U.K. was 15,200 km in 1978.

More significant in terms of fuel consumption is the congestion which is reflected in the number of vehicles per km road space, shown for 1976, 1977 or 1978 (according to available data) in Table 2.

Comparison of test procedures

In tabulating performance figures for comparison between vehicles a completely representative road fuel consumption is the most difficult to define. Maximum speed, time from 0 to 100 km/h and turning circle diameter will all be found by independent testers to be the same within a very small tolerance.

Official figures

The official answer has been to adapt for this purpose urban test cycles originally developed for the definition of exhaust emissions. Such cycles, originating in California, are now stipulated in many separate countries and by the E.E.C. It is this last, known as ECE15, which is adopted by the U.K. government as a basis for its urban fuel consumption figure published by the Department of Energy alongside that at two constant speeds.

A problem for the manufacturer is the sometimes conflicting demands of authorities in all the markets in which one vehicle type is sold. The different patterns of use evident in these markets preclude any realistic common test procedure.

INDEX JAN 1970 = 100

Fig. 1. Typical U.K. price of premium gasoline.
Although reasonably constant on a long term basis compared with other prices, the apparently increasing cost of fuel illustrated in Fig. 1 has encouraged purchasers of vehicles to consider economy data more carefully. The requirement, dating from 1978, to post "official" figures on new cars for sale in the U.K. is designed to help in this consideration since a list of comparative values for all other cars has to be provided too. Such figures are only for one sample vehicle of each class (used for at least 3000 km) and so a customer's expectation may not be fulfilled by another sample. The constant speed values may be measured on track or dynamometer whereas the urban cycle must be on a dynamometer. Manufacturers conduct the tests with the Department of Energy having the right to witness.

_Dynamometer testing_

Variations in results between laboratories testing the same vehicle on the same cycle occur for many reasons some of which are listed:

(a) smoothness of control in following speed-time graph varies between drivers;
(b) gear change effects on manual vehicles cannot be the same for all drivers;
(c) exact setting of absorption in comparison with road load can vary;
(d) dynamometer maintenance and calibration;
(e) cooling air direction and flowrate affect air inlet and lubricating oil temperatures;
(f) fuel metering accuracy (especially at low rates on idling and retardation) can vary;
(g) diameter and type of rollers (which affects distortion of tyre compared with road surface) range from 0.2 to 0.5 m diameter for double rollers with larger diameters for single rollers;
(h) dynamic alignment on rollers creates "uphill" or "downhill" effects;
(i) vehicle mass affects true consumption but dynamometer inertia only alters in 9 distinct steps (in some cases as large as 20%).

_On-the-road testing_

A test procedure developed by one of the authors [4] aims to provide a more realistic figure than the dynamometer results discussed above. After a check of all recommended settings on a standard vehicle as sold to the public, a fuel flow meter is installed using the positive displacement principle in conjunction with a Hall effect proximity transducer. Special procedures have been developed for all types of fuel system including fuel injection. A standard test procedure for 1000 miles (1600 km) is strictly followed including four distinctly different driving modes shown in Table 3 with results for four typical cars.

_Single indication of fuel economy_

Existing recommendations are given by various bodies, combining separate figures into an overall value:
TABLE 3
Automobile Association (A.A.) fuel consumption programme

<table>
<thead>
<tr>
<th>Mode</th>
<th>Description</th>
<th>Driving style</th>
<th>Fuel economy for typical vehicles (l/100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Suburban Cold start, reverse, 4.8 km circuit, halts, junctions, cruise, repeat warm</td>
<td>Gentle to brisk</td>
<td>7.85 7.06 10.46 13.45</td>
</tr>
<tr>
<td>2 A + B</td>
<td>roads Cold start, reverse, 16 km single carriage-way A roads, lanes, town, village, repeat warm</td>
<td>Brisk</td>
<td>6.31 5.77 8.25 10.27</td>
</tr>
<tr>
<td>3 Quiet</td>
<td>rural Route as 2 but max. speed limit 64 km/h and lower acceleration</td>
<td>Gentle</td>
<td>5.46 5.14 7.24 6.85</td>
</tr>
<tr>
<td>4 Motorway</td>
<td>Constant legal limit (112 km/h) or 85% max. speed if lower (107 km/h) (96 km/h)</td>
<td>–</td>
<td>8.13 6.81 9.66 10.27</td>
</tr>
<tr>
<td>Unweighted</td>
<td>mean based on fuel based on distance</td>
<td>6.9 6.1 6.2 6.8</td>
<td>10.2 10.6</td>
</tr>
</tbody>
</table>

(a) Vehicles not capable of 130 km/h
CMCC (Common Market Constructors Committee), 0.5 (urban cycle) + 0.5 (steady 90 km/h)
SMMT (Society of Motor Manufacturers + Traders), urban cycle

(b) Vehicles capable of 130 km/h +
CMCC, ((urban cycle) + (90 km/h) + (120 km/h))/3
SMMT, 0.4 (urban cycle) + 0.5 (90 km/h) + 0.1 (120 km/h)
VW, 0.5 (urban cycle) + 0.25 (90 km/h) + 0.25 (120 km/h)

By comparison the A.A. figure shown in Table 3 is the unweighted mean of the four test modes and has been found to correlate well with the fuel consumption of a full 1600 km road test. Drivers affect the consumption heavily in certain modes and hardly at all in others. It has been found in this programme that drivers trained for this purpose rarely produce differences of more than 2% in their results for a given car and can reproduce their own values within a smaller tolerance.
Attempts have been made by various workers to explore the effects of deliberately different driving methods, the difference between “aggressive” and “normal” generally being greater than that between “normal” and “gentle”. Figures quoted are: (+21%, -15%); (+28%, -13%); (+45%, -15%); (+30%, -30%).

Widely differing results obtained by different motoring journals on road tests of the same vehicle have often been noted even when the same example has been submitted for test in each case.

**Effect of operating variables**

Examination of the wide range of variables which have an effect on fuel consumption points to means of energy conservation by improved driving methods, road planning and traffic management.

**Actual rate of progress**

Experiments were conducted [4] on a number of cars and fuel consumptions plotted against actual rate of progress (rather than cruising speed). A family of plots for different driving methods (Fig. 2) indicates clearly some important factors and comparison of vehicles by drawing curves on the same axes indicates the range in which each has better economy.

![Fig. 2. Effect of driving style and rate of progress on fuel consumption.](image)

<table>
<thead>
<tr>
<th>Journey time (min/km)</th>
<th>Rate of progress (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>120</td>
</tr>
<tr>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

1. Brisk  
2. Normal  
3. Economy  
4. Steady speed  
(for comparison)
### TABLE 4

Regional comparison of fleet vehicles

<table>
<thead>
<tr>
<th>Region</th>
<th>Hourly distance (km)</th>
<th>Road type</th>
<th>Fuel consumption (l/100 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Actual</td>
<td>Predicted</td>
</tr>
<tr>
<td>Northampton</td>
<td>80–88</td>
<td>Motorway</td>
<td>10.8</td>
</tr>
<tr>
<td>West and Wales</td>
<td>26–27</td>
<td>Cross-country</td>
<td>10.5</td>
</tr>
<tr>
<td>Cambridge</td>
<td>77–88</td>
<td>Trunk, flat</td>
<td>10.7</td>
</tr>
<tr>
<td>Scotland and North Ireland</td>
<td>26–36</td>
<td>Mostly cross-country</td>
<td>10.9</td>
</tr>
<tr>
<td>North</td>
<td>21–32</td>
<td>Trunk, urban</td>
<td>12.8</td>
</tr>
<tr>
<td>Midlands</td>
<td>21–29</td>
<td>Urban, motorway</td>
<td>14.1</td>
</tr>
<tr>
<td>South East</td>
<td>21–34</td>
<td>Cross-country, urban</td>
<td>12.6</td>
</tr>
<tr>
<td>Greater London</td>
<td>19–29</td>
<td>Urban, suburban</td>
<td>14.9</td>
</tr>
</tbody>
</table>

*Type of service — A regional phenomenon*

A fleet of 1800 similar vehicles operated by the Automobile Association is driven by 2200 drivers. Each van is based in one of the regions of the U.K. and all cover about the same distance annually. Thus, a useful statistical survey is possible. Results comparing the actual annual mean consumption with that predicted from short tests described in Table 3 and shown in Table 4 give good correlation.

*Traffic conditions*

Data from the tests described in the two sections immediately above show that, for a given vehicle, *urban* fuel consumption is lower in free flow situations and that for traversing a given road distance, the higher the average speed the lower the fuel consumption. This accords well with data from Australia [5,6] and the U.S.A. [7]. Externally imposed speed limits are seen to have an adverse effect by encouraging “bunching” of dissimilar vehicles, each of which has a different optimum speed.

*Other factors*

Fuel consumption is also seen to depend upon other operating factors including:

(a) cold start, choke operation, manual or automatic (steady running consumption rate was reached in experiments 4–15 minutes after cold start according to weather conditions);
(b) driving style of the individual driver (attitude, state of mind, fatigue);
(c) terrain, choice of road for given journey (types of road, congestion, hills, corners);
(d) time of day or night (traffic conditions);
(e) weather (especially wind but also snow and rain);
(f) unusual road conditions (holiday time congestion, road works, special events); and
(g) vehicle maintenance (e.g. braking system, ignition and carburation settings).

Effect of design

Factors inherent in the vehicle are linked with those discussed above since each car is designed with a certain range of operation in mind. Results of the type shown in Fig. 2 have been obtained for a large number of cars and comparisons made based on a number of design variables.

Vehicle mass

Seen by the authors as the most significant design factor, the vehicle mass has the strong correlation with fuel consumption which would be expected from theory, wherever hill climbing and acceleration is involved.

More than 100 different vehicles were tested to produce the relationships shown in Table 5.

Automatic transmissions were seen to add, on average, 13% in mode 1, 10% in mode 2, 10% in mode 3 and very little in mode 4. Sports cars show poor performance in mode 1 for which their engine curves and gears are inappropriate.

Opportunities for reduction in mass include: (a) reduction in thickness of metal using new alloys; (b) replacement of steel and cast iron by light alloys; (c) replacement of metals by plastics; (d) reduction in thickness of glass; and (e) mass-conscious structural design.

TABLE 5
Fuel consumption related to mass

<table>
<thead>
<tr>
<th>Mode of travel (see Table 3)</th>
<th>Fuel consumption (l/100 km)</th>
<th>Tolerance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Suburban</td>
<td>0.62 + 9.3 m</td>
<td>8</td>
</tr>
<tr>
<td>2 A and B roads</td>
<td>1.01 + 6.9 m</td>
<td>10</td>
</tr>
<tr>
<td>3 Rural</td>
<td>1.44 + 5.7 m</td>
<td>8</td>
</tr>
<tr>
<td>4 Motorway</td>
<td>3.9 + 5.1 m</td>
<td>6</td>
</tr>
</tbody>
</table>

* m = vehicle mass (tonne).

Engine capacity

It is not clear that the relationship claimed in some quarters between engine swept volume and fuel consumption is valid for European cars. Larger engines are mostly associated with heavy cars. A plot of the results from the same 100 cars against the ECE15 fuel consumption shows a range of 30% for
each of the major European engine sizes 1.3, 1.5 and 2.0 litres and, thus, a considerable overlap between these sizes. Indeed the same vehicle with two sizes of engine often gives better economy overall with the larger engine.

**Aerodynamics**
Most significant in high speed operation, the drag depends at a given speed on $C_dA$ (the product of drag coefficient and frontal area). The value of $A$ depends on the style of car, and reduction is limited by ease of access. Care must be exercised in drag reduction as it is sometimes accompanied by increased sensitivity to cross winds.

**Engine design**
One of the most profound effects on fuel consumption has been that of emission control legislation, since this has resulted in lower compression ratio, use of unleaded fuel and moving carburation and ignition from optimum economy settings.

Other features relating to economy include: (a) degree of turbulence affecting cyclic variation; (b) compression ratio; (c) combustion chamber surface: volume ratio; (d) manifold design; (e) thermal loading (new materials allow higher loading); (f) improved carburation; (g) turbocharging; and (h) microprocessor engine management giving optimum ignition and air:fuel ratio at all running conditions.

Because of production lead time there is a long delay before many of these changes can be introduced.

**Other design factors**
(a) Gearing determines the ability of the engine to operate at its most efficient at any road speed and load. A large range of operation can only be covered appropriately by a wide range of ratios. A fifth gear or overdrive extends the economic range but other means such as new automatic transmissions without the energy losses of most existing types are anticipated.

(b) Cooling system, air intake and manifolding design all affect warm-up time. Continuous fan drives are energy-wasting at high speed as well as in the warm-up period.

(c) Advantages of the diesel engine at part-load are not available at full load but a comparison based on required mix of use will show whether a worthwhile gain is demonstrated and Fig. 3 compares the two engine types for a typical vehicle.

(d) Component efficiency and ancillary loads are significant, especially at low engine outputs.

(e) Tyre design provides little scope for improvement since most European cars have radial tyres. Correct pressures are required for maximum economy and safety.

(f) Front wheel drive associated with transverse engine shows a reduction of 15—20% in transmission power loss over hypoid rear axle drive.
(g) Improved roadholding reduces the necessity for fuel-expensive speed changes on corners and bends.

All the above may involve a price penalty which must be traded off against reduced running costs over anticipated life.

MANUFACTURING ENERGY REQUIREMENT

There is a natural reticence on the part of manufacturers to reveal the data necessary for the composition of an overall energy input figure for the construction of a typical car. Personal observation of the procedures employed in a wide range of works in many countries have been combined with published analyses of energy required for individual operations (such as casting iron, manufacturing glass) and studies of the proportions of each material or product in each vehicle.

Figures published by the Japanese Institute of Energy Economics claim a fall from 13.65 GJ per vehicle in 1973 to 10.8 GJ per vehicle in 1978. In comparison, General Motors claims that for U.S.A. and Canada energy per vehicle fell from 40.32 GJ in 1972 to 31.44 GJ in 1978. This is for a vehicle mass 1.8 times that of the Japanese model. Energy per unit mass is lower in the Japanese case but, as only the energy used “in-house” is included, there are differences in the proportion actually used by the car maker. British manufacturers building cars comparable with the Japanese in size claim figures of 22 to 30 GJ per vehicle.
TABLE 6

Relative energy use for steel production (Japan, 1973 = 100)

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>126</td>
<td>115</td>
<td>103</td>
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<td>U.K.</td>
<td>173</td>
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<td>163</td>
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<td>143</td>
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<tr>
<td>W. Germany</td>
<td>140</td>
<td>129</td>
<td>121</td>
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</table>

Materials, components and manufacture

Looking at the major material, steel, representing 350 kg per vehicle in sheet alone, variations in process depending on the age of plant are wide. Table 6 shows comparisons based on the most economical country, Japan in 1973, as 100.

Economies are made by the use of continuous hot casting and by energy recovery from blast furnaces.

For the glass industry the overall figures need to be modified for the product used in cars. Some extra energy is used in the toughening process but the distribution of products is less dispersed than for building glass. Calculations suggest that 29.5 GJ/Mg is an appropriate figure giving 1.15 GJ per vehicle for windows and 0.18 GJ for light units.

Similar detailed analysis has been made for the production of automotive parts from zinc and aluminium alloys, plastics and rubber. In the case of plastics the basic feedstock is itself an energy source and must be included in the true energy cost.

The materials used in vehicles vary in energy use and the proportion of each varies considerably. A typical breakdown of proportions of seven types and energy per unit mass (from 100 to 170 GJ/Mg) has been used in producing figures used later of 118 GJ/Mg. One of the problems with aluminium products is that primary energy requirement depends heavily on the source of the necessary electricity. Often an aluminium plant is located near a hydroelectric power station and the ratio of thermal/electric energy cannot be applied.

Table 7 presents a summary of the authors' analyses of material energy requirements for three typical vehicles.

It is believed that comparable totals for Japanese cars equivalent to the European Medium and Small types would be 56 and 39.6 GJ respectively. The VW figure for materials for a 1977 Golf was 49.4 GJ. Added to the tabulated materials figures are those for the automobile factory itself. The estimates shown exceed those in U.S. and Australia reports which often consider only energy purchased as such by the manufacturer. It is considered that, in the U.K., between 32 and 45 GJ per car are required as gross thermal energy. In addition, energy use for components and suppliers is taken as equal to that of the manufacturer in the typical European production pattern.
TABLE 7

Vehicle energy requirement analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass vehicle (kg)</th>
<th>Gross energy/vehicle (GJ/Mg)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>U.S. compact</td>
<td>Euro medium</td>
</tr>
<tr>
<td>Sheet steel</td>
<td>680</td>
<td>550</td>
</tr>
<tr>
<td>Other steel</td>
<td>252</td>
<td>227</td>
</tr>
<tr>
<td>Cast iron</td>
<td>285</td>
<td>131</td>
</tr>
<tr>
<td>Aluminium (alloys)</td>
<td>52</td>
<td>15</td>
</tr>
<tr>
<td>Lead</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Zinc (+ alloys)</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Copper (+ alloys)</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>Glass</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>Rubber</td>
<td>65</td>
<td>55</td>
</tr>
<tr>
<td>Plastics</td>
<td>72</td>
<td>44</td>
</tr>
<tr>
<td>Paint</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Paper, cloth, board</td>
<td>51</td>
<td>15</td>
</tr>
<tr>
<td>Total materials</td>
<td>1563</td>
<td>1112</td>
</tr>
<tr>
<td>Manufacture</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Suppliers' energy</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Grand total</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

A major advantage is obtained by siting factories in temperate areas where heating and cooling loads are minimised. Further benefit results from building the whole vehicle on one site, preferably under one roof, thus reducing transport energy, factory heating and air changes, and avoiding protection and cleaning of components for transit [12]. Japanese companies appear to gain by following these principles.

Economy measures in production

The major scope for energy conservation in materials and processes is in the following areas.
(a) reduction of mass of material;
(b) simplification of components;
(c) compactness of production plant avoiding movement of sub-assemblies between sites;
(d) double shift use of production facilities;
(e) reduction of manual labour content;
(f) improved factory insulation, door design to reduce heating requirements;
(g) new steel-making methods;
(h) heat recovery from process; and
(i) training employees to save energy.
TABLE 8

Comparison of energy use per vehicle (GJ)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Car and component manufacture</td>
<td>36*</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Spares and repairs</td>
<td>22.5*</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>Fuel and oil</td>
<td>482</td>
<td>594</td>
<td>490</td>
</tr>
<tr>
<td>Garage trade</td>
<td>10</td>
<td>3.6</td>
<td>3</td>
</tr>
<tr>
<td>Roads, etc.</td>
<td>10</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>560.5</td>
<td>657.6</td>
<td>720</td>
</tr>
</tbody>
</table>

*Does not include energy used outside Australia.

CONCLUSION

The energy use of a vehicle comprises the two important areas of manufacture gross energy requirement and energy supplied during use (mainly for fuel). A summary of these findings compared with other workers are shown in Table 8.

The authors' value of running energy use as 62% of the total energy requirement compares with others of 87.5% [11], 90.3% [13] and 76.8% [1].

ACKNOWLEDGEMENTS

The authors are grateful to the Committee and Directorate of the Automobile Association under whose auspices the collection of data by road testing and the visits to industrial sites were carried out and to members of staff who assisted in the gathering and processing of information. The analysis was originally carried out in connection with a Master of Science dissertation at the University of Surrey.

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Energy conservation - transport

A W E Henham
INSTITUTION OF MECHANICAL ENGINEERS


Energy Conservation - Transport

A.W.E. Henham,
Course Director,
Energy Engineering,
University of Surrey,
Guildford GU2 5XH

1.0 Introduction

The energy used in transportation is for 'capital' and 'running' purposes. This paper is concerned almost entirely with the running energy since the opportunities for conservation in capital energy content are not of significantly different type from those for other manufactured articles covered elsewhere in this seminar.

1.1 Energy Use in UK transport

To place this field in perspective as a user of energy, statistics show gradual increases in quantity of energy but more significantly in the proportion of total consumption for all purposes (table 1).

This trend suggests that transport is an activity from which there is considerable national advantage in encouraging energy conservation.

An additional cause for concern is the very high proportion of this energy which derives from petroleum. Table 2 shows the quantity and proportion of oil used for road transport during the period covered in table 1.

As alternative fuels have replaced oil in some other applications, road transport represents a larger proportion of total oil used. This factor requires particular attention as we approach the peak of the oil supply curve. The drop in percentage of total oil in 1984 is caused by increased oil use in power stations during the coal dispute.

1.2 Scope for Energy Conservation

Of more fundamental value than exploring detailed means of reducing consumption of energy per tonne km or energy per seat km, is questioning the necessity for present levels of freight and passenger movement. There is, for example, considerable variation in the distance travelled annually per capita of the population between various countries. In Europe this is from 1200 to 1600 km/capita annum at an average consumption 150 g/km for commercial vehicles and from 3000 to 4000 km/capita annum at an average consumption 75 g/km for private cars (including business use). (2).

1.2.1 Traffic reduction in traditional methods of travel

Possibilities include:

(a) Movement of bulk materials on fixed routes is more energy efficient by pipeline.
(b) Urban organisation can be used on a long term basis to reduce distances travelled by residents between home and work, although this is likely to be of limited value in the UK society.

(c) Industrial organisation can be used to reduce movement of components and sub-assemblies between different locations, a practice prevalent in UK, especially in the motor industry.

(d) Telecommunications developments reduce the necessity for movement of staff between locations for meetings and many other work activities.

(e) Computer routing of transport activities can be used to optimise transport utilisation.

1.2.2 Balance between modes of transport and between energy sources

Estimates of energy use have been calculated for passenger travel and are shown in table 3.

Although the fuels are not identical the calorific values are in a very small range and so table 3 indicates a measure of the fuel utilisation of the various modes of transport for passengers. The necessity for some forms of travel (rail, bus, air) to be supplemented by other forms at each end of the main route must be allowed for in any true comparison.

Similar comparisons are made for freight transport in table 4.

Railways have the additional advantage that on densely used routes, where the expense of electrification can be justified, they are independent of primary fuel source. This enables nuclear resources to provide energy for transport using existing technology.

Choice of mode of transport often depends upon deeply ingrained personal preferences, especially in the case of passenger transport. Private investment in a vehicle is not based on the same financial calculations as an industrial concern would employ. Lifestyle has an unquantifiable effect in this field which would only be affected by considerable price differences in terms of pence/km. These may arise by market changes but government action in terms of subsidies, taxation (e.g. for use of private vehicles in inner cities) and controls are advocated in some circles.

1.2.3 Energy storage

A distinctive feature of the energy requirements of transport is that, with the exception of fixed track systems, the fuel or other energy store has to be carried at the expense of passenger or freight space and mass. The energy/unit mass and energy/unit volume are thus important properties of such energy stores, including the containment required. It is for this reason that transport is claimed to be a premium use of liquid hydrocarbons. In the most serious case, the aircraft has not only to carry its energy store but to lift it off the ground at the beginning of the journey when its mass is highest. A table of relative values for the specific energy of different storage systems is given in table 5 and the subject is dealt with in more detail in reference 7.

2.0 Engineering changes in vehicles and power plant

2.1 Road vehicles

The vast majority of road vehicles employ the internal-combustion engine.
In the UK about half the energy used in transport is by private cars and motorcycles using gasoline, a highly refined product to which lead alkyls have been added as combustion control agents. It is this type of fuel that is most sensitive to changes in methods of manufacture. Diesels will penetrate this market gradually.

2.1.1 Spark-ignition engines

Possible developments include:

(a) Improved control methods for ignition and carburation.

(b) Microprocessor-based engine management systems to optimise items in (a). The success of this could be jeopardised by the adoption of widely differing fuel specifications by various nations.

(c) Stratified-charge engines. These would enable a weaker mixture to be used at part load, a region in which present engines give low efficiency. (9)

(d) Homogeneous lean-burn engines. Possibly this concept would be combined with high compression ratio to give higher output for a given size than would otherwise be the case. (10) Need to retain high ON fuels is a disadvantage unless alcohol fuels (from biomass) become widely available.

(e) Greater knowledge, through new computing and measuring techniques, of the gas exchange and combustion processes in engines.

2.1.2 Compression-ignition engines

Possible developments include:

(a) Wider adoption of turbocharging, at increased pressure ratios.

(b) Improved control of fuel injection.

(c) Reduced cooling (22)

(d) Improved design of combustion chambers, based on methods of (e) in 2.1.1 (e).

(e) Compound cycles (23)

(f) Extended use of direct injection for smaller engines.

References 11, 12 outline some of the problems of these developments.

2.1.3 Gas turbines

Interest in the gas turbine as a potential land transport engine has increased recently with the possibilities of much higher thermal efficiencies than in the first generation of such units. Again the value would be in the wide range of fuels acceptable to power plants using continuous rather than cyclic combustion. (13)

2.1.4 Electric power

Increased use of electric power would render the road vehicle less vulnerable to the very sensitive oil supply situation. With current technology this development is seen as concentrating on the very large proportion of journeys made by the majority of road vehicles at short range from home bases. Considerable effort needs to be added to that already in progress on storage, control systems and motors. Of these the most critical to progress is storage, present day lead-acid batteries
storing about three thousandths of the energy in the same mass of hydrocarbon liquid fuels. Commercial vehicles and public service vehicles are operating using existing methods and rapid development would bring about a useful reduction in oil consumption. (14, 15, 16)

2.1.5 Hybrid systems

Many of the advantages of the electric vehicle can be retained, while increasing the range, using a hybrid system of small prime mover and electricity generation on-board. This engine can run under limited conditions removing many of the problems of transient operation.

2.1.6 Vehicle design

Possible areas for improvement include:

(a) Transmission/power plant matching to allow power unit to work at optimum conditions, especially by development in continuously variable transmissions (24).

(b) Vehicle aerodynamics. This brings greater benefits on long distance, high-speed operation. Improvements beyond a certain point are not possible, especially on small cars, because of the short length.

(c) Lower mass through use of light alloys and reinforced plastics. This is of greatest benefit in urban 'stop-start' motoring. There is an almost linear inverse relationship between mass and fuel economy under these conditions. Less important for heavy goods vehicles where payload is a larger part of total (except on empty return runs).

2.1.7 Road and traffic planning and driver education

Increased awareness of the need to conserve energy is to be expected among those planning road layouts. The avoidance of unnecessarily tight bends, for example, reduces the need for rapid speed changes which are very costly in fuel. Similarly, traffic sequencing in towns to avoid long idle periods and 'stop-start' conditions will reduce both fuel consumption and atmospheric pollution. (17). The effect of both road conditions and driving methods on fuel consumption can be quite dramatic (18).

2.2 Railways

Railways present a different picture since there is effectively only one operator in the UK. Decisions made can be implemented much more widely. Equipment, however, has a much longer lifespan than for road vehicles and so replacement by improved types is inevitably slower. Ref. 4 includes a section on rail transport, while ref.26 presents a recent review of rail energy considerations.

2.2.1 Power units - Compression-ignition

Many of the power unit topics mentioned under 2.1.2 above are applicable to rail diesel engines. Greater efficiency can be expected here since the transients are less severe.
2.2.2 Power units - Electric

Improved motors and control systems could provide a steady, but not dramatic, reduction in energy consumption. Linear motors and devices developed from these such as Maglev would appear to be of limited application in the near future. (19)

2.2.3 Design and operation

Possible areas of development include:

(a) Aerodynamic improvements are of particular value on long distance trains. The length of a train lends itself to good aerodynamics. Improvements have been made by mass and drag reduction resulting in energy savings from traditional to HST and APT designs of 33% and 45% respectively.

(b) Track/vehicle design to eliminate excessive speed variation to negotiate bends. (e.g. tilting coaches).

(c) Reduction in mass, especially for local trains.

(d) Carefully planned operating schedules for acceleration and braking, especially on local trains for which this is a large part of their operation.

(e) Regenerative braking.

(f) Use of battery railcars on branch lines, charged while running part of journey on electrified main line.

(g) Improved access to rail, especially for goods, encouraging use in preference to road.

2.3 Air Transport

This is largely an international form of transport as far as the UK is concerned. Internal air travel is mainly for business purposes where time is at a premium. In recent times British engines have held a larger share of the market than British airframes. Fuel now represents about 25% of the direct operating costs of medium haul routes. Growth in air travel is expected to be greater than for other forms in the next 50 years.

2.3.1 Airframe developments

Improvements are expected (4) to stem from:

(a) Development of materials including new alloys, reinforced plastics, structural methods.

(b) Avionics systems requiring much smaller space and of lower mass.

(c) Advanced active control concepts allowing lighter, lower drag flying surfaces.

(d) Greater aerodynamic efficiency, especially of high lift coefficient wings.

(e) Larger capacity aircraft.

It has been suggested that airships could offer a saving in energy. This is only true when speeds are very much lower than for conventional
aircraft carrying the same loads. The principal advantages of airships lie in their ability to make "beeline" journeys between simple terminals and in their capacity for using alternative energy sources (gaseous fuels, solar and nuclear energy in particular).

2.3.2 Power plants

Any marked improvement in one step appears unlikely but possible changes include:

(a) Use of higher pressure ratios.
(b) Use of higher by pass ratios for some aircraft tyres.
(c) Increase in efficiency of components by careful detailed design.
(d) Exploration of possible alternative fuels, e.g. liquid hydrogen and synthetic hydrocarbons.
(e) Improved engine controls optimising operating conditions.
(f) Better integration of engine with airframe, laminar flow control.
(g) Possible use of propfan engines in certain speed ranges.

Ref.26 indicates the possible scope of various schemes.

2.3.3 Operations

Air transport would appear to have more to gain than other transport forms from more carefully optimised operation. This would include:

(a) Load factor improvement.
(b) More sophisticated computer control to optimise flight path and for air traffic control to reduce time in the air for a given journey.
(c) Route planning to reduce number of flights required.
(d) Improved air-ground interchange and surface connections by economic public transport.

2.4 Water transport

The great majority of international freight movements are by sea representing about 2.5% of world fossil fuel use. Passenger transport is mainly over short distances such as cross-channel ferries between UK and mainland Europe. As for aircraft, fuel represents about a quarter of direct operating costs, more for very large crude carriers.

2.4.1 Hull development

(a) Design changes could reduce fuel consumption of future generations of ships.
(b) Fewer, larger ships would give lower average energy/tonne km values.
(c) Maintenance of underwater surface and new anti-fouling treatment methods could be applied to existing stock.

2.4.2 Power plants

(a) Improved detail design and some cycle modifications could contribute to higher efficiencies in steam and diesel units.
(b) Availability of larger diesels would enable less efficient steam plant to be replaced. Acceptance of lower speeds would allow existing diesel engines to be used in the largest ships.

(c) As oil becomes more difficult to obtain, coal or coal-oil suspensions may be introduced, the latter for use in modified diesel engines.

(d) Design and infrastructure implications of such fuels would need early consideration.

(e) Wind power assistance in various forms is proposed using modern technology. This would be combined with smaller diesel engines which, alone, would handle adverse conditions and manoeuvring.

2.4.3 Operations

(a) Lower service speeds giving lower energy/tonne km.

(b) Improved route planning to increase load factors and to take advantage of sea and wind conditions.

(c) More carefully controlled engine management could provide some increase in overall efficiency with the help of microelectronics.

(d) Inland waterways could carry a larger proportion of traffic further inland than at present at lower energy costs than for land-based methods.

3.0 Conclusions

The IMechE is in a good position to contribute to the public interest in the area of transport energy conservation. It can do this through its meetings, conferences and publications. These activities encourage collaboration between those working for the same objectives, avoid unnecessary repetition and overlap of effort and help to make research, design and development more cost effective. The Institution serves too as a meeting place for those working in various industries, in research organisations, government departments and universities and for those working in research, design, production and operation areas of the same industry. Co-operation with other appropriate societies, for example in the development of alternative fuels, should be pursued.

3.1 National priorities in the transport energy field.

There is a two stage pattern to the development of a more energy-efficient transport system.

(a) In the short term improvements must be sought using existing vehicle types and infrastructure, examples of which are:

- Power plant development
- Lighter structures based on improved materials and stress analysis techniques*
- Improved controls by applying microelectronics
- Better aerodynamics*
- Improved road layout and traffic control
- Optimised operating patterns

*These changes may only be possible in the medium term where vehicle life is longer (e.g. railway stock).
During this stage the special need of transport for a compact and light energy source must be recognised so that it is the priority for limited oil resources.

(b) In the longer term new types of vehicle, power unit and the associated infrastructure will be required. Early expenditure in research, design, development and pilot production will be needed to demonstrate these new concepts. Some of the areas to be covered are:

Replacement liquid fuels (e.g. from coal, biomass) (20)
Engine types adapted to use these fuels (21)
Other power sources and storage systems (e.g. battery-electric, hybrid i.c.e.-electric)
Increased proportion of rail electrification
New vehicle designs

All the above measures have interrelationships with others and only a stated national transport policy will enable the priorities to be effectively evaluated. Each development has implications not only for UK energy consumption but also for export opportunities for UK industry.

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<tr>
<td>Transport energy/10^{18}J</td>
<td>1.09</td>
<td>1.36</td>
<td>1.48</td>
<td>1.43</td>
<td>1.51</td>
<td>1.58</td>
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<tr>
<td>% of gross inland</td>
<td>12.4</td>
<td>14.6</td>
<td>15.2</td>
<td>17.3</td>
<td>18.3</td>
<td>19.4</td>
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<tr>
<td>% of final inland</td>
<td>18.7</td>
<td>21.2</td>
<td>22.7</td>
<td>24.8</td>
<td>26.4</td>
<td>27.7</td>
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Table 1 Data from ref. 1

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<td>Road transport oil (10^{18}J)</td>
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<td>1.01</td>
<td>1.10</td>
<td>1.09</td>
<td>1.11</td>
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<td>% of total transport energy</td>
<td>72.4</td>
<td>74.5</td>
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<td>75.9</td>
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<td>% of total oil, all uses</td>
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<td>22.9</td>
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Table 2 Data from ref. 1
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<thead>
<tr>
<th>Mode</th>
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<th>Assumed Load Factor</th>
<th>Average MJ/passenger km</th>
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<tr>
<td><strong>International</strong></td>
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<td>Aircraft (Airbus type)</td>
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<td><strong>Inter City</strong></td>
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<tr>
<td>Electric Loco hauled train</td>
<td>0.46 - 0.47</td>
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<td>Diesel loco hauled train</td>
<td>0.38 - 0.41</td>
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<td>APT (200 km/h)</td>
<td>0.5</td>
<td>40</td>
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<td>Express Coach</td>
<td>0.20 - 0.26</td>
<td>65</td>
<td>0.4</td>
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<tr>
<td>Scheduled aircraft</td>
<td>2.20 - 3.00</td>
<td>65</td>
<td>3.9</td>
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<tr>
<td><strong>Suburban</strong></td>
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<tr>
<td>Electric train (AC)</td>
<td>0.30 - 0.45</td>
<td>25</td>
<td>1.6</td>
</tr>
<tr>
<td>Electric train (DC)</td>
<td>0.24 - 0.32</td>
<td>25</td>
<td>1.1</td>
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<tr>
<td>Express bus</td>
<td>0.22 - 0.27</td>
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<td>Double decker bus</td>
<td>0.15 - 0.23</td>
<td>25</td>
<td>0.8</td>
</tr>
<tr>
<td>Underground train</td>
<td>0.20 - 0.24</td>
<td>14</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>Rural</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel multiple unit train</td>
<td>0.29 - 0.36</td>
<td>20</td>
<td>1.6</td>
</tr>
<tr>
<td>Single decker bus</td>
<td>0.19 - 0.23</td>
<td>15</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Load</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Occupants</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motorway</td>
<td>0.55 - 0.65</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Urban</td>
<td>0.6 - 0.7</td>
<td>1.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Rural</td>
<td>0.5 - 0.55</td>
<td>1.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Motorcycle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motorcycle</td>
<td>0.94</td>
<td>1.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Moped</td>
<td>0.94</td>
<td>1.0</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 3 Primary Energy Consumption Estimates for Passenger Transport

Data based on ref. 3, 4, 5, 18, 26, 27.
<table>
<thead>
<tr>
<th>Mode</th>
<th>Approximate MJ/tonne km</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RAIL</strong></td>
<td></td>
</tr>
<tr>
<td>Merry-go-round</td>
<td>1.1 - 0.4</td>
</tr>
<tr>
<td>Freightliner</td>
<td>1.6 - 0.5</td>
</tr>
<tr>
<td>Other trainload</td>
<td>1.2 - 0.4</td>
</tr>
<tr>
<td>Wagonload</td>
<td>1.7 - 0.6</td>
</tr>
<tr>
<td><strong>ROAD</strong></td>
<td></td>
</tr>
<tr>
<td>Heavy Lorry (Load over 10 t)</td>
<td></td>
</tr>
<tr>
<td>Bulk materials</td>
<td>2.4 - 1.4</td>
</tr>
<tr>
<td>Bulk chemicals</td>
<td>2.2 - 1.1</td>
</tr>
<tr>
<td>General Goods</td>
<td>3.5 - 0.9</td>
</tr>
<tr>
<td>Containers</td>
<td>2.4 - 0.9</td>
</tr>
<tr>
<td>Delivery work</td>
<td>2.7 - 1.4</td>
</tr>
<tr>
<td>Medium Lorry (Load over 3 t)</td>
<td></td>
</tr>
<tr>
<td>General Goods</td>
<td>2.9 - 1.1</td>
</tr>
<tr>
<td>Tipping</td>
<td>3.2 - 1.3</td>
</tr>
<tr>
<td>Furniture</td>
<td>7 - 2</td>
</tr>
<tr>
<td>Light Vehicles</td>
<td></td>
</tr>
<tr>
<td>Delivery work</td>
<td>24 - 3</td>
</tr>
<tr>
<td>Parcels trunking</td>
<td>5 - 2.4</td>
</tr>
<tr>
<td>Parcels delivery</td>
<td>40 - 10</td>
</tr>
<tr>
<td><strong>WATER</strong></td>
<td></td>
</tr>
<tr>
<td>Coastal Shipping</td>
<td>0.4 - 0.1</td>
</tr>
<tr>
<td><strong>PIPELINES</strong></td>
<td></td>
</tr>
<tr>
<td>Oil pipelines</td>
<td>0.3 - 0.1</td>
</tr>
</tbody>
</table>

Note: The wide ranges given reflect the diversity of users and load factors in each category. The high and low figures are not the extreme limits of energy utilisation.

Table 4 Primary Energy Consumption Estimates for Freight Transport

<table>
<thead>
<tr>
<th>Storage form of Energy</th>
<th>Energy/mass</th>
<th>Energy/volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kJ/kg</td>
<td>MJ/m³</td>
</tr>
<tr>
<td>kinetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>flywheel</td>
<td>77</td>
<td>413</td>
</tr>
<tr>
<td>strain</td>
<td>43</td>
<td>48</td>
</tr>
<tr>
<td>electrical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lead acid cell</td>
<td>120</td>
<td>286</td>
</tr>
<tr>
<td>sodium sulphur cell</td>
<td>790</td>
<td>1 325</td>
</tr>
<tr>
<td>thermal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lithium fluoride</td>
<td>1 810</td>
<td>2 970</td>
</tr>
<tr>
<td>chemical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hydrogen (as hydride)</td>
<td>8 100</td>
<td>7 910</td>
</tr>
<tr>
<td>methanol</td>
<td>18 700</td>
<td>14 840</td>
</tr>
<tr>
<td>gasoline</td>
<td>39 800</td>
<td>30 630</td>
</tr>
</tbody>
</table>

Table 5 Data from ref. 8
Demand-side energy management - transport

A W E Henham
A POLICY FOR ENERGY IN THE UNITED KINGDOM

THE INSTITUTION OF MECHANICAL ENGINEERS
A Policy for Energy in The United Kingdom

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Introduction 1
1 UK energy supply 2
2 Demand-side energy management 4
3 Matching of energy supply and demand 8
4 Conclusions 12
Introduction

The purpose of an energy policy is to support, through proper management of the processes of supply and consumption of energy, the advancement of the economy. The energy consumed in the UK by final users in 1982 had a market value of £30 billion or 11 per cent of Gross Domestic Product. This was comparable with the Social Security expenditure in the same year of £34 billion and almost twice as much as the Defence budget of £16 billion. Two-thirds of the energy, high as it may seem to be, does not properly reflect its crucial importance to many spheres of activity: industrial, commercial, transport, and social.

It is not sufficient that the management of such a vital national resource be left to parochial market forces, particularly as the UK energy consumption in relation to GDP is over 40 per cent greater than in countries such as West Germany and Japan, with which the UK has to compete in world markets. This excess consumption is despite a climate which makes minimum demands on energy for heating or air conditioning. Without an energy policy, the only factor which will encourage effective energy management and reduced consumption will be high energy cost, the very feature that we do not want. It is necessary to limit the cost of energy, desirable to reduce it, and at the same time to use energy prudently. These objectives cannot be achieved without planning and some degree of control.

Sound decision making requires a full understanding of the interaction between the politics and the economics of energy supply and demand. Where this is associated with conservation by the public, sociological constraining factors must also be considered. The energy scene in the UK, as in other developed countries, is poorly balanced. On the supply side is a small number of large, powerful bodies — the Generating Boards, British Gas, the Coal Board, the major oil companies. This contrasts strongly with the fragmented consumer side, which consists mainly of individuals or small companies with only a few large transport and industrial concerns, for all of whom energy is only one part of their livelihood. With such a bias in the decision-taking structure, it is easier to produce more energy than to ensure its efficient use. It is clearly possible for both the big supply industries and the multitude of small consumers to act in their own self-interests in ways which are not consistent and are inimical to the economy of the country as a whole.

The consumer, subject to free market forces, will require a short repayment period for any investment he makes to save energy. The producer will feel compelled to secure maximum financial return for an investment committed many years previously. A national energy policy, expressed by price adjustments and incentives, would create an economic climate for both producers and consumers which will hold the competing demands for investment in production and conservation in reasonable balance and relate both to a long term view of world energy developments.

Government and corporate conventional wisdom has, in the main, allowed prices to influence policies. But after the oil price shock of 1973 there began an energy era in which policies have as much influence on prices as vice versa. This can be understood once it is realised that the large economic rents imposed by OPEC on oil have left a lot of financial leeway for policies on taxes and new energy investments. The degree of uncertainty in forecasting energy futures, for demand or supply, has increased by an order of magnitude. By way of example, the unexpected acceleration of capital costs in response to shock oil price rises caused several casualties in energy investment, such as the cancellation of synthetic fuel projects, despite the high prices of oil and gas.

This new uncertainty in energy futures is enough of a problem in itself, but, when coupled to the lengthening lead times required by most capital projects, it has also disturbed economic thinking. Thus, the traditional view that energy investment should be on the side of surplus, because the economic penalties of surplus are small compared to the penalties of shortfall, is often set aside. The very cause of recent recessions, high oil prices leading to abnormal inflation rates, has also produced adverse side effects, such as a monetary policy of high interest rates which penalises capital projects with long lead times. However, within the timescale allotted to solve this new type of energy crisis, say 20 years, these setbacks must be seen as temporary, and those who make decisions for the long term should not be overly influenced by them.

Next in importance to prices in the economic analysis of capital projects is the discount rate. Strict adherence to Treasury and business guidelines has made the discount rate a very blunt instrument indeed, particularly when it is applied to demonstration plants. It is inconsistent for governments to give grants for research and then to constrain the commercial introduction of the fruits of such research for the sake of a few points in the discount rate. This is particularly true when the value of the product, in this case either increased energy production or decreased consumption, is expected to rise with time.

For the United Kingdom there is an extra factor in energy policies quite unique for a major industrial country — the warm prospect of self-sufficiency in hydrocarbon fuel for some centuries. In the short term there are the options of maximizing oil production now or having a planned depletion policy. There is, effectively, a depletion policy based on high production-related taxes which have led to the postponement or cancellation of some oil field developments. Withdrawal of government sponsorship of the North Sea gas-gathering project will also restrict natural gas production in step with the fall in demand.

In the light of all these factors it is the objective of this document to develop a policy for the supply, conversion, and usage of energy in the United Kingdom. Complete self-sufficiency in energy should not be an objective if this is to be at the expense of economic efficiency. However, some protection against future supply shocks is desirable, and can be provided by stand-by indigenous production and the diversification of energy sources.
1 UK energy supply

COAL
Since the industrial revolution the traditional source of UK energy has been coal. Even as late as the mid-1950s coal supplied 85 per cent of our primary energy. Thereafter, with the advent of cheap oil and natural gas, output fell steadily. In 1982 coal production was 125 million tonnes and contributed 35 per cent of primary energy. The potential contribution of coal to our future energy requirements is very great; known reserves exceed $100 \times 10^9$ tonnes, of which $33 \times 10^9$ tonnes can be recovered using present day practice. Thus more than 250 years supply at current levels of consumption is known to be available without assuming any improvement in extraction rates or discovery of further resources.

There are three problems associated with increasing the importance of coal as an energy source. One is to make coal-burning more attractive to small industrial and domestic consumers by the development of more flexible and automatic appliances, and ultimately its use in fluid form. Another is to achieve the required output of raw coal economically. During the late 1970s the NCB set a production target of 170 million tonnes per year by the year 2000. Due to a levelling off in the demand for energy and a contraction in the demand base for coal, this target now looks both unnecessary and unrealistic, although it has not been officially revised. The importance of opening new, large, more economic mines is thus somewhat diminished but nevertheless remains an essential part of any long term plan for revitalising the coal industry. The third problem is the growing resistance to the use of coal on environmental grounds. It is responsible for much of the accumulation of $\text{CO}_2$ in the atmosphere. It is blamed for acid rain throughout Europe. Transport of large volumes of coal and the disposal of ash will become matters for public concern. The cost of overcoming or minimizing these effects could constrain any desired growth in coal production.

Coal can also compensate directly for some falling-off in the availability of natural gas and oil through the further development of conversion processes. Such processes are already available but their role in the energy scene would be enhanced by improvements in economics and efficiency, greater tolerance in handling a wide range of coals and more flexibility in output mix.

OIL AND GAS
The UK reserves of oil and gas are much more limited and will last for only about 30–50 years at current rates of consumption. This is a key factor in our energy situation which is given added importance because it is not at present possible to substitute other fuels for certain vital applications such as road and air transport and as a chemical feedstock. Unless coal production is increased and a large-scale industry for its conversion to oil and gas established, the UK cannot be substantially independent of the world position. Although world oil reserves are extensive, they will become progressively more difficult and costly to extract. Furthermore, the developing countries can be expected to claim an increasing share of the world's energy supply, in a form which is readily portable.

The UK is now virtually self-sufficient in North Sea oil; the depletion policy of the government is, however, of great importance. Essentially there is a choice between high early production, with its immediate financial benefits, and deliberately delayed production, yielding larger supplies later when world oil is becoming increasingly scarce. The expected recovery in the North Sea of up to 40 per cent is high by world standards, but there is the possibility of improving the technology to increase this. Such development would be of great value to the overall energy mix. Every encouragement should be given by the government to achieve increased recovery and to bring smaller and less accessible fields into economic production.

While gas supplies from existing contracts will begin to decline from the mid-1980s, there is a reasonable prospect of further off-shore purchases to offset this decline for some time. Ultimately, however, a reduction in off-shore gas supplies is inevitable and the gas industry must then either diminish in size or look to other sources, of which the most promising would appear to be the manufacture of synthetic natural gas from coal.

NUCLEAR POWER
In 1982 nuclear power stations produced 5 per cent of the UK's primary energy. The UK has no significant reserves of uranium ore; however, ore-costs at present represent less than 10 per cent of the total cost of electric power from a thermal reactor and it is therefore feasible to purchase significant quantities in advance as a cushion against variations in world price. World resources are considerable and the current world demand of 30 000 tonnes of $\text{UO}_2$ per year is well below the current production capability of 50 000 tonnes per year. Although this situation appears secure, at least until the end of the century, steps need to be taken now to extend the resource base by exploration and to limit long term requirements by the planned development of fast reactors.

The role for which nuclear energy is best suited is to supplement or replace fossil fuels in electricity generation. It is desirable for the UK to have an ample programme of nuclear plant installation to avoid dependence on increasingly expensive fossil fuels next century. The build-up of such a programme and the transfer of coal from power station use to its conversion to oil or gas cannot be matched exactly. Phasing will require constant review of supply and demand for all fuels, careful planning and special financial arrangements.

Less than 1 per cent of the fission energy in natural uranium is released in thermal reactors. The adoption of the fast reactor would enable some 60 times more energy eventually to be obtained from a given quantity of uranium. The present UK store of this material represents a basic energy source for many years' operation and is of such magnitude as to be comparable with our coal reserves.

The precise timing of the introduction of fast reactors will be an economic question decided by the relative capital costs of thermal and fast reactors, and their relative fuel cycle costs as determined by the price of uranium. Fast reactors should be contributing to global nuclear generation for the first half of the next century, on the assumption that fusion reactors, if successful, will become competitive with them before the end of this period.
'RENEWABLE' ENERGY SOURCES

in 1982 hydro power contributed about 0.5 per cent of total energy in the UK. Although there may be a place for small, new hydro-electric plants, these cannot augment the energy supply significantly.

The engineering problems of large-scale harnessing of wave energy are now being appreciated and the latest assessment predicts a unit electricity cost from this source to be an order of magnitude above present levels. Windmills have the least difficult engineering problems of the renewable sources and the design for a 3.7 MW aero-generator with 60m diameter rotor has been completed. The annual load factor from such a machine would be about 30 per cent and some 250 of them would be required to save one million tonnes coal equivalent energy in a year. Most renewable energy sources are intermittent and dispersed, requiring large areas for collection; so they are bound to be capital intensive.

Solar panels are already available for water heating and solar voltaic cells are in an advanced stage of development. Either of these could make a useful contribution to the energy mix. The economics are not very favourable at the moment but can be expected to improve. The exploitation of solar energy via biomass is under development in certain parts of the world. There is a potential reserve in the UK although, with high population density, intensive land use and cool climate, this is limited.

Tidal power sites are limited to very few major estuaries, notably the Severn. The potential energy yield is considerable, but the capital investment is very high. There are also strong environmental implications.

Municipal and industrial waste with an energy content 12 to 18 million tonnes coal equivalent is produced annually in the UK. Incineration with heat recovery is now well-proven and economic in large urban areas. Four incinerator plants in the UK have significant heat recovery from approximately ¼ million tonnes of municipal waste per year. Development work is already in hand to produce waste derived fuel but further work is still required on handling, combustion, and disposal of residues.

It is difficult to say how successful the development of renewable sources of energy will be in the next 20 to 30 years. The best prospects in the UK are anticipated for wind power and for solar heating of domestic water, with geothermal heat a possible third. In the longer term, fusion is so outstanding a prospect that it must be pursued to determine its engineering feasibility. There is a consensus of opinion that it will be well into the next century before the combined contribution of renewable sources amounts to 5 per cent of our energy supply. Their development must be encouraged, but so far they can be regarded as interesting possibilities, not a main component in our fuels policy.
2  Demand-side energy management

Energy management, 'the economic, efficient, and rational use of energy', is as much a demand-side function as a supply-side function. Now that electricity in the UK is generated at near maximum possible efficiency in condensing power stations, and while supply prices for fuels are dependent upon the OPEC cartel, Middle East wars, and deficit financing or intervention in our state prices for coal and gas, the remaining control on the cost of energy is for the end user to be more energy efficient. For this, government must provide a monitoring and financial framework.

In 1982 the UK had an annual expenditure by final energy users of nearly £30 billion, and total estimated maximum recoverable reserves of coal, oil, and gas are probably worth some £2 000 billion (Fig. 1 and Table 1). The UK Department of Energy's 'Delivered Energy Projections 1982' gave forward projections on a 'high' and 'low' total delivered energy by the year 2010 of 7500 and 5400 petajoules per annum, respectively, compared with a current value of 5800. The difference in the projected values is dependent on the degree of energy efficiency achieved and is worth £11 billion in a maximum projected use worth £39 billion. The UK government is therefore faced with a formidable challenge in formulating its policy on energy use so as to bring consumption near to the lower value.

As a country we must not disregard the fact that our use of energy per GDP is poor compared with that of our major industrial competitors. Latest (1982) data from the International Energy Agency indicate that the UK used in 1980 0.80 Mtoe (million tonnes oil equivalent) energy per billion US dollars of GDP. This contrasts with West Germany at 0.54 and Japan at 0.58. Only the USA, with 0.99, has a higher specific energy consumption.

The Departments of Energy and Industry have undertaken comprehensive preliminary audits on the potential for energy savings in the UK and recorded these in the 'Energy Audit Series' and the 'Industrial Energy Thrift Schemes'. They indicate possible savings amounting to some 120 Mtoe (million tonnes coal equivalent) in a total energy supply of 320 Mtoe or 38 per cent savings, thus confirming that the 'low' side projection is credible. Areas of major potential include waste heat recovery, 6–8 Mtoe, and waste as fuel (e.g., incineration with heat recovery), 3–5 Mtoe. A recent study has demonstrated a potential for combined heat and power with district heating (CHP/DH) in nine major cities amounting to 14 Mtoe. This represents about 25 per cent of the full realisable potential in the UK.

Investment criteria for the public sector supply industries for electricity, coal, and gas and the numerous smaller, diversified users of energy very widely. There can be a 5 per cent rate of return over investment periods of up to 25 years for the large supply industries to similar rates of return over 15 years for public sector users, and well under 10 years for private sector investment. In basic terms the difference can be a debt charge of 12–18 per cent for the public sector and 30–40 per cent for the private sector. Regional development grants up to 22 per cent, and grants for coal conversions or selective energy conservation demonstration, both 25 per cent, can help to alleviate this situation, but are often taken as 'the gilt on the ginerbread', with a scheme standing or falling in its own right without them.

### Table 1. 1983 value of estimated energy reserves in UK (maximum recoverable)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value (£10⁶)</th>
<th>Exajoules (10²⁰ joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>33 × 10⁶ tonne</td>
<td>1300 900</td>
</tr>
<tr>
<td>Oil</td>
<td>4.3 × 10⁶ tonne</td>
<td>450 200</td>
</tr>
<tr>
<td>Gas</td>
<td>2250 × 10⁶ m³</td>
<td>250 100</td>
</tr>
<tr>
<td>U_{in}</td>
<td>20000 tonne</td>
<td>1100 2300</td>
</tr>
</tbody>
</table>

What is needed is for government, public sector, and private sector to appreciate that the energy resources of the UK are unique for an industrialised country. We will be self-sufficient in oil and gas for a period of, say, 20 years before starting to import again. We have very large reserves of coal. This, coupled with our high energy usage in relation to GDP, means that we should set aside appropriate finance over the next 20 years to improve our patterns of energy usage, the prize being the difference between the 'high' and 'low' projections equal to some £11 billion a year by the year 2010.

### HEATING AND HEAT RECOVERY

There are many areas in which low temperature heat is rejected. A big energy saving will be made if better control over generation and rejection can be achieved.

One area with such potential is in building design and development. Buildings of all types require at least 43 per cent of total primary energy in low temperature form. Besides the well-known practices of loft, cavity wall, and double glazing insulation, measures to prevent rain penetration of external walls and heat losses from edges and corners could contribute significantly to a reduction in this heat load. In addition, passive heat gains from solar thermal storage, proper orientation of new buildings and houses to take full advantage of winter insolation, and heat transfer from kitchen and hot water tanks could well be cost-effective. Greater use of more efficient lighting systems (fluorescent and sodium vapour) are already offering substantial savings in energy usage.

In commercial premises automatic controls of lighting levels in relation to both sunlight levels and room occupancy appear to offer some electricity savings but await the introduction of an economic system. Already practical are thermostatic and timing controls of heat loads in building complexes, glass houses, etc, perhaps in association with heat recovery of exhaust air streams and variable speed fan motors.

Other near-term developments judged promising include electric heat pumps, small-scale CHP (combined heat and power) packages, heat recovery from hot water effluent, and more sophisticated control of air-condition-
Demand-side energy management

Expenditure by final users

By fuel

- Petroleum
- Gas
- Electricity
- Solid fuels

By sector

- Agriculture
- Domestic
- Transport
- Industry

Sales

By major suppliers

- Oil Companies
  - & others
  - e.g.
  - imported coal
  - & other electricity
  - (6%)
- British Gas Corporation
- CEGB
  - (inc. NCB coal, nuclear & hydro)
- NCB excl. to CEGB

Energy expenditure/ Sales
(£ billion)
ing needs. In the longer term, large-scale CHP with district heating, as in lead city schemes already recommended, will become more economic with respect to fossil fuels and particularly natural gas, when the latter has to be supplemented by coal-derive substitutes. Such economies are dependent on load characteristics, the optimum being a combination of high density domestic and office loads to even out the day/night demand variations. Flexibility in adjusting the heat/electricity ratio is also important, and, here, steam turbines are more attractive than gas turbines or diesels, which is fortunate as coal rather than oil can be used.

In industry, despite widespread heat recovery measures, it appears that much could still be done. Recent government energy audits in industry have revealed an estimated potential for energy savings of 22 Mice per annum, of which 60 per cent would be for waste heat recovery and use of waste as a fuel, amounting to 4 per cent of current UK energy usage. The technology exists for most types of recovery scheme and is less of a problem than financing because of the high discount rate imposed on the extra capital investment. One area where technology is still under development is industrial heat pumps, where a need exists for pumps capable of upgrading low quality heat to a much higher temperature than is currently available (50°C) in commercial or household units. Such heat pumps would be suitable for drying processes, which account for 10 per cent of the total energy used in industry. In the direct use of low temperature heat the past few years have seen considerable commercial use of power station reject heat for fish farming and vegetable cultivation. Low grade heat can also be applied to the biological processing of sewage and to accelerate chemical reactions.

MANUFACTURING AND MATERIALS
The potential for energy savings in manufacturing and materials processing may be classified under the broad headings:
- better housekeeping practices and material flow paths;
- more recycling of materials;
- substitution of low energy materials for high energy materials wherever economically justifiable.

Under 'better housekeeping' some techniques on heat management have already been described but may be re-emphasised in the industrial context: moving large volumes of air at low cost, the recovery and upgrading of waste heat, the optimisation at current energy prices of heat transfer equipment, and elimination of leakages and losses through better insulation.

Many small improvements have surprised plant managers by their large aggregate results, especially in steel manufacturing. Apart from heat management, better housekeeping practices include reduction of friction in machines (tribology), prolonging the life cycle of equipment through conscious management of maintenance (terotechnology), better corrosion control, and smoother flow of materials. In tribology and terotechnology, potential savings have been estimated at about 2 per cent and 1 per cent respectively, of the total energy consumed by industry. The benefits of tribology, in the broadest sense, include longer operating life and reduction in frequency of plant shutdowns and replacement of parts. Better maintenance includes the use of radio-isotopes to detect wear, metal spraying and ion implantation to harden surfaces, vastly greater usage of non-destructive testing, and high-speed cameras for regular monitoring.

Perhaps the most dramatic result achieved has been the wholesale transformation of the steel industry led by Japan, where the widespread use of continuous casting (better flow path) has been responsible for half of the energy saved, while some 20–60 per cent improvement in blast furnace efficiencies was obtained over three years through better coke making and ore blending. Economic incentive was the driving force; in the UK some 22 per cent of the cost of steel manufacture lies in the energy consumed.

In non-ferrous metals, much saving could be achieved through re-cycling, since the reduction of ores to metal accounts for the major part of the energy budget. This is especially so in aluminium, where many decades of work to find a purely chemical process less energy-intensive than electrolysis have so far failed on a commercial basis (although the Alcoa electrothermal process is an improvement).

Generally, new or process scrap metal is easier to re-cycle than used scrap. The latter needs a practicable collection and treatment system. One partial success here is the recovery and detinning of cans from refuse incinerators. The potential for recovering used scrap appears largely untouched. An estimate for copper in the UK suggests that out of the 15 million tonnes consumed between 1920 and 1975 only 100 000 tonnes per year is now recovered.

In the case of material derived from fossil fuel, such as plastics, an appropriate energy saving response, with economic promise, could be its substitution by low energy materials, such as the newly developed tensile cement.

The renewables should perhaps be used to a greater extent. Natural rubber production, for instance, can now be accelerated by ethylene injection of rubber trees to accommodate the fluctuation in market demand, and recent research on the re-use of rubber, especially in the form of used tyres, suggests the possibility of pyrolysis to gasoline and tar.

In the cement and paper industries much energy is expended in cyclic wetting and drying. In the long term new, wholly dry processes should be developed and justified economically to replace these methods. (We may, of course, find alternatives to paper itself). In the meantime, small improvements in existing plants, such as greater use of radiant heat for paper drying and more efficient cyclones for gas-powder heat exchange in cement plants, may be worthwhile. More careful matching of equipment capacity with required performance should be given higher priority than hitherto. Typical savings here are of the order of 15 per cent. The much publicised Exxon entry into electronic motor manufacturing is in this category; new variable speed electronically controlled motors are under development to achieve a constant high efficiency at most load levels.

TRANSPORT
Road vehicles use 76 per cent of the energy expended on transport in the UK, and they are almost entirely oil based, consuming 37 per cent of refinery output. Work on reducing specific fuel consumption, triggered by fuel price increases in the last decade, is well under way. This should result in about 20–30 per cent reduction in a 10 year generation of vehicles. Immediate benefits arise from weight reduction in passenger cars, changing from rear to front wheel drive, engine mixture preparation and
Demand-side energy management

combustion improvements and some attention to aerodynamics.

Future trends, based on research in hand, are likely to be more use of lightweight materials, greater share of the passenger car market for diesels, lean-burn high-compression petrol engines (and possibly some stratified-charge designs), and turbocharged engines at the top end of the range. Greater application of microprocessors in engine management systems will ensure that engines operate at the most economic conditions for each output power required. Eventually, this should apply to the drivetrain, and the more efficient mechanical automatic transmissions under development offer the means of linking this to best effect.

Further, more dramatic, changes may depend upon the economic incentive of even higher oil prices compared with other costs, resulting in the use of hydrogen fuel and in the faster development of electric vehicles and of the advanced battery types which would overcome the problems of short range and long recharging times. Hybrid plants, already successfully demonstrated on a pilot scale for buses, are likely to prove too complex for wide acceptance in private cars.

Traffic density within towns may remain sensibly constant because of the effects of congestion and parking problems and, in the longer term, the more widespread use of electronic communication. Consideration must be given, however, to the population migration to rural areas, recently about 3 per cent per decade, which is resulting in increased annual distance per vehicle and less opportunity to use public transport.

In air travel the strong upward trend in traffic is easing, but, in the long term, is expected to rise at a rate greater than GDP. Efforts to reduce specific fuel consumption now include increased structural efficiency (higher payload/empty mass ratio), improvements in aerodynamics (supercritical wings), new control techniques and engines of higher bypass ratios and turbine entry temperatures. After 1990 more advanced alloys and composites should be available and after 2000 a possible move towards hydrogen fuels. In the interim some gains could result from improved route planning and scheduling.

In shipping slower speeds were introduced as an immediate response to fuel price rises; container vessels were thus able to accept less powerful but more efficient diesels in place of steam turbines. Other current and potential measures are wider use of improved bow designs, ducted screws, reaction fins, and anti-fouling and self-polishing coatings. Less obvious solutions include wind assistance (reported to save about 10 per cent in Japanese experiments). Ocean traffic has increased in the last decade and, based on history, is expected to continue to rise faster than GDP.

The railway system offers one opportunity for travel independent of oil and its future lies mainly in its electrification programme. Major improvements are already in progress for improved efficiency of intercity and suburban services, the latter depending upon lighter structures and improved electric motor control systems. Any means of reducing the cost of rail freight and passenger transport is potentially an energy saving device since traffic may then be diverted from roads. This improves the efficiency of the remaining road traffic through removal of congestion and carries the load by rail at improved figures of fuel used per passenger or tonne kilometre.
3 Matching of energy supply and demand

Following the review of the current problems of energy production and consumption, and then the potential for energy conservation, we are left with trends in both supply and demand which may not be consistent with each other or with continued improvement in the economy. This chapter is concerned with the criteria to be adopted and actions to be taken in matching supply with demand, not only in quantity of energy, but also in the form in which it is available for use.

Investment decisions in the energy field have generally been directed toward four objectives of changing priority. These objectives are continuity of supply, minimization of cost, protection of the environment and spreading of risk. They are not always achievable without compromise, because of limited availability of funds. Before 1973, minimization of cost and protection of the environment had priority. After 1973, in the aftermath of the oil price rise and fears of politically induced cuts in production, continuity of supply and spreading of risk became the most important in government and industry thinking. However, it must be expected through experience that one might get better at preventing shocks and dealing with their consequences, through measures such as proper stock policies and political realignment. Evidence for this, measures is at hand and it is therefore, probable that minimization of cost may again become the dominant objective, with spreading risk as a secondary one.

Given these objectives, certain future supply patterns will emerge with a reasonable measure of self-consistency. Thus, some coal imports, increasingly steadily until the oil becomes a price leader, are obviously desirable to help minimize the costs. Coal imports may not at present be permissible for government-owned utilities and steel producers, but should be no barrier to other industrial users. Further nuclear penetration in the generation of electricity is consistent with minimization of cost and spreading of risk. Similar objectives will demand the oil use be shifted to the premium markets of transport and feed stocks, the latter being a special case where wet gases from the North Sea oil fields are likely to play a major role.

Gas consumption is now governed by price-induced conservation so that growth of demand has been reduced to a pace more in keeping with that of a mature market. This has caused the electricity/gas price ratio to drop towards the pre-1973 level and thereby allows electricity to compete on its former basis. Coal-fired district heating and combined heat and power generation should now be competitive with gas earlier than was projected in the Marshall Report.

Present government 'ground rules', tantamount to an energy policy, are:

- gas prices are to become a substantial fraction of the world oil price, per unit of energy, despite the small production costs;
- crude oil prices should match OPEC African levels;
- coal prices may reflect miners' strengths due to producers' current share of the market;
- petroleum product taxes will encourage a shift away from oil;
- electricity prices should reflect rising fossil fuel costs and self-financing of forward investments.

As and when these policies are modified the pattern of supply will alter. For instance, if the real price of gas were to rise further, the time could come when coal gasification, partly using imported coal, would be a viable option. A controlled depletion policy for oil would mean that substitutes would be required earlier, but the pace of introduction could be more leisurely. If coal import quotas are steadily relaxed, industrial demand will be boosted. If excise duties on diesel oil became somewhat less than for petrol, as in some EEC countries, then there should be more efficient fuel use in private transport. If electricity prices continue to reflect full forward investment costs, then growth in electricity demand will fall and coal consumption likewise.

These issues are likely to dominate the UK energy scene for the next 20 years rather than gross effects such as resource exhaustion. However, early in the next century, domestic reserves of oil and gas are bound to decline and additional policies, such as the fiscal encouragement of electric vehicles, would almost certainly be needed. Even economic coal reserves could be under pressure, accelerating the shift to nuclear fuel and coal imports.

Decreasing natural gas production is likely to be offset, partly by switching to electricity and partly by coal gasification and LNG and liquefied SNG imports. If imported LNG incurs a higher landed cost than switching to electricity, it would appear desirable that the distribution cost be subsidised since it is inconceivable that the pipeline network, representing an important element of the risk spreading objective, could be allowed to fall into disuse. With uranium the supply to the UK is, and will be, very much dependent on world market conditions, for which any big price increase can only be countered by technological change, namely switching from thermal to fast breeder reactors.

Uncertainties in future supply methods can be reduced through selective government and industry funding for research, development and demonstration and by encouragement of proven energy-saving schemes. However, the course of events to be influenced by such funding, other than for proven energy-saving schemes, cannot always be secured. Since research and development are essentially 'seeding' operations, no amount of support could bring forward the desired chemical application if a new system is not yet viable. Most of the renewable energy sources are in this category: the timing of their commercial introduction depends on cost savings in displacing coal-burn in electricity generation, and could be delayed further if quantities of coal were to be obtained from cheaper pits. Similarly, in competition with thermal reactors, the viability of a breeder reactor with a capital cost higher than that of a thermal reactor would depend on the current and projected cost of uranium.

It is fundamental that the oil price rises of 1973 and 1979/80 have begun a new energy era. With oil now priced at an arbitrary level within the economic bandwidths of near substitutes, it is clear that future supply patterns will see greater production of these substitutes, including very heavy oil, liquefied natural gas and reconversion to coal burning (in applications such as cement plant). These are relatively straightforward changes in response to the 1973 shock. More capital intensive solutions (substituting capital for energy) will include the exploitation of shale
oil, enhanced recovery of oil, nuclear power, gasification and liquefaction of coal, CHP, and heat pumps, which are all becoming competitive.

Analyses since 1973 have revealed at least four distinct mechanisms that govern market behaviour in regard to the substitution of one energy form for another. These may be identified as the dynamics of resource depletion, market share, prices, and costs.

In ‘depletion dynamics’ it is first observed that the unconstrained production profile of an exhaustible resource is typically Gaussian in shape. Unconstrained demand, however, has an exponential profile. Thus production will be unable to satisfy demand not at the peak of production but earlier, when the rate of growth of production begins to fall. This occurs at about half the peak and is clearly the latest moment for the introduction of substitutes unless demand is abnormally constrained.

For conventional crude oil there is ample evidence that the critical point was reached in the mid 1970s and may have contributed to the increase in price, the reason being usually given as ‘oil is being exhausted at too high a rate’.

In ‘market share dynamics’ the study of several cases has shown that once a new supply sector technology captures more than 10 per cent of the market its share will accelerate at the expense of competing sectors until some indeterminate limit, say half of the total market, when it could begin to decline. In this way, oil displaced coal in the 1950s. Reasons for the phenomenon come from the maturity, and hence reliability, of the technology, which enable the economics of scale to apply and investment finance to be obtained more cheaply, so increasing profits and securing the future of the technology.

It is worthy of note that nuclear power now accounts for 3 per cent of total primary energy consumed in the UK, and is not expected to reach 10 per cent until the mid 1990s.

‘Price dynamics’ attempt to show, through technical mechanisms, as distinct from fundamental factors such as resource exhaustion, how it was possible for oil producers to raise prices so sharply in 1973/74 and 1979/80, and how these mechanisms could be employed again for resources other than oil. The cartel-like actions of OPEC in these two periods were only possible because of coincident dominant features such as (a) their sustained loss of real earnings and dollar reserves due to US inflation and exchange losses, and (b) a temporary surge in demand due to a rush to stockpile, resulting in spot prices much higher than contract prices. While the existence of OPEC is a factor, a formalised cartel is probably not necessary for pricing intentions to be known rapidly, providing producers are few in number.

‘Cost dynamics’ are the newest of the four mechanisms and attempt to explain the rather unexpected way in which capital costs can escalate out of all proportion to general inflation in a period of sharp rises in energy costs. As soon as the price of oil rises to make synthetic oil economic, the plant costs escalate to make it uncompetitive again. This occurred after both the oil price increases and is now partly responsible for the cancellation of several synfuel projects. These cost escalations are variously ascribed to the energy cost components of the plants, to increases in labour and management costs higher than inflation rate, and to high interest rates. However, some programmes with sufficient momentum and economies of scale, such as the French nuclear programme or the conversion of cement plants to coal-firing in Japan, appear to have escaped such cost escalations.

These four dynamic mechanisms taken together will influence the balance of supply and demand across a matrix of supply sectors (oil, gas, coal, nuclear, and renewables) and consumption sectors (domestic, industrial, commercial, and transport). These mechanisms are complex and increase the difficulty of making forward predictions, but the outcome should be more credible than traditional linear or exponential extrapolation. The projection of UK primary energy consumption given in Table 2 is a result of the application of the mechanisms just described. Credibility of this scenario may be judged by the projected per capita consumptions presented in Table 3.

### Table 2. Projected UK primary energy consumption

(1 exajoule = 10^18 joule)

<table>
<thead>
<tr>
<th>Year</th>
<th>Exajoule/year</th>
</tr>
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<tbody>
<tr>
<td>1980</td>
<td>9.3</td>
</tr>
<tr>
<td>1990</td>
<td>10.5</td>
</tr>
<tr>
<td>2000</td>
<td>12.05</td>
</tr>
<tr>
<td>2010</td>
<td>12.8</td>
</tr>
<tr>
<td>2020</td>
<td>12.4</td>
</tr>
<tr>
<td>2030</td>
<td>11.75</td>
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</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Exajoule/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>3.9 4.1 3.9 3.3 2.7 2.2</td>
</tr>
<tr>
<td>Gas</td>
<td>1.9 2.0 1.9 1.4 0.85 0.5</td>
</tr>
<tr>
<td>Coal</td>
<td>3.1 3.6 4.5 5.2 5.4 4.9</td>
</tr>
<tr>
<td>Nuclear</td>
<td>0.36 0.75 1.6 2.6 3.0 3.5</td>
</tr>
<tr>
<td>Renewables</td>
<td>0.04 0.05 0.15 0.3 0.45 0.65</td>
</tr>
<tr>
<td>Total (rounded)</td>
<td>9.3 10.5 12.05 12.8 12.4 11.75</td>
</tr>
</tbody>
</table>

### Percentages

<table>
<thead>
<tr>
<th>Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>41.9 39.2 32.7 25.8 21.8 19.0</td>
</tr>
<tr>
<td>Gas</td>
<td>20.3 19.4 15.8 11.1 6.8 4.3</td>
</tr>
<tr>
<td>Coal</td>
<td>33.4 34.1 37.3 40.7 43.2 42.1</td>
</tr>
<tr>
<td>Nuclear</td>
<td>3.9 6.9 13.1 20.0 25.8 29.9</td>
</tr>
<tr>
<td>Renewables</td>
<td>0.5 0.4 1.2 2.4 3.6 5.7</td>
</tr>
</tbody>
</table>

### Net imports

<table>
<thead>
<tr>
<th>Type</th>
<th>Exajoule</th>
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</thead>
<tbody>
<tr>
<td>Oil</td>
<td>0.5 1.2 3.6 4.9 4.6 3.2</td>
</tr>
<tr>
<td>% of Primary</td>
<td>5.6 11.4 30.2 38.3 36.9 27.8</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td></td>
</tr>
</tbody>
</table>

(1) Includes non-energy use and transfer to bunkers. Reduced by 0.27 Exajoule by 2030 if half of aviation requirement met by hydrogen (produced from nuclear heat).
(2) Excludes SNG.
(3) Includes coal for liquefaction and gasification.
(4) Includes nuclear heat for coal liquefaction and gasification, refinery and oil fields nuclear heat.
(5) From fuel equivalent of electricity generated.
(6) Includes pipeline gas and uranium for thermal reactors.
Table 3. Projected UK per capita energy statistics

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Population (millions)</td>
<td>55.9</td>
<td>57.6</td>
<td>59.4</td>
<td>60.6</td>
<td>61.8</td>
<td>63.0</td>
</tr>
<tr>
<td>GDP/capita (£ 1980)</td>
<td>3990</td>
<td>4810</td>
<td>5800</td>
<td>6800</td>
<td>7960</td>
<td>8970</td>
</tr>
<tr>
<td>Index</td>
<td>100</td>
<td>121</td>
<td>146</td>
<td>171</td>
<td>200</td>
<td>225</td>
</tr>
<tr>
<td>Primary energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GJ/person</td>
<td>165</td>
<td>181</td>
<td>202</td>
<td>214</td>
<td>203</td>
<td>189</td>
</tr>
<tr>
<td>tce/person</td>
<td>6.3</td>
<td>6.9</td>
<td>7.6</td>
<td>8.1</td>
<td>7.7</td>
<td>7.2</td>
</tr>
<tr>
<td>Index</td>
<td>100</td>
<td>109</td>
<td>122</td>
<td>130</td>
<td>123</td>
<td>115</td>
</tr>
<tr>
<td>Delivered energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GJ/person</td>
<td>118</td>
<td>123</td>
<td>137</td>
<td>139</td>
<td>132</td>
<td>121</td>
</tr>
<tr>
<td>Index</td>
<td>100</td>
<td>104</td>
<td>116</td>
<td>118</td>
<td>111</td>
<td>102</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generated (MWh/person)</td>
<td>4.5</td>
<td>5.9</td>
<td>8.0</td>
<td>10.0</td>
<td>11.3</td>
<td>12.0</td>
</tr>
<tr>
<td>Index</td>
<td>100</td>
<td>130</td>
<td>176</td>
<td>221</td>
<td>248</td>
<td>263</td>
</tr>
<tr>
<td>Capacity (kW/person)</td>
<td>1.23</td>
<td>1.40</td>
<td>1.69</td>
<td>2.04</td>
<td>2.17</td>
<td>2.23</td>
</tr>
<tr>
<td>Index</td>
<td>100</td>
<td>114</td>
<td>137</td>
<td>166</td>
<td>176</td>
<td>181</td>
</tr>
</tbody>
</table>

It is assumed that price-controlled demand will still largely dictate supply patterns, as before 1973, but with the important difference that a large part of the price structure will be set up, and perhaps altered from time to time, by Governments. Detailed projections altered from time to time, by Governments. Detailed projections arising from such an exercise for individual supply sectors follow.

OIL
A near constant demand to the end of the century, followed by a steady decline, is now the most probable demand profile. This may conceal many internal changes, such as decreasing demand for heating oil offset by increasing demand for private transport. In power generation new oil capacities have recently been commissioned but could still be economic for peaking and load-following generation. Electric road vehicles and hydrogen powered long range aircraft are the most likely ways to reduce oil demand after 2000. In supply terms indigenous coal liquefaction, even of the allothermal kind using nuclear heat, cannot possibly compete with imported coal-liquids produced in cheap coal countries like Australia, and only a small insurance programme of plants appears justified. Scottish shale oil is unlikely to be economic since most of the high grade shales have been exhausted. Possibly the best prospect for prolonging supply after the decline of North Sea conventional oil production (including enhanced recoveries) is the discovery of oil under the deep ocean floor, where the tenfold increase in water depth will require sub-sea production systems. Imports of conventional and heavy crude will remain a practical option well into the next century, though in declining quantities.

GAS
Demand for natural gas will soon saturate because of price-induced conservation measures (of which a pro-

mising technology is the heat pump) and limitations imposed by density of consumers. This will remove the need for rapid off-shore development, so that a relatively strain-free depletion policy is likely.

New Norwegian supplies will not in future be so easy to obtain due to competition from Europe: LNG imports will be costly in energy as well as money and will probably serve peaking loads only. However, SNG production using indigenous as well as imported coal should be competitive with LNG imports and could well form, at the turn of the century, the second largest source of supply after indigenous natural gas. In second generation plants SNG could be more economically produced using nuclear heat with coal only as feedstock. If this promise is fulfilled, SNG could form the bulk of supply by 2030. Otherwise, the gap caused by the decline of indigenous off-shore gas would have to be filled, expensively, by LNG imports.

COAL
Coal has, since 1973, regained its former competitive edge vis-a-vis oil, but in the meantime, the demand for cleaner secondary fuel has moved to a level beyond consideration of costs alone. The direct use of coal in large quantities in industry, offices, and houses will require highly efficient gas cleaning or scrubbing, or will have to await the commercialisation of processes such as fluidized bed boilers which can transform coal into cleaner, usable energy. This is an example of the importance of technological change in determining the supply demand balance. Thus, to a large extent, this technological change reflects an environmental cost, albeit one which in the short to medium term admits to economically acceptable solutions. However, in the long term, some way into the next century, control of sulphur and nitrogen oxide and carbon dioxide emissions may be necessary to minimize environmental and climatic distortions. In this regard there does not appear to be any viable technological 'fix' and the growth in coal usage will, in all probability, have to be considerably curtailed.

On more specific issues, there is a possibility that through district heating and CHP schemes, coal usage in the home and office heating and the industrial sector may be revived. In industry, excluding coking coal for steel, use in boilers as substitute for oil and gas appears inevitable, though the rate of increase is bound to depend strongly on the stability of the mining industry and whether foreign coal is freely admitted. Coal burn for power generation will, on the basis of risk spreading, remain substantial even with nuclear competition, and may eventually account for some 35–40 per cent of electricity's primary fuel.

NUCLEAR
Given a continuing cost advantage over coal, nuclear energy, either as electricity or heat producer, should take an increasing share of the primary energy market: 13 per cent by 2000 and 30 per cent by 2030.

In responding to demand the main advantage of nuclear energy is that its supply is more akin to a manufacturing operation than is the extraction character of the other sectors. This means that, given the political will, as in France recently, the rate of growth can be rapid (over 30 per cent/year) and can therefore better match demand under shock conditions.

With the modest objective to diversify from excessive dependence on coal, a programme of one thermal reactor
Matching of energy supply and demand

A station a year is envisaged until summer nuclear capacity exceeds minimum summer demand, about 2010.

Breeder reactor development is now to be undertaken jointly with the other countries of Europe, with one demonstration plant in the UK before 2000. Fully commercial plants will be operational by 2010 and, with anticipated rises in uranium prices about then, reactor ordering should switch from thermal to breeders by 2020.

High temperature reactors for coal gasification may have to be developed under licence before 2000 when natural gas production declines and the import of LNG on a large scale is resumed. Initially, coal gasification uses the autothermal process where 40 per cent of the coal is used to heat the reactions, but even as early as 1995 the economics of nuclear heat will show an advantage and development will only be constrained by the lack of a continuing HTR programme. Coal liquefaction represents a much smaller programme (due to cheaper coal-liquid imports). Only two HTRs are envisaged for 2030.

**RENEWABLE ENERGY SOURCES**

With the exception of hydro power, most renewables are classified as negative demand in that their proper economic role is seen to be the displacement of fossil fuel. This is a significant change from the earlier role of generation plus storage to give base load operation. The prime reason for the change is that the elimination of storage greatly reduces the cost of renewable energy, although the energy available may not always be utilised. While the ratio of fossil capacity to renewable capacity is large, it is unlikely that any renewable energy will be lost because of lack of fossil displacement capacity. It should be noted that it is fossil fuel consumption, not capacity, that is being replaced.

Since unit generation costs of renewables are almost entirely made up of capital depreciation, a utility would want to have much greater assurance of the plant's useful life span. If, for example, a wind generator collapses after only serving half its stated life, the unit generation costs would be doubled. The implication of such uncertainty is that either development will be very slow, to accumulate experience, or that high insurance premiums must be paid.

Given the above factors, and especially the economics of displacing coal generated electricity, renewables will only have a big impact when coal prices rise substantially, probably after 2000.
4 Conclusions

(a) An energy policy is required to secure a reasonable balance of investment between energy production and efficient energy consumption to support continued growth in the economy. The UK is currently profligate of energy, not only in the total amount consumed, but also in the cost which many consumers are required to bear.

(b) Because energy is becoming more expensive and there is expected to be a shortage of premium fuels, the first need of an energy policy is to ensure security of supply. The most significant resource problem during the next half-century will be the material depletion of oil and gas reserves, first in the UK and then worldwide. This will call for the development of substitutes for these fuels or the conversion of energy consumers to use alternative fuels. Such developments will require an impartial study of future needs and of the cost benefit of alternative investments.

(c) Secondly, it is desirable that the energy demands of the UK be met at an acceptable price. In some industries the cost of energy is a dominant factor, but in most of them energy does not represent a sufficient fraction of costs to warrant serious complaint. Established practices, safety requirements, social obligations, and even political obligations can add materially to the price charged to the consumer. These costs might be held in check if producers are made accountable for their major decisions to a government-appointed technical body.

(d) Thirdly, the effect of energy consumption on the environment is now gaining in importance. The operation of energy related processes and the disposal of their wastes are attracting attention which will have to be taken fully into account in future energy plans.

(e) Coal is the UK’s most abundant energy resource and every effort should be made to convert to its use in an efficient and environmentally acceptable manner. Oil and gas are already too valuable to be used in anything but high added-value industrial processes, transport, and the localized heating sector (preferably at true market cost). Nuclear power should be pursued in the knowledge that it will provide a cheaper and environmentally preferable source of electricity. Renewable energy sources, of which wind and tidal power seem the most promising in the UK, could all contribute in favourable situations. Their development should also be pursued.

(f) For the efficient exploitation of energy from these sources, many economic and proven devices are already available. These include insulation, low energy lighting, optimising controls, improved firing systems and combustion engines, combined heat and power, combined cycle plant, waste incineration, and process heat recovery. Developments in heat pumps, fluidised bed combustion, and low energy materials should all provide an economic return within a few years.

(g) The commercial effects of many technical decisions being made in the energy field will only be felt in the long term, beyond the timescale in which market forces operate. This places a heavy responsibility on the few large and influential energy producers who can be expected to promote growth in their own energy sector and to foster only lines of development that they themselves have conceived. It will not be easy to carry out an objective cost benefit calculation on schemes they put forward.

(h) The economic success of the UK now depends increasingly on the efficient production and use of energy. Accordingly, the Government, while seeking the advice of specialist organizations working in the field, will wish to know that proposals they make will lead to a proper balance between:
   - creation of real wealth;
   - wise allocation of existing resources;
   - international competitiveness;
   - safety and environmental protection.

(i) For this reason it is strongly recommended that a Royal Commission be appointed, with members experienced and competent in all energy fields but independent of the main vested interests, to oversee the policy of energy in fuel producing organizations and, to a lesser extent, consumers.

(j) The terms of reference of such a Commission should be:
   - to set objectives for reinvestment in all energy sectors of the profits from sales of energy and of any government subventions;
   - to determine financial and fiscal incentives which will encourage a move toward lower UK energy consumption in relation to industrial output;
   - to advise Government on legislation for energy efficiency in new buildings, energy management in business concerns, and the disposal of waste which can be burnt or recycled.

(k) The Commission should have a full-time staff sufficiently qualified to examine and interpret any proposals put in front of it. It should also be empowered to call for technical studies where necessary to frame the policies to be pursued.
The performance of a divided-chamber, single-cylinder, engine with lean methanol mixtures

R A Johns & A W E Henham
THE PERFORMANCE OF A DIVIDED CHAMBER SINGLE CYLINDER ENGINE WITH LEAN METHANOL MIXTURES

R A Johns and A W E Henham
Department of Mechanical Engineering, University of Surrey, Guildford.

SUMMARY

Small diesel engines are in common use for electrical power generation in many remote areas. These engines may be readily converted to burn alternative fuels such as alcohols which may be produced locally from indigenous raw materials. The highly turbulent combustion chambers in these rugged engines are ideally suited to burning lean, spark-ignited mixtures thereby improving economy whilst reducing exhaust emissions. This paper describes the conversion of a 7.5 kW divided chamber engine to spark ignition and its combustion performance with lean methanol mixtures. The influence of equivalence ratio on burning rates and stable operation in the lean burning regime is compared for M100 and iso-octane using a computer combustion model to analyse experimentally acquired pressure data. The results indicate that these engines may be run successfully on M100 with stable operation extended further into the lean burning regime through reduced delay periods and higher burning rates.

1 INTRODUCTION

The most widely used small engines, of less than 10 kW, in Third World Countries are those developed, and often built, in industrialised countries. They are usually single or twin cylinder, spark-ignition (two or four-stroke) or compression ignition (four-stroke) types. Such engines are only equipped to prepare and burn the traditional refined hydrocarbon fuels - motor gasoline and gas oil respectively. Certain small spark-ignition engines are available additionally in forms able to use lpg and, with low compression ratio, kerosine where this is widely distributed for other purposes such as cooking. All these fuels are, of course, linked to the World oil market. For the many developing countries dependent upon imported petroleum, their use involves the problems of fluctuating prices of crude oil and products, and the generally declining value of most local currencies against the dollar.
1.1 Alternative fuel-engine combinations

The traditional types of spark-ignition engines used for stationary applications and for small agricultural transport are often of low compression ratio because the hydrocarbons available locally have a low research octane number (RON). Consequently they have low thermal efficiency. The basic engines could be converted to run on fuels locally produced from biomass, e.g. alcohols and methane. In order to derive maximum benefit from the better anti-knock properties of methanol, ethanol or methane, RON = 114, 111 and 105 respectively (1), it is necessary to increase the compression ratio. Many engines in current use have limited bearing areas and employ primitive bearing types and lubrication systems to simplify production and reduce first cost. In these cases they are not suitable for increased combustion pressures. In a period of establishment of the facilities to produce and distribute alcohol, methanol may be used as a gasoline extender (M10, for example, being 90% mogas, 10% methanol) yielding RON values greater than those of the gasoline itself (2).

Existing diesel engines on the other hand, are designed for high compression ratios of the order 20, so are more rugged. Their continued use in the situations under consideration depends upon the undiminished availability of conventional hydrocarbon fuels of cetane number (CN) of 40 to 50.

The consumption of these fuels can be reduced by the adoption of dual fuel engines using a weak methane air mixture and pilot oil injection to initiate combustion. The complexity of this system is only justified for relatively large engines used where the gaseous fuel is cheap and widely available. Synthetic liquid fuels from coal can be produced at efficiencies up to 56% (3) but, after treatment to give a suitable CN, these efficiencies fall to 30 to 50% according to the type of process (4). Methanol has the opposite properties to those required, having CN = 3 (1). Additional problems are anticipated through increased demand for middle distillate output from refineries throughout the world. In view of these points the small diesel engine does not offer the best prospect if independence from market pressures is required.

1.2 Combustion systems

It can be concluded from 1.1 that the engine type with the broadest range of possible fuel options for the application outlined is the spark-ignited, four-stroke engine. This leads to consideration of the exact combustion system to meet the purpose best.

Two combustion systems are widely advocated for future spark-ignition engines. The first of these, having been researched in various parts of the world for some years uses a stratified charge. Involving, as it does, either a fuel injection system or parallel streams of carburation for rich and lean mixtures, this is regarded by the authors as too complicated for this application. Control incorporates mixture homogeneity variation thereby adding further cost.
The second approach is the high compression ratio, lean burn engine. This has the advantage of high thermal efficiency and the use of methanol enhances the operating range and combustion quality when compared with mogas. This derives from its higher RON and its ability to extend the lean mixture limit. This type of combustion system requires a turbulent chamber for consistent results. This can be achieved either by a pre-chamber or by compact open chamber. The authors are working with both types, using for this purpose single cylinder, four-stroke engines converted from diesel operation by the addition of carburation and ignition equipment.

Only the pre-chamber type is described here as this is the type most readily provided by minimum alteration of existing rugged diesel engine structures and mechanisms in widespread use. Although a programmable electronic ignition system is used, together with an adjustable constant vacuum carburettor, for experimental purposes, simpler systems would suffice in a production conversion kit.

2.0 ENGINE MODIFICATION

The single cylinder 7.5 kW Farymann diesel engine used in these tests had been converted previously to a variable compression engine by the installation of a contra-piston to vary the volume of the 16 mm radius spherical pre-chamber as shown in Fig 1. Compression ratios ranged from 12 to 22:1. A steel plate and annealed copper gaskets were inserted between the cylinder head and the block to reduce the compression ratio range to 8.6 to 12:1. The engine was converted to spark ignition by installing an SU carburettor and an electronic ignition system which is shown schematically in Fig 2. A degree and BDC encoder, fitted to the camshaft, is used to trigger a proprietary electronic ignition unit through a programmable timing interface; the ignition timing being set with programmable TTL downcounters.

Noguchi et al (5) reported that tests on a Toyota divided chamber engine indicated the optimum position for the spark plug as in the neck of the turbulence generating pre-chamber. This position enabled stable operation to be extended further into the lean burning regime. The cylinder head geometry of the Farymann engine, however, precluded optimisation of the spark plug position and it was fitted into the original tapping for the injector. Methanol has a high enthalpy of vaporisation, 1105 kJ/kg, and to avoid the formation of ice in the carburettor an electrical heating element was fitted in the air inlet duct. Whilst acceptable in a test rig, attention needs to be given in a commercial application to the design of an inlet duct with adequate heat transfer from the exhaust to the fuel mixture.

3 TEST RESULTS

3.1 Data acquisition

Cylinder pressures were measured at each degree of crank-angle using a Kistler 7055B piezoelectric pressure transducer which was fitted into the face of the contra-piston. The analogue signal from the
5077 charge amplifier was converted into a 10-bit digital signal in the A to D converter of a Datalab Transient Recorder and stored in memory for subsequent reduction on the University's Prime 750 computer installation. The acquisition system is shown schematically in Fig 2. As the memory available was limited to 4K an electronic interface was built into the data recording system to enable the transient recorder at 120° BTDC and to disable it at 120° ATDC during firing strokes. The data recorded was thus maximised at 16 consecutive cycles.

3.2 Cyclic dispersion

Typical pressure-crank angle recordings for the combustion of methanol at a compression ratio of 9:1 and equivalence ratios varying from 0.8 to 0.6 are shown in Fig 3. The extent of cyclic variation in maximum cylinder pressure increased significantly as operation in the lean burning regime was extended below an equivalence ratio of 0.8. Stable operation was not possible with equivalence ratios below 0.7. The cyclic variations in combustion were quantified by evaluation of the cyclic dispersion which was defined as the ratio of the standard deviation to the mean value of the maximum cylinder pressure for the cycles recorded:

\[ a = \frac{s}{p} \]

The influence of type of fuel and equivalence ratio on the cyclic variation in maximum pressure is shown in Fig 4. For the base-line fuel, iso-octane, the cyclic dispersion increased from about 4% with stoichiometric mixtures to over 30% with equivalence ratios of less than 0.85; the limit to stable operation being at about 0.9. With methanol it was possible to extend stable operation further into the lean burning zone to an equivalence ratio of about 0.8 before the cyclic dispersion increased to 5%.

3.3 Engine combustion model

The combustion performance was analysed by computing the instantaneous mass burning rate at each degree of crank angle from the experimentally acquired cylinder pressure data for each cycle recorded. The shifting equilibrium engine combustion model of Krieger and Borman (6) was used. In this model the First Law of Thermodynamics is applied to two zones: a burnt zone containing a uniform composition of the products of combustion and an unburnt zone containing a homogenous mixture of reactants. Both zones are considered to be at the measured cylinder pressure. The thermodynamic properties of the two fuels used were derived from the American Petroleum Institute's Research Project 44 (7) and the Thermodynamics Properties of Aliphatic Alcohols (8). The equilibrium computer program of Olikara and Borman (9) is used to determine the properties, and their derivatives, of the products of combustion in the burnt zone. The heat transfer rates for both zones were modelled on the empirically derived relationship of Woschni (10).
Typical curves of the computed mass burning rate and the cumulative mass fraction burnt are shown in Fig 5 for the combustion of a lean mixture of iso-octane. The individual cycles recorded were classified into five categories which were characterised by:

A. Normal combustion with a short delay period, high burning rate and complete combustion at EVO.

B. As in A above but with a reduced burning rate.

C. Partial burning at a low rate and flame extinction before EVO.

D. Cycles in which the establishment of the flame kernel takes a considerable time, resulting in long delay periods and low burning rates.

E. Eight stroking.

The analysis of 152 individual cycles with low equivalence ratios, shown in Table 1, indicates the incidence of the various types of cycle. With methanol the incidence of misfiring was reduced at equivalence ratios lower than those for iso-octane.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Compression ratio</th>
<th>Equivalence ratio</th>
<th>Number of cycles</th>
<th>Percentage of cycle type recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>iso-octane 9:1</td>
<td>0.75-0.85</td>
<td>64</td>
<td>A  25.0</td>
</tr>
<tr>
<td></td>
<td>methanol 9:1</td>
<td>0.60-0.75</td>
<td>88</td>
<td>B  37.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>C  0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>D  12.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>E  25.0</td>
</tr>
</tbody>
</table>
Table 2: Comparison of pre-chamber and standard chamber results

<table>
<thead>
<tr>
<th>Engine</th>
<th>Farymann</th>
<th>Ricardo</th>
</tr>
</thead>
<tbody>
<tr>
<td>combustion chamber type</td>
<td>spherical pre-chamber</td>
<td>cylindrical open</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Speed rev/min</td>
<td>1000</td>
<td>1009</td>
</tr>
<tr>
<td>Ignition timing °BTDC</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Fuel</td>
<td>iso-octane</td>
<td>iso-octane</td>
</tr>
<tr>
<td>Air Flow kg/h</td>
<td>11.9</td>
<td>14.7</td>
</tr>
<tr>
<td>Equivalence ratio</td>
<td>0.845</td>
<td>0.830</td>
</tr>
<tr>
<td>Delay (0-10%) °CA</td>
<td>29.0</td>
<td>35.5</td>
</tr>
<tr>
<td>Maximum burning rate %/°CA</td>
<td>3.53</td>
<td>2.48</td>
</tr>
</tbody>
</table>

4.1 Turbulence generating pre-chamber

In the original diesel engine configuration the fuel was injected into a 16 mm radius spherical pre-chamber to increase swirl at the end of the compression stroke and thus reduce the ignition delay period associated with compression ignition. In the modified form for spark ignition, the plug was fitted into the original tapping for the injector and the flame was initiated in the highly turbulent flow in the swirl pre-chamber. The influence of flame initiation in the pre-chamber may be seen from a comparison of test results from the converted Farymann engine with similar results from a quiescent combustion chamber of a Ricardo E6 engine shown in Table 2.

At this lean equivalence ratio the delay period, defined here as the degrees of crank angle from ignition to a mass fraction of 10% burnt, was reduced by about 18% through the action of flame initiation in a highly turbulent flow. This would in effect reduce the spark advance required for best torque and aid the establishment of the flame kernel as the unburnt gas temperature at the ignition point would be higher. The high rate at which the unburnt gas was entrained into the propagating flame front through the use of a swirl pre-chamber also resulted in a significant increase in the maximum mass burning rate of about 42%.

4.2 Influence of delay

The importance of the behaviour of the spark ignited flame during the initial stages of flame development is the subject of current research. De Soete (11) stated that, 'The subsequent flame propagation, during which the major portion of the fuel is burnt, depends substantially on the transitory period during which the flame kernel is being established'. This phenomenon was exemplified
in these tests by the existence of individual cycles in which a long delay period resulted in low burning rates - type D cycles as shown in Fig 5. The influence of the delay period on the maximum burning rates computed for 152 individual cycles with the combustion of methanol and iso-octane in the lean burning regime at a compression ratio of 9:1 may be seen in Fig 6. The high maximum burning rates, associated with complete combustion, resulted from a short delay period. The initial development of the flame kernel was more rapid with lean methanol mixtures than with lean iso-octane mixtures and maximum burning rates were correspondingly higher with methanol at about 5.5%/°CA for delay periods of about 15°CA.

4.3 Combustion performance

The performance of the divided combustion chamber with methanol mixtures is compared with that of the baseline fuel, iso-octane, in Fig 7. Mean values of the maximum mass burning rate for 16 consecutive cycles are plotted against the equivalence ratio as the mixture strength was weakened. The results demonstrate the higher burning rates obtained with the combustion of methanol mixtures and the degree to which the equivalence ratio could be weakened below that for iso-octane before cyclic variations made stable operation impossible.

5 CONCLUSIONS

Small diesel engines with swirl pre-chambers, that are in common use for power generation in many countries, may be easily converted to spark-ignition to burn alcohol fuels which may be produced locally from indigenous raw materials. Combustion of these fuels is more easily controlled with spark ignition than with compression ignition. The highly turbulent divided combustion chambers are well suited to the combustion of lean mixtures. Stable operation may be extended into the lean burning regime. The period of initial flame development is short. This period has a marked influence on subsequent maximum burning rates which were correspondingly high with the highly turbulent combustion of methanol. Although the durability of the modified engine has not been proved, the cylinder head has been dismantled and no unusual effects have been observed.

6 ACKNOWLEDGEMENT

The authors wish to thank E Marshall of BP Research Centre, Sunbury-on-Thames for his interest in this work and the provision of test results from a Ricardo E6 engine for comparative purposes.
REFERENCES


FIG 1 CYLINDER HEAD GEOMETRY

FIG 2 SCHEMATIC DIAGRAM OF TEST RIG

FIG 3 TYPICAL PRESSURE-CRANK ANGLE RECORDINGS
FIG 4 INFLUENCE OF EQUIVALENCE RATIO ON CYCLIC VARIATIONS IN MAXIMUM PRESSURE

FIG 5 TYPICAL BURNING CURVES
FIG 6 INFLUENCE OF DELAY PERIOD ON MAXIMUM BURNING RATE

FIG 7 INFLUENCE OF EQUIVALENCE RATIO ON MAXIMUM BURNING RATE
Flame development in spark-ignition engines burning lean methanol mixtures

R A Johns & A W E Henham
FLAME DEVELOPMENT IN SPARK-IGNITION
ENGINES BURNING LEAN METHANOL MIXTURES

R A Johns and A W E Henham
University of Surrey, Guildford, England

Summary

Small diesel engines may be readily converted to spark-ignition to
burn alcohols. The highly turbulent pre-chambers in these engines
are ideally suited to burning lean mixtures, thereby improving fuel
economy whilst reducing exhaust emissions. This paper describes
the application of a diagnostic engine computer combustion model to
the analysis of flame development in such an engine. The results
exhibit characteristic features of flame development; a period of
heat transfer to the unburnt gas between the spark plug electrodes,
instantaneous self-ignition and a period of decelerating flame
propagation. These characteristics were modelled for use in engine
computer simulations.

1. INTRODUCTION

Alcohol fuels, either methanol, produced from indigenous deposits
of natural gas, or ethanol, produced from biomass, offer attractive
alternative fuels to oil. With RON of 114 and 111 respectively, they
are well suited as fuels for high compression spark-ignition engines.
Evaluation programmes are already in progress; mainly with captive
vehicle fleets which are largely independent of extensive fuel
distribution systems. On the other hand, both these oxygenates have
extremely low cetane numbers and are, therefore, difficult to ignite by
compression ignition, particularly at loads below 25% of the engine
rating. The small stationary diesel engines, in common use for power
generation and pumping in remote areas may, however, be easily converted
to spark ignition to burn the locally produced alcohol fuels. The high
compression ratios and highly turbulent combustion chambers in these
ingines are ideal for the combustion of lean alcohol mixtures. Such an
ingine, a single cylinder 7.5 kW diesel with a spherical pre-chamber,
was converted to spark-ignition and performance tests with lean methanol
mixtures indicated that stable operation could be extended further into
the lean burning regime than was possible with the baseline fuel, iso-
octane (1). Analysis of the cylinder pressure readings using a computer
engine combustion model showed the existence of four different types of
burning cycles (2) which included cycles with partial burning. The
period of initial flame development was found to have a significant
influence on subsequent flame development. Complete combustion with
high maximum burning rates resulted from a short period of flame
development, whereas the partial burning cycles were a consequence of a
long flame development period.

The purpose of this work was to apply the engine computer
combustion model in a diagnostic manner to analyse the experimentally
acquired cylinder pressure data to identify the characteristic features
of flame development in spark-ignited lean methanol mixtures.
2. EXPERIMENTATION

The conversion of the diesel engine to an alcohol fuelled spark-ignition engine and a description of the associated data acquisition system is given in reference 1. Experimental pressure data were analysed using the shifting equilibrium combustion model of Krieger and Borman, with heat transfer rates determined from the empirical relationship of Woschni, as detailed in reference 2. Here the combustion chamber is divided into two zones; a burnt zone containing a uniform composition of products and an unburnt zone containing a homogeneous mixture of reactants. The First Law of Thermodynamics is applied to each zone at 1° intervals of crank angle to compute a mass of reactants burnt that is just sufficient to cause the measured pressure rise. The flame propagation velocity was computed assuming a spherical flame front propagating from the ignition source and intersecting the cylinder geometry. The laminar flame speed was calculated from the computed adiabatic flame temperature and unburnt gas temperature using the empirical relationship of Koda et al (3). Corrections were included for lean equivalence ratios and for cylinder pressure:

\[
S_L = 1.09 \times 10^{-4} (Tu \cdot Tad)^{2.45} \exp\left(-\frac{E}{RT}\right) \left(\frac{Tad}{Tu}\right)^{1.8} \left(\frac{p}{p_0}\right)^{0.2}
\]

The engine was run on M100 fuel at 1000 rev/min with equivalence ratios in the range 0.61<\phi<1.01, and an airflow of 11.9 kg/h.

3. ANALYSIS

The computed curves of propagation velocity and mass fraction burnt during initial flame development exhibited four distinct characteristic features:

A. A period of heat transfer immediately following spark discharge during which the cylindrical column of gas between the electrodes was heated to the self-ignition temperature.

B. Instantaneous self-ignition of the cylindrical column with a correspondingly high instantaneous value of flame propagation velocity.

C. A period during which the flame kernel was consolidated and established. Here unburnt gas was entrained into the small "expanding kernel with a cooling action that resulted in a decrease in the value of propagation velocity with time. Quenching could occur if the entrainment rate continuously exceeded the burning rate.

D. Establishment of a self-propagating turbulent flame with an accelerating flame front.

Mean values of the time elapsed from spark discharge to ignition of an unburnt volume of mixture between the spark plug electrodes, together with the associated standard deviation in time plotted as bars on the mean values are shown in Fig. 1. The heat transfer period increased with an inverse power law as the mixture strength was reduced, with the index being a function of compression ratio:

\[
\tau_{ht}/\tau_{ht=1} = (S_L/S_{L=1})^{0.22\xi - 2.54}
\]
Cycle-to-cycle variations in the heat transfer period increased with reductions in equivalence ratio although less markedly with the higher compression ratio.

The high instantaneous value of flame propagation velocity, resulting from the 'explosion' of the unburnt gas between the electrodes (Fig 2) varied from a mean value of 35 ms\(^{-1}\) with stoichiometric mixtures to 18 ms\(^{-1}\) with mixture strengths approaching the lean misfire limit. The compression ratio had little influence on this parameter and the results indicated a relationship of the form:

\[ S_{p1} = a + bS_{L}^{n} \]

where \( a = 18\text{m/s}, b = 6\text{s/m} \) and \( n = 2 \).

Immediately after self-ignition the flame front decelerates as cooler unburnt gas is entrained into the developing kernel until a turbulence controlled flame propagation is established. The computed results were in general agreement with Chioniak (4), who reported an inverse relationship between propagation velocity and time for the period immediately following self-ignition. Cycle-to-cycle variations in the index were significant, particularly at the higher compression ratio; typically the cyclic dispersion was 0.32 at an equivalence ratio of 0.81.

The flame kernel may be considered to be established when the flame front accelerates immediately following the period of decreasing propagation velocity. Generally the total period between spark discharge and a positive rate of change of propagation velocity increased with reductions in mixture strength. With stoichiometric mixtures the onset of an accelerating flame front was clearly discernable but with lean mixtures it was difficult to specify the exact time at which the flame could be said to be established. Typically at an equivalence ratio of 0.69 the propagation acceleration varied between positive and negative values from 5° BTDC to 7° ATDC. A comparison between the period of flame establishment, defined by \( dS_{p}/dt \) becoming positive, and the time elapsed from spark discharge to a mass fraction burnt of 1% is shown in Fig 3, with a resolution of 1°CA superimposed. The cyclic dispersions in propagation acceleration and in a mass fraction burnt of 1% is given in table 1.

For equivalence ratios between 0.8 and 1.0 there was good agreement between \( dS_{p}/dt \) becoming positive and the corresponding time to 1% mass burnt. The problem of ascertaining flame establishment from \( dS_{p}/dt \) becoming positive became increasingly more difficult with equivalence ratios less than 0.8. For this reason a definition of 1% burnt was adopted. The variation in this period with laminar flame speed is shown in Fig 4. The relationship took the form of a power law:

\[ \tau_{1\%\phi=1}/\tau_{1\%\phi=1} = (S_{L}/S_{L,\phi=1})^{n} \]

where \( n \) was evaluated as a function of compression ratio:

\[ n = 0.22 \xi - 3.0 \]
Fig. 1 Variation in heat transfer period with laminar flame speed.

Fig. 2 Variation in instantaneous propagation velocity with laminar flame speed.

Fig. 3 Comparison of flame establishment definitions.

Fig. 4 Variation in flame establishment period with laminar flame speed.
Table I: Cyclic dispersion in flame establishment period.

<table>
<thead>
<tr>
<th>Compression ratio</th>
<th>Equivalence ratio</th>
<th>$\frac{dS_p}{dt}$ + ve $\theta_{eq}$ mean dispersion</th>
<th>1% burnt $\theta_{eq}$ mean dispersion</th>
</tr>
</thead>
<tbody>
<tr>
<td>9:1</td>
<td>0.65</td>
<td>11.1 0.297</td>
<td>23.3 0.155</td>
</tr>
<tr>
<td></td>
<td>0.69</td>
<td>12.1 0.256</td>
<td>20.6 0.155</td>
</tr>
<tr>
<td>11:1</td>
<td>0.56</td>
<td>8.9 0.236</td>
<td>16.6 0.157</td>
</tr>
<tr>
<td></td>
<td>0.61</td>
<td>7.6 0.276</td>
<td>15.9 0.157</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS

The period of flame establishment in the divided-chamber methanol engine exhibited four characteristic features which were related to the laminar flame speed and could be modelled for use in engine computer simulations.

Flame establishment was difficult to ascertain in terms of the onset of a propagation acceleration with lean mixtures below an equivalence ratio of 0.8 and a definition in terms of a mass fraction burnt of 1% was considered to be more definitive. This technique of employing diagnostic engine combustion models provides an inexpensive method of analysing engine combustion performance with alternative fuels.

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Comparison of combustion systems for spark-ignition engines using alcohol and hydrocarbon fuels

A W E Henham & R A Johns

Published as a Report, University of Surrey, Guildford

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UNIVERSITY OF SURREY
Department of Mechanical Engineering

Internal Report

COMPARISON OF COMBUSTION SYSTEMS FOR SPARK-IGNITION ENGINES USING ALCOHOL AND HYDROCARBON FUELS

A W E Henham and R A Johns

1984
ABSTRACT

The use of a wider range of fuels in spark-ignition engines is becoming an important issue in certain parts of the world. In order to derive the maximum performance and efficiency from most alternative fuels it is necessary to use higher compression ratios and leaner mixtures. This is generally believed to require a turbulent combustion chamber. A secondary advantage of this combustion system is the low CO and NO\textsubscript{x} emission associated with mixtures well to the weak side of stoichiometric.

In order to investigate the potential of such a combustion system the authors have constructed two research engines, one with open chamber using inlet swirl and an asymmetrical piston recess and the other with a divided chamber.

A computer engine combustion model has been developed. This uses the data acquired from the tests on both engines to plot mass burning rates for each cycle. In addition batches of cycles are analysed for cyclic dispersion which increases at the weaker end of the mixture range.

Comparative tests using methanol and iso-octane clearly demonstrate the wider equivalence ratio band acceptable when running on the former fuel.
1.0 INTRODUCTION

The present work was initiated to examine the potential for development of the well-proven and widely accepted spark-ignition (otto cycle) engine. The areas for development considered have been:

a) combustion of mixtures considerably leaner than stoichiometric to improve brake thermal efficiency while limiting CO, HC and NO\textsubscript{x} emissions;

b) operation at higher compression ratios to improve brake thermal efficiency and to restore specific output reduced by the use of leaner mixtures;

c) extension of the range of fuels from the traditional hydrocarbons to oxygenates.

It was felt that these three were compatible objectives of a development programme and two engines were built to enable practical testing to begin. Preliminary studies by the authors encouraged them to pursue the homogenous combustion system rather than stratified-charge to provide lean mixture operation. At the same time a computer engine combustion model (ECM) was developed. The model is used to analyse data acquired during tests of the two engines to predict mass burning rate. From this model conclusions are drawn about the types of combustion processes taking place within cycles at different operating conditions and about the variation between successive cycles.

2.0 ENGINE DESIGN

In order to proceed as rapidly as possible in the early stages of the programme, it was decided to employ single-cylinder engines and to convert existing examples available in the University laboratory. As compression ratios were to be high and, in the development stages, loadings uncertain, conversion of four-stroke compression-ignition engines was undertaken. The rugged construction of these was regarded as appropriate and the engines available enable parallel approaches to be made with divided and open chamber combustion systems.

2.1 Divided Chamber Engine

The divided chamber engine was based on a Farymann water-cooled compression-ignition engine which already incorporated a variable compression-ratio device using a contra-piston to vary the volume of the pre-chamber. Modifications comprised:

a) a steel spacer and annealed copper gaskets inserted between the cylinder and the head (the range of compression ratio became 8.6 to 12 compared with that for the diesel version, 12 to 22);

b) fitting an SU constant vacuum air valve carburettor in place of the fuel injection system;

c) adapting the head to take a spark plug, fired by an electronic ignition system.
The layout of the cylinder head is shown in figure 1 to comprise a disk combustion chamber between the flat topped piston and flat cylinder head, a 16 mm radius spherical pre-chamber connected by 15 mm diameter port to the main chamber and bounded by the flat 32 mm diameter contra piston on the opposite side. The pressure transducer is located in the face of the contrapiston. The spark plug is located, parallel to the cylinder axis at the top of the pre-chamber. Although the only information available at the time suggested that the neck of the prechamber was the preferred site this was not practicable within this engine structure.

The ignition system was purpose built and is driven by an encoder which is also used for the data acquisition system. Programmable TTL downcounters are used to set timing from a BDC trigger.

In order to avoid problems created by the high enthalpy of evaporation of alcohol fuels an electrical heating element was fitted in the supply pipe from the air flowmeter. While this proved not to be necessary under the conditions of the laboratory it would be a requirement in practice to arrange for a coolant or exhaust heated duct where lower ambient temperatures are anticipated. It has been claimed that considerable increases in efficiency can be obtained when preheating by this means (3). Presumably this refers to part load where volumetric efficiency is not a problem.

The engine is installed on a bed with a swinging-field d.c. motor-generator unit as a dynamometer. Air and fuel flow meters are fitted.

2.2 Open Chamber Engine

The open chamber engine was based on a Petter BAI air-cooled compression-ignition engine. Modifications comprised:

a) Shims placed between the cylinder barrel and crankcase to vary the compression ratio;

b) lengthening pushrods necessitated by (a);

c) fitting an SU constant vacuum air valve carburettor in place of the fuel injection system;

d) adapting the head to take a spark plug fired by an electronic ignition system;

e) machining pistons from blanks supplied by the manufacturers.

Under item (e) above, it is possible to use this engine to examine the effect of combustion chamber design. The two designs employed so far have been the disk between flat piston and the flat cylinder head and a turbulent chamber in which an offset cylindrical recess in the piston is placed below the exhaust valve. The latter was thought to give some of the benefits claimed by May (4) for the Fireball chamber but without the complexity of a recessed valve chamber in the head. Also the increased surface volume ratio should have less effect on efficiency if the additional surface is in the piston and, therefore, uncooled. In each case, the inlet valve is masked and the port designed to give inlet mixture swirl. For the purposes of this paper only results for the recessed piston
chamber are discussed. The pressure transducer is located in the head with a straight tapping to the combustion chamber. The chamber design is shown in figure 2.

The ignition system employed is broadly similar to that described in 2.1.

The engine is installed on a bed with water dynamometer. A viscous flow air meter and fuel flow metering are fitted.

2.3 Engine data

Data for the two engines is given below:

<table>
<thead>
<tr>
<th>Engine</th>
<th>I</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber Based on</td>
<td>Divided</td>
<td>Open Compact</td>
</tr>
<tr>
<td>Cooling</td>
<td>Water</td>
<td>Air</td>
</tr>
<tr>
<td>Bore/mm</td>
<td>90</td>
<td>88.9</td>
</tr>
<tr>
<td>Stroke/mm</td>
<td>110</td>
<td>92.1</td>
</tr>
<tr>
<td>Swept Volume/cm$^3$</td>
<td>700</td>
<td>573</td>
</tr>
<tr>
<td>Carburettor</td>
<td>SU HS2</td>
<td>SU HS2</td>
</tr>
<tr>
<td>Spark plug</td>
<td>10 mm</td>
<td>12 mm</td>
</tr>
<tr>
<td></td>
<td>Champion G63</td>
<td>Champion P8Y</td>
</tr>
</tbody>
</table>

3.0 TEST PROCEDURE

3.1 Method of data acquisition

For each engine the experimental set-up is as shown in figure 3. In each case pressure readings from a Kistler piezoelectric transducer were taken through a charge amplifier to an A to D converter by which a 10-bit digital signal was produced. The transient recorder stored the information for a series of cycles for subsequent reduction by the University's Prime Computer installation. The reading intervals were determined by shaft encoders fitted to each engine. To reduce the amount of data to enable the recorder to hold a reasonable number of cycles the recorder can be enabled at 120° before top dead centre on the compression stroke and disabled at 120° after on the firing stroke. Thus 241 readings are acquired for each cycle and data for a maximum of 16 consecutive cycles can be stored. The results may be displayed on a storage oscilloscope before processing for inspection in outline.

Operating parameters - speed, fuel and air flow rates are recorded. CO and HC readings from NDIR and NO$_x$ from chemiluminescent analysers are taken.
3.2 Engine Combustion Model

The model, described by one of the authors in a recent paper (1) computes the instantaneous mass burning rate at each degree of crank angle for which the pressure signal is obtained during tests. The model is based upon the shifting equilibrium model of Krieger and Borman (5) in which a homogenous mixture of reactants comprises an unburnt zone and a homogenous mixture of products the burnt zone, both at cylinder pressure. The burnt zone gas properties are from Olikara and Borman (6) while the heat transfer rates were based on the relationships of Woschni (7).

4.0 TEST RESULTS

Ranges of typical burning curves from engines I and II are shown in figures 4 and 5 respectively.

These have been divided into the categories according to their characteristic curve shape as follows:

A. combustion: short delay period, high burning rate, complete combustion at EVO;

B. as A but with reduced burning rate;

C. partial burning at low rate, flame extinction before EVO;

D. long period of establishment of flame kernel, long delay periods, low burning rate;

E. (not illustrated) eight-stroking.

4.1 Analysis of Results

The incidence of cycles of type C and D is greater at low equivalence ratios but this effect is much less marked in the tests using methanol than in those using iso-octane (8). The proportion of cycles A and B for engine I tests in the range $\phi = 0.61 - 0.81$ was found to be 100% in one test series at 11:1 compression ratio on methanol (1).

The reliability of combustion under these conditions is an inverse function of ignition delay. The program described prints the % mass burned at degree crank angle increments. This has been used to determine the delay. Various definitions have been proposed including the crank angle from ignition to 10% mass of fuel burned. The authors are of the opinion that the important characteristics of combustion are determined in a much shorter period than this.

Delays from ignition to the point at which 1 or 2% is burned are felt to be more significant and the latter is plotted for both engines using methanol and iso-octane in figure 6. This shows the lower delay for each engine using methanol and that engine I, with the turbulence generating prechamber, shows reduced delay over a wide range of values of $\phi$. 
A set of typical delay values is tabulated below for the two engines on both fuels. Included in the table is a set of results, processed using the authors' program, but of readings taken from tests in another laboratory on a range of combustion chamber shapes. These were only available for iso-octane, however. Although no far-reaching conclusions can be reached from these few samples, the underlying trends and the significance of the 2% mass burnt point is apparent.

<table>
<thead>
<tr>
<th>ENGINE</th>
<th>COMBUSTION CHAMBER</th>
<th>CR</th>
<th>FUEL</th>
<th>$\phi$</th>
<th>IGNITION $^\circ$BTDC</th>
<th>$t_{2%}^\circ$CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>DIVIDED</td>
<td>9</td>
<td>ISO-OCTANE</td>
<td>0.85</td>
<td>15</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>METHANOL</td>
<td>0.61</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>II</td>
<td>COMPACT</td>
<td>12</td>
<td>ISO-OCTANE</td>
<td>0.9</td>
<td>20</td>
<td>25.5</td>
</tr>
<tr>
<td></td>
<td>OPEN</td>
<td>12</td>
<td>METHANOL</td>
<td>0.67</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>RICARDO</td>
<td>DISK</td>
<td>10</td>
<td>ISO-OCTANE</td>
<td>0.9</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>DISK + SWIRL</td>
<td>10</td>
<td>ISO-OCTANE</td>
<td>0.9</td>
<td>20</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>BOWL IN PISTON</td>
<td>10</td>
<td>ISO-OCTANE</td>
<td>0.9</td>
<td>28</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>BIP + SWIRL</td>
<td>10</td>
<td>ISO-OCTANE</td>
<td>0.9</td>
<td>22</td>
<td>18.5</td>
</tr>
</tbody>
</table>

TABLE showing delay from ignition to 2% mass burnt.

5.0 CONCLUSIONS

These tests on two medium-speed single-cylinder engines show that the rate of burning, and hence stability of combustion, is greater for each type of engine when methanol is used than with iso-octane, representing the traditional hydrocarbon fuel.

The lean-burning regime gives stable burning down to much lower equivalence ratios with methanol than with iso-octane.

The deliberate production of turbulence at an early stage, thought to be a feature of the divided chamber engine, is favourable to the combustion of very lean mixtures at least when judged by the crank angle delay for 2% burnt. The recessed piston compact open chamber, producing turbulence at a late stage in the compression process, appears to give slower burning conditions. This type proved, however, less sensitive to equivalence ratio in the lower part of the range. Tests at lower compression ratios are in process on engine II.

The authors conclude that there is considerable scope for further work in the lean-burn region using a range of alternative fuels. In addition to the engines described an automotive four-cylinder engine is in process of installation for this purpose. The effect of the combustion chamber shape on emissions and efficiency, not reported here, will be pursued in this programme.
6.0 REFERENCES


12E/Washington
Figure 1. Engine I, divided chamber head geometry

Figure 2. Engine II, compact open chamber geometry
Figure 3. Test rig layout
Figure 4. Typical burning curves, Engine I divided chamber

Figure 5. Typical burning curves, Engine II open chamber
Figure 6. Delay from ignition to 2% mass burnt, $\tau_{2\%}$, plotted against equivalence ratio, $\phi$.
Combustion chamber development through diagnostic modelling

R A Johns, A W E Henham & P Marshall
Combustion chamber development through diagnostic modelling

Die Entwicklung von Verbrennungskammern durch Anwendung von diagnostischen Modellen

Mise au point des Chambres de combustion par le moyen de modèles diagnostiques

Faculty of Engineering, University of Surrey, Guildford, U.K.

ABSTRACT

The use of a wider range of fuels in spark-ignition engines and the quest for fuel economy with low exhaust emissions are important issues in engine design today. The performance of current and proposed combustion chamber designs needs to be assessed with both conventional and alternative fuels. The parameters defining combustion chamber performance, such as mass burning characteristics, initial flame development and cyclic variations in these parameters, may be readily determined using computer combustion models. These are used here in a diagnostic manner to reduce experimentally acquired cylinder pressure data.

This paper describes an equilibrium theory model and its use in determining the combustion performance parameters from test bed results taken from three engines. The results obtained indicate the significant phases of flame development, its influence on subsequent burning rates, and the influence of differing geometries on combustion performance.
ZUSAMMENFASSUNG

Der Gebrauch von weit verschiedenen Brennstoffen in Zündermotoren und das ewige Suchen nach immer mehr ökonomischen Verbrauch, mit niedrigen Auspuffemissionen, spielt heute eine bedeutende Rolle bei der Konstruktion von Motoren.


Die Parameters die die Arbeitsleistung von Verbrennungskammern festsetzen, zum Beispiel die Mass-Verbrennung Charakteristiken, das Anfangsstadium von Flammenentwicklung und die zyklischen Variationen in diesen Parameters, kennen alle beim anwendten von Computer Verbrennungsmodellen leicht festgestellt werden.

Diese Modelle werden hier auf diagnostische Weise angewandt um die experimentell erhaltenen Verbrennungsdaten zu reduzieren.

Der Beitrag beschreibt ein theoretisches Gleichgewicht Modell und seinen Gebrauch zur Ermittlung von Verbrennungsleistung Parameters gewonnen an drei Versuchsständen.

Die erhaltenen Resultate zeigen die wesentlichen Phasen von Flammenentwicklung, deren Einfluss auf subsekutive Brenngeschwindigkeit und den Einfluss von verschiedenen Gestalten der Verbrennungskammern auf die Verbrennungsleistung.

SOMMAIRE

L'emploi d'une gamme plus étendue de carburants dans les moteurs à allumage par étincelle électrique et la recherche d'une consommation réduite accompagnée d'un faible échappement des gas, ce sont actuellement des questions importantes pour l'étude des moteurs. Il faut évaluer le comportement de la géométrie des chambres de combustion existantes ainsi qu'en projet pour des combustibles conventionnels et pour d'autres. Les paramètres relatifs au comportement de combustion, tels les caractéristiques concernant l'efficacité de cette combustion, le développement initial de la flamme et les variations cycliques de ces paramètres, peuvent être déterminés facilement en utilisant des modèles de combustion sur ordinateur. Ici, on emploie ceux-ci de façon diagnostique, afin d'analyser des renseignements fournis au cours d'expériences sur la pression cylindrique.

Ce mémoire décrit un modèle basé sur la théorie de l'équilibre, et son emploi pour déterminer les paramètres du comportement de la combustion à partir des résultats obtenus de trois moteurs au banc d'essai. Ces résultats démontrent les phases significantes de la période initiale du développement de la flamme, son influence sur la rapidité de combustion qui s'ensuit, et l'influence d'une géométrie variée sur la combustion.
INTRODUCTION

The quest for fuel economy with minimal exhaust emissions has stimulated research and development of automotive combustion chambers. Compact, highly turbulent, chambers with short flame travels and associated high burning rates have been developed for the combustion of lean mixtures with low cyclic variations in combustion thus overcoming the impairment of driveability. Whilst fuel economy continues to be a primary consideration in the design of engines, manufacturers also need to have data readily available on the performance of their engines with alternative fuels in particular the alcohols and alcohol gasoline blends which some countries are introducing in an effort to reduce their dependence on imported oil.

In assessing the performance of different combustion chambers with both conventional and alternative fuels, the analyst needs to be able to evaluate the various parameters describing performance easily from test bed data. Typical parameters describing combustion chamber performance which may be used for comparative purposes are listed in Table 1. Hot wire anemometer and laser techniques may be used to determine local fluid velocities and turbulence levels. High speed photography may be used to study flame propagation rates. These methods are expensive to use and generally require engine modifications such as fitting quartz windows in cylinder heads or piston crowns to accommodate the particular technique employed. The location of probes may be restricted by engine geometry and inaccuracy of measurements may be questioned because of the intrusion of the probe into the actual flow, modifications to geometry, and the need to calibrate for transient pressures and temperatures. Such techniques are considered to be best suited to research work. With production engines an inexpensive non-intrusive comparative technique with rapid data reduction is needed. Computer models of engine combustion, although limited by their predictive nature, are relatively inexpensive to use in a diagnostic manner. The combustion chamber performance parameters may be rapidly predicted from easily acquired experimental cylinder pressure data with use of non-intrusive pressure transducers. Two computational techniques are in general use. One is based on the summation of incremental rises in pressure caused by combustion over each °CA (after Rassweiller and Withrow) and the second derives from the application of the First Law of Thermodynamics to the combustion of sufficient fuel to cause an increase in cylinder pressure equal to that measured experimentally (after Krieger and Borman). The former technique is ideally suited for use on-line with the microcomputers in use for data acquisition whereas the latter is a more comprehensive method more suited to mainframe machines.
Table 1  Combustion chamber performance parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial flame development period</td>
<td>Minimise to reduce spark advance needed for best torque and to initiate combustion with highest possible unburnt gas temperature.</td>
</tr>
<tr>
<td>Mass burning rate</td>
<td>Maximise to approximate to constant volume combustion of Otto cycle without detonation.</td>
</tr>
<tr>
<td>Mass fraction burnt</td>
<td>Maximise to achieve best fuel economy and low hydrocarbon emissions.</td>
</tr>
<tr>
<td>Cyclic dispersion in combustion parameters</td>
<td>Minimise to maintain driveability and reduce eight-stroking when burning lean mixtures.</td>
</tr>
<tr>
<td>Emissions</td>
<td>Minimise CO, HC and NO\textsubscript{x} emissions to comply with regulations. For alcohols reduce aldehyde emissions.</td>
</tr>
</tbody>
</table>

**COMPUTER MODELLING**

The performance of combustion chambers has been evaluated by the prediction of heat release rates from indicator diagrams and pressure-crank angle data for a considerable time. Early methods utilised indicator diagrams to determine the polytropic index of expansion and hence calculate the energy transfer during a small change in volume from

$$\frac{dq}{dv} = \frac{y-n}{1-r_v} p$$

(1)

Rassweiler and Withrow (1938) related the summation of the incremental rise in pressure due to combustion over one degree of crank angle to the mass burning rate in a correlation of motion pictures of flames with indicator diagrams. This technique may be applied readily to the on-line reduction of experimental data but it is limited to the analysis of cycles in which combustion is complete before the exhaust valve opens, since the mass fraction burnt is assumed to be unity when the incremental pressure rise from combustion becomes zero. With partial burning, combustion is incomplete and a more comprehensive computer model is needed. Such a model has been developed by Krieger and Borman (1966) in which the mass burning rate is calculated from the application of the First Law of Thermodynamics to the combustion of sufficient mixture to cause an increase in pressure equal to that measured experimentally.

The model uses two zones; a burnt zone containing a uniform composition of the products of combustion and an unburnt zone containing a homogenous mixture of reactants. Both zones are considered to be at the
measured cylinder pressure. The thermodynamic properties of the two fuels used were derived from the American Petroleum Institute's Research Project 44 (1953) and the Thermodynamic Properties of Aliphatic Alcohols (1973). The equilibrium computer program of Olikara and Borman (1975) is used to determine the properties, and their derivatives, of the products of combustion in the burnt zone. The heat transfer rates for both zones were modelled on the empirically derived relationship of Woschni (1967).

The turbulent flame speed, defined as the rate of propagation relative to the unburnt mixture, is calculated using the geometry of a spherical flame front propagating from the ignition source.

$$S = \frac{\dot{n}_b}{\rho_u A_f}$$  \hspace{1cm} (2)

The propagation velocity of the flame relative to the combustion chamber is computed from the flame radius

$$S_p = \frac{d}{dt} (\text{flame radius})$$  \hspace{1cm} (3)

The expansion velocity may then be evaluated as

$$S_E = S_p - S_\tau$$  \hspace{1cm} (4)

Laminar flame speeds are determined from the adiabatic flame temperatures and unburnt gas temperatures for methanol using the empirical relationship derived by Koda et al (1982). Corrections were included for lean equivalence ratios and for cylinder pressure with simple power law relationships quantifying the dependence of laminar flame speed as

$$S_\infty = 1.8 \left( \frac{P_0}{P} \right)^{0.2}$$  \hspace{1cm} (5)

DATA REDUCTION

Test data were acquired from two single cylinder engines at the University of Surrey which had been converted from compression-ignition engines to spark-ignition engines as part of a continuing programme in the combustion of lean alcohol mixtures. In the Farvann engine the combustion chamber was divided with a disk zone between the flat topped piston and the flat cylinder head, and an offset 16 mm radius spherical turbulence generating pre-chamber connected to the main chamber by a 15 mm diameter port. The second engine was based on a Petter BA air cooled engine. Two designs of combustion chamber were studied; a conventional disk shape between the flat piston and flat head, and compact turbulent chamber in which an offset cylindrical recess was machined into the piston crown below the exhaust valve. The latter was thought to give some of the benefits claimed by May (1979) for the Fireball chamber but without the complexity of a recessed valve chamber in the head. Further data was kindly supplied by BP Research Centre from a Ricardo E6 variable compression engine fitted with a standard flat cylindrical combustion chamber and subsequently with a turbulent bowl in the piston crown.
Table 2

<table>
<thead>
<tr>
<th>Engine</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>Farymann</td>
<td>Petter BAL</td>
<td>Ricardo E6</td>
</tr>
<tr>
<td>Combustion chamber</td>
<td>Divided chamber</td>
<td>Open disk or compact in piston crown</td>
<td>Standard disk or bowl in piston crown</td>
</tr>
<tr>
<td>Bore stroke mm</td>
<td>90 x 110</td>
<td>88.9 x 92.1</td>
<td>76 x 111</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>9:1 and 12:1</td>
<td>12:1</td>
<td>10.1</td>
</tr>
<tr>
<td>Speed rev/min</td>
<td>1000</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>Timing</td>
<td>15° BTDC</td>
<td>20° BTDC</td>
<td>MBT</td>
</tr>
<tr>
<td>Airflow kg/h</td>
<td>11.9</td>
<td>9.8</td>
<td>14.7</td>
</tr>
</tbody>
</table>

Cylinder pressures in engines I and II were measured at each degree of crank-angle using a Kistler 7055B piezoelectric pressure transducer and associated 5077 charge amplifier. The analogue signal from the charge amplifier was converted to a 12-bit digital signal in a 40kHz analogue-to-digital converter, which was clocked from TTL encoders fitted to the camshaft of engine I and the crankshaft of engine II. The test data was acquired using a microcomputer system based on a Z80A central processor unit and a dual 5 1/4", 700 kByte floppy disk drive. Software for the data acquisition system was written in microsoft MACRO-80 with supporting CP/M software. File transfer packages were also written to transfer test data stored on floppy disk to the University's Prime mainframe computers for subsequent reduction.

Reduction of the experimentally acquired pressure data produces results typified by the burning curves of figure 1 and the flame propagation velocity graph of figure 2. The computed results for both figures were taken from the turbulence generating divided combustion chamber of engine I - the mass burning curves for a lean iso-octane mixture ($\phi = 0.7$) and the flame propagation speed for a methanol mixture with an equivalence ratio of 1.0. Both tests were at a compression ratio of 9:1.

**Cyclical Variations**

Cyclical variations in combustion significantly influence driveability and are more prevalent in the lean burning regime. The analysis of individual burning cycles showed cyclical variations in burning rate as mixture strengths were weakened to the lean misfire limit. The individual cycles recorded in these tests were classified into five categories which were characterised by:

A. Normal combustion with a short delay period, high burning rate and complete combustion at EVO.

B. As in A above but with a reduced burning rate.
C. Partial burning at a low rate and flame extinction before EVO.

D. Cycles in which the establishment of the flame kernel takes a considerable time, resulting in long delay periods and low burning rates.

E. Eight-stroking.

The analysis of 152 individual cycles with low equivalence ratios for two different fuels, iso-octane and methanol, recorded on engine I are shown in table 3 below. With methanol the incidence of misfiring was reduced at equivalence ratios leaner than those for iso-octane.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Incidence of cycle types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>iso-octane</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>9:1</td>
</tr>
<tr>
<td>Equivalence ratio</td>
<td>0.75 - 0.85</td>
</tr>
<tr>
<td>Number of cycles</td>
<td>64</td>
</tr>
<tr>
<td>Percentage of cycle type recorded</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>25.0</td>
</tr>
<tr>
<td>B</td>
<td>37.5</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>12.5</td>
</tr>
<tr>
<td>E</td>
<td>25.0</td>
</tr>
</tbody>
</table>

COMBUSTION CHAMBER GEOMETRY

Different combustion chamber designs may be readily compared using diagnostic modelling. The influence of incorporating inlet swirl, by use of a shrouded inlet valve, together with a comparison between a standard cylindrical combustion chamber and a highly turbulent bowl in the piston crown, is exemplified by the graph of maximum burning rate against 10% burn time in figure 3 taken from engine III. The maximum burning rate was about 44% higher with the increased turbulence of the bowl in piston design. The initial period of flame propagation, here quantified as the 0-10% burn time, was reduced by 5.4%. The addition of a shroud to the inlet valve reduced the period of flame development and increased the maximum burning rate by 80% for the standard combustion chamber and by 34% in the case of the bowl in piston design.

FUEL TYPE

This is particularly pertinent today as there is a trend towards wider fuel specifications and the introduction of alternatives. The performance of the divided combustion chamber with methanol mixtures was compared with that of the base-line fuel, iso-octane, in figure 4. Mean values of the maximum mass burning rate for 16 consecutive cycles was plotted against the equivalence ratio as the mixture strength was weakened. The results indicate the higher burning rates obtained with the combustion of methanol mixtures and the degree to which the equivalence ratio could be weakened below that for iso-octane before cyclic variations made stable operation impossible.
INITIAL FLAME DEVELOPMENT

The characteristics of initial flame development are important as they have a direct bearing on subsequent propagation. The application of the diagnostic engine computer model to the analysis of initial flame development in engine I when burning lean methanol mixtures was reported by the authors (1985). The computed curves of flame propagation velocity and mass fraction burnt, typified in figure 2, exhibited the four distinct features described below.

A. A period of heat transfer immediately following spark discharge during which the cylindrical column of gas between the electrodes was heated to the self-ignition temperature.

The heat transfer period was related to the laminar flame speed with an inverse power law, the index of which was a function of compression ratio.

B. Instantaneous self-ignition of the cylindrical column with a correspondingly high instantaneous value of flame propagation velocity.

The high instantaneous value of flame propagation velocity, resulting from the 'explosion' of the unburnt gas between the electrodes, varied from 35m/s with stoichiometric mixtures to 18m/s for mixture strengths approaching the lean misfire limit.

C. A period during which the flame kernel was consolidated and established. Here unburnt gas was entrained into the small expanding kernel with a cooling action that resulted in a decrease in the value of propagation velocity with time. Quenching could occur if the entrainment rate continuously exceeded the burning rate.

The computed results demonstrated an inverse relationship between propagation velocity and time during this phase of flame development.

D. Establishment of a self-propagating turbulent flame with an accelerating flame front.

With stoichiometric mixtures the onset of an accelerating flame front was clearly discernable but with lean mixtures it was difficult to specify the exact point at which the flame could be said to be established. For this reason a definition of 1% burnt was adopted. The variation in total period of flame establishment with laminar flame speed for engine I burning methanol with compression ratios of 9:1 and 11:1 is shown in figure 5. This characteristic was found to be represented by

\[
\frac{\tau_{1%}}{\tau_{12} \phi = 1} = \left(\frac{S_L}{S_{L=1}}\right)^n
\]

where \(n\) was evaluated as a function of compression ratio

\[
n = 0.22 \xi - 3.0
\]

INFLUENCE OF INITIAL FLAME DEVELOPMENT AREA

The importance of the behaviour of the spark ignition flame during the initial stages of flame development is the subject of current research.
de Soete (1983) stated that, 'The subsequent flame propagation, during which the major portion of the fuel is burnt, depends substantially on the transitory period during which the flame kernel is being established'. This phenomenon was exemplified in these tests by the existence of individual cycles in which a long delay period resulted in low burning rates - type D cycles. The influence of the delay period on the maximum burning rates computed for individual cycles; using methanol in the lean burning regime at a compression ratio of 9:1 may be seen in Fig.6. The high maximum burning rates, associated with complete combustion, resulted from a short delay period. The initial development of the flame kernel was more rapid with lean methanol mixtures than with lean iso-octane mixtures and maximum burning rates were correspondingly higher with methanol at about 5.5%/°CA for flame establishment periods of 10 to 15° CA.

CONCLUSIONS

Diagnostic engine combustion models may be used relatively inexpensively to predict combustion performance parameters from readily acquired cylinder pressure data. Computer data acquisition systems need not be sophisticated. Microcomputer based CPUs and floppy disk systems are adequate for this purpose. The pressure increment technique is suitable for use directly on microcomputer systems but file transfer packages to mainframe computers are needed for the equilibrium theory analysis. Tests undertaken on three engines, with iso-octane as a baseline fuel and with methanol, demonstrated that higher burning rates and shorter periods of initial flame development are possible with increased levels of turbulence. Stable operation could be extended further into the lean burning regime using compact combustion chambers particularly with alcohol fuel.

ACKNOWLEDGEMENT

The authors wish to thank E Marshall of BP Research Centre for the interest that he has shown in this work and for the provision of test results from a Ricardo E6 engine for comparative purposes, and the Research Committee of the University of Surrey for an award to initiate this work.
REFERENCES


Fig 1 Typical mass burning curves
Fig 2 Typical burning and propagation speed curves

Fig 3 Influence of geometry on combustion performance

Maximum burning rate / % CA⁻¹

Engine III
MBT timing
Compression ratio 10:1
Iso-octane
Speed 1000 rev/min
Ø disc
Δ bowl in piston

0 - 10% burn time / ms
Fig 4 Influence of equivalence ratio on maximum burning rate

Maximum burning rate / %°CA⁻¹

0 0.6 0.8 1.0
Equivalence ratio

Methanol

 Iso-octane

Fig 5 Variation in flame establishment period with laminar flame speed

Flame establishment period / ms

0 1.5
Laminar flame speed / ms⁻¹
Fig 6 Influence of flame establishment period on maximum mass burning rate.

Maximum mass burning rate / % $^{\circ}\text{CA}^{-1}$

Engine 1
Fuel methanol
Compression ratio 9:1

Flame establishment period / $^{\circ}\text{CA}$
Alcohol fuels for diesel engines

R A Johns, A W E Henham & S Newnham
Alcohol fuel for diesel engines

R. A. Johns*, A. W. E. Henham, * and S Newnham*

SYNOPSIS
The paper begins by examining the reasons for using alcohol fuels as a replacement for petroleum-derived fuels. The wide range of sources of alcohols enable most nations to undertake production of indigenous supplies. In general alcohols are excellent fuels for the spark-ignition engine of traditional design. Alcohol is quite unsuited in combustion properties for the more efficient unthrottled compression-ignition (diesel) engine. The reasons for this are explained and various means of overcoming the problems are outlined – additives for cetane improvement, alcohol-diesel emulsions, dual injection, fumigation, surface ignition and spark ignition. In each case the practical drawbacks as well as the benefits are discussed. Finally some conclusions are drawn about the potential for alcohol-fuelled diesel engines based on the authors' studies and experimental work.

INTRODUCTION
The versatility of oil has made it an attractive fuel for industry and transport. It is, however, a finite resource that is becoming increasingly more difficult and more expensive to find. Whilst many varied estimates of the life of the world's oil resources have been made, it is generally agreed that by the end of this century oil supplies will approach a critical level. Severe restrictions will be placed on the use of oil and prices are forecast to rise significantly above those of today in real terms. Whilst it is possible to employ alternative sources of energy such as nuclear power, wind and solar energy and coal in static industries and domestic applications, transport will remain dependent on liquid fuels which have a high specific energy content, are readily transportable and easily stored.

Alcohol fuels, either methanol produced from natural gas deposits or ethanol produced by fermentation and distillation of biomass, are recognized as attractive alternatives to oil derived fuels for automotive and truck engines [1, 2]. There is currently a world surplus of methanol but production costs per energy unit exceed those for petroleum fuels. Other considerations such as the establishment of alternative fuel supplies strategically independent of imported oil or environmental legislation on engine emissions may accelerate the introduction of alcohol fuels. Ethanol from biomass is particularly suited to localized production and immediate use in engines thereby alleviating the need to develop sophisticated distribution systems in remote areas. The potential is high with conversion rates of up to 40 t of alcohol per annum from each hectare. Problems of quality control with small scale production could, however, lead to poor engine performance and reduced reliability especially with fuel injection equipment.

* R. A. Johns MSc(Eng), PhD, DIC, CEng, FiMarE, MiMechE, course tutor Maritime and Offshore Engineering; A. W. E. Henham BSc(Eng), CEng, FInstE, MiMechE, MRAeS, Director of Energy Engineering; S. Newnham BSc. Research Assistant; Energy & Thermodynamics Group of the Department of Mechanical Engineering, University of Surrey, Guildford, England. © Ambient Press Limited 1988
The introduction of alcohol fuels on a large scale gives rise to the proverbial "chicken and egg syndrome". The fuel supplies and the requisite technology exist but distribution systems need to be developed at exactly the same time as the markets are penetrated with alcohol compatible engines. Is the supply infrastructure to be installed first in anticipation of the market potential or are alcohol fuelled engines to be introduced before fuel supplies are established on a wide scale? Possible answers to this fundamental question include the increasing use of alcohol–gasoline blends, the production of engines with a multifuel capability, and large scale fleet operations or mass transit systems with limited fuel distribution points.

Both methanol and ethanol have high octane ratings (RON), 114 and 111 respectively and are, therefore, well suited for use in high-compression, spark-ignition engines. These two oxygenate fuels can be used directly as a fuel, as an octane booster in place of lead or mixed with gasoline to extend oil reserves. Environmental pressures to eliminate lead in gasoline may well provide the stimulus required to increase methanol production for the introduction of gasoline-alcohol blends on an economic scale. Ethanol, produced locally from corn, is already blended with gasoline in mid-west states in the US in proportions up to 15% while the use of ethanol from sugar cane in Brazil has been widely publicised. There do not appear to be any unsurmountable engineering problems to be overcome for the introduction of alcohol fuels in automotive spark-ignition engines. Compression ratios should be raised to take advantage of higher RON in providing higher efficiency. Metallic components exposed to alcohol fuels need to be nickel plated to resist corrosive attack. Some types of rubber and plastic components need to be replaced with alcohol resistant materials. Increased cylinder wear resulting from washing the lubricating oil film from cylinder walls by alcohol liquid and poor cold starting performance in severe climatic conditions have been identified as the main engineering problems.

**DIESEL ENGINES**

In the case of considering the diesel engine, however, both methanol and ethanol are not attractive fuels for compression ignition. The quality of ignition for diesel engine fuels is defined by the cetane number. This is a measure of the delay period between the start of injecting fuel and ignition of the atomized fuel spray by the high temperatures produced in the air charge through high compression ratios (Figure 1). For good combustion this delay needs to be very short. Typically the quality of high-speed diesel engine fuels is maintained with cetane numbers in the range 50–56 in the UK. In other countries diesel engines are run on degraded fuels with cetane numbers as low as 37. With low cetane numbers the delay period is long. This results in the accumulation of a large volume of unburnt fuel in the cylinder before ignition occurs. Combustion is rapid and uncontrolled with high rates of pressure rise. Pistons are exposed to excessive stresses at high temperature which results in erosion problems on piston crowns. Noise levels, the characteristic diesel knock, are increased and performance deteriorates. With cetane numbers below 30 the diesel engine will not run without aids to initiate ignition or additives to improve the cetane number. Oxygenate fuels have cetane numbers very much lower than that at the compression-ignition limit of 30. In the case of methanol the cetane number is 3. Alcohol fuels are unsuitable for use in diesel engines without ignition-enhancing devices or cetane number-improving additives.

It has been suggested, however, that cetane number, while being an effective criterion for the comparison of traditional hydrocarbon fuels, is not appropriate as a means of judging alternative fuels. A wide range of alternative fuels, especially vegetable oils, is under consideration as substitutes for gas oil and it seems right to ask now whether cetane number can remain as the best assessment of these. A parallel problem has been experienced with spark-ignition fuels. Unleaded fuels of octane number equal to that of leaded gasoline are seen to have inferior combustion characteristics on-the-road.

The apparent variation in the characteristics of fuels for compression-ignition engines may be because of the differences in the contribution of the two phases of the ignition delay. The first is a physical process – the heating of fuel droplets and subsequent evaporation. This is sensitive to the air temperature towards the end of compression, droplet size and distribution and the presence and
position of hot surfaces in the chamber. This is modified mainly by design-geometry, materials (e.g. insulation in limited-cooled engines) and turbocharging. The second phase is chemical and is more directly controlled by the chemical kinetics of the reactions involved. Both phases, of course, are heavily dependent upon the properties of the fuel itself.

The diesel engine is inherently more efficient than its spark-ignition counterpart. Power is controlled in the diesel by varying the fuel-to-air ratio rather than by throttling the mixture in the inlet manifold as in the spark-ignition engine. As a consequence the diesel engine has found widespread applications in both static installations and transportation. It is considered to be the most economic engine for future use especially when fuel prices are forecast to rise significantly as oil reserves are depleted. It has been acknowledged by many informed researchers that the problem of igniting low cetane number alcohol fuels will need to be addressed before any successful programme of distribution alternative fuels can be introduced on a wide scale. Current research and development work is directed at several techniques to reduce the ignition delay — notably cetane improving additives, diesel-alcohol emulsions, dual injection, fumigation, surface ignition glow plugs and spark assistance.

CETANE NUMBER IMPROVERS

The key to successful operation of diesel engines on alcohol fuels lies in reducing the long ignition delay period associated with these fuels to times comparable with those for good quality automotive gas oil (AGO). That is improvement of the cetane number. Commercially available ignition improvers, such as ethyl D113 and cyclohexynitrates, have been formulated for addition to AGO to increase the cetane number. These are suitable as additives for both ethanol and methanol. Other compounds currently receiving attention, particularly with ethanol, are the nitrate esters, triethyleneglycol dinitrate (TEGON) and tetrahydrofurfuryl nitrate (THF). The ignition performance of these improved alcohols is comparable with that for AGO at high compression ratios but deteriorates more rapidly than that for AGO as the compression ratio is reduced. The main advantage in using ignition improving additives is that alcohol fuels can be used in unmodified engines. However the serious disadvantage is that the quantity of additive required can be as high as 15% by volume thus making cetane number improved alcohol fuels an uneconomic proposition at today's prices.

EMULSIONS

Alcohols can be mixed with diesel oil. Substitutions of up to 20% alcohol by volume are possible before the specific fuel consumption of the diesel engine is impaired. The alcohol can be held suspended in the oil in the form of sub-micron sized droplets to make an emulsion, but these two fuels tend to separate and alcohol/diesel oil emulsions are unstable. Unstable emulsions may be used economically in large installations where it is possible to store the two components in separate tanks and to mix them in the correct proportions immediately before injection. These emulsions can be made stable with the addition of surfactants but fuel costs will be increased with the addition of a third component. The main problem here is the strong affinity of alcohol for water. If water contaminated fuel is allowed to enter fuel metering and fuel injection equipment excessive corrosion occurs thereby severely affecting reliable operation. Purging fuel systems by running on diesel oil only before shutting the engine down reduces corrosion and aids cold starting.

DUAL INJECTION

Higher proportions of alcohol, up to 95% [3], may be substituted using dual injection systems (Figure 2). Combustion is started with a pilot injection of diesel oil before a larger quantity of alcohol is injected through the main injector nozzle. The pilot injection acts as an ignition source for the alcohol fuel. Whilst mixing and separation problems associated with emulsions are eliminated, use of a dual injection system requires expensive engine modifications. Complex fuel control systems are needed to meter and time two separate fuel flows accurately. The volume of alcohol injected is about twice that for diesel oil as the alcohols have specific energy content of about one-half that of conventional diesel fuels. Injection and fuel metering equipment thus has to be specifically designed to match the increased volumetric fuel flowrate. Additives are also required in alcohol fuels to lubricate pump plungers and injector

![Figure 2 Dual injection into piston bowl.](image-url)
needles to ensure a satisfactory life between services. Degummed castor oil has been used successfully as a lubricating additive in ethanol; about 1% by volume. This is an expensive additive and high quality castor oil is in short supply. The authors currently use castorene as a suitable alternative.

**FUMIGATION**

In the fumigation technique alcohol fuel is introduced into the engine with the intake air. Two techniques are currently in use — the injection of alcohol into the turbocharger diffuser scroll (Figure 3) and the use of a carburettor in the air intake. Both techniques require less engine modification than with dual injection systems and are suited to retrofitting. Limitations in physical space may also preclude fitting dual injectors into existing cylinder head designs. The amount of alcohol substitution is limited to about 50% by detonation of the air-fuel mixture; "knock" [3].

Accurate control of the alcohol flow is needed especially when running on light loads to prevent misfiring and at high loads to reduce knocking.

The ignition delay period is increased with fumigation and combustion shifts significantly into the expansion stroke. The air charge is reduced owing to the inclusion of alcohol and the maximum power output is, therefore, reduced below that for diesel fuel only. Turbocharger compressors are subjected to erosion by the impinging fuel droplets with this technique.

**GLOWPLUGS**

Alcohol fuels have a poor resistance to ignition on hot surfaces. For methanol the surface ignition resistance (SIR) is zero compared with 100 for iso-octane. Whilst this can have detrimental effects in carburetted engines, such as pre-ignition of the mixture before spark discharge or running on when the ignition is turned off, surface ignition can be used to ignite injected alcohol fuel sprays in diesel engines (Figure 4). Complete substitution of diesel oil with either methanol or ethanol is possible using surface ignition. At 25 bar a surface temperature of about 825°C will ignite an atomized methanol spray in the time scale required for high speed diesel engines. The ignition delay period can be reduced with increased surface temperatures up to 975°C. Below 725°C combustion may be erratic with large cycle-to-cycle variations and below about 675°C surface ignition of methanol is not possible.

The glow plugs normally used to improve cold starting in diesel engines can be utilized as hot surfaces to ignite alcohol fuels. The injector position is important. It should be located ahead of the glow plug in the direction of swirl to
prevent fuel droplets from impinging directly on to the glow plugs. Quenching on glow plugs can result in loss of ignition. At full load metal temperatures may be sufficiently high to ignite the fuel without using glow plugs. Engines not already equipped with starting glow plugs would not all have a convenient space for access to the combustion chamber.

SPARK ASSISTANCE
Spark-ignition of alcohol fuels in unthrottled diesel engines offers an attractive method for the complete substitution of diesel oil with alcohol (Figure 5). Positive ignition ensures minimal ignition delay periods and results in smooth combustion. Diesel engines with high swirl combustion chambers machined into piston crowns or those with turbulence prechambers are ideally suited to the combustion of lean alcohol mixtures by spark-ignition. Conversion to spark ignition need not be prohibitively expensive. Electronic ignition systems, driven from a bottom dead centre camshaft marker through programmable integrated circuits can be readily installed without major engine modifications. Space is required in the cylinder head to install a spark plug although those designed for glowplugs are readily adaptable. The original fuel injection equipment could be retained but the maximum power output would be reduced due to the lower specific energy content of alcohol fuels. Ideally higher capacity fuel pumps and injector nozzles need to be fitted. The alcohol fuelled diesel engine is not smoke limited and engine torque can be increased at slow speeds. Injection timings need to be advanced over those for diesel fuel to allow sufficient time for vapourized fuel to reach the spark plug. Multi-strike capacitive discharge ignition systems have been used successfully in alcohol fuelled diesel engines. Spark discharge durations of 50 degrees of crank angle were used to ensure ignition over a wide range of speeds and loads. It is this approach which the authors are pursuing in a current project [4]. Conventional automotive single spark ignition systems have also been installed on a methanol injected engine. In this case the spark advance was limited by detonation of the fuel air mixture.

As an alternative solution carburettors or port injectors can be used instead of in-cylinder injection in spark-ignited diesel engines burning 100% alcohol fuels. The high compression ratios result in thermal efficiencies higher than in the conventional spark ignition engine and the turbulent combustion chambers associated with diesel engines are suited to stable operation with alcohol fuels well into the lean burning regime. However control of power output by throttling the intake mixture in these engines results in reduced efficiency at part load.

CONCLUSIONS
The concept of a world-wide fuel as enjoyed with oil will no longer be valid as oil resources are depleted and fuel prices "take-off". Different solutions to the transport fuel problem will be adopted by each nation depending on its indigenous supplies of raw materials. Ethanol fuels are suited to local production and use in countries with sufficient agricultural capacity. Methanol will find increasing use in countries with large natural gas or coal deposits. Engine manufacturers will need to know how their products operate on a variety of alternative fuels. The varied techniques available to reduce the ignition delay period in diesel engines when using alcohol fuels ensure their continued application as an economic source of power in the future. Considerable advantage in world markets will accrue to the manufacturers of those engines with the most versatile combustion systems.

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Spark-assisted, ethanol-fuelled diesel engine

R A Johns, A W E Henham & S Newnham

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SPARK-ASSISTED ETHANOL FUELED DIESEL ENGINE

R A Johns, A W E Henham and S Newnham
Department of Mechanical Engineering, University of Surrey, Guildford, Surrey, England.

SUMMARY

Whilst ethanol is well suited to use in spark-ignition engines, its low cetane number makes this alternative fuel unsuitable for direct use in compression-ignition engines. Various techniques are in use to initiate combustion of ethanol in diesel engines. One such technique, which is relatively inexpensive, is to convert the diesel to spark-assistance. This paper describes the conversion of a typical small scale power unit, the Petter PH1 air-cooled diesel, which is in widespread use throughout the world.

1. Introduction

The development of alternatives to petroleum derived fuels for reciprocating engines became an attractive proposition for oil importing countries following the OPEC price rises of the early 1970s and the escalation of oil prices as a consequence of the Iran-Iraq conflict. The urgency to diversify fuels has been reduced substantially following the recent dramatic falls in the price of crude oil. However, development of alternatives remains a valid proposition particularly in developing nations where indigenous sources of fuel could reduce adverse oil balance of payments. Alcohols, either methanol produced from natural gas, or ethanol produced from fermentation of biomass and distillation, are recognised as alternative fuels for spark-ignition and diesel engines. Both have high octane numbers and are, therefore, well suited for use in spark-ignition engines. These oxygenates have cetane numbers much lower than that of about 30 which is considered to be the limit for compression ignition. Alcohol fuels are thus unsuitable for direct use in diesel engines. Ignition enhancing devices or additives to improve the cetane number are required for satisfactory operation.

The diesel engine is inherently more efficient than its spark-ignition counterpart. Power is controlled by varying the fuel-to-air ratio rather than by throttling the mixture in the inlet manifold as is the case in spark-ignition engines. As a consequence the diesel has found widespread applications, particularly as a small power unit in rural locations. The problem of increasing the diesel engine's fuel tolerance especially in relation to alcohol fuels, which may be available locally, needs to be resolved. This paper describes the
conversion of a Fetter PHI engine, typical of those in widespread use throughout the world, to spark-assistance for use with ethanol.

2. Ignition Techniques

Various techniques are available to reduce the delay period between injection and ignition by compression in diesel engines. Commercially available ignition improvers, such as ethyl DII3 and cyclohexylnitrate, have been formulated for addition to automotive gas oil to increase the cetane number. Both are suitable additives for cetane improvement in alcohol fuels. Other compounds receiving attention for use with ethanol include triethyleneglycol dinitrate (TECON) and tetrahydrofurfuryl nitrate (THFN). The main advantage in using additives is that the alternative fuels may be used directly in unmodified engines. However, the serious disadvantage is that the quantity of expensive additive required can be as high as 15% by volume. This technique may thus be uneconomic, especially if the cetane enhancing compounds need to be imported.

Retention of the diesel oil injection equipment, as a pilot system to initiate combustion, is an alternative technique. The main charge of alcohol may be injected directly into the combustion chamber once ignition has commenced or introduced into the air inlet through use of a carburettor or manifold injector (fumigation). The volume of alcohol injected is about twice that of conventional diesel oil. The oxygenate fuels have specific energy contents of about one-half that of diesel fuels. Injection and metering equipment need to be uprated to match the increased flow rate. Adoption of a dual fuel system requires extensive modification to the engine and the installation of a complex control system to accurately meter and time two separate fuel flows. The fumigation technique needs less modification of the engine and is well suited to retrofitting. Knock considerations, however, limit the amount of alcohol substitution to about 50%. Accurate control of the alcohol flow is required especially when running lightly loaded, to prevent misfiring, and also at high loads to reduce knock.

Alcohols have a poor resistance to ignition on hot surfaces. At 25 bar a surface temperature of about 825 °C will ignite an atomised spray of ethanol in the timescale needed for use in high speed diesels. The glow plugs, which are normally used to improve cold starting, can be used to good effect to ignite alcohol fuels. This is an attractive technique for burning alcohols in diesel engines fitted with electrical systems and glow plugs.

The high swirl and high squish combustion chambers machined into piston crowns or turbulence generating pre-chambers in diesel engines are ideal for promoting combustion of lean mixtures by spark-ignition. Positive ignition ensures optimisation of delay periods. Spark assistance in unthrottled diesel engines is considered to be a viable alternative technique for the complete
substitution of gas oil with alcohol. Conversion to spark-ignition need not increase the technical complexity of the diesel unduly or be prohibitively expensive. Electronic ignition systems, driven from single bottom-dead-centre markers on the flywheel through robust TTL circuitry, are commercially available. These can be easily installed without major modification to the engine. The main problem with existing designs is that of finding sufficient space in the cylinder head to locate the spark plug.

3. ENGINE CONVERSION

A Petter PH1 single cylinder, air cooled, diesel engine was selected for conversion to burn alcohols with spark assistance. This engine was considered to be typical of those used throughout the world for small scale power generation and pumping duties. Originally designed over 40 years ago, in single or twin cylinder form with air or water cooling, these engines are still in continuous production in the UK and are built under licence in many countries including India. Continuous development incorporating modern technology over the years has resulted in a range of designs suitable for many applications. Power may be taken off both ends of the crankshaft or at half speed off both ends of the camshaft. Ease of servicing with limited resources in rural locations has made these engines eminently suitable for use in the developing world.

Table 1

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore/Stroke</td>
<td>87.3/110 mm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16.5:1</td>
</tr>
<tr>
<td>Speed range</td>
<td>850-2200 rev/min</td>
</tr>
<tr>
<td>Continuous rating (gas oil) at 2200 rev/min</td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>32.1 Nm</td>
</tr>
<tr>
<td>Specific fuel consumption</td>
<td>262 g/kWh</td>
</tr>
</tbody>
</table>

Taking the rural applications of this engine and the potential locations of ethanol fuel supplies into consideration, resulted in the adoption of a philosophy that readily available automotive components should be used in the conversion to spark-assistance wherever possible. This would enable retrofitting in the field and ensure the ready availability of spares. With this particular installation, however, the engine is the research vehicle for optimising ignition and injection timing, and studying the associated combustion performance of spark-assisted diesels with low cetane number fuels. A compromise was thus adopted and the ignition system installed was controlled from an encoder, fitted to the crankshaft, through an electronic timing circuit. In field applications a fixed ignition timing system driven from a single BDC marker would be utilised. A piezo-electronic pressure transducer was fitted into the cylinder head for research purposes.

The ignition system fitted is shown schematically in figure 1.
Since the fuel distribution in the combustion chamber is not homogeneous with direct injection, particularly at light loads, a multistrike discharge system was used. In keeping with the philosophy adopted this was centred on a conventional high tension coil. To reduce the recovery time in the coil following discharge and thereby enable a high frequency multistrike rate the low tension side was energised by means of a 100V supply. This was provided from a typical automotive 12V supply by use of a switch mode step converter. The current in the low tension winding of the coil was limited to 5A using component MOSFETs. For research purposes the ignition system was controlled through a separate TTL timing circuit.

The geometry of the cylinder head and the associated valve gear severely restricted the location of the spark plug. This was further exacerbated by the need to provide cylinder pressure tappings for the transducer. Ideally the electrodes should be located in the vaporised fuel spray. In practice the geometry dictated the plug location. The position of the spark plug and the pressure transducer tapping may be seen in the photographs of figure 2. The plug tapping is angled through the cooling fins with the electrodes positioned close to the valve seat. A standard long reach 14 mm plug was used.

An over capacity fuel pump is fitted on the PHI engine and a spacer is provided on the rack to overfuel the engine on cold starting. This pump can meet the increased fuel flow required with the lower energy density fuel. The injection period is, however, increased and this resulted in late burning with high exhaust temperatures. A replacement pump with a delivery rate of about twice that of the existing one and a compatible injector nozzle is to be fitted shortly.

Injection timing on the PHI engine is by spill. This was advanced by some 10% of that required for gas oil, to about 31° BTDC by adjusting the cam follower length. The advanced timing was to allow vaporised fuel to reach the spark plug electrodes and the flame kernel to become established. For stoichiometric mixtures the flame establishment period (0-1% burnt) may be about 5° CA. With leaner mixtures this period increases; about 15-20° CA for equivalence ratios of 0.7(2). The use of the multistrike system, with long spark discharge periods, ensures ignition and smooth running over a wide range of loads and speeds.

The operating envelope of diesel engines is usually limited at reduced speeds by exhaust smoke. Alcohols burn with a clean blue flame and smoke is no longer a limiting criterion. Preliminary testing of the converted engine has, however, been restricted to the makers continuous rating for gas oil rather than uprating the engine to the structural limit.

4. Conclusions

The Petter PHI engine was readily adapted to spark assistance for
burning ethanol. Injection timings were advanced over those for conventional compression ignition fuels to allow for vaporisation and the increased volumetric fuel flow rate. A multi-strike spark discharge system based on a conventional coil was designed and fitted to ensure smooth operation over a wide range of speeds and loads.

5. Acknowledgements

The authors wish to acknowledge the financial support provided by the SERC and the help given by BP Research Centre and Hawker Siddeley Diesels.

6. References


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Figure 1 Experimental Ignition System
Figure 2. Modified Cylinder Head
Evaluation testing of a spark-assisted diesel with ethanol fuel

R A Johns, S Newnham, P Marshall & A W E Henham

EVALUATION TESTING OF A SPARK-ASSISTED DIESEL WITH ETHANOL FUEL

R A Johns, S Newnham, P Marshall and A W E Henham
University of Surrey, Guildford, England.

ABSTRACT

Small diesel engines of less than 10 kW are in common use throughout the world for power generation and water pumping, particularly in rural areas. Ethanol produced locally from biomass is an attractive alternative fuel but its low cetane number makes it unsuitable for direct use in compression ignition engines. Various techniques are available to initiate combustion of low cetane number fuels. Pilot injection of diesel oil complicates the fuel system and the addition of cetane improvers to ethanol is expensive. Conversion to spark assistance is relatively simple and inexpensive and results in a diesel with a multifuel capability. This paper describes the conversion of a typical small engine, a Petter PHI air-cooled diesel. The philosophy adopted was that the ignition system installed in the field could be made up of readily available automotive type components and incur minimum modification to the engine. Preliminary testing indicates that injection timings need to be advanced over those for conventional fuels, to allow good mixing before ignition. The fuel flow rate needs to be increased to accommodate the lower energy density of ethanol.

INTRODUCTION

The small diesel engines used widely throughout the Third World for power generation and pumping duties are well suited for conversion to the alcohol fuels which are recognised as attractive alternatives to oil. Methanol and ethanol, with RONs of 114 and 111 respectively, are ideally suited for use in the high compression, highly turbulent combustion chambers of these engines when supplied as a homogeneous mixture and ignited with spark discharge systems (1). It is, however, recognised that the problems of igniting alcohol fuels in direct injection diesel engines needs to be addressed before a successful programme of supply and distribution of alcohol fuels can be established. Both methanol and ethanol have low cetane numbers and are therefore difficult to ignite by compression, particularly at loads below 25% of maximum rating. Various techniques, such as the use of cetane enhancing additives, pilot injection of diesel oil, fumigation and surface ignition may be employed to initiate combustion. Pilot injection results in a complex dual fuel system and, whilst additives may be used directly in unmodified engines, the high quantity required may make this technique uneconomic. Spark assistance was considered to be a viable alternative for the complete substitution of diesel oil with alcohols. Conversion to spark-ignition need not increase
the technical complexity unduly or be prohibitively expensive. Electronic ignition systems, driven from markers on the flywheel are commercially available. The inherent advantage of high efficiency with unthrottled diesel engines could therefore be retained in the so called spark assisted diesel engine.

IGNITION SYSTEM

Taking the rural applications of this engine and the potential locations of ethanol fuel supplies into consideration, resulted in the adoption of a philosophy that readily available automotive components should be used in the conversion to spark-assistance wherever possible. With this particular installation, however, the engine is a research vehicle for optimising ignition and injection timings, and studying the associated combustion performance. A compromise was thus adopted and the ignition system installed was controlled from an encoder, fitted to the crankshaft, through an electronic timing circuit. In field applications a fixed ignition timing system driven from a single RDC marker would be utilised.

The ignition system fitted is shown schematically in figure 1. Since the fuel distribution in the combustion chamber is not homogeneous with direct injection, a multistrike discharge system was used. In keeping with the philosophy adopted this was centred on a conventional high tension coil. To reduce the recovery time following discharge, and thereby enable a high frequency multistrike rate, the low tension side was energised by means of a 100V supply. This was provided from a 12V supply by use of a switch mode step converter. The current in the low tension winding of the coil was limited to 5A using power transistors.

ENGINE MODIFICATION

A Petter PHI single cylinder, air-cooled direct injection diesel engine was selected for conversion. Originally designed over 40 years ago, in single or twin cylinder form with air or water cooling, these engines are still in continuous production in the UK and are built under licence in many countries including India. Robust construction and ease of servicing with limited resources in rural locations has made these engines eminently suitable for use in the developing world.

The main modification to the engine was the addition of a spark
IGNITION SYSTEM

Figure 1
plug. The geometry of the cylinder head and the associated valve gear severely limited possible sites for the spark plug. This problem was further exacerbated by the need to fit a pressure transducer in order to record cylinder pressure. Ideally the spark plug electrodes should be located centrally in the combustion space and also in the vapourised fuel spray. In practise the geometry dictated its position. (Figure 1) The plug is angled through the cooling fins and protrudes into the combustion bowl cut in the piston crown. The plug seating was made to accept 14 mm plugs so that the widest range of automotive plugs could be used.

Initially standard reach plugs were used, but since they were out of the fuel spray severe misfiring occurred. The air/fuel ratio varies across the spray cone produced by the injector, from neat fuel, through a zone where the mixture is within the limits of flammability, to an unignitable lean zone. Therefore correct positioning of the spark gap is vital to enable good establishment of the initial flame kernel. Subsequent use of a long electrode plug put the spark gap into a more favourable position in relation to the fuel spray and eliminated misfiring; although differences in the delay before flame establishment were still observable at different engine speeds due to the effects of swirl on the fuel spray distribution.

An over capacity fuel pump is fitted to this engine. This pump can meet the increased fuel flow required with the lower energy density of ethanol. The injection period is, however, increased with ethanol and this resulted in late burning, high exhaust temperatures and a high specific fuel consumption. The ignition delay and burning rate are a function of mixture strength. For stoichiometric mixtures the flame establishment period (0 – 1% fuel burnt) may be about 5°C. With leaner mixtures this period increases; about 10 – 15°C for equivalence ratios of 0.7 (2). Injection timing is by spill, and this was advanced by 10° by adjusting the cam follower length to allow more time for the fuel to vaporise, reach the spark plug electrodes and the flame kernel to become well established. The spill timing adjustment was limited and although it improved the running of the engine, a shaft driven pump has been installed to give greater variation in injection timing.
CONCLUSIONS

The Petter PHI diesel was readily adapted to spark assistance for burning ethanol. Injection timings were advanced over those for conventional compression ignition fuels to allow for good mixing before ignition, the high enthalpy of vaporisation and the long delay period for flame establishment associated with the lean mixtures in the ignition zone. This necessitated the installation of a separate shaft driven fuel pump as the spill timing on the original pump could not be advanced sufficiently. Initiation of combustion was sensitive to spark location and commercially available long electrode spark plugs were used to avoid misfiring. A multistrike spark discharge system was designed and fitted to ensure smooth operation and facilitate optimisation of spark timing and duration.

ACKNOWLEDGEMENTS

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Practical experience of operating small diesel engines with alcohol fuels

R A Johns, A W E Henham & S Newnham
Practical experience of operating small engines with alcohol fuels

R A Johns, A W E Henham and S Newnham
University of Surrey, Guildford, Surrey, UK

SUMMARY

Energy conservation and fuel diversification in the wake of the crude oil 'price hikes' of the 1970's provided the initial stimuli to develop alternative fuels such as ethanol and methanol. These alcohols can be produced from indigenous energy resources such as renewable biomass or coal and natural gas to derive economic benefits and strategic independence. Recently, however, environmental considerations of air quality have reinforced the stimuli to implement 'clean' alternative fuels. The combustion characteristics make alcohols suitable for use in spark-ignition engines but the low cetane number makes ignition by compression in diesel engines difficult. The diesel is inherently more efficient than its spark-ignition counterpart and this problem thus needs to be addressed before alcohol fuels implementation policies will be successful.

This paper outlines the environmental and financial benefits that may be realised with alternatives, such as ethanol and methanol, presents techniques for improving the combustion of alcohols in diesel engines and reports the authors' experience to date with carburetted and with direct-injection, spark-assisted engines.

INTRODUCTION

The hikes in the price of crude oil during the 1970's provided the initial stimuli to conserving energy and developing alternatives for petroleum derived fuels. Whilst it is possible to employ alternative sources of energy, such as coal or nuclear fission, and the renewables, such as wind, tidal or solar power, in static industries and domestic applications, transport will remain dependent on liquid fuels. These are easily stored and readily transported. The potential of using alcohols as fuels for internal combustion engines has been recognised and policies to support implementation and development introduced in many countries. These policies emphasise different objectives in different countries with the introduction of alternative fuels on a regional basis. The concept of a single world-wide fuel, as is the case with oil, will in the future no longer be valid. All of the countries have, however, responded to two principal influences;

a. strategic concern for perceived shortages and supply of crude oil arising from the geographical distribution of the resource.
b. economic benefits of using alternatives to oil integrated with the opportunity to use indigenous energy resources.

Alcohols are already in widespread use, as octane boosters in gasoline, as petroleum extenders or as neat fuels. The Brazilian proalcool programme to reduce oil imports by 80% is the most notable. In 1986/87 11.7 billion litres of ethanol were produced from sugar cane to fuel 2.7 million alcohol vehicles and 5.3 million vehicles using gasoline alcohol blends (1).

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Today, however, with crude oil priced at about $19 a barrel, alcohol fuels are not economically viable alternative fuels on the basis of energy alone. The stimulus to implementing alcohol fuels has now changed to that of reducing environmental pollution. Legislation to reduce lead levels in gasoline has provided an incentive to market substitute octane enhancers such as methanol itself and methyl tertiary butyl ether (MTBE) which is produced from methanol feedstock. In comparison with petroleum fuels methanol is clean burning and ozone levels could be substantially reduced with methanol substitution. Both ethanol and methanol have high octane ratings, 111 and 114 RON respectively, and are consequently most suitable for use in high compression, lean-burning spark-ignition engines. Lean combustion results in reduced emission levels of oxides of nitrogen (NO\textsubscript{x}), hydro-carbons (HC) and carbon monoxide (CO). Conversion of diesel engines to burn alcohol fuels is particularly attractive from the emissions perspective. Both particulates and oxides of nitrogen emissions may be reduced substantially thereby improving air quality. Cost comparisons between fuels should, consequently, not be based on production costs alone. In the future economic comparisons between fuels should include the through-life costs of emission control. On this basis methanol substitution for gasoline or gas oil is becoming economically competitive. Smith (2) quotes US costs at (1985) leaded gasoline 32.0¢/mile, diesel fuel 20.4¢/mile and methanol 25.7¢/mile for heavy duty vehicles, with emission control costs included.

**SMALL ENGINES**

The authors have concentrated their research effort on the adaption of small diesel engines of less than 10 kW to burn alcohol fuels. Such engines are widely used throughout the Third World for micro-power generation and pumping duties. Local production of ethanol as a fuel for this type of engine is particularly attractive for reducing adverse balance of payments in developing countries. Lately the proliferation of micro diesel-generators in the urban centres in some of these countries has resulted in high CO and NO\textsubscript{x} pollution levels. This problem could be addressed with the implementation of an alcohol fuels policy. The highly-turbulent, high-compression combustion chambers in these engines are ideally suited to burning homogeneous mixtures of alcohol and air which is ignited by spark discharge systems. Further the mixture strength may be leaned substantially to reduce pollution emissions as the fluid motion in the combustion chamber is highly turbulent. Two single cylinder diesels were converted to throttle controlled, spark ignition engines, by fitting carburettors and electronic ignition systems. Both run satisfactorily with methanol fuel (3).

In the case of ignition by compression, however, the alcohols are unsuitable without the application of ignition enhancing devices or addition of cetane number improvers to the fuel. The cetane number for methanol is 3, whereas the combustion quality of high-speed diesel engine fuel is maintained in the UK with cetane numbers in the range 50 - 56. Whilst alcohol fuels for compression-ignition engines thus present a problem it is important that this is addressed for the successful introduction of alcohols as alternative fuels. The diesel is inherently more efficient than its petrol engine counterpart owing to power being controlled by fuel-to-air ratio rather than by throttling the mixture in the inlet manifold. Consequently diesel engines are in widespread use. Recently the authors have directed their research on the problem of igniting alcohol fuels in direct injection unthrottled diesel engines. In particular spark-assistance has been used to initiate combustion of ethanol in diesels. (4).
SPARK-IGNITION ENGINES

The high resistance to knock offered by the alcohols as fuels in spark-ignition engines can be exploited by increasing the compression ratio. This produces an increase in thermal efficiency over lower compression versions of engines demanded by the unleaded gasolines to which legislation in many countries is creating a move.

A proven result of the use of alcohols in spark-ignition engines is the ability to run much weaker mixtures than can be achieved reliably with hydrocarbons. As for other lean-burn engines, those using alcohols require highly turbulent combustion chambers to realize the full potential of the fuel. This improves the initial burning rate which, in the authors experience, is the main predictor of the reliability of complete combustion. Experiments (3) using two engines, one with a divided combustion chamber and one with a turbulent open chamber, using a swirl inlet port and recessed piston, demonstrated these effects. Figure 1 shows the range of equivalence ratios obtainable in the two engine designs and the degrees of crank angle required to burn 2% of the fuel. This is determined by computer analysis of pressure-crank angle data acquired in tests.

The environmental benefit derived from this ability to burn with considerable excess air derives from the shape of the curves of exhaust CO, HC and NO\textsubscript{X} against equivalence ratio (figure 2). Since the NO\textsubscript{X} peaks on the weak side of stoichiometric, it is necessary to move into a very lean region in order to combine low CO with low NO\textsubscript{X}. When hydrocarbon fuels are used in these very lean ratios misfiring occurs frequently, resulting in very high unburnt fuel proportions in the exhaust and, of course, an inefficient cycle. The disadvantage of lean operation is the lower specific output but this can be compensated to some extent by the higher compression ratio permitted by the use of alcohol. At full power only mixtures closer to stoichiometric can be used to restore the peak output. Under these conditions the high enthalpy of evaporation of alcohols gives higher volumetric efficiency.

DIESEL ENGINES

Ignition Techniques

Techniques are available to enhance ignition of alcohol fuels in diesel engines with partial or whole substitution of gas oil. The cetane number may be improved by the addition of nitrogen based compounds such as triethyleneglycol dinitrate (TEGDN) and tetrahydrofurfuryl nitrate (THFN). The quantity of additive may be as high as 10 - 15% by volume and these compounds are more expensive to produce than the raw fuel. These additives do, however, allow complete substitution of gas oil with alcohol and few modifications are needed to the engine; the changes being limited to the increased volumetric flow through injectors and pumps to accommodate the lower calorific value of the fuel, and injection timing. The main disadvantages are the high cost of cetane-enhancing compounds, which are often imported, and increased NO\textsubscript{X} emissions.

Alcohol/gas oil emulsions and solutions share many advantages and disadvantages. Solutions are the most direct and simplest method but are limited to about 20%
Figure 1. Influence of equivalence ratio on initial burning rate.

Figure 2. Influence of equivalence ratio on relative emission concentration.

Figure 3. Comparison of specific fuel consumption with gas oil and ethanol in spark-assisted diesel.
substitution with alcohol if the solution is to remain stable. Emulsions facilitate the addition of larger quantities of alcohol, about 40%, but for stability approximately equal quantities of emulsifier are needed. Little modification is needed to the engine but, the quantity of alcohol replacing the diesel fuel is small.

A larger quantity of alcohol may be used with dual injection systems in modified engines. A small pilot injection of gas oil, about 10% of the total, initiates combustion before the main power producing injection of alcohol. This technique adds to the complexity and cost of the engine with the need for a second fuel injection system and extensive engine modification.

Fumigation is, possibly, a simpler technique of substitution. Here a homogeneous alcohol-air mixture can be introduced into the cylinder through a carburettor or inlet manifold injector. Combustion is then initiated by direct injection of a small quantity of oil through a pilot injector. The ignition delay period is increased with fumigation and may cause late burning.

Combustion may be readily initiated in alcohol fuels by surface ignition. The glow plugs fitted for cold starting can be used for this purpose. Surface ignition facilitates complete substitution of gas oil with alcohols. Glowplug positioning may be critical as liquid impingement on the hot surface can result in quenching.

**Spark-Assisted Diesel**

An alternative technique for complete substitution is the utilisation of a spark-ignition system. This has been used by the authors for the conversion of a single cylinder Petter PHI direct-injection, air-cooled engine to burn ethanol. The main modification was the installation of a programmable electronic ignition system with timing synchronised by an encoder fitted to the crankshaft. As this engine is in common use in rural locations throughout the developing world the philosophy adopted for modification was that of using readily available automotive ignition components. However, recognition that this particular application is used for research, has resulted in an ignition system with complete flexibility over timing and spark duration. In field applications a fixed timing driven from a mark on the flywheel would be used. The spark-plug was fitted at an angle through the cooling fins of the cylinder head with electrodes projecting into the bowl in the piston crown. The plug position was severely limited by geometric considerations.

The calorific value of ethanol is about two-thirds that for gas oil and it was necessary, therefore, to uprate the fuel pump capacity. Further, as the injection control on the original system was by spill and very limited, a separate higher capacity, belt-driven fuel pump was mounted on the bedplate. This enabled flexibility in injection timing to facilitate the optimisation of injection and, with the programmable ignition system, ignition timings. A piezo-electric pressure transducer was fitted in the cylinder head and a needle lift transducer in the injector for combustion analysis. A microprocessor based data acquisition system, clocked from the crankshaft encoder, is used to enable cylinder pressures to be recorded at each degree of crank-angle over 50 cycles at speeds up to 2200 rev/min. The data is transferred to the University's Prime mainframe computers for reduction.

The performance of the spark-assisted engine burning ethanol is compared with that when configured as a diesel engine in figure 3. The graph of brake specific
fuel consumption, expressed in energy terms as gas oil equivalent, against brake mean effective pressure is comparable. Consumption of ethanol is higher but these results are preliminary ones taken before optimisation of the injection and ignition timings. As ethanol burns without producing the particulate emissions associated with traditional diesel fuels the engine is not limited by smoke considerations. The engine may be uprated, with the operating envelope enlarged, provided that thermal and structural limits are not exceeded.

CONCLUSIONS

Energy - Year of the Environment plus 50 - Environmental considerations of air quality will need to be integrated into the economic equations used for formulating policy on the implementation of alternative fuels. When the through-life costs of emission control equipment are included in the equation, alternatives such as methanol and ethanol will become economically competitive with petroleum derived fuels. It is unlikely that a single fuel will dominate as has been the case with oil. Individual countries are more likely to implement different alternative fuels which derive economic and strategic benefit from the use of indigenous energy resources.

Ethanol produced from renewable biomass is an attractive fuel for spark-ignition engines. The high octane rating makes ethanol particularly suitable for use in lean-burning, high-compression engines, thus improving fuel economy whilst reducing pollutant emissions. However, the widespread use of diesel engines makes it desirable to address the problem of burning low cetane number fuels, such as alcohols, for the successful introduction of an alternative fuels programme. Ignition improving compounds may be added to the fuel but surface ignition or spark assistance techniques which address the problem at source are more likely to be incorporated in the fuel tolerant diesel engines of EYE+50.

ACKNOWLEDGEMENT

The authors wish to acknowledge the financial support of the SERC and the help provided by BP Research Centre, Lister-Petter Diesels, Lucas CAV and NGK Spark Plugs

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Optimisation of ignition and injection timings in a spark-assisted, alcohol-fuelled diesel

R A Johns, A W E Henham & S Newnham
Optimisation of Ignition and Injection Timings
in a Spark-Assisted Alcohol Fuelled Diesel

Johns, R. A., Henham, A. W. E., Newnham, S.

University of Surrey, Guildford, U. K.

Abstract

Successful introduction of alcohol fuels on a widespread basis, particularly in rural areas, will depend substantially on overcoming the problems of burning alcohols in diesel engines. This paper describes the conversion of a small diesel, typical of those used throughout the world for micro-power generation, to a spark-assisted engine, the optimisation of ignition and injection timings, and the performance obtained with direct injection of ethanol. The power rating of this engine proved to be limited by thermal stress considerations.

Introduction

Eight years of experience of operating small diesel engines on alcohol fuels has been gained at the University of Surrey. The engines concerned are less than 10 kW and typical of the many small diesel engines used throughout the world for micro-power generation and pumping duties, particularly in rural areas in the developing world. Initially, recognising the high octane rating of alcohols, the work was focussed on the modification of diesels to burn spark-ignited, homogenous alcohol/air mixtures (1). However, successful implementation of alcohol fuels on a widespread basis will depend substantially on overcoming the problems of burning alcohols in small diesels. Various techniques such as cetane number improving additives, emulsions, dual injection systems, fumigation and surface or spark-ignition can be used. Some allow complete substitution of alcohol whilst others are limited by the quantity of gasoil required for ignition by compression.

This study has concentrated on the complete substitution by alcohol in a spark-assisted, direct-injection diesel. Such an engine is considered to be the most fuel tolerant and, therefore, the most versatile for use with alternative fuels. With spark-assistance advantage can be taken of both the high octane rating and the high enthalpy of vaporisation of alcohols. The high compression ratio of the diesel coupled with positive ignition by spark discharge results in smooth combustion with a high thermal efficiency.

This paper reports the conversion of a Petter PH1 air-cooled diesel to a spark-assisted engine, the optimisation of ignition and injection timings, the performance obtained with direct injection of ethanol and the practical problems experienced.

Engine modification

The Petter PH1 diesel was selected as being typical of the small diesels in use throughout the world for static installations. It is a development from a line of successful engines originally designed some forty years ago. These engines are still in continuous production in the UK and are built in many other countries under licence. The engine specification is shown in table 1.

Consideration of the typical applications of this type of diesel led to the adoption of a conversion philosophy that modifications should be minimal and that wherever possible readily available automotive components should be used. The spark discharge system developed, shown schematically in figure 1, is based on a conventional HT coil. Provision has, however,

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Petter PH1 specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore/stroke</td>
<td>87.3/110 mm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16.5:1</td>
</tr>
<tr>
<td>Speed range</td>
<td>750-2200 rev/min</td>
</tr>
<tr>
<td>Continuous maximum rating (gasoil) at</td>
<td>2200 rev/min</td>
</tr>
<tr>
<td>brake specific fuel consumption</td>
<td>262 g/kWh</td>
</tr>
<tr>
<td>brake power</td>
<td>7.4 kW</td>
</tr>
</tbody>
</table>
been made on this particular installation, which is used primarily for research, to programme the spark timing and the duration of the discharge. As the fuel distribution is not homogeneous in the combustion chamber of a direct-injection engine a high frequency, multi-strike spark assistance system was used to ensure positive ignition. The coil is recharged rapidly with the high voltage output from the switch mode converter applied to the primary winding. The current is limited to 5 A. The system is synchronised by BDC and crank angle signals from a crankshaft encoder and runs at 13.2 kHz. In field applications the spark-assistance system would be fixed at the optimum timing and duration, and driven from a single BDC synchronising signal provided by an opto-electronic sensor triggered by a single timing mark on the flywheel.

Timing optimisation tests

Alcohol fuels burn with a 'clean' blue flame and alcohol fuelled diesels are not limited by smoke considerations when running off-design. It may be possible to uprate such an engine. It was decided, however, that the manufacturer's maximum continuous rating, with gasoil, 5.6 kW at 1800 rev/min, would be used as the limit for timing optimisation tests. The tests were made with fuel injection timing varied in 10° steps from 40° to 80° BTDC and ignition timing varied in 2° intervals from 16° to 28° BTDC. Cylinder pressure was recorded at 1° intervals for 50 consecutive cycles at each test point for subsequent combustion analysis.

The effect of injection and ignition timings on fuel economy is shown on the brake specific fuel consumption map in figure 2.

The minimum value of brake specific fuel consumption (expressed in terms of gasoil equivalent) achieved was 263 g/kWh. This compares well with the value of 259 g/kWh obtained with the engine configured as a conventional diesel. Maximum fuel economy occurred within the area bounded by injection and ignition timings of 48° to 52° and 20° to 24° BTDC respectively. Within this region ignition timing had little effect but this may be owing to the long spark duration of 12° used that reduced significantly cyclic variations in combustion. The compression ratio was reduced to 16.0:1.

The original cam driven fuel pump was capable of meeting the increased flowrate required to compensate for the lower energy density of alcohol fuels. The injection timing could, however, be advanced over only a few degrees. This proved to be inadequate and to ensure good mixing and vapourisation of the alcohol for ignition by spark discharge. To resolve this problem a separate Lucas CAV belt-driven fuel pump with provision to vary injection timing over a range of 120° in 2° intervals was installed. Having a larger swept volume this pump also restored the rate of fuel energy supply to that of the diesel fuel version.

Figure 1 High Frequency spark assistance system.

A hemispherical combustion chamber is machined centrally in the piston crown of the Petter PHI diesel. Fuel is injected at an angle into the highly turbulent air motion which results from the squish action. Ideally the spark gap should be located centrally in the combustion chamber to ensure ignition in a 'rich' mixture zone. The cylinder head geometry severely limited possible tappings for the spark plug and a compromise was adopted. A tapping for 14 mm long reach plugs, of the type used by Japanese motor manufacturers in their lean-burn engines, was machined on the inlet side of the cylinder head. Some material was machined from the edge of the combustion chamber to enable the electrodes to protrude into the hemispherical bowl in the piston crown. The removal of this metal improved the air flow in the vicinity of the spark discharge and consequently had a beneficial action in reducing significantly cyclic variations in combustion. The compression ratio was reduced to 16.0:1.

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Figure 2. Influence of injection and ignition timings on brake specific fuel consumption.

Outside the area of the timing map of figure 2, operation was limited by severe knocking with excessive maximum cylinder pressures, combustion continuing late into the expansion stroke or excessive temperatures in the cylinder head metal. During prolonged running the earth electrode on a spark plug broke off and damaged the ceramic insulator. On stripping the engine it was found that the loose fragments had caused impact damage to the piston crown, cylinder head and exhaust valve seating. More importantly inspection revealed thermal stress cracks running from the injector tapping to both inlet and exhaust ports, crossing the valve seats in both cases. A third crack ran from the spark plug tapping to the inlet valve seat. Discussions with the manufacturer confirmed the diagnosis that the cracks resulted from overheating. Cracks are likely to develop in the grey cast iron cylinder head if the metal temperature exceeds 350° C. The maximum continuous rating for the PHI when configured as an ethanol-fuelled, spark assisted diesel was thus limited by thermal stress considerations only.

Combustion analysis

The pressure rise attributable to combustion was calculated at each degree of crank angle from the acquired cylinder pressure data. The 0 - 1% and 1 - 50% combustion pressure rise times were computed at each test point. The 0 - 1% rise time is considered by the authors (3) to be a good indicator of the initial flame establishment period as defined by a positive acceleration of the flame front. The 1 - 50% rise time indicates the burning rate for the established flame. Table 2 shows that minimum 0 - 1% rise times occur at injector timings of 70° BTDC and also at 50° BTDC.

Table 2

<table>
<thead>
<tr>
<th>Injection Timing/°BTDC</th>
<th>80</th>
<th>70</th>
<th>60</th>
<th>50</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition Timing</td>
<td>1.7</td>
<td>1.4</td>
<td>1.8</td>
<td>-</td>
<td>1.7</td>
</tr>
<tr>
<td>1.7</td>
<td>1.5</td>
<td>1.7</td>
<td>1.5</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>1.7</td>
<td>1.5</td>
<td>1.7</td>
<td>1.5</td>
<td>1.7</td>
<td>20</td>
</tr>
<tr>
<td>1.7</td>
<td>1.5</td>
<td>1.7</td>
<td>1.5</td>
<td>1.6</td>
<td>22</td>
</tr>
<tr>
<td>1.6</td>
<td>1.5</td>
<td>1.6</td>
<td>1.5</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>1.5</td>
<td>1.4</td>
<td>1.5</td>
<td>1.5</td>
<td>-</td>
<td>26</td>
</tr>
<tr>
<td>-</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>28</td>
</tr>
</tbody>
</table>

It is deduced that the spark-assisted engine behaves more like a manifold-injected gasoline engine with well advanced injector timings whereas, the effects of a true compression-ignition engine are exhibited with injection timings at 50° BTDC and below. Further, at well advanced injection timings more fuel is needed to maintain the rated power. The overall equivalence ratio is, therefore, increased and the flame establishment period is accordingly reduced.

A surface plot showing the influence of injection and ignition timings on the 1 - 50% combustion pressure rise time is shown in figure 3.
Conclusions

The Petier PH1 diesel was converted to a spark-assisted engine to realise a multifuel capability. The engine has been tested with direct injection of ethanol into the hemispherical combustion chamber in the piston crown. Power output was limited by thermal stressing considerations in the grey cast iron of the cylinder head to a metal temperature of 350°C. Temperatures in excess of 350°C cause cracks to develop from the injector tapping across both valve seats to the inlet and exhaust ports. The brake specific fuel consumption, expressed as gasoil equivalent on an energy basis, was found to be comparable; about 1.5% greater than that for gasoil when run at 1800 rev/min with a brake load of 5.6 kW. Optimization tests for maximum fuel economy indicated appropriate injection and ignition timings of 50° BTDC and 24° BTDC respectively.

Figure 3. Influence of injection and ignition timing on 1 - 50% combustion pressure rise time.

The surface plot shows that the long burning periods result from late ignition timing and from early injection. The timings for maximum burn rate correspond to those for maximum fuel economy. The hypothesis, previously advanced, that the spark-assisted alcohol-fuelled diesel is operating in two distinct ways is supported in the surface plot indicating the burning rate. A distinct ridge in burning rate occurs with an injection timing of 60° BTDC. At well advanced injector timings a more nearly homogeneous fuel-air mixture is formed with a low overall equivalence ratio. Burning rates are, therefore, low. With late injection timings the charge is still stratified in the vicinity of the injector and ignition occurs in a 'fuel rich' region. The charge burns with a correspondingly higher flame speed. Although reference has been made to equivalence ratio, this parameter is inadequate in defining the nature of the fuel-air mixture in the spark-assisted diesel. The duration of the injection period was not available during these tests with the result that overlap of the injection period on the ignition timing was not quantified. In the most extreme case of injection at 40° BTDC with ignition at 26° BTDC it is highly likely that injection continues once the flame has been established by the spark discharge.

Acknowledgments

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References


Development of a fuel-tolerant diesel for alternative fuels

A W E Henham, R A Johns & S Newnham
Development of a fuel tolerant diesel for alternative fuels

Le développement d'un moteur diesel, tolerant des carburants, pour les carburants alternatifs

A.W.E Henham, R.A. Johns, S. Newnham
Dept. of Mechanical Engineering, University of Surrey, United Kingdom

SUMMARY

There is a growing requirement for engines operating on a wider range of fuels than has been necessary in the past when fuel supplies were more stable. The diesel engine, with its high compression ratio and absence of part-load throttling, offers high efficiency. Some widely available alternative fuels, in particular alcohol from biomass, present problems because of their low cetane numbers. The authors report the development of a diesel engine using a combustion system incorporating a high-energy, multi-strike spark to promote smooth combustion. Results obtained with this engine using ethanol are presented to illustrate its ability to handle fuels of very low cetane number.

RESUME

L'instabilité des sources d'approvisionnements de carburant a créé une demande accrue pour des moteurs pouvant utiliser une variété de carburant. Le moteur diesel, grâce à son haut taux de compression et l'absence d'étranglement des gaz à charge partielle, offre un rendement très élevé. Quelques uns des carburants alternatifs les plus courants, tel l'alcool obtenue de la biomasse, sont difficiles d'emploi à cause de leurs bas niveau d'indice de cetane. Cet article
rend compte du développement d'un moteur diesel qui utilise une étincelle répétée à haute énergie pour stimuler une combustion continu et sans à-coups. L'aptitude du moteur à brûler des combustibles à très bas indice de cetane est démontrée à l'aide de résultat obtenu avec de l'éthanol.

INTRODUCTION

The driving force for the initiation of the work described here was the rapid increase in oil prices during the 1970's. This affected most those less developed countries which had no indigenous petroleum resources. It was for this reason that ethanol was used as the first alternative fuel to be explored in this programme for its potential use in diesel engines. Such countries often have large quantities of underdeveloped agricultural land and welcome the rural employment opportunities which a programme of biomass development would provide. In Brazil this development, using sugar cane as an alcohol source, has already taken place and the use of this fuel as an enhancer and as a total substitute for gasoline is well established. The production of alcohol, expressed as litre/hectare of land use is greater for this crop than for others exploited but other sources are viable in various parts of the world. This has been widely reported, for example by Elkington (1984) and by Trindade and Carvalho (1988). The work of the latter reports that in 1987 sales of cars in Brazil comprised 387 000 alcohol and 23 000 gasoline engined. and even light commercial vehicles were three times more likely to have an alcohol spark-ignition engine than a diesel engine. It is suggested that in the present situation of low oil prices, local oil production and alcohol production costs it may be necessary to modify the programme, possibly allowing some increase in gasoline use for private vehicles and a move towards alcohol for heavy commercial vehicles, at present almost entirely diesel-engined. Although the suggestion is that this would be by conversion to heavy Otto (ie spark-ignition) engines, the authors believe that a more cost effective solution would be to convert diesel engines to run on alcohol fuels.

ALTERNATIVE FUELS FOR DIESEL ENGINES

The emphasis on the use of alcohol fuels in spark-ignition engines rather than in compression-ignition engines derives from their high Octane numbers and low Cetane numbers. On the basis of combustion quality alone (as expressed by these two criteria) it is clear that ethanol and methanol offer advantages over gasoline and, at the same time, suffer disadvantages when compared with
automotive diesel fuels. The significant factors, from Goodger (1982) are shown in table 1.

Table 1: Properties of alcohol fuels compared with hydrocarbons

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gasoline</th>
<th>Diesel fuel</th>
<th>Methanol</th>
<th>Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calorific value MJ/kg</strong></td>
<td>43.0</td>
<td>41.8</td>
<td>19.9</td>
<td>27.2</td>
</tr>
<tr>
<td><strong>Energy density MJ/litre</strong></td>
<td>32.3</td>
<td>36.4</td>
<td>15.9</td>
<td>21.6</td>
</tr>
<tr>
<td><strong>Octane number RON (premium)</strong></td>
<td>98</td>
<td>na</td>
<td>114</td>
<td>111</td>
</tr>
<tr>
<td><strong>Cetane number</strong></td>
<td>na</td>
<td>45</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td><strong>Spontaneous ign temp °C</strong></td>
<td>400</td>
<td>245</td>
<td>385</td>
<td>365</td>
</tr>
</tbody>
</table>

* net or lower calorific value and energy density given.

All these characteristics show much closer relationships between the alcohols and gasoline than they have with diesel fuel. In particular the low cetane number and high spontaneous ignition temperatures create problems in the initiation of combustion by spraying fuel into the compressed air near the end of the compression stroke. Where the fuel is ignited it will burn only with prolonged ignition delay which leads to knocking in diesel engines. The authors' original work with alcohol fuels was in connection with the combustion of lean mixtures in spark-ignition engines and in the analysis of combustion using computer modelling combined with simple pressure crank angle instrumentation. This has been reported by Johns and Henham (1984,1985).

Spark-ignition engines generally exhibit inferior brake specific fuel consumption than diesel engines, through the effect of lower compression ratio and of throttling. The latter factor is especially important at part load which makes it especially significant for vehicle operation.
POSSIBLE SOLUTIONS

A number of possible approaches exist which can improve the combustion of low cetane number fuels in diesel engines. These are listed in Table 2 with some of their advantages and disadvantages.

Table 2: Combustion systems for low cetane number fuels

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical cetane improvers</td>
<td>No engine modification</td>
<td>High cost of additives, large quantity required</td>
</tr>
<tr>
<td>(added to fuel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emulsions</td>
<td>Minimum engine modification</td>
<td>Still needs over 50% diesel fuel, two fuel supplies needed.</td>
</tr>
<tr>
<td>(produced at engine or by emulsifying agent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dual injection</td>
<td>Small amount of diesel fuel for pilot injection</td>
<td>Complex control, needs two complete injection systems</td>
</tr>
<tr>
<td>(Alcohol and diesel injectors)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fumigation</td>
<td>Cheaper than dual injection</td>
<td>Still needs about 50% diesel fuel, two fuel supplies needed</td>
</tr>
<tr>
<td>(Alcohol air mixture ignited by diesel fuel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface ignition</td>
<td>Only one fuel required</td>
<td>Large energy input to hot surface, insertion through head</td>
</tr>
<tr>
<td>(permanently hot additional surface)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spark assistance</td>
<td>Only one fuel required</td>
<td>Additional insertion through head, cost of ignition system</td>
</tr>
<tr>
<td>(alcohol injected, spark-ignition)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At the time when the work was initiated some of these approaches had been given considerable attention but the last had been given very little attention. It was thought that an engine could be relatively easily modified to incorporate the necessary spark-ignition system. The advantage of requiring only one fuel was considered important for use in developing countries where the
considered important for use in developing countries where the additional infrastructure for the supply of two fuels would be unlikely to become developed. There are also problems with untrained staff in the possibility of placing the two fuels in the wrong tanks. Most people engaged in engine maintenance understand the automotive ignition system as well as the diesel injection system which are fundamental to this type of engine.

DESIGN OF RESEARCH ENGINE

The engine was selected on the basis of its simple design and the ease with which it could be modified and instrumented for the purpose. Since it was air-cooled the provision of an additional tapping into the cylinder head did not introduce complications with water passages. It was also necessary for the combustion analysis programme to tap the head for a pressure transducer and this, too, was facilitated by the absence of water passages. To represent current trends it was also felt to be important to have an engine with direct injection. Additionally the engine is of rugged construction, designed for applications in construction and agricultural industries. The structure is of cast iron and the crankshaft and connecting rod, forged steel. There are full and half speed drives from the crankshaft and camshaft respectively. The engine specification is given below in table 3.

An additional advantage of this engine making it appropriate for work connected with the use of alternative fuels in developing countries is the widespread use of this type and others closely resembling it in many such countries throughout the world. It is, therefore, at the same time demonstrating a directly applicable technology and providing a testbed for later application of the methods developed to more complex, automotive type, engines.
Table 3: Experimental engine specification

<table>
<thead>
<tr>
<th>Make and type</th>
<th>Petter PH 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle</td>
<td>Four-stroke</td>
</tr>
<tr>
<td>Bore x Stroke</td>
<td>87.3 x 110 mm</td>
</tr>
<tr>
<td>Cylinders</td>
<td>one</td>
</tr>
<tr>
<td>Swept volume</td>
<td>658 cm³</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>16.5</td>
</tr>
<tr>
<td>Speed range</td>
<td>750-2200 rev/min</td>
</tr>
<tr>
<td>Continuous rating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(diesel fuel)</td>
</tr>
<tr>
<td>power</td>
<td>7.4 kW</td>
</tr>
<tr>
<td>torque</td>
<td>32.1 Nm</td>
</tr>
<tr>
<td>bsfc</td>
<td>0.262 kg/kWh</td>
</tr>
</tbody>
</table>

The cylinder head, modified to accept the spark plug and pressure transducer, is illustrated in figure 1.
In order to use alcohol in a standard diesel-type fuel pump it is necessary to provide some lubrication of the pump elements. This is provided by the addition of a lubricant to the alcohol fuel tank. A more significant difference between the fuels is in the lower energy density of alcohol fuels when compared with hydrocarbons as shown in table 1. Since most pumps operate at constant rate and vary the duration of fuel delivery to control the total quantity, injection of the greater quantity of alcohol would involve injection over a long period. This changes the nature of the cycle diagram as the injection would last well into the expansion stroke at the higher loads. Single-cylinder engines generally have fuel injection pumps built into the casing so that there are no external drive elements. This makes it virtually impossible to optimise the
quantity and timing of the injection of fuel. For these two reasons an independent fuel injection pump having a larger swept volume was obtained providing a higher flow rate and a drive system built which enabled variation of timing. It is emphasised that this complication would not be needed in a production engine since the built in pump would be appropriately sized and timed for the intended fuel. For automotive engines the ability to vary timing is usually present in the standard system.

**Ignition system**

A simple ignition system would again be unable to allow optimisation of all the variables when exploring new ground although it is hoped that once this exercise is completed it may be possible to revert to this. For development a complex system providing multiple, high-energy; sparks was developed. This enables independent control of the variables - initiation of spark (degrees of crank angle after bottom dead centre), duration of spark (degrees of crank angle), frequency of multiple spark (Hz). For the experimental engine the trigger for this system is the crankshaft encoder, which also gives the signals to the data acquisition system, but in production versions a simple flywheel trigger could be incorporated. A standard automotive coil is used, the low tension side being driven by a semiconductor circuit. The spark plug presented a problem in that it was understood from published work by Komiyama (1981) that the location relative to the injector spray was critical. This implied the use of longer electrodes than were thought to be available. Contact with the manufacturer of spark plugs for lean-burn gasoline engines resulted in the supply from Japan of plugs with a range of extended electrodes covering the lengths required.

**Other engine modification**

To clear the spark plug it was necessary to relieve the edge of the combustion chamber bowl in the piston crown. This appears to assist the flow round the electrodes but it is difficult to know exactly what is the pattern of fuel and air flow in this region. The compression ratio is reduced from 16.5 to 16 by this modification.

**EXPERIMENTAL INSTALLATION**

The engine is mounted on a test bed having a d.c dynamometer with motoring facility used also for starting. There are facilities for the storage and supply of three different fuels in parallel tank systems. Instrumentation is provided for the following:

- torque
- speed
fuel flow
cylinder pressure
injector needle lift
crank angle (360 and 1 pulse per revolution channels)
inlet air temperature
exhaust temperature
cylinder head temperature

and, in addition although not reported here, exhaust gas analysis for oxygen, carbon monoxide and unburned hydrocarbons is available in the laboratory.

EXPERIENCE WITH ALCOHOL FUELS

After initial baseline tests with the engine in standard form and using gas oil, the engine was converted as described above. A series of tests were undertaken to prove the system and to develop the spark-ignition system. During these tests the engine suffered damage and, on stripping it down, cracks were discovered in the cylinder head and damage to the piston crown was also noticed. The cracks were between the two valve seats and the injector aperture and between one seat and the spark plug aperture. On discussing this damage with the engine manufacturer it was found that similar damage had been experienced with the standard engine on diesel fuels when conducting overload tests. It was thought appropriate to limit the cylinder head metal temperature to 300°C since this had been found to prevent damage in the case of the standard engine. Since alcohol fuels do not limit the performance of an engine by excessive smoke it appears that the head temperature provides a thermal limit on performance instead. The limit also had the advantage of protecting the cylinder pressure transducer, one of which suffered damage at the same time as the head. The damage to the piston was partly thermal and partly the result of the impact of pieces of the spark plug, which was also damaged during the failure. The readings at this time showed combustion continuing late into the expansion stroke, with consequently high exhaust temperatures, and high peak pressure.

RESULTS

Further tests, after fitting a new cylinder head with thermocouple embedded and a new piston, concentrated on the establishment of the optimum timings of fuel injection and spark ignition. The first set of tests was conducted at constant power, 5.6 kW, and speed, 1800 rev/min. Results are shown as a brake specific fuel consumption map against the two sets of timings in figure 2. The injection timing is shown from 80 to 40 degrees before top dead
centre in 10 degree steps and the ignition timing from 26 to 16 degrees before top dead centre in two degree increments. The duration of ignition run in each case was 12 degrees of crank angle at approximately one pulse per degree. It is seen that the brake specific fuel consumption minimum is at an injection timing 50 degrees before TDC with 20 to 24 degrees of spark advance. The value of 265 g/kWh gas oil equivalent is comparable with the rated value for the standard engine which is 259 g/kWh at the same load and speed.

Figure 2: Map of brake specific fuel consumption on a gas oil basis against timings of fuel injection and ignition

Analysis of combustion data
The data from the pressure transducer was sampled at every degree of crank angle by means of a Sirton microcomputer with 12-bit analogue to digital converter. This information was automatically sampled for the first 50 consecutive cycles after the sampling instruction. The computer system, which is shown in figure 3, includes a dual disk drive, keyboard, vdu and printer in the outer room of the engine test cell. Software enables this equipment to
emulate a terminal of the University's PR1ME computer system. This facilitates the transfer of data for combustion analysis programs which are much too large for the microcomputer. For each 50-cycle batch the rise times for 0-1% and 1-50% of maximum pressure rise were computed. The former is regarded by Johns, Henham and Marshall (1985) as an indication of the effective establishment of the initial flame. As a measure of the stability of the combustion the cyclic dispersion of a parameter can also be determined by the program and that for maximum pressure is shown in figure 4, also plotted against injection and ignition timings.

**Figure 3: Computer system for data acquisition and analysis**
CONCLUSIONS

The standard diesel engine can be readily adapted to burn alcohol fuels with the provision of a high-energy spark ignition system.

The combustion depends upon the fuel injection timing in that early fuel injection creates premixed combustion conditions similar to those in a traditional spark-ignition engine whereas late injection gives a stratified charge more in keeping with the true diesel. Stable operation is available under both approaches (as indicated by low cyclic dispersion) but the latter gives more economical operation under the conditions of the first set of tests.

Brake specific fuel consumption at the test load (three-quarters full load power) was comparable with that for gas oil on an energy basis.
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Operation of a spark-assisted diesel for stationary applications on alcohol fuels

S Newnham, R A Johns & A W E Henham
Operation of a spark-assisted diesel for stationary applications on alcohol fuels

S NEWNHAM, BSc, MIDGTE, R A JOHNS, MSc, PhD, CEng, MIMechE, FIMarE and A W E HENHAM, BSc(Eng), CEng, MIMechE, FInstE, MRAeS
Department of Mechanical Engineering, University of Surrey

SYNOPSIS Modifications were made to a Fetter PHI air-cooled diesel to convert it to a spark-assisted, alcohol-fuelled engine. The performance obtained after optimisation of ignition and injection timings and some practical problems encountered are described. The modifications included the fitting of a multi-strike, high frequency ignition system and a separate fuel injection pump to meet the increased flow required by the lower calorific value fuels and advanced injection timings. The engine was limited by thermal stress considerations.

NOTATION

\[ p_{\text{max}} \] average maximum cycle pressure
\[ \sigma \] cyclic dispersion in cylinder pressure
\[ \sigma \] standard deviation in maximum cycle pressure

1 INTRODUCTION

The introduction of alternatives to petroleum derived fuels for internal-combustion engines became a financially attractive possibility for oil importing countries following the OPEC price hikes of the 1970s. The escalation of crude oil prices as a consequence of the start of the Iran/Iraq conflict reinforced the implementation of alternative fuels. The dramatic fall in the price of crude oil with overproduction in recent years, however, has reduced the economic impetus to replace petroleum fuels. Environmental stimuli to reduce exhaust emissions from reciprocating engines remain. In the longer term oil will remain a finite resource that is becoming increasingly more difficult and increasingly more expensive to find.

The concept of a world-wide single fuel, oil, is unlikely in the future. Many economies, particularly in developing countries, need to reduce balance of payments deficits by replacing oil imports with fuels produced from indigenous resources. The alternatives developed will depend substantially on the availability of local feedstocks. Fuel type and quality may vary from region to region and country to country, depending on the raw materials and process production facilities available. For the engine manufacturer a wide fuel tolerance will be a prerequisite for world-wide sales. The Brazilian proalcool programme is the most notable alternative fuel implementation and is well documented (1). Ethanol produced in local refineries from sugar cane has displaced gasoline as the prime automotive fuel. However, the majority of engines burn ethanol or ethanol gasoline blends and have been specifically adapted for these fuels. These engines do not have a true multifuel capability where a wide range of fuels can be burnt with the minimum of modifications carried out in the field.

Alcohols have a high octane rating and are, therefore, well suited as either replacement fuels or gasoline extenders in blends for high-compression, spark-ignition engines. From the environmental viewpoint the introduction of alcohols as octane boosters in blends is an attractive alternative to lead alkyls. Experimental engine programmes and captive fleet tests have shown the viability of implementing alcohol fuels, both methanol and ethanol, in spark-ignition engines. Successful introduction on a wide-scale basis, however, will depend substantially on overcoming the problems of burning alcohols in compression-ignition engines. The diesel, with power controlled by variation of the fuel-to-air ratio in place of throttling a near stoichiometric fuel-air mixture, is inherently more efficient than its spark-ignition counterpart. As a consequence the diesel has found wide-scale applications in both static installations and vehicles. It is considered the most economic type of engine for future use, especially with increased fuel prices and depleted oil reserves.

The initiation of combustion by compression ignition presents a problem. A cetane number of about 30 is considered to be the lower limit for compression-ignition fuels. Yet, ethanol and methanol have cetane numbers of 8 and 3 respectively. If low cetane number fuels are to be used as alternatives to gas oil the cetane rating needs to be improved with additives or positive means of initiating combustion included in the engine design. Various techniques, such as cetane number improving additives, gasoil/alcohol emulsions, dual injection systems, fumigation, and surface or spark ignition can be used. Some allow complete substitution of alcohol for gasoil whilst for others this is limited by the amount of gasoil required for ignition purposes (2).

This study has concentrated on the complete displacement of gasoil in a small spark-assisted diesel, which may be considered as a fuel tolerant engine. The engine selected was a Petter PHI...
which is typical of the small engines used throughout the world for micro-power generation and pumping duties. The philosophy used in converting the diesel to spark-assistance was that readily available automotive components should be used for ignition systems to facilitate easy conversion and straightforward maintenance in remote locations. With spark ignition advantage can be taken of both the high octane ratings of alcohol fuels and the high enthalpy of vaporisation. The high compression ratio of the diesel engine and the positive nature of spark ignition results in smooth combustion with a high thermal efficiency. The alcohol fuelled diesel is not smouldered at part load, as combustion of alcohol is 'clean' with low particulate formation. At low speeds the torque may be increased above that for gasoil provided that structural and/or thermal limitations are not exceeded. This paper describes the conversion of the Petter PHI diesel, the performance obtained with direct injection of ethanol and the optimisation of ignition and injection timings.

2 SPARK-ASSISTED DIESEL

Careful consideration was given to the selection of a small diesel. With a limited budget the engine needed to be easily converted to spark assistance, without major redesign and modification of the cylinder head, whilst being typical of the small diesels in use throughout the world in static power installations. The engine chosen was a Petter PHI single-cylinder, direct-injection, air-cooled diesel. It is a development from a line of successful engines originally designed some forty years ago. These engines are still in continuous production in the UK and are built in many other countries under licence. The rugged construction in cast iron with forged steel crankshaft and connecting rod, aluminium piston and replaceable shell bearings have contributed to its continued success as a small scale power unit especially in rural locations. The engine is versatile, in that power may be taken off either end of the crankshaft or at half speed of the camshaft. The air-cooled cylinder head facilitated easy installation of a pressure transducer and thermocouple. The engine specification is shown in table 1.

<table>
<thead>
<tr>
<th>Table 1 Petter PHI specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore/stroke</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Speed range</td>
</tr>
<tr>
<td>Continuous maximum rating (gasoil)</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Brake specific fuel consumption</td>
</tr>
<tr>
<td>Continuous maximum rating (ethanol)</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Brake specific fuel consumption</td>
</tr>
</tbody>
</table>

2.1 Engine Modification

The principal requirement for conversion to a spark-assisted diesel was the incorporation of an ignition system. Taking the applications of this particular design of engine into account, namely in rural locations, lead to the adoption of a philosophy that readily available automotive components should be used wherever possible.

With this particular installation, however, a compromise solution was adopted as this engine is a research vehicle for evaluating alcohol and other low cetane number fuels. The ignition system designed, whilst being based on a conventional coil, has a multi-strike discharge capability which may be programmed for ignition timing, ignition duration and multi-strike frequency. The system is shown schematically in figure 1.

Ignition timing and duration are controlled through a timing interface which receives synchronising signals of BDC and crank angle from the encoder. To enable the multi-strike system to run at high frequencies the coil needs to be recharged rapidly and a high voltage is, thus, applied to the primary windings. There is no ballast resistor to limit the current in the primary circuit; instead the primary current is sensed and limited to 5A by means of a power transistor. The system can generate a spark discharge at a frequency of 13.2 kHz. This is equivalent to one spark at every degree of crank angle with the engine running at 2200 rev/min. As the fuel distribution in a direct-injection engine will not be homogeneous in the combustion chamber the multi-strike, high-frequency system will ensure positive ignition. In field applications the ignition system would be set at the optimised timing and duration and along with angle BDC synchronising pulse from an opto-electronic sensor triggered by a timing mark on the flywheel.

In the Petter PHI engine a hemispherical combustion chamber is machined centrally in the piston crown. Fuel is injected at an angle into the highly turbulent air motion resulting from the squish action. Ideally the spark gap should be located centrally in the hemispherical combustion chamber to ensure ignition in a 'rich' mixture zone and to reduce the possibility of spontaneous combustion of the end gases. The geometry of the cylinder head, principally the valves, injector tapping and studs, severely limits possible spark plug tappings. Once it was decided to use 14mm automotive type plugs to enable the use of the widest possible range, only one location on the inlet side of the head was suitable. The spark plug electrodes needed to protrude into the hemispherical bowl in the piston crown and it was necessary to remove some material from the edge of the combustion chamber to locate the plug gap. The removal of material from the piston improved the air flow in the vicinity of the spark discharge had a beneficial effect of reducing cyclic variations in ignition and accommodated the use of long reach spark plugs. The spark discharge position in the combustion chamber could, thus, be varied by the use of different plugs. The compression ratio was reduced through the removal of material from the piston crown from 16.5:1 to 16.0:1.

Both ethanol and methanol have calorific values lower than that for gasoil, about two thirds and one half respectively. To compensate for this lower energy density a larger volume of alcohol needs to be injected than for gasoil to produce the same brake power. The original cam driven fuel pump was capable of meeting the increased fuel flow required but the injection duration was increased and the injection timing could only be adjusted over a few degrees of crank angle. This adjustment proved to be inadequate when
commissioning the spark-assisted diesel on ethanol. For alcohol fuels the injection timings need to be advanced significantly to ensure adequate mixing and vaporisation before ignition by spark discharge. To meet the requirement for increased flow rates and facilitate a wide range of injection timings in this research engine, a separate belt-driven fuel pump was installed on the test bed. The pump is driven by a toothed belt from the camshaft. An indexing mechanism fitted to the pump pulley enables the injection timing to be varied over a range of 120° in 2° intervals.

2.2 Instrumentation

The evaluation of the spark-assisted diesel includes analysis of the combustion performance using the Rassweiler and Withrow technique described in reference (3). A Kistler 6123A1 piezo electric pressure transducer was, therefore, mounted in the cylinder head to measure the pressure in the combustion chamber. An inductive transducer was fitted to the injector to indicate the needle lift and thus measure the injection timing and duration. Engine speed and crankshaft position are determined from the opto-electronic shaft encoder fitted to the crankshaft. The brake power developed was absorbed by a dc swinging arm dynamometer loaded with an external bank of resitors.

Alcohols burn with a 'clean' blue flame and the engine was, therefore, not limited at part-load by smoke emissions. The cylinder head was machined from grey cast iron and the metal temperature was limited to about 350°C. The pressure transducer fitted in the cylinder head was also limited to a temperature of about 350°C. A thermocouple was fitted into a tapping in the cylinder head. The engine was run early in the programme with cylinder head temperatures in excess of 350°C and thermal stress cracks developed between the injector tapping and the valve seats. Subsequently fuel flow rates were limited so that the metal temperatures in the grey iron cylinder head did not exceed 350°C.

3 DATA ACQUISITION SYSTEM

A Sirton micro-computer based on a Z80A central processing unit was used to acquire cylinder pressure readings through a 12-bit A/D convertor. The micro-computer was clocked by the crank angle degree signals from the encoder fitted to the crankshaft. Pressure data for 50 cycles at each test point were stored on floppy discs for subsequent reduction on the University's Prime mainframe computers.

Software has been written to analyse and present the cylinder pressure data. A statistical analysis program may be used to determine peak cylinder pressures and evaluate the cyclic dispersion in peak pressure. The pressure rise owing to combustion, the associated flame initiation period and combustion duration can be evaluated using a second program based on the Rassweiler and Withrow technique. A graphical package is also available to present combustion performance for individual cycles and overall performance. Fig. 2 shows examples of combustion performance for two typical cycles. Both cycles were recorded under the same load, speed and ignition timing conditions but with the injection timing changed. It can be seen that advancing the injection timing has led to an increase in the burn time of the fuel.

4 TESTS WITH ETHANOL

4.1 Initial tests

Initial tests with ethanol were made with the original camshaft driven fuel pump timed to inject at 28° BTDC. Two percent (by volume) of Castorene R30 was added to the ethanol to lubricate the fuel pump plunger and the injector needle. Although the engine ran, severe misfiring occurred. The peak combustion pressures were achieved very late in the expansion stroke. These problems were the direct result of the severe limitation to injection timing advance with the engine fitted fuel pump and the non-availability of long reach electrodes on the sparking plug. The injection timing needs to be advanced significantly to give sufficient time for the fuel to vaporise before spark ignition. Further, the fuel flow rate needed to be increased by a factor of about two to maintain the equivalent rate of energy transfer. The misfiring experienced was attributed primarily to the fact that the spark plug electrodes did not reach sufficiently into the hemispherical combustion chamber where the mixture is rich.

A separate higher capacity Lucas-CAV belt-driven pump was installed to give complete flexibility over injection timing and NGK supplied a series of long reach spark plugs of the type used by Japanese automotive manufacturers in their lean burning gasoline engines. A set of long reach plugs with 10-30 mm long electrodes in 2 mm steps was also manufactured specially for use in optimising the spark location. With the injection timing set at 36° BTDC the engine ran noticeably more smoothly although occasional misfiring occurred. The performance of the spark-assisted engine burning ethanol was compared with that when configured as a diesel with gasoil at 2000 rev/min. The brake specific fuel consumption, expressed in energy terms as gas oil equivalent, as a function of brake mean effective pressure was comparable. The bsfc with ethanol was about 20% higher than that for gas oil at the maximum continuous rating, but injection and ignition timings had not been optimised at this stage.

During prolonged running the earth electrode on a spark plug broke off and severely damaged the ceramic insulator. After stripping the engine to examine the damage it was found that loose fragments from the spark plug had caused severe impact damage to the piston crown, the cylinder head and exhaust valve seating. Further inspection revealed several cracks on the underside of the cylinder head and overheating damage to the piston crown in the vicinity of the inlet valve. The cracks ran from the injector tapping to both inlet and exhaust ports crossing the valve seats in both cases. A third crack ran from the spark plug tapping to the inlet valve seat. Consultation with Lister-Petter Diesels confirmed that the cracks resulted from overheating. Cracks are likely to develop in the grey cast iron cylinder head if the metal temperature exceeds 350°C. The power output of this spark-assisted alcohol-fuelled engine was thus limited by thermal considerations. The piston and cylinder head were replaced and the head metal temperature is now monitored and limited to 350°C.
4.2 Optimisation

The factors listed below are variables in the optimisation equation for maximum fuel economy in the spark-assisted diesel:

- Spark gap; width and location
- Spark plug type
- Spark energy
- Ignition timing
- Ignition duration
- Injection pressure
- Injection timing
- Injection duration
- Injector spray pattern

There are also physical limitations restricting the operating envelope, namely:

- Cylinder head temperature
- Engine speed
- Maximum in-cylinder pressure

The ignition and the injection timings have the greatest effects on optimisation. The other variables were, therefore, fixed to reduce the number of possible combinations to a manageable proportion. The electrode gap was set at 0.5 mm. A larger gap caused excess electrical noise, which resulted in interference on the TTL logic circuit thereby affecting the ignition timing. The plug type, NGK BE527YII, was retained throughout the optimisation exercise as this proved satisfactory during earlier tests. The injection pressure was increased marginally to give good atomisation. The engine was run with a brake power of 5.6 kW at a speed of 1800 rev/min for all variations in timings.

Previous experimentation had established the need for a spark duration of 12° CA to reduce misfires to a minimum. It is thought that the long duration may be required because of the lean state of the mixture in the direct injection process in the unthrottled engine and the non-homogeneous nature of the fuel/air mixture in the combustion chamber, especially in the vicinity of the spark discharge. Further experimentation with different length electrodes may establish an optimum location for the spark discharge and thereby facilitate a reduction in the spark duration. The spark energy was varied during the first test run to determine the level required to minimise cyclic dispersions in cylinder pressure. The energy level determined was then fixed and used throughout the subsequent tests.

Preliminary optimisation tests were made with varying injection and ignition timings to define the stable operating range of timings. The area defined extended from 40° to 80° BTDC for injection timing and from 16° to 28° BTDC for ignition timing. Outside of this area on the timing map, operation was limited by the cylinder head metal temperature exceeding 350°C, severe knocking with excessive maximum cylinder pressures or burning continued late into the expansion stroke. Subsequently, optimisation tests were carried out with the fuel injection timing varied in 10° steps from 40° to 80° BTDC and the ignition timing varied in 2° intervals from 16° to 28° BTDC.

At each test point the cylinder pressure was recorded at 1°CA intervals for 50 cycles for subsequent combustion analysis.

The effect of injection and ignition timings on maximum fuel economy is shown on the brake specific fuel consumption contour map of Fig. 3. The optimum brake specific fuel consumption achieved was 263 g/kWh (gas oil equivalent). This compares well with the value obtained, 259 g/kWh, for the engine configured as a conventional diesel. The area of minimum brake specific fuel consumption occurred with injection and ignition timings of 50° and 20° to 24° BTDC respectively. The map shows that ignition timing has little effect on brake specific fuel consumption in this minimum region. This may be attributed to the long spark duration which has still to be optimised. With the ignition advanced beyond 20° BTDC, injection timing has the major influence on brake specific fuel consumption.

4.3 Cyclic Dispersion

In 18 out of the 28 cylinder pressure data files some eight-stroking had occurred. This was to be expected towards the limits of stable operation considering the overall equivalence ratio which varied from 0.85 to 0.64 and the variation in mixture strength throughout the combustion chamber. The cyclic dispersion in cylinder pressure was calculated, from 50 consecutive cycles, as:

\[ \alpha = \frac{\sigma}{P_{\text{max}}} \]  

The variation in the cyclic dispersion of maximum cycle pressure with injection and ignition timing is shown in Fig. 4. The minimum cyclic dispersion of about 0.038 occurred with timings that corresponded with those for optimum fuel economy. The engine ran noticeably more quietly and more smoothly with an injection timing of 50° BTDC and ignition timings in the range 20° to 26° BTDC.

4.4 Combustion pressure analysis

The pressure rise, attributable to combustion, at each degree of crank angle was calculated using the Rasswieler and Withrow technique (4). In their original work the combustion pressure rise was correlated to the combustion chamber volume at the ignition timing. With the wide variation in ignition timing used throughout the optimisation tests the combustion pressure rise was correlated to the cylinder clearance volume. An ensemble average of the 50 cycles recorded at each test point was used in the interests of economy in computer time. The 0-1% combustion pressure rise times for each timing test point are shown in Table 2 below.
Table 2  
0-1% combustion pressure rise times in ms

<table>
<thead>
<tr>
<th>Injection timing°BTDC</th>
<th>80</th>
<th>70</th>
<th>60</th>
<th>50</th>
<th>40</th>
</tr>
</thead>
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<td>1.7</td>
<td>1.5</td>
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<td>1.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>28</td>
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</table>

The 0-1% rise time was considered by Johns and Henham (5) to be a good indicator of the initial flame establishment period, as defined by the acceleration of the flame front becoming positive, in their work on lean burning methanol-fuelled spark-ignition engines. Table 2 shows that minimum 0-1% rise times occur at injector timings of 70° BTDC and also at 50° BTDC. It may be assumed that the spark-assisted engine behaves more like a manifold-injected gasoline engine with well advanced injection timings whereas, the effects of a true compression ignition engine are exhibited with injection timings at 50° BTDC and below. Further, at the well advanced injection timings more fuel was needed. This would give an increased overall equivalence ratio and would reduce the flame establishment period.

Surface plots, showing the influence of injection and ignition timings on the 1-50% and 1-90% combustion pressure rise times, are shown in Fig.5 and Fig.6 respectively. Both exhibit similar features with long ‘burning periods for late ignition timings and early injection. The timings for maximum burn rate correspond to those for maximum fuel economy. The hypothesis previously advanced that the spark-assisted alcohol-fuelled diesel is operating in two distinct ways is supported in the surface plots indicating the burning rate. Both show distinct ‘ridges’ at an injection timing of 60° BTDC. At well advanced injection timings a more nearly homogeneous fuel-air mixture is formed with a low equivalence ratio. Burning rates are, therefore, low. With late injection timings the charge is still stratified in the vicinity of the spark and ignition occurs in a ‘fuel rich’ region and burns with a correspondingly higher flame speed. Although reference has been made to equivalence ratio, this parameter is inadequate in defining the nature of the fuel-air mixture in the spark-assisted diesel. The duration of the injection period was not available during these tests with the result that overlap of the injection period on the ignition timing was not quantified. In the most extreme case of injection at 40° BTDC with ignition at 26° BTDC it is highly likely that injection continues once the flame has been established by the spark discharge.

5. CONCLUSIONS

The Fetter PHI diesel was converted to a spark-assisted engine to realise a multifuel capability. The engine has been tested with direct injection of ethanol into the hemispherical combustion chamber in the piston crown. Power output was limited by thermal stressing considerations in the grey cast iron of the cylinder head to a metal temperature of 350°C. Temperatures in excess of 350°C cause cracks to develop from the injector tapping across both valve seats to the inlet and exhaust ports. The brake specific fuel consumption, expressed as gasoil equivalent on an energy basis, was found to be comparable; about 1.5% greater than that for gasoil when run at 1800 rev/min with a brake load of 5.6 kW. Optimisation tests for maximum fuel economy indicated appropriate injection and ignition timings of 50° BTDC and 24° BTDC respectively.

ACKNOWLEDGMENTS

The authors wish to acknowledge the financial support provided by the Science and Engineering Research Council and the help provided by BP Research Centre, Lister-Petter Diesels, Lucas-CAV and NGK Spark Plugs.

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C372/016 © IMechE 1989
Fig 1  Multi-strike, high-frequency ignition system

Fig 2  Typical examples of combustion performance for two individual cycles
Fig 3  Brake specific fuel consumption map with varying injection and ignition timings

Fig 4  Cyclic dispersion of maximum cylinder pressure
Fig 5  Effect of injection timing and ignition timing on 1—50 per cent combustion pressure rise times

Fig 6  Effect of injection timing and ignition timing on 1—90 per cent combustion pressure rise times
Performance of an optimised direct-injection, spark-assisted diesel burning ethanol or methanol

A W E Henham, R A Johns, S Newnham & C Bennett
PERFORMANCE OF AN OPTIMISED DIRECT-INJECTION, SPARK-ASSISTED DIESEL BURNING ETHANOL OR METHANOL

A W E Henham, R A Johns, S Newnham, C Bennett
Department of Mechanical Engineering
University of Surrey, Guildford. GU2 5XH UK

Summary
Experience has been gained over the past four years of operating a small, stationary, direct-injection, diesel engine, with combustion initiated by spark discharge, on ethanol and methanol fuels. The injection and ignition timings have been optimised to minimise fuel consumption. Combustion performance has been analysed over the operating range.

This paper describes the results obtained using both alcohols and illustrates the ability of this fuel-tolerant engine to handle low cetane number fuels. This engine retains the high efficiency associated with diesels as it is operating with a high compression ratio and in the unthrottled mode. Performance is comparable with that of the same engine operating on gas oil in the traditional mode.

1. Introduction - the Problem
The project was undertaken originally to investigate means of utilizing indigenous fuel resources in agricultural communities. It was seen as a means of avoiding the problems of importing petroleum, at the expense of the balance of payments, into developing countries. The most efficient engines are diesel engines, because of their high compression ratio and unthrottled operation, and this type was chosen as the basis for the work. Since the project began a further requirement has appeared in the difficulty of meeting proposed U.S. particulate emission legislation when burning gas oil in diesel engines.

The most widely available fuels derived from biomass are the alcohols. From the point of view of diesel engine combustion there is a problem, however, in the low cetane number. This makes it difficult to initiate combustion, especially with the small fuel quantities injected at low load. Under these conditions, because of the lack of throttling, air quantities are the same as at full load. Some form of assistance is required to provide a full load range when using alcohol fuels. Those investigated include fuel additives, pilot oil injection, fumigation, emulsions and glowplugs (1).

2. Solution adopted
After examination of the alternatives the approach adopted by the Energy and Thermodynamics Research Group at Surrey was to use spark assistance. The traditional features of the diesel engine, i.e. unthrottled aspiration throughout the load range and with all the fuel injected directly into the combustion chamber through a standard injector, were retained. It was decided to base the experimental engine on a widely used single cylinder air-cooled, direct-injection, four stroke, stationary engine - the Petter PHI.
Because of the much lower calorific value of alcohol, injection with the original fuel pump was required over a longer period and this changed the rate of burning beyond acceptable limits. For the experimental engine an independent fuel pump was fitted with an indexing drive enabling optimisation of injection timing. The ignition system gave a high energy, pulsed, spark, the timing and duration of which were controllable. This equipment was developed specially for this application within the University of Surrey. Fuel ignition and data acquisition systems have been described in an earlier paper (2). A modified cylinder head, with provision for a long electrode spark plug, was manufactured and is shown in figure 1. The combustion analysis technique used, required the cylinder pressure to be measured at each degree of crank angle. So an encoder was already fitted. This was also used to provide a bottom dead centre signal for the ignition timing. The timing of injection could also be checked using signals from the encoder since a needle lift transducer was fitted.

Successful operation of the spark-assisted experimental diesel engine on alcohol fuel had already been established using this relatively complicated injection and ignition equipment. The present test programme was initiated to prove that the engine could be developed into a production version, able to burn both ethanol and methanol, with fixed timings. It should be noted that, with the spark plug hole blanked, the engine’s ability to burn traditional diesel fuel is retained although the fuel rate will not be optimum.

3 Injection and Ignition Optimisation Tests

3.1 Ethanol Tests

The engine test programme with ethanol was divided into 3 parts.

Preliminary tests were made with fuel injection timings varied in 10° steps and spark ignition timings varied in 5° steps to establish the envelope of stable operation. The engine was run at a constant speed of 1500 rev/min at a brake power of 4 kW. The area of stable operation extended from 40° to 80° BTDC for injection timing and from 15° to 35° BTDC for ignition timing. Outside this area operation was limited by the cylinder head metal temperature exceeding 350°C, severe knocking with excessively high maximum in-cylinder pressures or combustion continuing late into the expansion stroke.

A second set of tests were then undertaken within the timing limits established to determine the optimum fuel injection timing and spark ignition timing as defined by minimum brake specific fuel consumption. The contour plot of the variation of brake specific fuel consumption with injection and ignition timings using ethanol is shown in figure 2. The brake specific fuel consumption is expressed in terms of equivalent gas oil consumption on the basis of lower calorific values. The optimum injection/ignition timing was 50°/30° BTDC with a specific fuel consumption of 255 g/kWh equivalent. This compares favourably with the value of 259 g/kWh obtained at this load and speed with gas oil.

In-cylinder pressure data were acquired at each timing setting at 1°CA intervals for 50 sequential 4-stroke cycles. These data were reduced using the Rasswieler and Withrow technique developed by Dye (3) to determine combustion performance. An ensemble average of the 50 cycles was used throughout in the interests of computational economy. A typical pressure-crank angle diagram and derived percentage combustion rise rates and percentage cumulative combustion pressure rises are shown in figure 3.

The 0 - 1% combustion pressure rise time is considered to be a good indicator of initial flame establishment. This parameter is plotted in figure 4 as a contour plot against injection and ignition timings over the operating map. Flame establishment is influenced, primarily, by ignition timing. With ignition timing retarded from 30° BTDC to 20° BTDC the flame
establishment period increases from 0.2 ms to 1.2 ms for injection timings under 70°
BTDC. It may be assumed that at injection timings advanced beyond about 60° BTDC
the engine operates in the manner of a manifold injected gasoline engine whereas at
injection timings below this figure the effects of a true compression ignition engine are
seen. At the later injection timings the fuel-air mixture in the region of the spark
discharge is likely to be richer and flame establishment periods are, therefore, shorter.

The exhaust temperatures measured in the optimisation tests are shown in figure 5.
Early injection and late ignition result in slow burning cycles with incomplete
combustion at exhaust valve opening. The exhaust temperatures were
correspondingly high. The cylinder head metal temperatures exhibited the opposite
trend thereby confirming slow, late burning cycles which were substantiated by the
combustion analysis.

The ethanol tests were concluded with variable load tests at speeds of 1500, 1800 and
2000 rev/min to determine the variation of brake specific fuel consumption with brake
mean effective pressure. The results are shown in figure 6 as gas oil equivalent values
and are compared with those obtained with the engine operating in its original
configuration as a diesel on gas oil.

Fuel consumption with ethanol was comparable with brake mean effective pressures in
excess of about 350 kPa. Below this value the curve for ethanol departs substantially
from that for the engine running on gas oil. This indicates that optimisation at one
particular load is insufficient and that a further programme is needed to optimise the
injection and ignition timings at the lower torque values. The problems of ignition of
alcohol fuels at low loads especially below about 30% Maximum Continuous Rating
have been identified by other research teams (5). The departure from the original gas oil
curve below 350 kPa may be attributable to the fact that the fuel-air ratio in the vicinity of
the ignition source is lower at the lower torque values thereby increasing the flame
establishment period and reducing flame propagation speeds. Ignition timings may need
to be advanced accordingly. Earlier optimisation tests using ethanol with a speed of 1800
rev/min at a power of 5.6 kW indicated injection and ignition timings of 50° BTDC and
24° BTDC respectively (4).

3.2 Methanol Tests

The test programme for methanol was intended to follow a similar pattern to that for
ethanol. Operating limits for injection and ignition timings were established and
optimisation tests were undertaken at a constant speed of 1500 rev/min and brake load of 4-
kW. Injection timings were varied from 40° to 80° BTDC and ignition timings from 20° to
40° BTDC. Injector and fuel pump failures, attributed to the corrosive nature of methanol
and poor lubrication properties, despite the addition of 2% castorene, lead to an incomplete
programme. The fuel pump piston seized on a number of occasions only to be self-curing
after a cooling period of about 30 minutes. During the final set of optimisation tests
methanol leaked across the metal-to-metal seat between the nozzle and injector body. This
problem recurred with new injectors after a relatively short running period. Both failures
were restricted to operation with methanol.

The specific fuel consumption - timings contour plot for methanol is shown in figure 7.
The optimum injection and ignition timings for methanol were 50° BTDC and 35° BTDC
respectively with a minimum brake specific fuel consumption of 240 g/kWh. The
methanol map is less uniform than that for ethanol and shows two distinct regions.
With ignition advance less than 25° BTDC fuel consumption is reasonably independent
of injection timing. With ignition advance greater than 25° BTDC injection timing
appears to be the dominant factor.
The results obtained from the combustion analysis for methanol were comparable with those for ethanol although the burning durations were shorter with methanol in all cases. The pressure analysis curves for methanol at the optimum timing are shown in figure 8. The combustion analysis indicated two regimes. Early injection produces a weaker, more homogeneous mixture at the ignition point whereas later injection results in a richer but stratified charge. The initial burning rates were slower in the weaker mixtures resulting from early injection.

4. Conclusions

The injection and ignition timings for this spark-assisted, direct injection engine were optimised to give minimum brake specific fuel consumption at 1500 rev/min with a brake power of 4 kW for both ethanol and methanol. Tests at 3 different speeds with varying brake load indicated the need to extend the optimisation work to brake mean effective pressures below 300 kPa. In the higher torque ranges the brake specific fuel consumption, expressed on the basis of gas oil equivalence, was directly comparable to that of the engine running in its original configuration. Injection equipment failed with methanol in spite of the addition of 2% castorene to improve the lubrication properties.

Acknowledgements

The authors wish to acknowledge the financial support provided by the Science and Engineering Research Council and the help provided by BP Research Centre, Lister-Petter Diesels, Lucas-CAV and NGK Spark Plugs.

References


Fig 1 Combustion chamber of spark-assisted diesel

Fig 2 Specific fuel consumption (g/kWh) - Ethanol

Fig 3 Combustion performance - Ethanol

Fig 4 0-1% burning time (ms) map - Ethanol
Fig 5 Exhaust temperatures - Ethanol (°C)

Fig 6 Comparison of brake specific fuel consumptions

Fig 7 Specific fuel consumption (g/kWh) - Methanol

Fig 8 Combustion performance - Methanol
The combustion of alcohol fuels in a stationary spark-assisted diesel engine

R A Johns, A W E Henham & S Newnham
The combustion of alcohol fuels in a stationary spark-assisted diesel engine

SYNOPSIS
This project addressed the need to establish combustion performance data for small stationary diesel engines adapted to burn alternative fuels, in particular alcohols. A single-cylinder, direct-injection engine, typical of those in use throughout the world for micro-power installations, was adapted to spark-assistance as an ignition aid. Injection and ignition timings were optimised to give minimum brake specific fuel consumption with ethanol and methanol fuels. Combustion performance data were evaluated to determine the effects of these timings on the flame establishment and burning periods. Work is continuing at higher compression ratios and with exhaust gas recirculation to investigate performance in the higher load ranges without the use of external aids to initiate combustion.

INTRODUCTION
This project, funded by SERC, was instigated to address the need to establish combustion performance data for small stationary diesel engines adapted to burn alternative, low cetane number, fuels and in particular alcohols. With oil reserves declining the concept of a world-wide single dominant fuel is unlikely to continue into the future and engine manufacturers will need to develop engines with a wide fuel tolerance if full export potential is to be realised. Alcohols are particularly suited to use in spark-ignition engines but before any alternative fuel implementation policies are introduced and, if maximum benefit is to be derived from them, the problems associated with using alcohols in compression-ignition engines needs to be overcome.

The diesel engine is inherently more efficient than a comparable spark-ignition engine, especially at part load. Consequently it is considered to be the most economic engine for future use, especially when oil reserves are depleting and fuel prices increase. The combustion of alcohol fuels in diesel engines, however, presents major problems. With oil reserves declining the concept of a world-wide single dominant fuel is unlikely to continue into the future and engine manufacturers will need to develop engines with a wide fuel tolerance if full export potential is to be realised. Alcohols have low cetane numbers and so will not ignite spontaneously under the high temperatures and pressures found in diesel combustion chambers. A cetane number of thirty is considered the lower limit for compression-ignition fuels (figure 1). Ethanol and methanol have cetane numbers in single figures. (It is recognized, however, that cetane number, whilst being an effective criterion for the comparison of traditional hydrocarbon fuels, is not an appropriate parameter for alternative fuels.) With these oxygenates either cetane number improving additives or aids to initiate combustion are needed for use in alcohol-fuelled diesel engines.

In common with surface ignition, spark ignition provides a way of displacing 100% of the gas oil with alcohol. The injection system can be retained, a spark plug fitted into the combustion chamber and the associated ignition system components fitted to the engine. This approach is very attractive as it uses the high energy of vaporization of alcohols and their high octane numbers to good advantage. The high compression ratio improves the thermal efficiency and positive ignition leads to smooth combustion. A spark ignition system requires less energy than a glow ignition system where electrical energy needs to be supplied to the glow plug continuously. The spark-assisted diesel was, therefore, considered to be the most appropriate for the implementation of alcohol fuels.

The spark ignited diesel engine need not be smoke limited as alcohols burn with a clean blue flame and so engine torque can be increased at low speeds, providing the structural and thermal limits of the engine are not exceeded. Injection timings need to be advanced over those for gas oil to allow sufficient time for the vaporized fuel to reach the spark plug. Some form of lubricant needs to be added to the alcohol to lubricate the injector and fuel pump. The original fuel injection equipment may need uprating to cope with the larger volumetric flow of fuel required since alcohols have about 1/2 - 2/3 the specific energy of gas oil.

From the viewpoint of developing countries the advantage of requiring a single fuel is of prime importance, especially in remote areas. It also alleviates the potential problem of untrained staff placing the two fuels in the wrong tanks if a dual fuel system is used. The technology associated with the spark-assisted diesel need not be complicated and most people engaged in the engine maintenance field would already be familiar with the automotive type ignition system and conventional diesel engine injection equipment used on such an engine.
The objectives of this research work were to develop a diesel engine capable of burning alcohols as a fuel, with brake specific fuel consumption (on an energy equivalent basis) and power rating comparable with the original diesel engine specification, and to analyse the combustion performance from experimentally acquired in-cylinder pressure data.

2 TEST-BED

The engine chosen was a Petter PHI single-cylinder direct-injection, air-cooled diesel. It is a development from a line of successful engines originally designed some forty years ago. The Petter PHI is still in continuous production in the UK and has been built under licence in other countries. The engine is versatile, in that power may be taken off either end of the crankshaft or at half-speed of the camshaft. The air-cooled cylinder head facilitated easy installation of a pressure transducer and a spark-plug.

Table 1 Petter PHI Specification

<table>
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<th>Specification</th>
<th>Value</th>
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<td>Bore/stroke</td>
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<td>Swept volume</td>
<td>659 cm³</td>
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<td>Compression ratio</td>
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<td>Injection timing</td>
<td>28°btdec</td>
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<tr>
<td>Fuel injection pressure</td>
<td>200 bar</td>
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<td>Speed range</td>
<td>750-2200 rev/min</td>
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<tr>
<td>Continuous rating gas</td>
<td>2000 rev/min</td>
</tr>
<tr>
<td>Speed</td>
<td>6.15 kW</td>
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<tr>
<td>Bsfc</td>
<td>277 g/kWh</td>
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Several modifications had to be carried out to configure the engine to burn alcohol. Instrumentation was also fitted to the engine to monitor and record its operation. The principal requirement for conversion to a spark-assisted diesel was the incorporation of an ignition system. Taking the applications of this particular design of engine into account, namely in rural locations, led to the adoption of a philosophy that readily available automotive components should be used wherever possible. With this particular installation, however, a compromise solution was adopted as this engine is a research vehicle for evaluating the combustion of alcohol and other low cetane number fuels. The ignition system designed specifically for this project was based on a conventional coil and had a high energy multi-strike discharge capability which may be programmed for ignition duration, timing and multi-strike frequency.

Ignition timing and duration were controlled through a timing interface which received synchronizing signals of bottom-dead-centre and each degree of crank angle from an encoder mounted on the crankshaft. To enable the multi-strike system to run at high frequencies the coil needed to be re-charged rapidly and a high voltage was therefore, applied to the primary windings. There was no ballast resistor to limit the current in the primary circuit. The primary current was sensed and limited to 5 A by means of a power transistor. The system can generate a spark discharge at a frequency of 13.2 kHz. This is equivalent to one spark at every degree of crank angle with the engine running at 2200 rev/min. As the fuel distribution in the direct injection engine is unlikely to be homogeneous in the combustion chamber, the multi-strike, high-frequency system ensures positive ignition. In field applications the ignition system would be supplied from an optical or electronic sensor triggered by a timing mark on the flywheel. Ignition advance would be varied by either mechanical or electronic means.

The Petter PHI has a hemispherical combustion chamber machined centrally in the piston crown. Fuel is injected at an angle into the highly turbulent air motion resulting from the squish action. Ideally the spark gap should have been located centrally in the combustion bowl to ensure ignition in a rich mixture zone and reduce the possibility of spontaneous ignition of the end gases. The geometry of the cylinder head, principally the valves, injector, hole and studs, severely limited possible positions for the spark-plug. Once it was decided to use 14 mm spark-plugs to give as wide a range of plugs as possible, only one location on the inlet side of the head was suitable. The plug was angled into the combustion space at 45° degrees, through the cooling fins. The spark-plug electrodes needed to protrude into the piston bowl and it was necessary to remove some material from the lip of the bowl to give enough clearance for the plug electrodes. The removal of material from the piston allowed the use of very long reach plugs and also improved the air flow around the vicinity of the spark discharge. This had a beneficial effect on reducing cyclic variations. The spark discharge position in the combustion chamber can be varied by the use of plugs with different reaches. The compression ratio was reduced from 16.5:1 to 16.0:1 as a result of this modification.

Both ethanol and methanol have calorific values lower than that for gasoil, about two thirds and one half respectively. To compensate for this lower energy density a larger volume of alcohol needed to be injected than for gasoil to produce the same brake power. The original cam driven fuel pump was capable of meeting the increased flow over a longer injection period required but the injection timing could only be adjusted over a few degrees. This adjustment proved to be inadequate when commissioning the spark-assisted diesel on ethanol. For alcohol fuels the injection had to be advanced significantly to ensure adequate mixing and vaporization of the fuel before ignition occurred. To meet the requirement for increased flow rates and facilitate a wide range of injection timings, a separate belt-driven fuel pump was installed on the test bed. The pump was driven from the camshaft with a toothed belt. An indexing mechanism was fitted to the pump pulley to enable the injection timing to be varied over the range of 120° in 2° intervals.

An inductive needle lift transducer was fitted to the injector. This allowed the injector needle position to be displayed on an oscilloscope which, in conjunction with the ignition timing interface, enabled the injection timing and duration to be determined. A pressure transducer was fitted to the engine, mounted deep in the cylinder head. The
transducer was linked to a microcomputer for data capture.

3 ETHANOL TESTS

Since the applications of this kind of engine are likely to be in stationary installations it was decided to optimise the engine for best brake specific fuel consumption rather than for maximum power or operating flexibility. The engine was run with a brake power of 5.6 kW at a speed of 1800 rev/min for all variations in injection and ignition timings.

Preliminary optimisation tests were made with varying injection and ignition timings to define the stable operating range of timings (figure 2). The area defined extended from 40° to 80° BTDC for injection timing and from 15° to 35° BTDC for ignition timing. Outside this area on the timing map operation was limited by the cylinder head metal temperature exceeding 350 °C, severe knocking with excessive maximum cylinder pressures or burning continuing to the exhaust valve opening. Consequently, optimisation tests were carried out with the fuel injection timing varied in 10° steps from 40° to 80° BTDC and the ignition timing varied in 2° intervals from 16° to 28° BTDC. At each test point the cylinder pressure was recorded at 1° CA intervals for 50 consecutive cycles to be used in analysing the combustion characteristics.

The effect of injection and ignition timings on brake specific fuel consumption is shown on the contour map in figure 3. The minimum bsfc achieved with ethanol as the fuel was 263 g/kWh (gasoil energy equivalent). This compares well with 259 g/kWh, the value obtained with the engine burning gasoil. The area of minimum bsfc occurs with injection and ignition timings of 50° to 55° and 20° to 26° BTDC respectively. The map shows that ignition timing has little effect on bsfc in this region. This may be attributed to the long spark duration. With the ignition advanced beyond 20° BTDC, injection timing has the major influence on bsfc.

Power output was limited by thermal stressing considerations in the grey cast iron cylinder head which was limited to 350 °C. Temperatures in excess of 350 °C caused cracks to develop from the injection tapping across both the inlet and exhaust valve seats.

4 COMBUSTION ANALYSIS

The combustion performance in the spark-assisted diesel engine was evaluated from the experimentally acquired cylinder pressure data using both the Krieger and Borman, and the Rassweiler and Withrow techniques as appropriate. Figure 4 shows the effect of injection and ignition timings on the 0-1% burn time expressed in degrees of crank angle, evaluated by the Rassweiler and Withrow technique. The 0-1% burn period is considered to be representative of the flame kernel establishment period. The slight incline of the surface shows that the ignition timing has more effect on increasing the 0-1% time than the injection timing. The flame establishment period remains almost constant regardless of the injection timing, whereas the flame establishment period tends to increase as the ignition timing is advanced. In the early stages of combustion the ignition timing is more dominant than the injection timing in controlling the ignition delay and flame establishment.

Figure 5 shows the effect of injection and ignition timings on the 1-90% combustion pressure rise times expressed in degrees of crank angle. The 1-90% period represents the duration of the combustion of the main portion of the charge neglecting the delay and flame establishment periods and the final slower stages of combustion. The highest point on the surface is at advanced injection timings and retarded ignition timings. At these timings the main combustion part of cycle after flame establishment is longest in duration. The lowest point occurs at retarded injection and advanced ignition timings where the 1-90% time is shortest. Injection timing has the main effect during this part of the combustion. This orientation of the surface indicates that the 1-90% burn times are mainly controlled by the mixture preparation period i.e. the time between injection and ignition. With a long injection delay between injection and ignition the 1-90% burn period is longer than with a short delay. This can be explained by realizing that the longer the time between injection and ignition the less stratified and more homogeneous the mixture becomes with lower local equivalence ratios. The flame speed decreases with falling equivalence ratio and the combustion time, therefore, increases.

The effect of the time separating injection and ignition on the brake specific fuel consumption can be seen in figure 6. There is clearly an optimum number of degrees crank angle between injection and ignition in order to give the best brake specific fuel consumption, namely 20° degrees. This suggests that optimisation of brake specific fuel consumption is not dependent on any particular injection or ignition timing but rather on the time taken for preparation of the mixture.

Unlike combustion in a conventional gasoline engine where the mass fraction burnt curve is characteristically a Wiebe curve, some of the ethanol tests produced mass fraction burnt curves having two distinct phases. The two stage burn curves are caused either by an interaction between the propagating flame and the fuel plumes or by geometrical effects. It is suggested that at short mixing times the zones between the fuel plumes are so lean that flame propagation occurs by one plume spreading toward the centre of the combustion chamber then igniting the other two plumes issuing from the three hole injector nozzle.

The flame speed increases as the equivalence ratio increases up to the stoichiometric ratio so the flame speed would initially be slow owing to the leanness of the mixture at the edge of the plume (figure 7). The flame speed would increase, however, as it envelopes the richer centre portions.
of the plume. There eventually becomes a point where the flame front has reached the centre of the combustion chamber. Now the flame has two paths along which it can progress and, although the flame speed would be the same as when it was consuming a single plume, the rate of pressure rise increases significantly (approximately double) since the flame will be consuming twice as much fuel per unit time as it previously did. The flame propagation velocity will decrease as the front moves away from the centre of the combustion chamber and toward the tips of the plumes where the local mixture strength will lessen off.

5 METHANOL TESTS

The test programme for methanol was intended to follow a similar pattern to that for ethanol. Operating limits for injection and ignition timings were established and optimisation tests were undertaken at a constant speed of 1500 rev/min and brake load of 4 kW. Injection timings were varied from 40° to 80° BTDC and ignition timings from 20° to 40° BTDC. Injector and fuel pump failures, attributed to the corrosive nature of methanol and poor lubrication properties, despite the addition of 2% Castorene, led to an incomplete programme. The fuel pump piston seized on a number of occasions only to be self-curing after a cooling period of about 30 minutes. During the final set of optimisation tests methanol leaked across the metal-to-metal seal between the nozzle and injector body. This problem recurred with new injectors after a relatively short running period. Both failures were restricted to operation with methanol.

The optimum injection and ignition timings for methanol were 50° BTDC and 35° BTDC respectively with a minimum brake specific fuel consumption of 240 g/kWh. With ignition advance less than 25° BTDC specific fuel consumption was reasonably independent of injection timing. With ignition advance greater than 25° BTDC injection timing appears to be the dominant factor.

The results obtained from the combustion analysis for methanol were comparable with those for ethanol although the burning durations were shorter with methanol in all cases. The combustion analysis indicated two regimes. Early injection produced a weaker, more homogeneous mixture at the ignition point whereas later injection resulted in a richer but stratified charge. The initial burning rates were slower in the weaker mixtures resulting from early injection.

6 HIGH COMPRESSION CONFIGURATION

Research in the US in the field of alcohol fuel technology includes work on diesel engines to meet the proposed 1991 emissions legislation for urban buses. The methanol fuelled diesel is considered likely to meet the required limit for particulates of 0.134 g/kWh. The Detroit 6V-927A two-stoke diesel operates on methanol in the mid to full load range without ignition aids. The compression ratio has been increased and the scavenging reduced to retain a higher level of residual gases in the cylinders. With this in mind the Petter PHI was modified to give a compression ratio of 22:1 and an exhaust gas recirculation system was fitted. Preliminary testing indicated that the engine will run without spark-assistance when the cylinder head metal temperature is in excess of 230 °C. The upper limit on the cylinder head temperature of 350 °C, however, severely derated the engine to 2.6 kW at 1800 rev/min. The use of a cast iron cylinder head is not suited to this application. The low thermal conductivity with long heat transfer transients led to unstable operation and overheating with surface ignition and knocking. Further modifications are needed, for example a water-cooled aluminium head, before this work can be continued.

7 CONCLUSIONS

The Petter PHI diesel engine was successfully converted to a spark-assisted engine giving it a multifuel capability. The engine has been run on ethanol and methanol. Changing the engine to burn gasoil again can be accomplished simply by changing the injection timing. It should be possible to burn other low cetane number fuels in this engine.

Power output was limited by thermal stressing considerations in the grey cast iron cylinder head which was limited to 350 °C. Temperatures in excess of 350 °C caused cracks to develop from the injection tapping across both the inlet and exhaust valve seats. The engine has been extensively tested when running on ethanol to optimize the injection and ignition timings, and a detailed study of the effect of these two parameters on the fuel burning rate has been completed.

It has been proved that a multifuel diesel engine can be optimised to give a bsfc when running on the new fuel comparable to that for gasoil. The bsfc, expressed as gasoil equivalent on an energy basis, was 1.5% greater than that for gasoil when the engine was run at 5.6 kW, 1800 rev/min using ethanol as the fuel. Optimisation tests for maximum fuel economy indicated appropriate injection and ignition timings of 50° and 24° BTDC respectively.

Data handling and processing software has been written to facilitate the reduction of the in-cylinder pressure measurements. Two combustion models have been used to compute fuel burning rates, firstly the Rassweiler and Withrow technique and secondly a 2-zone thermodynamic energy balance based on the work by Krieger and Borman.

8 ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support provided by the Science and Engineering Research Council and the help provided by BP Research Centre, Lister-Petter Diesels, Lucas-CAV and NGK Spark Plugs.

9 REFERENCES

Fig. 1: Effect of cetane number on the performance of a diesel engine (After Walker (1)).

Fig. 2: Satisfactory injection and ignition timings for ethanol.

Fig. 3: Influence of injection and ignition timing on bsfc from ethanol tests. Lines of constant bsfc gas oil energy equivalent shown (g/kWh).

Fig. 4: Effect of injection and ignition timing on the 0.1% burn times expressed in degrees of crank angle.
Figure 5 Effect of injection and ignition timing on the 1-90% burn time, expressed in degrees of crank angle.

Figure 6 Effect of °CA between injection and ignition on bsfc.

Figure 7 Effect of injection pattern on the flame propagation speed.
Preliminary results using palm oil in diesel engines

A W E Henham, M Afifi b Abdul Mukti & Azhar A Aziz

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PRELIMINARY RESULTS USING PALM OIL DERIVED FUELS IN DIESEL ENGINES

Alex Henham
University of Surrey, Guildford, England

Mohd Affi bin Abdul Mukti and Azhar Abdul Aziz
Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia

Summary
Vegetable oil products are of increasing interest as substitutes for hydrocarbon fuels in countries with large agricultural bases. Malaysia has palm oil production approaching half the world's total and, although a net exporter of petroleum, is interested in developing alternative sources.

Research into the utilisation of palm oil has included combustion in conventional diesel engines: long-term tests in typical vehicles and the laboratory work on single-cylinder engines which is described here. Tests comparing RED olein and methyl esters derived from palm oil with petroleum diesel fuel show that performance can be maintained. Although cetane numbers are somewhat lower than present diesel fuels this does not appear to create problems.

Introduction
Although Malaysia has been a net petroleum exporter for 10 years, the predicted exhaustion of reserves in 20 or 30 years if present demand continues has prompted this country to look for other fuel. Since vegetable oils are renewable they have good prospects as alternative fuels. They contain a large proportion of carbon.

Studies using coconut oil for diesel engines were successful in the Philippines (1). The performance and emissions characteristics of diesel engines using sunflower oil and peanut oil have also been studied (2, 3).

Malaysia is a leading producer of palm oil accounting for about 42% of world production and aiming to increase to 60 by 1990. The land area devoted to palm production is 4000 km². Trees grow for about 30 years.

Current research into the use of palm oil as a fuel is a collaborative project between the Universiti Teknologi Malaysia (UTM) (mechanical engineering aspects), Universiti Malaya (UK) (chemical aspects), Palm Oil Research Institute Malaysia (PORIM) and Petronas. The total programme has a budget 11.7 million Malaysian Ringgit.
Exploitation of palm oil as a diesel fuel would enable a reduction of heavy crude imports, the indigenous light crudes being exported because of their higher value. It may also establish an export market for palm-based fuels and for the technology developed. Self-sufficiency in energy is envisaged for farm complexes. Transport applications could be important as 40% of Malaysian energy is used for this purpose (4). Field tests on diesel-engined taxis and Land Rovers using palm oil are in progress alongside the work on stationary engines described here. Development of processing plant is similarly taking place in parallel with the engine research. There is now a pilot plant at PORIM capable of producing 3000 tonne/annum of methyl esters for this programme.

The cost of palm oil varies with the season, finished oil being cheaper than the raw oil because high value by-products are derived from processing. Under certain conditions palm oil of low quality is produced which has lower value in the traditional market.

This project investigated the possibility of using palm oil and its products as alternative fuels for diesel engines. The scope of work included the following studies:

i) physical properties of palm oil and palm oil derived fuels
ii) performance of diesel engines using palm oil derived fuels
iii) exhaust emissions

Properties of palm oil derived fuels

Chemical compositions of palm oils indicate that these are appropriate substitutes for diesel fuels. Typical composition ranges are shown in Table 1:

<table>
<thead>
<tr>
<th>Content</th>
<th>Percentage</th>
<th>Chemical Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myristic</td>
<td>1.1 - 2.5</td>
<td>( \text{CH}_3(\text{CH}_2)_2\text{CO}_2\text{H} )</td>
</tr>
<tr>
<td>Palmitic</td>
<td>40.0 - 46.0</td>
<td>( \text{CH}_3(\text{CH}<em>2)</em>{14}\text{CO}_2\text{H} )</td>
</tr>
<tr>
<td>Stearic</td>
<td>3.6 - 4.6</td>
<td>( \text{CH}_3(\text{CH}<em>2)</em>{16}\text{CO}_2\text{H} )</td>
</tr>
<tr>
<td>Oleic</td>
<td>39.0 - 45.0</td>
<td>( \text{CH}_3(\text{CH}<em>2)</em>{7}\text{CH}=\text{CH}(\text{CH}<em>2)</em>{7}\text{CO}_2\text{H} )</td>
</tr>
<tr>
<td>Linoleic</td>
<td>7.0 - 11.0</td>
<td>( \text{CH}_3(\text{CH}<em>2)</em>{4}\text{CH}=\text{CHCH}_2\text{CH}=\text{CH}(\text{CH}<em>2)</em>{7}\text{CHCO}_2\text{H} )</td>
</tr>
</tbody>
</table>

Relevant physical properties of products of palm oil are compared with those of conventional diesel fuel specification in Malaysia in Table 2. They were determined according to ASTM methods. It will be seen that the palm oil fuels are slightly more dense but of lower calorific value. The somewhat lower cetane number should not be significant for many applications and that of the methyl esters is comparable with average US values (5).
Table 2: Physical properties of palm oil and petroleum derived fuels for diesel engines

<table>
<thead>
<tr>
<th>Property</th>
<th>Petroleum Diesel</th>
<th>RBD Olein</th>
<th>Methyl esters from crude palm oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>0.827</td>
<td>0.912</td>
<td>0.878</td>
</tr>
<tr>
<td>Kinematic viscosity/cSt</td>
<td>3.33 (40°C)</td>
<td>6.36 (28°C)</td>
<td>4.73 (40°C)</td>
</tr>
<tr>
<td>Pour point/°C</td>
<td>12</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>Flash point/°C</td>
<td>76</td>
<td>-</td>
<td>160</td>
</tr>
<tr>
<td>Distillation/°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial BP</td>
<td>185</td>
<td>215</td>
<td>310</td>
</tr>
<tr>
<td>10%</td>
<td>223</td>
<td>298</td>
<td>323</td>
</tr>
<tr>
<td>20%</td>
<td>244</td>
<td>-</td>
<td>324</td>
</tr>
<tr>
<td>50%</td>
<td>281</td>
<td>318</td>
<td>328</td>
</tr>
<tr>
<td>90%</td>
<td>368</td>
<td>326</td>
<td>342</td>
</tr>
<tr>
<td>Final BP</td>
<td>403</td>
<td>337</td>
<td>347</td>
</tr>
<tr>
<td>Cetane No.</td>
<td>58</td>
<td>38</td>
<td>48</td>
</tr>
<tr>
<td>Calorific value/kJ/kg</td>
<td>46190</td>
<td>39750</td>
<td>39357</td>
</tr>
<tr>
<td></td>
<td>38200</td>
<td>36252</td>
<td>34555</td>
</tr>
</tbody>
</table>

RBD olein is a refined, bleached and deodorised form of palm oil commonly used as cooking oil. Methyl esters are produced from palm oil by transesterification processes (6). This allows the more valuable components of the crude palm oil to be used for premium purposes so reducing the feedstock cost.

Engines and Test Equipment

Initial tests on RBD-Olein were conducted on a Ricardo E-6 variable-compression research engine and on a Lister 8/1 typical of single-cylinder engines used for stationary power in agricultural communities.

More recently tests have been conducted on methyl esters using another single-cylinder engine typical of those used locally - a Yanmar TF 80. Engine data is given in Table 3.

Table 3: Engine data

<table>
<thead>
<tr>
<th>Type</th>
<th>Ricardo E-6 4-stroke</th>
<th>Lister 8/1 4-stroke</th>
<th>Yanmar TF 80 4-stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
</tr>
<tr>
<td>Swept volume/litre</td>
<td>0.507</td>
<td>1.433</td>
<td>0.437</td>
</tr>
<tr>
<td>Bore/mm</td>
<td>76</td>
<td>114.3</td>
<td>80</td>
</tr>
<tr>
<td>Stroke/mm</td>
<td>111</td>
<td>139.7</td>
<td>87</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>22 Max</td>
<td>direct</td>
<td>direct</td>
</tr>
<tr>
<td>Fuel injection</td>
<td>direct</td>
<td>direct</td>
<td>direct</td>
</tr>
<tr>
<td>Nominal power output/kW</td>
<td>9</td>
<td>6</td>
<td>5.2</td>
</tr>
<tr>
<td>at rev/min</td>
<td>2000</td>
<td>850</td>
<td>2200</td>
</tr>
</tbody>
</table>
Test results:

Tests on Ricardo E-6 engine
Tests were conducted with no modification to the engine or injection equipment. Injection timings for both diesel fuel and RBD olein were varied and the optimum value for both found to be 38° before TDC. At the optimum timing the power output was found to be marginally greater at all speeds than for diesel fuel (Fig 1) but the thermal efficiency was lower at the higher powers (Fig 2).

Tests on Lister 8/1 engine
Again no modifications were made before testing different fuels. The power output curve was found to be common for diesel fuel and RBD olein but, as for the Ricardo engine, thermal efficiency was somewhat lower (Fig 3). With this engine additional tests were conducted using blended fuels comprising RBD olein with 25%, 50% and 75% diesel fuel. Results of these tests show that the same power outputs can be obtained with all blends from 0 to 100% diesel fuel with the mixtures showing slightly better fuel consumption than either fuel by itself. Exhaust gas analysis showed that, for the same power, the air fuel ratio was much higher using diesel fuel, the palm oil being much closer to stoichiometric, suggesting a very modest rating of the original design. In neither case was significant CO present.

Tests on Yanmar TF 80 engine
This engine was used to test methyl esters derived from palm oil against the baseline performance of diesel fuel. The engine, being of standard production type, had fixed timing and rack settings. Pump delivery tests confirmed that the volume delivered per stroke was similar on both fuels giving diesel fuel a power advantage of 10% in terms of calorific value per unit volume (see Table 2). This is confirmed in the power obtainable for a given speed. Suitable adjustment to the injection equipment should rectify this. Fig 4 shows that the brake thermal efficiency of this engine running on methyl esters is better than on diesel fuel throughout the range.

Although other emissions results will be available from this programme initial readings are of smoke. Diesel fuel exhibits lower smoke numbers at low mep's but peaks at a higher value than for methyl esters. It appears unlikely that smoke would limit the output on the latter fuel (Fig 4).

Conclusions
These preliminary results suggest that palm oil is a valuable source of fuels for diesel engines. Although the paper only deals with single cylinder stationary engines, other work in parallel indicates that automotive diesels will run satisfactorily on palm oil based fuels. Small volume delivery adjustments are required if equal power is to be obtained. The slightly lower cetane number does not appear to create problems in the type of engine described and no cold starting problems have been experienced.
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Legend for graphs:
RBD Olein
Methyl esters
Diesel fuel

Fig 1 Ricardo engine power output
Fig 2 Ricardo engine thermal efficiency
Fig 3  Lister engine thermal efficiency

Fig 4  Yanmar engine thermal efficiency and smoke
Experience with palm oil derived fuels in small diesel engines

A W E Henham, M Afifi b Abdul Mukti & Azhar A Aziz

EXPERIENCE WITH PALM OIL DERIVED FUELS IN SMALL DIESEL ENGINES

AWE HENHAM
Department of Mechanical Engineering, University of Surrey, Guildford GU2 5XH
United Kingdom

MAFIFI A MKTI and AZHAR A AZIZ
Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Jalan Semarak
54100 Kuala Lumpur, Malaysia

ABSTRACT

Readily available supplies of palm oil in Malaysia, at a time when petroleum prices were high, provided the incentive for its exploitation as a resource for engine fuel production. Experimental work comparing the power output, efficiency and exhaust emissions of engines using petroleum and palm oil based fuels is reported. This shows that methyl esters derived from palm oil exhibit similar thermal efficiency, reduced smoke at high loads and lower CO and NOx emissions throughout the load range when compared with diesel fuel. Some injector fouling problems have been encountered.

INTRODUCTION

Since the year 1972 Malaysia has been the world's largest producer of palm oil, most of which is exported. With increasing production and a not unlimited export market, alternative uses offer potential for import substitution. Malaysia has petroleum reserves which could satisfy 20 or 30 years current domestic demand. Foreign currency earnings could arise from the use of palm oil products locally, thus releasing indigenous light crude petroleum for export and avoiding heavy crude imports.

Palm Oil Production

Malaysia produces over 70% of the world's palm oil which amounts to 3.7 million tonnes from 14 000 km$^2$ of cultivated land. Species of palm nut have been developed which produce a high oil yield of about 25-28% of the mass of the bunch of fruit.

Palm Oil Processing

It is possible to use crude palm oil (CPO) in diesel engines. A demonstration vehicle, a VW Golf with 3-cylinder ELKO engine, has been successfully operated on crude palm oil suitably heated to reduce viscosity. It is regarded as more practicable to base the majority of work on those fuels derived from palm oil that can be used without special adaptation of the engine or fuel storage and supply systems.

The first experiments on small stationary engines (1) were conducted using Refined, Bleached and Deodorised Olein (RBD Olein) which was readily available from existing edible oil processing plant. Further exploration of the possibilities of using palm oil derived products have shown that ethyl and methyl esters can be produced. There are advantages in this course of action since the transesterification process can convert separated high melting point components of the crude palm oil leaving those of lower melting point for use as edible oils. Using a catalyst and alcohol (which may also be derived from biomass) this fraction, largely palmitic and stearic glycerides, is converted to monoesters with glycerol as a valuable by-product.
Economics of this process depend upon fluctuating world prices for the raw materials by comparison with the by-products and of petroleum based fuels but a report (2) suggests that it could result in a cheaper fuel than diesel even without giving credit for by-product.

Properties of Fuels
Chemical composition of typical Malaysian palm oils, shown in Table 1, makes them suitable bases for engine fuel production, comprising a large proportion of carbon and hydrogen.

\[
\begin{array}{|c|c|c|}
\hline
\text{Component} & \text{percentage} & \text{chemical equation} \\
\hline
\text{Myristic} & 1.1 - 2.5 & \text{CH}_3(\text{CH}_2)_{12}\text{CO}_2\text{H} \\
\text{Palmitic} & 40.0 - 46.0 & \text{CH}_3(\text{CH}_2)_{14}\text{CO}_2\text{H} \\
\text{Stearic} & 3.6 - 4.6 & \text{CH}_3(\text{CH}_2)_{16}\text{CO}_2\text{H} \\
\text{Oleic} & 39.0 - 45.0 & \text{CH}_3(\text{CH}_2)\gamma\text{CH}=(\text{CH}_2)\gamma\text{CO}_2\text{H} \\
\text{Linoleic} & 7.0 - 11.0 & \text{CH}_3(\text{CH}_2)\delta\text{CH}=\text{CH(\text{CH}_2)\gamma\text{CHCO}_2\text{H} \\
\hline
\end{array}
\]

The physical properties of palm oil derived fuels are compared with those of traditional diesel fuel in Table 2, having been determined by ASTM methods. Recent CFR engine tests have shown that the cetane number is higher than less precise methods had earlier suggested and that it is now comparable with diesel fuel. This should be regarded as the single most significant property.

The higher specific gravity of methyl esters compared with petroleum diesel means that the 15% lower calorific value by mass becomes only a 10% reduction by volume. Since diesel injection equipment meters by volume, the maximum fuel delivery without modification is effectively reduced by 10%. This is only of effect in the maximum, over-design power, region. At other loads, however, it will reduce the rate of injection of energy into the combustion chamber since most diesel engines are governed by length of injection rather than by volume flowrate. Other noteworthy differences in properties are the much higher flashpoint of methyl esters, the much narrower boiling range and the slightly higher pour point. The latter, at 15°C for methyl esters, is not a problem in SE Asia though it would be in more temperate climates.

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Property} & \text{Petroleum Diesel} & \text{RBD Olein} & \text{Methylesters from CPO} \\
\hline
\text{Specific gravity} & 0.827 & 0.912 & 0.878 \\
\text{Kinematic Viscosity/ cSt} & 3.33 & 6.36 & 4.73 \\
 & (at 40°C) & (at 28°C) & (at 40°C) \\
\text{Pour point/ °C} & 12 & - & 15 \\
\text{Flash point/ °C} & 76 & - & 160 \\
\text{Distillation/ °C} & & & \\
\text{Initial BP} & 185 & 215 & 310 \\
\text{10%} & 223 & 298 & 323 \\
\text{20%} & 244 & - & 324 \\
\text{50%} & 281 & 318 & 328 \\
\text{90%} & 368 & 326 & 342 \\
\text{Final BP} & 403 & 337 & 347 \\
\text{Cetane no.} & 58 & 38 & 60 \\
\text{Calorific value/ kJ/kg} & 46 190 & 39 750 & 39 357 \\
\text{kJ/litre} & 38 200 & 36 252 & 34 555 \\
\hline
\end{array}
\]
RESEARCH PROGRAMME

The programme, of which the tests reported form a part, is of a collaborative national nature. Work on chemical aspects is undertaken by Universiti Malaya (UM), production aspects by the Palm Oil Research Institute of Malaysia (PORIM) and engine applications by the Universiti Teknologi Malaysia (UTM). There is also an input from Petronas, the Malaysian national oil company. In carrying out its part of the project, PORIM has built a pilot plant capable of producing methylesters at 3000 tonne/annum. Engine test work at UTM has involved a research engine, Ricardo E6, a traditional slow-speed single-cylinder Lister stationary engine and a lightweight modern single-cylinder Yanmar stationary engine. Additional to this investigation of engines used in agricultural applications has been a study of small automotive diesels. This has involved laboratory tests on an Isuzu engine and field trials on small fleets of taxis in Kuala Lumpur and four-wheel drive vehicles used in palm oil producing areas. This part of the programme is important since about 40% of primary energy use in Malaysia is for transport (3). The engine research programme includes performance plotting, fuel consumption and exhaust emissions analysis. There have also been inspections of components for any adverse effects of chemical properties of vegetable oils on standard materials used in engines.

TEST FACILITIES

Laboratory facilities at UTM are available for performance trials on a number of engines. In addition an exhaust gas analysis unit is available for application to any of these.

Yanmar TF80 Engine

Typical of recently-built small stationary engines used in SE Asia is this single-cylinder, water-cooled, four-stroke engine. The engine has a direct injection combustion chamber, shown in Fig 1, incorporating a slightly offset toroidal combustion chamber set in the piston.

![Figure 1. Combustion chamber of direct-injection Yanmar TF80 engine. The injector nozzle is surrounded by an insulator](image)

The major specification items for this engine are:

- **Bore**: 80 mm
- **Stroke**: 87 mm
- **Swept Volume**: 0.437 litre
- **Compression Ratio**: 18
- **Injection Timing**: 13.5° btdc
- **Continuous Rated Output**: 5.6kW
  - (Diesel Fuel): 2400 rev/min
- **1 Hour Rated Output**: 6.3kW
  - (Diesel Fuel): 2400 rev/min

No engine modifications were undertaken and injection timings and rack setting were as standard for this engine when using petroleum diesel fuel. The engine drives an electrical dynamometer.
Comparative tests were conducted on the Yanmar engine described using standard Malaysian diesel fuel and methyl esters processed from crude palm oil.

Performance
Brake specific fuel consumption, corrected to diesel fuel equivalent, is plotted against brake mean effective pressure in Fig 2. It can be clearly seen that the engine has a performance on each fuel which is almost identical. There appears to be no penalty in using palm oil derived methyl esters instead of diesel fuel, other than the slightly lower maximum output caused by volume limitation on the fuel pump delivery. This results in a smaller maximum energy delivery for methyl esters because of the lower energy per unit volume compared with diesel fuel.

![Figure 2. Brake specific fuel consumption on diesel fuel basis](image)

Emissions
Trials of the engine with gas analysis equipment continuously monitoring the exhaust composition were undertaken in the laboratory. The results are illustrated in Fig 3.

The CO is consistently lower with methyl esters than with diesel fuel near full load the sharp increase of the diesel fuel trial was not repeated with methyl ester. NOx concentrations followed similar curves for both fuels, that for methyl esters being 10-12% lower. Smoke level is about 25% better throughout the range with methyl esters. Only the curves for unburned hydrocarbons exhibit a more complex relationship, the diesel fuel curve surprisingly falling towards full load while that for methyl esters increases with load.

Overall exhaust emission results can be considered favourable to the use of methyl esters from crude palm oil.

Physical Effects
Care has to be taken in the choice of materials used in the fuel systems when vegetable oils are used. Certain plastics and rubbers harden or swell and can even dissolve. Metal parts are not usually affected. In these tests on the direct-injection engine some coking of the nozzle was experienced but deposits have not been a problem in field trials over extended periods with indirect-injection automotive engines.
Figure 3 Exhaust emissions.

CONCLUSIONS

The trials conducted so far indicate that methyl esters derived from crude palm oil provide an excellent substitute for petroleum fuels in a standard small stationary diesel engine. Efficiency appears to be unaffected and, for almost all pollutants, exhaust emissions are improved. On further investigation it is expected that a means of preventing excessive carbon deposits on the injector nozzle will be developed. Fuels of the type tested could substitute for imported petroleum in many developing countries. Similar results have been obtained from an indirect injection automotive diesel, again with reduction in smoke (4).

ACKNOWLEDGMENT

The support of the British Council in sponsoring the link between the two universities and of UAC Ltd in enabling a short visit to the UK by one of the authors from UTM is gratefully acknowledged. The Yanmar Diesel Engine Co Ltd has been very helpful in the provision of information.

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Experience with alternative fuels for small stationary diesel engines

A W E Henham & R A Johns
Experience with alternative fuels for small stationary diesel engines

A W E HENHAM, BSc, CEng, Eur Ing, FIMechE, FinstE, MRAeS and R A JOHNS, MSc, PhD, CEng, Eur Ing, FIMechE, FIMarE
Department of Mechanical Engineering, University of Surrey, UK

SYNOPSIS Fuels produced by the refining of petroleum crudes are not locally available in all countries and so often require the use of foreign currency which may create balance of payments problems. A wider range of liquid fuel characteristics than has been employed traditionally would result if other sources were to be used for their production. The paper discusses the effect on combustion in small stationary diesel engines of variations in properties from those of petroleum diesel fuels. Experience with a combustion system developed for oxygenate fuels and of the use of vegetable fuels in unmodified diesel engines is described.

1 INTRODUCTION

The two parallel programmes of work, parts of which are described in this paper, originated at a time of high crude oil prices. Many developing countries had no indigenous oil reserves and, for these, precious foreign currency was required to provide fuel for transport, agriculture and other essential services. Even where some oil was produced, this was seen as an export opportunity and any substitution released it for this purpose. On the other hand agricultural land was in plentiful supply, in many of these countries, and new uses for this and the additional employment provided would lead to a welcome improvement in their economies. Some vegetable matter yields oil as a natural product while, for other crops, a fuel is produced by distillation. Agricultural equipment in these situations often uses small diesel engines, either to generate electricity in the absence of mains supply in outlying areas or directly for water pumping, milling, grinding etc.

2 PALM OIL

2.1 Palm oil production and processing

Malaysia has some oil reserves which, at the time this programme began, had a potentially high value for export, especially to Japan. It produced over 70% of the world’s palm oil which amounts to 3.7 million tonnes from 14,000 km² of cultivated land. Species of palm nut have been developed, specifically as a fuel source, which produce a high oil yield of about 25-28% of the mass of the bunch of fruit. This is a good example of the efficient development of energy biomass rather than accepting what is left over from other uses.

It is possible to use crude palm oil (CPO) in diesel engines. To provide evidence and for public relations a demonstration vehicle, a VW Golf with 3-cylinder ELKO engine, was successfully operated on crude palm oil suitably heated to reduce viscosity. It is regarded as more practicable to base the majority of work on those fuels derived from palm oil that can be used without special adaptation of the engine or fuel storage and supply systems.

The first experiments on small stationary engines (1) were conducted using Refined, Bleached and Deodorised Olein (RBD Olein) which was readily available from existing edible oil processing plant. Further exploration of the possibilities of using palm oil derived products have shown that ethyl and methyl esters can be produced. There are advantages in this course of action since the transesterification process can convert separated high melting point components of the crude palm oil leaving those of lower melting point for use as edible oils. Using a catalyst and alcohol (which may also be derived from biomass) this fraction, largely palmitic and stearic glycerides, is converted to monoesters with glycerol as a valuable by-product. As part of a co-operative research programme between the Malaysian Government, universities, research centres and the national oil company, the Palm Oil Research Institute (PORIM) has built a 3000 tonne/annum pilot plant to produce methyl esters. This both proves the processing and provides sample output for experimental work on utilization and even for fleet trials.

Economies of this process depend upon fluctuating world prices for the raw materials by...
comparison with the by-products and of petroleum
based fuels but a report (2) suggests that it could
result in a cheaper fuel than diesel oil even without
giving credit for by-product.

2.2 Properties of fuels
Chemical composition of typical Malaysian palm
oils, shown in Table 1, makes them suitable bases
for engine fuel production as they comprise a large
proportion of carbon and hydrogen.

The physical properties of palm oil derived
fuels are compared with those of traditional diesel
fuel in Table 2, having been determined by ASTM
methods. Recent CFR engine tests have shown
that the cetane number is higher than less precise
methods had earlier suggested and that it is now
comparable with diesel fuel. This should be
regarded as the single most significant property
although it is not clear that present methods
accurately rate non-hydrocarbons.

The higher specific gravity of methyl esters
compared with petroleum diesel means that the
15% lower calorific value by mass becomes only a
10% reduction by volume. Since diesel injection
equipment meters by volume, the maximum fuel
energy delivery without modification is effectively
reduced by 10%. This is only of effect in the
maximum, over-design power, region. At other
loads, however, it will reduce the rate of injection
of energy into the combustion chamber since most
diesel engines are governed by length of injection
rather than by volume flowrate. It is not thought
that the 10% longer injection period would present
problems over the normal load range. Other
noteworthy differences in properties are the much

---

**TABLE 1**
Composition of typical palm oils.

<table>
<thead>
<tr>
<th>Component</th>
<th>percentage</th>
<th>chemical equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myristic</td>
<td>1.1 - 2.5</td>
<td>CH₃(CH₂)₁₂ CO₂H</td>
</tr>
<tr>
<td>Palmitic</td>
<td>40.0 - 46.0</td>
<td>CH₃(CH₂)₁₄ CO₂H</td>
</tr>
<tr>
<td>Stearic</td>
<td>3.6 - 4.6</td>
<td>CH₃(CH₂)₁₆ CO₂H</td>
</tr>
<tr>
<td>Oleic</td>
<td>39.0 - 45.0</td>
<td>CH₃(CH₂)₇CH≡CH(CH₂)₇CO₂H</td>
</tr>
<tr>
<td>Linoleic</td>
<td>7.0 - 11.0</td>
<td>CH₃(CH₂)₄CH=CH(CH₂)₇CH=CH(CH₂)₇CHCO₂H</td>
</tr>
</tbody>
</table>

---

**TABLE 2**
Physical properties of typical palm oil products compared with those of petroleum diesel fuel.

<table>
<thead>
<tr>
<th>Property</th>
<th>Petroleum Diesel (Malaysia)</th>
<th>RBD Olein</th>
<th>Methylesters from CPO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>0.827</td>
<td>0.912</td>
<td>0.878</td>
</tr>
<tr>
<td>Kinematic Viscosity/cSt</td>
<td>3.33 (at 40°C)</td>
<td>6.36 (at 28°C)</td>
<td>4.73 (at 40°C)</td>
</tr>
<tr>
<td>Pour point/ °C</td>
<td>12</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>Flash point/ °C</td>
<td>76</td>
<td>-</td>
<td>160</td>
</tr>
<tr>
<td>Distillation/°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial BP</td>
<td>185</td>
<td>215</td>
<td>310</td>
</tr>
<tr>
<td>10%</td>
<td>223</td>
<td>298</td>
<td>323</td>
</tr>
<tr>
<td>20%</td>
<td>244</td>
<td>-</td>
<td>324</td>
</tr>
<tr>
<td>50%</td>
<td>281</td>
<td>318</td>
<td>328</td>
</tr>
<tr>
<td>90%</td>
<td>368</td>
<td>326</td>
<td>342</td>
</tr>
<tr>
<td>Final BP</td>
<td>403</td>
<td>337</td>
<td>347</td>
</tr>
<tr>
<td>Cetane no. (typical)</td>
<td>58</td>
<td>38</td>
<td>60</td>
</tr>
<tr>
<td>Calorific value/ MJ/kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>46.2</td>
<td>39.8</td>
<td>39.4</td>
</tr>
<tr>
<td></td>
<td>38.2</td>
<td>36.3</td>
<td>34.6</td>
</tr>
</tbody>
</table>
higher flashpoint of methyl esters, the much narrower boiling range and the slightly higher pour point. The latter, at 15°C for methyl esters, is not a problem in SE Asia though it would be in more temperate climates.

2.3 Research programmes
Engine test work, based at the Universiti Teknologi Malaysia (UTM), has involved a research engine, Ricardo E6, a traditional slow-speed single-cylinder Lister stationary engine and a lightweight modern single-cylinder Yanmar stationary engine. Additional to this investigation of engines used in agricultural applications has been a study of small automotive diesels. This has involved laboratory tests on an Isuzu engine and field trials on small fleets of taxis in Kuala Lumpur and four-wheel drive vehicles used in palm oil producing areas. This part of the programme is important since about 40% of primary energy use in Malaysia is for transport (3).

The engine research programme includes performance plotting, fuel consumption and exhaust emissions analysis. There have also been inspections of components for any adverse effects of chemical properties of vegetable oils on standard materials used in engines. Laboratory facilities at UTM are available for performance trials on a number of engines. In addition an exhaust gas analysis unit is available for application to any of these.

Typical of recently-built small stationary engines used in SE Asia is the Yanmar TF80 single-cylinder, water-cooled, four-stroke engine. The engine has a direct-injection combustion chamber, shown in Fig 1, incorporating a slightly offset toroidal combustion chamber set in the piston. The major specification items for this engine are:

- cycle: four-stroke
- combustion chamber: direct-injection
- bore and stroke: 80 mm x 87 mm
- swept volume: 0.437 litre
- compression ratio: 18:1
- injection timing: 13.5° btdc
- continuous rated output: 5.2 kW (diesel fuel)
- brake specific fuel consumption at this output: 2200 rev/min

No engine modifications were undertaken and injection timings and rack setting were as standard for this engine when using petroleum diesel fuel. The engine drives an electrical dynamometer.

2.4 Engine test results
Comparative tests were conducted on the Yanmar engine described using standard Malaysian diesel fuel and methyl esters processed from crude palm oil.

Brake specific fuel consumption, corrected to diesel fuel equivalent, is plotted against brake mean effective pressure in Figure 2. It can be clearly seen that the engine has a performance on each fuel which is almost identical. There appears to be no performance penalty in using palm oil derived methyl esters instead of diesel fuel, other than the slightly lower maximum output caused by volume limitation on the fuel pump delivery. This results in a smaller maximum energy delivery for methyl esters because of the lower energy per unit volume compared with diesel fuel.

Trials of the engine with gas analysis equipment continuously monitoring the exhaust composition were undertaken in the laboratory. The CO is consistently lower with methyl esters than with diesel fuel. The sharp increase near full load of the diesel fuel trial was not repeated with methyl ester. NOX concentrations followed similar curves for both fuels; that for methyl esters being 10-12% lower. Smoke level is about 25% better throughout the range with methyl esters. Figure 3 shows the smoke values for each fuel as this is probably the most significant emission comparison for small diesels. Other emission values have been published in reference (4).

Overall exhaust emission results can be considered favourable to the use of methyl esters from crude palm oil. As with many alternative fuels care has to be taken in the choice of materials used in the fuel systems when vegetable oils are used. Certain plastics and rubbers harden or swell and can even dissolve. Metal parts are not usually affected. In these tests on the direct-injection engine some coking of the nozzle was experienced but these do not appear to have affected spray formation. Deposits have not been a problem in field trials over extended periods with indirect-injection automotive engines.

3. ALCOHOLS

3.1 Alcohol production and processing
Alcohols for engine fuels are generally either methanol or ethanol. Methanol may be produced from natural gas, coal or wood and so can be a means of converting gaseous or solid fossil resources into liquid fuels suitable for engines. Ethanol is produced by the fermentation and distillation of biomass. Both are recognized as attractive alternatives to oil derived fuels for stationary and automotive engines.
### Table 3
Properties of alcohols compared with UK hydrocarbon fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Gasoline 4-star BS 4040</th>
<th>Gas oil A1 BS 2869</th>
<th>Methanol CH₃OH</th>
<th>Ethanol C₂H₅OH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>C₄ to C₁₂ hydrocarbons</td>
<td>C₁₄ - C₁₉ hydrocarbons</td>
<td>CH₃OH</td>
<td>C₂H₅OH</td>
</tr>
<tr>
<td>Calorific value</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MJ/kg (net)</td>
<td>43.8</td>
<td>42.5</td>
<td>19.9</td>
<td>27.2</td>
</tr>
<tr>
<td>MJ/litre (net)</td>
<td>32.4</td>
<td>35.7</td>
<td>15.8</td>
<td>21.5</td>
</tr>
<tr>
<td>Mean molecular mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>114</td>
<td>236</td>
<td>32</td>
<td>46</td>
</tr>
<tr>
<td>Research octane no.</td>
<td></td>
<td></td>
<td>114</td>
<td>111</td>
</tr>
<tr>
<td>Cetane no.</td>
<td>97</td>
<td>na</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spon. ign. temp (°C)</td>
<td></td>
<td></td>
<td>470</td>
<td>400</td>
</tr>
<tr>
<td>Stoichiometric air-fuel ratio</td>
<td></td>
<td></td>
<td>6.46</td>
<td>8.94</td>
</tr>
<tr>
<td>Flammability range:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% vol of fuel in air</td>
<td></td>
<td></td>
<td>1-6</td>
<td>2-5</td>
</tr>
<tr>
<td>A/F ratio (mass)</td>
<td>25-4</td>
<td>21-3</td>
<td>13-2</td>
<td>14-3</td>
</tr>
<tr>
<td>Equivalence ratio</td>
<td>0.6-3.8</td>
<td>0.7-4.9</td>
<td>0.5-3.2</td>
<td>0.6-3.3</td>
</tr>
</tbody>
</table>

#### 3.2 Properties of alcohols

The properties of alcohol fuels which are relevant to their use in internal-combustion engines are shown in Table 3. It will be seen from this table that alcohols have a much lower energy per unit volume or per unit mass than hydrocarbon fuels. This is not a major disadvantage if the production facilities are close to the point of use as they could be when powering agricultural equipment is the requirement. It does, however, necessitate modification of the fuel system of any engine in which it is used, either spark-ignition or diesel. The high octane ratings are, of course, an advantage for spark-ignition engines in which their use is well known, either as neat fuels or as extenders and octane rating enhancers for gasoline (replacing lead alkyls). Since for diesel engines the operation depends upon the short ignition delay of fuels with high cetane numbers, there are serious problems in using alcohols with ratings in single figures for this type of engine.

#### 3.3 Research programmes

Consideration was given to means whereby diesel engines, with their inherently high thermal efficiencies, could utilize ethanol and methanol despite their low cetane ratings. A number of options were possible as lines of approach to this problem - cetane number improving additives, alcohol-oil emulsions, fumigation, dual injection and glowplugs - but spark-assistance was seen as a preferred solution (5). The original combustion system designed by the authors incorporated a multi-strike, high-energy spark system but, once optimised, a simple single spark device, based on standard automotive components, was found sufficient. A large capacity injection pump was fitted, to maintain the same energy addition rate compensating for the low energy per unit volume of alcohols. The opportunity was taken of providing variable injection timing for the experimental form of the engine. The combustion chamber layout is shown in Fig 4. This was limited by the need to modify a standard cylinder head but the fuel spray and the long electrode spark plug were placed in what was thought to be an effective relationship to each other. A small amount of metal was removed from the piston at the lip to the bowl to clear the plug.

The specification of the engine based on the Petter PH1, a type in widespread use throughout the world for remote site operation, with modified combustion system is given below:

<table>
<thead>
<tr>
<th>cycle</th>
<th>four-stroke</th>
</tr>
</thead>
<tbody>
<tr>
<td>combustion chamber</td>
<td>direct-injection</td>
</tr>
<tr>
<td>bore and stroke</td>
<td>87.3 mm x 110 mm</td>
</tr>
<tr>
<td>swept volume</td>
<td>0.658 litre</td>
</tr>
<tr>
<td>compression ratio</td>
<td>16.5:1</td>
</tr>
<tr>
<td>continuous rated output (diesel fuel)</td>
<td>7.4 kW</td>
</tr>
<tr>
<td>brake specific fuel consumption at this output</td>
<td>2200 rev/min</td>
</tr>
<tr>
<td></td>
<td>262 g/kWh</td>
</tr>
</tbody>
</table>

#### 3.4 Engine test results

The engine has been tested using ethanol and, less extensively, methanol. In both cases small proportions of vegetable oil were added to provide lubrication of the fuel injection equipment. A
considerable range of injection and ignition timings were explored and optimisation achieved at certain constant loads and speeds (6).

For alcohol performance comparable with that for diesel fuel in the unmodified engine has been obtained in terms of output and efficiency and the characteristics for ethanol and diesel fuel are shown in Fig 5. Results for methanol are comparable with those for ethanol.

4 CONCLUSIONS

4.1 Palm oil
The trials conducted so far indicate that methyl esters derived from crude palm oil provide an excellent substitute for petroleum fuels in a standard small stationary diesel engine. Efficiency appears to be unaffected and, for almost all pollutants, exhaust emissions are improved. On further investigation it is expected that a means of preventing excessive carbon deposits on the injector nozzle will be developed. Fuels of the type tested could substitute for imported petroleum in many developing countries. Similar results have been obtained from an indirect injection automotive diesel, again with reduction in smoke (7).

4.2 Alcohols
Ethanol and methanol have been shown to provide suitable fuels for use in a small stationary diesel engine when this is modified to allow spark assistance and to provide for the extra volume of fuel per cycle. Efficiency is the same within experimental limits and maximum power output is limited by thermal stress rather than by smoke as it would be for diesel fuel. This has been a more severe limit in the test engine with an air-cooled cast iron head than it would be for a water-cooled version. Particularly with methanol care has to be taken in the selection of materials for fuel handling.

REFERENCES


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ACKNOWLEDGMENTS

The contribution of Professor Mohammed Afifi bin Abdul Mukit and Mr Azhar Abdul Aziz of Universiti Teknologi Malaysia to the work on palm oil is gratefully acknowledged. The British Council has sponsored the link between the University of Surrey and UTM and additional help was given for travel by UAC Ltd. Information from the Yanmar Diesel Engine Co Ltd was also helpful.

Assistance with the alcohol fuels programme has been received in many ways from industry, including Lister-Petter Ltd, Lucas-CAV, BP Research Centre and NGK Spark Plugs, and from a Science and Engineering Research Council grant which supported the work for three years.
Fig 1  Combustion chamber of Yanmar TF80 engine. The injector nozzle is surrounded by an insulator.

Fig 2  Brake specific fuel consumption on diesel fuel basis.

Fig 3  Exhaust smoke comparison between diesel fuel and methyl esters from palm oil.

Fig 4  Combustion chamber layout for spark-assisted diesel engine, position A was used as it was downstream of the nearest spray.

Fig 5  Comparison between performance on diesel fuel and, with spark assistance, alcohols.
Choice of Fuels

A W E Henham

CHOICE OF FUELS

ALEX HENHAM
Course Director - Energy Engineering
University of Surrey England

1.0 INTRODUCTION

To set the topic of this seminar in the overall context of the effective utilization of available resources of energy, it is helpful to look first at the world's energy sources - income and capital. The income sources are those which will exist in future whether or not we utilise them today whereas the capital sources are those which, once consumed, are not available to later generations.
Some of the sources included in these classifications are shown in Table 1.

<table>
<thead>
<tr>
<th>INCOME</th>
<th>CAPITAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct solar energy</td>
<td>oil</td>
</tr>
<tr>
<td>wind energy</td>
<td>natural gas</td>
</tr>
<tr>
<td>wave energy</td>
<td>uranium</td>
</tr>
<tr>
<td>tidal energy</td>
<td></td>
</tr>
<tr>
<td>geothermal energy</td>
<td></td>
</tr>
<tr>
<td>biogas</td>
<td></td>
</tr>
<tr>
<td>liquids from biomass</td>
<td></td>
</tr>
<tr>
<td>solid biomass</td>
<td>coal</td>
</tr>
</tbody>
</table>

Table 1  Energy Sources

2.0 SOLID FUELS

Solid fuels, it is seen from Table 1, arise under both columns — the solid forms of biomass can be produced on a seasonal basis in some cases or over a period of years as for most trees. Coal is, of course, the result of plant life millions of years ago and of its subsequent changes through the development of the earth's surface.

Solid domestic and industrial wastes are also utilised in energy schemes in increasing quantities. Some of these waste materials arise from renewable materials (paper, wood, etc.) while others are from fossil fuel derived substances such as plastics. They are by nature heterogeneous.

2.1 BIOMASS

Even considering biomass as a solid fuel energy source it has to be divided into two broad categories. Some of the plants are used only as energy sources and are now cultivated to optimise their energy value. In particular this approach has been applied to the production of liquid alcohol fuels but is also applicable to the much older practices of using trees for direct wood-firing and for the production of charcoal.
The area of potentially rapid growth in the use of biomass, however, is in exploiting the energy potential of previously rejected by-products of plants produced for other purposes. In this category one can include bagasse, rice husks, straw and parts of trees unsuitable for prime purposes such as structural timber.

Further examination of the uses to which these solid biomass products are put, reveals a number of intermediate stages which can be used for convenient handling. Various forms of densification can be used, eg briquetting and pelletising, to give a transportable form and controllable and consistent combustion. Such approaches are currently under development in the Nordic countries (1) where wood represents about 10% of total energy use recorded despite fairly cheap hydroelectricity.

2.2 COAL

Widely varying estimates exist of the total energy stored in coal but what is certain is the much greater reserve than that in oil or gas. One source quotes $279 \times 10^{21} \text{J}$ out of a total $300 \times 10^{21} \text{J}$ for all fossil fuels (2). It has to be regarded, therefore, as the fossil fuel with the longest future. The demand for it would naturally increase as soon as any world shortage of oil or gas existed, if only because of its potential as a raw material for liquid synfuels and for SNG.

Like oil, coal has many different forms depending upon its historic origins and the temperature, pressure and surrounding rock formation.

Deep mined coal has a considerably lower moisture content than that from opencast operations and a correspondingly high heating value or calorific value. The main determinant of the calorific value is the ratio of carbon to hydrogen. This is normally indicated in the form of an ultimate dry mass analysis of the elements present, samples of which are given in table 2.

<table>
<thead>
<tr>
<th>Coal type</th>
<th>C</th>
<th>H</th>
<th>O</th>
<th>ASH</th>
<th>(Remainder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracite</td>
<td>90.3</td>
<td>3.0</td>
<td>2.3</td>
<td>3.0</td>
<td>is Sulphur</td>
</tr>
<tr>
<td>Bituminous</td>
<td>74.0</td>
<td>6.0</td>
<td>13.0</td>
<td>4.8</td>
<td>and Nitrogen</td>
</tr>
<tr>
<td>Lignite</td>
<td>56.5</td>
<td>5.7</td>
<td>31.9</td>
<td>4.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Some typical dry coal analyses
Dulong's formula or that of Grumell and Davies (3) enable an indication of the higher calorific value to be obtained from these analyses giving typical values for dry samples of (34) MJ/kg 31.5 MJ/kg and 31 MJ/kg respectively. For the last sample the 'as fired' value would be greatly reduced by the moisture present.

Coal is also supplied in various forms for use in different types of steam raising plants, hot water systems, etc and this affects its packing density in kg/m³.

3.0 CRITERIA FOR FUEL SELECTION

The criteria on which the choice of fuel is based are very much affected by the specific application. Some of the following criteria will be more important in the case of small power plants than for other applications.

3.1 AVAILABILITY

A fuel has to be available on a scale to meet the demand envisaged to match the chosen size of power plant and its anticipated load factor and efficiency.

\[ \dot{m} \eta |CV| = \dot{W} |LF| \times 365 \times 24 \times 60 \times 60 \]

where

- \( \dot{m} \) = mass rate of fuel supply/ kg/year
- \( \eta \) = overall efficiency of power plant based on fuel
- \( |CV| \) = calorific value of fuel/ MJ/kg
- \( \dot{W} \) = power output of plant/ MW
- \( |LF| \) = load factor, ie proportion of potential energy output actually produced when averaged over the year.

For this reason some commercially attractive solid fuels may be impracticable where the supply rate cannot keep pace with average demand. Storage space for fuel will be required to smooth out variations of demand or to cope with out of phase fuel supply and demand fluctuations.
3.2 SECURITY OF SUPPLY

Investment in plant will often depend on a decision upon the chosen fuel. In order to justify the capital cost of plant to utilise a given energy source some degree of assurance of future supplies at the appropriate rate must be established. There is an additional security problem when the source of fuel is outside the control of the country concerned. A multifuel capability in the power plant greatly reduces the risk of insecure supply whether the risk arises from possibilities of political, natural, labour or transport problems.

3.3 COMPETITIVE PRICE

This is the key factor in choosing a fuel when other, less easily quantifiable requirements are met. Care has to be exercised, of course, in assessing the true value of the fuel supplied given by:

\[ |EC| = \frac{p}{|CV|} \]

where \( p \) = price of fuel per kg delivered
\( |CV| = \) calorific value / MJ/kg purchased
\( |EC| = \) energy cost / price units/MJ

This allows for the incombustible portion of the fuel but not for any special cost of handling fuel, ash or flue gas. Where additional costs of plant are implied by an unconventional fuel the price of fuel must be low enough to allow capital to be repaid.

3.4 TRANSPORTABILITY

One of the more important factors in determining the price, \( p \), in 3.3 above is the cost of transporting the fuel from source to site. Obviously this depends upon the distance between the source of the fuel and the site of the power plant. Once the loading and unloading costs have been met this will be a fairly linear function of distance. For the traditional forms of energy competing with solid fuels long pipelines are common where larger plants are to be served. This is unlikely to be the case for small scale plants so oil, for example, would usually need to be delivered by the same methods as solid fuel - by road, rail or water transport. The ease of
packing the appropriate vehicle could be significant if a solid fuel resource is to be transported by these means. Some preprocessing of fuels may help in this part of the operation.

3.5 ENERGY DENSITY

By energy density is meant here measures of the compactness of a fuel source. This is especially significant in determining the transportation economy in 3.4 above. A fuel with a high useful energy content per unit mass (MJ/kg) and with high useful energy content per unit volume (MJ/m^3) is more easily transported, stored and handled than other fuels. Prime use of the high energy density fuels is, of course, for transportation itself. From the point of view of the operator of a stationary power plant, however, many solid fuels (eg coal) do have a high energy content per unit mass and volume. Where this is not the case it is probable that only a very local source of the fuel will be an economically viable supplier. This will often be true for biomass-fired plant where it is most appropriately sited to serve the agricultural community and associated industries. The cost of such fuels, especially if waste derived, will presumably be extremely low, compensating for the extra handling problems. They are not really part of the open market in fuels which exists for universally traded substances such as crude oil and oil products.

3.6 ENVIRONMENTAL CONSIDERATIONS

Control on environmental intrusion of various kinds is now widely exercised by governments nationally and locally. This may include visual, acoustic, atmospheric and water pollution. The delivery and storage of fuels must be such as to minimise effect on local residents while the other aspects can affect a much wider area than this. In general the larger the plant and the more densely populated the area in which it is sited, the greater are the problems to be overcome although the very high chimney has its advantages. As far as the actual products of combustion are concerned there is a considerable effect related to the exact fuel. Sulphur content, particulates carried over into the flue and unburned organic substances are variables to be examined when combustion systems for new fuels are being developed.
4.0 CONCLUSION

In evaluating the criteria suggested above there are no short cuts. Each country, each locality, each site, each size of plant, each workforce will create its own requirements and impose its own limitations.

Establishing an order of priority is one way of coming to a reasonable conclusion as to the appropriate compromise for a given plant. In a few cases it may well be that the fuel is pre-determined by the location as the site will have been chosen to make use of a specific resource. Major differences exist between optimum fuels for large and small scale power plant. Handling, price structures, transport, quantities available and environmental control will all vary with scale.

It has been estimated (4), for example, that about 5.5% of the European Community's energy could be obtained from biomass. For rural areas of China, however, 68.6% of the energy supply is already obtained from this source (5), over half from straw and stalks. Of the remainder only 14% came from oil and electricity, which constitute the majority of final energy supplies in most urban societies.

Reliability is at a premium, in particular, in most small scale power plants which will very likely be stand-alone providers of electricity to a local district or industry. Where stations are linked in a grid with spare capacity (as in the UK) such considerations can be given a lower priority than where everyone and everything depends upon one station.
REFERENCES


Education in energy management -
a UK viewpoint

A W E Henham
1.0 INTRODUCTION

Education in the effective employment of our energy resources did not begin with the 'Energy Crisis' of the early seventies when the general public suddenly became aware of the importance of this topic. University courses, especially in departments of engineering have long drawn attention to the concepts of overall plant efficiency based upon primary energy resource usage. From this point of view the argument could be put forward that nothing else is needed. Certainly the interest taken in this subject by undergraduates has been sharpened in recent years. There is a requirement, however, for a more detailed and directional attack on the problems of effective energy utilization, which on a cost-benefit basis has become more significant with the increasing costs of energy compared with those of other products and materials.

2.0 EDUCATIONAL REQUIREMENTS

At many levels it is necessary to communicate: a) the need for energy conservation, and b) a knowledge of the means whereby energy may be conserved. In a report published by the Watt Committee on Energy (a U.K. body coordinating the energy interests of all-relevant professional societies) it is recommended that: "Every effort should be made to make all consumers more aware of the importance of the more rational use of energy in all walks of life."

Everyone is an energy user and most people have some control over the amount of energy they use.

In this general category emphasis has to be placed on communicating with the largest number. This has been done in the U.K. by various means, the most central of which is the Department of Energy's 'SAVE IT' campaign. Many ways of drawing public attention have been utilized: television advertising; television documentary features; newspaper advertising; posters; leaflets from domestic energy suppliers; school lesson topics; publicity for-home insulation grant scheme.

The second largest group of people is the workforce in factories, offices and retail distribution.

Here general information methods of the type listed above are employed together with specific instruction aimed at energy saving in each industry or process. Some of this can be arranged as part of a national scheme. (For example, the training of boiler house operatives.) Government agencies, fuel supply authorities and companies and equipment manufacturers all play a part in this. Other training has to be locally organized and the extent to which this exists depends heavily upon the interest and enthusiasm of managerial staff.
The involvement of senior management is sought in various ways. The financial press carries both editorial and advertising material on energy matters; suppliers of energy, of energy equipment and of conservation measures all make available printed matter and the advice of visiting representatives. Incentive is provided by government grants towards the fees of energy consultants brought in to make preliminary surveys of energy conservation possibilities in industrial premises. Other financial concessions are sometimes available to those companies proposing schemes which have long-term saving possibilities.

More direct methods of communication may often be used with the still small, but growing, number of 'Energy Managers'. In a company the Energy Manager will be the focus of all the means employed to utilize energy well. He will monitor consumption, advise on conservation measures, prepare proposals for consideration by the senior management, arrange training and publicity. Channels of contact with (and between) Energy Managers are numerous and include: specific journals (e.g. Energy Management and Energy Manager\(^3\)); series publications (e.g. Fuel Efficiency Series\(^4\), No. 4, Compressed Air and Energy Use); books (e.g. The Energy Managers' Handbook\(^5\)); short courses on particular topics (e.g. Energy Audit, Controls) – these may be arranged by Government departments, industrial concerns and by trade, professional and academic bodies; exhibitions (e.g. the annual 'Energy Show'); Energy Managers Groups or Clubs; films (e.g. Managing Energy Series: Heating and Ventilation in Factories).

In a survey of over 2000 manufacturing sites in 1977, however, only a half were found to be using any form of Department of Energy publication.\(^6\)

3.0 THE UNIVERSITY CONTRIBUTION

These publications, training schemes, courses and other means by which information is disseminated naturally take a specific area and treat this largely in isolation from the broader concerns of world energy resource management. The control of environmental effects is often neglected except where legal imposition requires it. The cost effectiveness of a particular measure is sometimes omitted from the discussion as is, even more often, the energy content of additional plant or materials. The main function at this stage is simply to reduce the fuel bill.

A graduate involved in this type of occupation in industry will want to exercise a fully professional responsibility, not only to his employer but also to the rest of mankind. He will feel this need to be informed about the broader implications of his immediate pre-occupation. In giving advice to his employer or in drafting new proposals he will try to base his recommendations on a consideration of all the relevant factors. A postgraduate course is a method of providing both the background education and the specific technical training required.

4.0 A POSTGRADUATE COURSE

Traditional University Masters' courses take a specialized area from an undergraduate course in one discipline and extend this much further, often in conjunction with a research school in the same field. Large scale industries and government research centers provide appropriate opportunities for this type of graduate to pursue a specialization.

Recently there has been some variation in this pattern, not opposed to it, but existing in parallel with it to meet different needs. Leonard and Rathmill\(^6\) comment on the increasing pressure under which universities come to ensure that courses are relevant to the real needs of society. They indicate that students often express the desire for broadly based work which will prepare them for industrial careers.
Energy Engineering was thought by the University of Surrey to be an industrial area which justified a course along these lines. Proposals for both undergraduate and post-graduate courses were prepared by a working party of the Faculty of Engineering. As a starting point the post-graduate courses seemed to offer a more appropriate starting point and to have a more rapid effect. Undergraduate courses, including a year in industry, are of four years duration and considerable lead time has to be added for inclusion in the British system of centralized handling of applications for admission. Another, perhaps the most significant, consideration was the possibility of arranging for a part-time, in-service format to run alongside the full-time standard course. The accelerated effect of the course is emphasized since the student returns to industry each week after spending time at the University and so he is able to make immediate use of some aspects and even to feed the results back into the course.

The method by which these parallel patterns are achieved is illustrated in Fig. 1. Both patterns include the same lecture courses and facilities for other work are available equally to full-time and part-time students.

The course outline produced by the working party was circulated to many industrial concerns, local authorities, professional societies, other academics, and to the relevant government departments and agencies for comment. Representatives of all these bodies were invited to a conference where they were able to hear the University ideas presented, and to discuss with staff involved possible changes to meet the needs of industry and other potential employers. The syllabus was reviewed in the light of this discussion and of written comments submitted by those not attending.

5.0 COURSE CONTENT

The Faculty of Engineering is comprised of four departments: Chemical Engineering, Civil Engineering, Electronic and Electrical Engineering and Mechanical Engineering. It offers single honors courses in each of these disciplines, certain combined honors courses with Business Economics, and as a joint effort, an honors degree in Engineering. Several postgraduate courses include part-time study provision and the success of that in Systems Engineering encouraged the adoption of the same arrangement in Energy Engineering. Contributions from the four departments are joined by those from others outside Engineering principally Economics and Metallurgy and Materials Technology. Responsibility for the course is delegated by the Dean to a Course Director who, for administrative purposes, works through the Department of Mechanical Engineering. An Academic Board comprising all members of the course teaching team meets three times each year to discuss and decide academic matters.

The syllabus is divided into eight teaching subjects:

1. Introduction to Energy Engineering (20 h). A fuel technologist discusses energy resources, their relative importance, means of exploitation and the effects of political, economic, social and technical factors.

2. Introduction to Energy Management (30 h). A practicing energy management consultant is an associate lecturer for his course which shows how the principles of energy conservation may be applied to industrial, commercial and institutional situations.

3. Materials (20 h). Members of the Metallurgy and Materials Technology and of the Civil Engineering Departments combine to present a picture of the availability, properties and energy
content of a variety of materials used in building structures and in energy conversion plant.

4. Systems & Management Studies (80 h). Members of the Economics Department introduce the concepts of energy modelling, energy economics and project appraisal. On the engineering side, control systems are covered including the application of microprocessors to energy using plant.

5. Energy conversion and Prime Movers (30 h). The Laws of Thermodynamics are used as a basis for the analysis of processes and cycles leading to the comparison and selection of plant.


7. Energy Utilization I (40 h). The principles of subjects 1, 5 and 6 are taken further to examine typical applications to industrial processes and to the heating and ventilation of buildings.

8. Energy Utilization II (40 h). The use of fossil fuels in industrial situations is dealt with in detail together with the selection of appropriate plant such as furnaces, boilers and waste heat recovery equipment.

In many of these subjects visiting lecturers from industry are widely employed to provide up-to-the-minute inputs of current technological progress. Questions put by the students during these sessions indicate that they find these external contributions stimulating.

In addition, time is allocated to the consideration of Energy Schemes (60 h). These are graded from paper exercises based on tightly specified situations, through the analysis of single pieces of plant and of single buildings to the critical assessment of given case study problems. Case studies are drawn from the University and from industry (Fig. 2).

Although laboratory plant is used occasionally in the Energy Studies Course to form the basis of an analysis, there is no separate formal laboratory time during the main course. A concentrated vacation course (15 h) in energy instrumentation is held concentrating on the monitoring of installations not already adequately instrumented (i.e., the typical industrial situation).

The final individual project is selected by the student in a field of special interest to him. This can be undertaken in the University or in the student's normal place of work or in an industrial situation arranged by the University. It is this part which enables a detailed study to be made of a topic which may be only briefly mentioned in the course.

Assessment of the student's performance is made at the end of the taught course and depends upon written examinations (75%) and the Energy Schemes course work (25%). Successful candidates proceed to produce a report on their individual project over the summer period and the degree is awarded when this work satisfies the examining board.
6.0 COMPLEMENTARY ACTIVITIES

The University is involved in a range of energy activities in engineering and other departments. In addition to individual research topics there is an Energy Sub-Committee of the University's Research Committee. There are active postgraduate research groups in Fuel Technology and in Energy Economics. Much of the work undertaken is financed by industrial concerns and involvement in these fields ensures that members of staff do not become remote in an ivory tower atmosphere isolated from the problems experienced by industry and commerce.

7.0 EXPERIENCE

Participation by industry and government departments exists at various levels, some of which have been mentioned above: Formulation of the course structure and syllabus; secondment of full-time students; day-release of part-time students; visiting lecturers; information; provision of projects; case study material and visits.

Although the interest of employers of students is shown in these forms of cooperation, it is rarely the employer who initiates the student's connection with the course. This is a characteristic shared by other sources of this pattern according to a recent survey. A much larger proportion of the students in the course described than those in the total survey receive full financial support from the employers. Very few applications are withdrawn because the employer is unwilling to allow study.

The sponsored student intake in the first two years represents a wide range of employment; County Councils and New Town Development Corporations; manufacturers of energy equipment (boilers, air conditioning); building services consultants; nationalized energy supply industries; motoring organizations; food processing industry; property services agency (government buildings); London buying office of overseas electric power authority; technical colleges and polytechnics; energy consultants.

Appointments held also cover a wide range including energy conservation officers, project engineers, chief engineers and even a managing director.

Contributions made by these students during seminars, tutorials and discussion are a valuable contribution to the total experience of the course. The average age is, of course, much higher than that of the newly graduated who make up the majority in most postgraduate courses. Since all part-time and some full-time students are in this category, the majority is always able to bring work-based insights to the course.

Other courses based on industrial technologies and having large proportions of mature students report similar advantages and some exclude those without experience even from the full-time pattern of study.

The course is recognized by the Institute of Energy as an approved advanced course and by the government's Training Services Division as a suitable course for which grants may be made to certain adults seeking re-training.

8.0 CONCLUSION

The importance of energy education at all levels cannot be overlooked. In the course described, a particular contribution which the University is equipped to make has been attempted. The course as designed will develop as experience is gained in the needs of students and the employers, existing and potential. The
structure of the post-graduate course is one which is particularly adaptable.

Acknowledgment is made to all members of the University and our many friends outside it, who have contributed in so many ways to the establishment of this course and who have provided it with continuing support.

REFERENCES


Development of education in energy management

A W E Henham

DEVELOPMENT OF EDUCATION
IN ENERGY MANAGEMENT

A.W.E. Henham
Course Director of the M.Sc. in Energy Engineering,
University of Surrey.
1.0 Introduction.

In a document circulated (1) recently for comment the Department of Education and Science indicates a strong belief in the importance of mid-career courses of vocational education for those at work. It argues that the qualifications and skills needed in the Country's workforce must be developed if managers and employees at all levels are to be able to meet successfully the complex challenges facing them. Such courses are quoted as offering, inter alia:

a) updating in specialist areas of theoretical knowledge or general advances in the field
b) appreciation of new technologies or processes and the knowledge to apply them effectively
c) acquisition of new skills or qualifications relevant to employment
d) preparation for new responsibilities or for upgrading
e) packages of skills necessary for a new article or process to be developed.

Enrolments of students aged 25 and over in all types of existing courses in the maintained and assisted sector in England and Wales totalled over 314 000 and those in Universities 43 000 (27 000 at postgraduate level) in 1978-9(1). A Directory of postgraduate short courses and fuller courses available part-time was published in 1979(2). Alongside this nationally expressed need for mid-career education is the specific requirement for education and training in energy management. Questions asked at the National Meeting for Chairmen and Secretaries of Energy Managers' Groups with the Secretary of State for Energy on 17 February 1981 indicated that not all were aware of the present activity in this field and in other aspects of energy in which co-operative relationships between education and industry were active. This paper seeks to make existing work more widely known and to point to means of continuing and expanding this in the future.

2.0 Education in Energy Management

Education in the effective employment of our energy resources is a well-established feature of traditional University undergraduate courses, especially those in Chemical and Mechanical Engineering and in Fuel Technology. Academics involved with such courses have a responsibility to ensure that future industrial managers and government and other research staff are aware of the implications of the concepts of plant efficiency. It is necessary, of course, to see the energy input to the manufacturing process as one among others such as raw materials and manpower. The current importance of energy as a factor depends mostly upon the more rapid increase in its cost over the last eight years than in that of other factors.

Training in-service may be expected to provide sufficient information to enable the professional engineer to make appropriate decisions about the use (or avoidance of use) of energy. The types of described in the accompanying paper(3) serve an excellent purpose in introducing managers and operatives to appropriate proven techniques of energy conservation.
Education seeks to fulfil a somewhat broader need since the specific operation is here seen as just one small part of the overall activity. The claim to educate rather than (or, perhaps, as well as) train professional energy managers implies a broader concern for world resource management of energy, money, materials and manpower. The effect of our energy use on the environment in general is considered whereas in training local environmental control only may be of interest and that because legal restrictions require it. Thus the graduate should be in a position to base recommendations for action to his employer on a substantial background of understanding all the relevant implications. These would include not only the factors affecting the employer immediately but the longer term matters such as likely availability of chosen energy source, transportation, staffing, air pollution, life of plant and possibility of plant obsolescence. The financial aspects should also involve these broader issues in the analysis presented for any project. By these means it is hoped to make a permanent contribution to the understanding of energy management.

2.1 Qualification

There is no nationally required qualification to be an 'energy manager' but individual employers may ask for any qualification thought necessary. This may well vary from industry to industry and, since few people have specifically qualified so far, will usually be based on a background in the industry concerned. So, for an oil refinery, a chemical engineer may be sought while, for a large chain of department stores, a building services engineer may be more appropriate.

It is hoped that what the new breed of graduate energy engineers will do is to provide expertise spanning these traditional discipline sectors.

Professional engineers are usually seeking status as Chartered Engineers which can be obtained only by membership of one of the member institutions of the CEI. The possible routes to achieve this vary with the particular institution but a typical pattern is shown in figure 1.

<table>
<thead>
<tr>
<th>ACADEMIC REQUIREMENTS</th>
<th>Professional Training</th>
<th>Professional Review</th>
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<tbody>
<tr>
<td>A DEGREE IN THE APPROPRIATE BRANCH OF ENGINEERING FROM UK UNIVERSITY OR CNAA OR CEI PART I EXAMINATION</td>
<td>a) ENGINEER IN SOCIETY PAPER (if not included in degree or CEI PartII)</td>
<td>CHARTERED ENGINEER</td>
</tr>
<tr>
<td>OR</td>
<td>b) REPORT ON PROFESSIONAL EXPERIENCE AND RESPONSIBILITIES</td>
<td></td>
</tr>
<tr>
<td>CEI PART II EXAMINATION</td>
<td>(Part of which may be included in a sandwich degree course)</td>
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<td>OR</td>
<td>c) PROFESSIONAL INTERVIEW (may be required)</td>
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<td>OR</td>
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<td>HND</td>
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<tr>
<td>APPROPRIATE HIGHER DEGREE</td>
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</table>

*Figure 1: Simplified representation of routes to Chartered Engineer status.*
Implementation of the Finniston Report proposals could affect this pattern but a current situation is depicted here. A particular scheme of interest in this respect is that by which an engineer who has already satisfied the CEI requirements in one field of engineering may be eligible for Membership of the Institute of Energy by taking an Approved Advanced Course at postgraduate level. Such courses are available at the Universities of Birmingham, Leeds, London (Imperial and Queen Mary Colleges), Newcastle-upon-Tyne, Sheffield and Surrey, at Cranfield Institute of Technology and at Middlesex, Newcastle-upon-Tyne and Portsmouth Polytechnics.

2.2 A Master's degree in Energy Engineering

Traditional University masters' courses take a specialised area from an undergraduate course in one discipline and extend this much further, often in conjunction with a research school in the same field. Large scale industries and government research centres provide appropriate opportunities for this type of graduate to pursue a specialisation.

Recently there has been some variation in this pattern, not opposed to it, but existing in parallel with it to meet different needs. Leonard and Rathmell comment on the increasing pressure under which Universities come to ensure that courses are relevant to the real needs of society. They indicate that students often express the desire for broadly based work which will prepare them for industrial careers.

Energy Engineering was thought by the University of Surrey to be an industrial area which justified a course along these lines. Proposals for both undergraduate and postgraduate courses were prepared by a working party of the Faculty of Engineering. At this time the postgraduate courses seemed to offer a more appropriate starting point and to have a more rapid effect. Undergraduate courses, including a year in industry, are of four years duration and considerable lead time has to be added for inclusion in the system of centralised handling of applications for admission. Another, perhaps the most significant, consideration was the possibility of arranging for a part-time, in-service format to run alongside the full-time standard course. The accelerated effect of the course is emphasised since the student returns to industry each week after spending time at the University and so he is able to make immediate use of some aspects and even to feed the results back into the course.

2.2.1 The method by which these parallel patterns are achieved is illustrated in figure 2
Both patterns include the same lecture courses and facilities for other work are available equally to full-time and part-time students.

2.2.2 The course outline produced by the working party was circulated to many industrial concerns, local authorities, professional societies, other academics, and to relevant government departments and agencies for comment. Representatives of all these bodies were invited to a conference where they were able to hear the University's ideas presented, and to discuss with staff involved possible changes to meet the needs of industry and other potential employers. The syllabus was reviewed in the light of this discussion and of written comments submitted by those not attending and has been up-dated through further discussions with interested parties.

2.2.3 The course is divided into a number of subjects, each of which constitutes a series of lectures reinforced, where appropriate, by tutorials and practical demonstrations. In some subjects all the lectures are given by one member of staff in others by a team comprising University and external lecturers. The breakdown into subjects is given in figure 3 and a more detailed syllabus in the Appendix. The choice of subject matter is influenced by the broad range of students admitted from all branches of engineering and from many backgrounds of experience in employment. Some review of the underlying engineering science is required in order to bring everyone to a common base from which to begin looking at applications in the field of energy engineering management. Here again the interaction between students is important as graduate mechanical engineers assist their electrical or civil counterparts in an understanding of thermodynamics while the reverse applies in the electrical distribution and building materials fields.

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**Figure 3 - MSc Energy Engineering Subjects.**

**Figure 2** PATTERN OF PART-TIME AND FULL-TIME COURSES

<table>
<thead>
<tr>
<th>Year</th>
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<tbody>
<tr>
<td>OCT</td>
<td>DEC</td>
</tr>
<tr>
<td>x</td>
<td>x+1</td>
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</tbody>
</table>

10 week teaching term 1 day/week
10 week teaching term full-time
Project in industry
Project in industry or University
In addition to these separate subjects there is an 'Energy Schemes' content. This comprises a series of group case studies of typical situations encountered in energy management and an individual study in depth for the final project. In the group studies a progression is made from straightforward calculations of tightly specified problems through laboratory-based open-ended investigations to case studies based on site visits. Considerable scope for everyone to contribute is available in these sessions since the lecturer poses the problems and acts as chairman in the subsequent discussion.

The final project is of special importance in that it gives depth to an otherwise broadly-based course in one field of special interest to the student. Part-time and some full-time students will come with a fairly well-defined project title from their current or past industrial involvement. For others there are many on-going research topics in the University in the energy field into which MSc students can slot, making a specific contribution. It is also possible for a student to be allocated to an industrial concern for the investigation of a particular problem which he can do with the backing of a University supervisor. The University is always interested in having such projects suggested by industry, commerce or institutions. The wide range of projects is illustrated by some examples in figure 4.

<table>
<thead>
<tr>
<th>UNIVERSITY BASED</th>
<th>INDUSTRY BASED</th>
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<tbody>
<tr>
<td>Combustion of municipal waste</td>
<td>Estimation of plant capacity (PSA)</td>
</tr>
<tr>
<td>Infra-red-combustion control system</td>
<td>Lighting control in group space offices (PSA)</td>
</tr>
<tr>
<td>Solar energy-storage analysis</td>
<td>Energy recovery in hospital air conditioning systems (Contair)</td>
</tr>
<tr>
<td>Small scale hydro-power plant</td>
<td>Control of building energy services (IBM)</td>
</tr>
<tr>
<td>Energy use in alternative means of communication</td>
<td>Combined heat and power for frozen food plant (Birds Eye)</td>
</tr>
<tr>
<td>Lean-burn, spark-ignition automotive engine</td>
<td>Thermal performance of low thermal capacity buildings (E. Sussex C.C.)</td>
</tr>
<tr>
<td>Wind power assessment</td>
<td>Total energy requirements of private cars (AA)</td>
</tr>
<tr>
<td></td>
<td>Furnace heat exchangers</td>
</tr>
<tr>
<td></td>
<td>Energy education (Surrey C.C.)</td>
</tr>
</tbody>
</table>

Figure 4: Typical project titles

2.2.4 The background of students varies very considerably and this variation contributes greatly to the atmosphere of the group. Initially it was expected that full-time students would be young and relatively inexperienced whereas part-timers would be mature and wise in the ways of the big world. In the event the recognition of the course for TOPS award and for sponsorship by the PSA and other bodies for their employees has resulted in a more experienced full-time class. There is a difference in average age at entry - 29 years for part-time - 40 years for full-time, but the range of ages overlaps considerably. The first three intakes have demonstrated that experience in industry is necessary to get the most out of the course and only exceptionally would anyone be admitted now with only vacation experience in industry.
The gap which previously precluded most U.K. students under 27 from obtaining a grant to attend has been filled by recognition for SERC advanced course studentships. Typical sponsors are listed in figure 5.

County Councils
Manufacturers of energy equipment (boilers, air conditioning)
Building services consultants
Nationalised energy supply industries
Motoring organisations
Food processing industry
Retail food chains
Property Services Agency (government buildings)
London buying office of overseas electric power authority
Technical colleges and polytechnics
Energy consultants
Building contractors
Oil corporations
Iron and steel industry
Overseas governments

Figure 5 : Sponsors of students on MSc course

2.2.5 The question is often asked "What motivates people to join your course"? There is no simple answer since not every student will offer to express his feelings about this. There is a desire on the part of some, older, candidates to show their juniors at work that they are capable of higher academic achievement, some want a recognised energy qualification having qualified in a traditional branch of engineering in the past, some come to build into a firm structure their ideas about energy which may be too specialised, some overseas students need a higher degree to practice or teach in their own country while others in more senior positions are encouraged to broaden their outlook by studying in the U.K. for a year and are supported by their government, employer or by an award from bodies such as the British Council. It is hoped that all genuinely want a sound knowledge of the principles that will enable them, in whatever occupation they later find themselves, to promote the wiser use of all types of energy resources. Incidentally there is a great opportunity for U.K. suppliers of energy conservation equipment in the presence here of mature overseas students on such an applied technology course.

3.0 Technical Co-operation between Educational and Industrial Bodies.

It has been suggested that Universities, Polytechnics and Technical Colleges should co-operate more with those involved in energy affairs in industry, commerce, local government, and other institutions. A great deal of collaboration already exists but perhaps is not widely published. More is possible but will only come about as those who wish to work together make contacts at an individual level.
Some of the prospects are given here in the hope that such contacts will be made to explore the process appropriate to a particular need.

3.1 Universities and Colleges provide a suitable base for meetings of local Energy Managers' Groups, for short courses (either open or for employees of one organisation) and for conferences. The facilities for meetings of all sizes, audio-visual aids, catering and so on are all available and often through Bureaux of Industrial Liaison, there is good contact with all those in the district likely to be interested. For example, the University took the initiative in the formation of the Guildford Energy Managers' Group for which it provides accommodation and administrative backing and the short courses offered at South Bank Polytechnic have been described in the accompanying paper by H.A. Rudgard (3).

3.2 Advice on specialised matters within the expertise of the staff of a particular educational establishment is usually readily available to local industry. If not at the nearest University or College it is quite probable that needs could be rapidly passed on to another, more appropriate, centre since there is a general awareness of the skills of other members of the network.

Individual members of the staff undertake work for outside concerns in a variety of way. 'One-off' tests, designs, investigations, analyses can often be arranged on an ad hoc basis. Some members act as consultants to particular firms on a 'retainer' basis so that continuity is ensured. Longer term specific projects are usually the subject of a contract negotiated between the sponsor, the University and the member of staff.

In all these cases the sponsor will pay a fee and expenses to the member of staff. Where, for experimental work or other activity, University ancillary staff and materials are involved, these will be charged (with overheads) by the University.

3.3 Projects can be undertaken, under the supervision of expert staff, by full-time research students who are able to devote their whole time to the task. These projects would need to have an academic content suitable for 2 years (for M.Phil.) or 3 years (for Ph.D.) work. The student during this time is based in the University and makes use of its laboratory, computer and library facilities. The sponsor pays the student's fees, a maintenance allowance and any specific costs for equipment and technical assistance.

The SERC operates "Co-operative Awards in Science and Technology" (CASE) through which students are encouraged to participate in a project jointly set up by a University and an outside body (company, organisation, government laboratory etc.). The outside body's financial involvement is shared with the SERC in a way which is best understood by reference to the appropriate documents obtainable from the SERC.

3.4 Collaborative research is pursued by an employee working in house (under the supervision of an industrial supervisor and an appropriate University teacher) for a higher degree. He receives normal salary and the employer pays a small annual fee to the University.
3.5 Shorter, less demanding topics can be the subject of final year undergraduate and postgraduate course students' projects which last for one to three months full-time or the equivalent spread over a longer period. Again specific costs would be met by the sponsor but there are no students' fees to be met. The timescale and costs can be smaller for this approach which is preferable for projects which the sponsor has no suitably qualified employee free to undertake.

3.6 The Teaching Company is a much more formalised means of working together in which a Research Associate supported technically by the University works in an industrial concern. Especially appropriate for the introduction of new methods or processes into manufacturing industry this scheme is supported by the Department of Industry and the SERC from whom details are available (Teaching Company Directorate, SERC, P O Box 18, Swindon SN2 1ET).

3.7 Informal groupings of companies in association with an educational establishment have been initiated in some areas. For example, the Manufacturing Industries Development Association in Surrey seeks to offer small companies a readily available backing of up-to-the-minute technology in specific areas.

4.0 Conclusion

In his foreword to the Watt Committee's report on Energy Education Dr. Chesters states, "The need for closer collaboration between universities and industry has long been stressed but little appears to have been done which is effective. Those concerned with energy should know more clearly what universities, polytechnics and technical colleges have to offer and what industry seems to want ... If we are to have any chance in the energy Olympics race, we must train now and train as one rather than two or more teams".

Through presentations at conferences such as this it is hoped that those on industrial and educational fronts will seek each other out to find ways of co-operating to their mutual benefit. Since this must also be to the benefit of the nation, Government should be expected to provide the financial facilities where these are needed. Traditional support of education activities in a time of general cut-back should be supplemented by specific incentives to those meeting the national need in the task of energy conservation and the better use of our total resources. This should apply to the whole range of courses and other forms of co-operation for which the present support rules are often restrictive and rigid. This country's educational establishments represent a substantial energy resource in the potential effect of a greater spread of knowledge in making considerable reduction in the nation's energy bill.
References


APPENDIX

MSc in Energy Engineering: University of Surrey.
Course Content

Introduction to Energy Engineering
A concentrated introduction to the course designed to provide perspective for the more detailed subsequent material. It deals with the various resources of energy in the world and the means by which they are exploited.

Systems and Management Studies
This deals with the technical concepts of systems and appropriate control methods.
The rapid increasing applications of microprocessors are included.
Modelling is a central feature of this course and the various aspects of economic modelling are applied to national and company situations. Project appraisal and cost-benefit analysis are applied to energy projects.

Introduction to Energy Management
This unit is staffed by associate and visiting lecturers from industry and is concerned with the application of energy conservation measures in buildings, industrial processes, transport. It includes consideration of the human issues of involvement of employees in this activity.

Energy Utilisation I
Particular activities and equipment involving energy use are given more detailed consideration. Examples are heat exchangers, insulation, building services, and electric motors.

Energy Utilisation II
The efficient use of fossil fuels is the subject of this unit which includes combustion theory, furnace, boiler and burner design and selection.

Materials
The energy analysis of production is considered and materials compared on an energy basis.

Energy Conversion and Prime Movers
The value of thermodynamics as an analytical approach to the understanding of energy conversion is emphasised in this unit which also deals with cycles for power plant, refrigeration and air conditioning.

Energy Conversion and Distribution
As essential background to the use of electricity the principles of generation and distribution are discussed. On-site generation and total energy schemes are included.

Laboratory
Laboratory work emphasises monitoring and includes on-site measurement and control of electrical quantities, combustion parameters, temperature and fluid flow.
Continuing education in energy management

A W E Henham
This paper describes the development of a postgraduate course in the utilisation, optimisation and management of energy. The course is closely related to industry in a number of ways. About half the students are released one day a week to participate in the course over two years. Most of the rest, completing the course full time in one year, have served for many years in industry or the public sector. They are seconded from their employment and are supported by the employer or receive a grant from the government or EEC. Students come from the UK, other European countries, Asia, Africa and South America. Those from the last three continents are often given assistance by their governments, employers or by the British Council.

The course seeks to provide a background in the sources of energy and in energy conversion processes but is primarily concerned with the efficient management of energy use in private and public sectors. Project work, whenever possible, is undertaken in conjunction with the student's employer or with an industry with which the University has research or consultancy links. A few students, however, contribute to one of the ongoing energy research programmes of the University.

The paper describes the setting up of the course in conjunction with industry and emphasises the various forms of contribution made by industry to the course content, as well as that made by the course to the development of concepts of energy management in industry and the institutions. The course programme is outlined and examples of case study and project work presented.
ALEX HENHAM

Alex Henham is Course Director of the MSc. in Energy Engineering at the University of Surrey, students of which are mostly from industry or governmental bodies. After working as a research and development engineer in the aircraft industry, he joined the University where he has taught thermodynamics and energy topics to engineering, economics, home economics and general studies courses. He has given short courses in energy management in the UK and abroad.

Research interests are in the efficient use of energy resources particularly in automotive engines. He also acts as a consultant in energy utilisation in industry. He is a chartered mechanical, automobile and aeronautical engineer, a member of the I. Mech. E. Energy Committee and Chairman of the Guildford Energy Managers' Group.

He is concerned with encouraging interest in energy matters and in engineering in schools, has given lectures to VI forms and taken part in careers exhibitions, is a school governor and a Chief Examiner in A-level Engineering Science.
1.0 INTRODUCTION

Education and training in energy management may be undertaken in many different and complementary ways. This variety was outlined by the author in an earlier paper(1). Most of the provision of energy education in the U.K. revealed in a survey(2) was either at undergraduate level, usually as an option or modification of an existing science or engineering course, or as short courses aimed at postgraduate or general audiences. The latter may be better described as training rather than as education and covers the range of those involved in energy utilisation from caretakers to directors(3). Universities and similar establishments have much to contribute in the field of energy management not only in teaching but also in promoting interest in the subject and providing a back-up of advisory and research services(4). Most of the people responsible for energy matters in industry, commerce and the public services are mature engineers. In the United Kingdom there are estimated to be about 27 000 postgraduate students over 25 years of age(5) and it is largely into this 'market' that the University of Surrey moved with the introduction of its Master of Science Energy Engineering course in 1978.

2.0 INITIATION OF POSTGRADUATE COURSE

2.1 Planning

On looking into the needs for education a Future Planning Committee of the Faculty of Engineering decided to look more deeply at two specific areas, one of them Energy Engineering. After this a working party produced syllabus drafts for both undergraduate and postgraduate courses. On discussion with representative members of industrial concerns, Government departments and professional institutions it was felt that the maximum impact in the shortest time would be obtained from the postgraduate version. The reasons for this are many but the more important are: undergraduate course lead time is longer because of the unified admissions system, the course itself would be longer (four years instead of one), graduates would not have responsible or influential positions for some time after graduation and the course could not be as easily offered to those in full-time employment. Success with a Systems Engineering MSc course in the University encouraged the Faculty to consider the new course for both part-time and full-time students in parallel. This not only makes the course available to an additional number of students who would not be able to obtain full-time secondment but also increases the possibility that senior people could attend. This view has been justified by experience as
recorded in Section 4.0. These students can begin to apply the course content from their first day of attendance.

2.2 Consultation

Having made the decision to opt for the postgraduate course a brochure was produced and circulated to those outside the University thought most likely to be able to comment. Representatives of process and manufacturing industries, government departments, local authorities and the professional bodies were sent the proposals with an invitation to an afternoon consultation at the University. After an introduction to the proposal members of the working party chaired small groups of the visitors and recorded their comments and suggestions. Questionnaires for the same purpose were sent to those unable to accept the invitation.

As a result of all these reactions a final form of the course brochure was produced and circulated to external contacts which were likely to have suitable candidates. At the same time the technical and educational press was notified.

2.3 Pattern

Figure 1 shows how full-time and part-time patterns of study co-exist.

![Diagram of part-time and full-time courses]

**Figure 1.** Pattern of part-time and full-time courses.
Partly in order not to take on too large a step increase in teaching load in one year and partly to assess the requirements of the representative actual students who joined the first intake, only the part-time course was given in year 1. The second year saw the beginning of the full-time course joining the first and second part-time intakes.

3.0 COURSE CONTENT
3.1 Objectives

The course, subtitled The Utilisation, Optimisation and Management of Energy, is open to graduates of all engineering and applied physical science disciplines and to Chartered Engineers (i.e. of full professional status). It seeks to provide them with the necessary skills to tackle energy management in the real world and to give some experience of dealing with typical problems. Although the students are encouraged to work on a scale appropriate to their existing or potential employment, there is an awareness of the broader issues of world resource management of energy, money, materials and manpower.

3.2 Syllabus

The course is divided into a number of subjects, each of which constitutes a series of lectures reinforced, where appropriate, by tutorials and practical demonstrations. In some subjects all the lectures are given by one member of staff, in others by a team comprising University and external lecturers. The breakdown into subjects is:

- Introduction to Energy Engineering
- Systems and Management Studies
- Energy Utilisation I
- Energy Utilisation II
- Introduction to Energy Management
- Materials
- Energy Conversion and Prime Movers
- Laboratory
- Energy Conversion and Distribution
- Instrumentation

The choice of subject matter is influenced by the broad range of students admitted from all branches of engineering and from many backgrounds of experience in employment. Some review of the underlying engineering science is required in order to bring everyone to a common base from which to begin looking at applications in the field of energy engineering management. Here again the interaction between students is important as graduate mechanical engineers assist their electrical or civil counterparts in an understanding of thermodynamics while the reverse applies in the electrical distribution and building materials fields.
In addition to these separate subjects there is an 'Energy Schemes' content. This comprises a series of group case studies of typical situations encountered in energy management and an individual study in depth for the final project. In the group studies a progression is made from straightforward calculations of tightly specified problems through laboratory-based open-ended investigations to case studies based on site visits. Considerable scope for everyone to contribute is available in these sessions since the lecturer poses the problems and acts as chairman in the subsequent discussion.

3.2.1 Projects

The wide range of projects is illustrated by some examples in Figure 2.

<table>
<thead>
<tr>
<th>University-based</th>
<th>&quot;Industry-based&quot;</th>
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</thead>
<tbody>
<tr>
<td>Combustion of municipal waste</td>
<td>Rotary heat exchanger matrix (CEGB)</td>
</tr>
<tr>
<td>Infra-red combustion control</td>
<td>Energy recovery in hospital air-</td>
</tr>
<tr>
<td>Combustion in rotary cement kilns</td>
<td>conditioning (Contair)</td>
</tr>
<tr>
<td>Energy applications of flowmeters</td>
<td>Thermal performance of low thermal</td>
</tr>
<tr>
<td>Electric motor control system</td>
<td>inertia Buildings (E Sussex C C)</td>
</tr>
<tr>
<td>Wind turbines</td>
<td>Computer control of building energy</td>
</tr>
<tr>
<td>Solar energy storage</td>
<td>services (IBM)</td>
</tr>
<tr>
<td>Small-scale hydro plant for Sri Lanka</td>
<td>Lighting control in offices (PSA)</td>
</tr>
<tr>
<td>Fuel economy in passenger cars</td>
<td>Energy considerations of school</td>
</tr>
<tr>
<td>Lean-burn spark-ignition engine</td>
<td>(Essex C C)</td>
</tr>
<tr>
<td>Energy costs of electric vehicles</td>
<td>Combined heat and power for freezing</td>
</tr>
<tr>
<td>Energy comparison of communication methods</td>
<td>plant (Birds Eye - Walls)</td>
</tr>
<tr>
<td>Energy policy studies for Turkey and for Cyprus</td>
<td>Energy utilisation at Slough College</td>
</tr>
</tbody>
</table>

Figure 2. Some typical projects.

The final project is of special importance in that it gives depth to an otherwise broadly-based course in one field of special interest to the student. Part-time and some full-time students will come with a fairly well-defined project title from their current or past industrial
involvement. For others there are many on-going research topics in the University in the energy field into which MSc students can slot, making a specific contribution. It is also possible for a student to be allocated to an industrial concern for the investigation of a particular problem which he can do with the backing of a University supervisor.

4.0 EXPERIENCE

The background of students varies very considerably and this variation contributes greatly to the atmosphere of the group. Initially it was expected that full-time students would be young and relatively inexperienced whereas part-timers would be mature and wise in the ways of the big world. In the event the recognition of the course for awards for UK and overseas students and for sponsorship for employees has resulted in a more experienced full-time class. There is a difference in average age at entry - 43 years for part-time, 32 years for full-time, but the range of ages overlaps considerably. The first three intakes have demonstrated that experience in industry is necessary to get the most out of the course, and this is now a course requirement.

To give an indication of the type of group such a programme produces the present full-time intake includes a former small company development engineer, an ex scientific civil servant, an RN Commander on secondment, a young environmental engineering graduate with building services experience, a refinery engineer from Malaysia, a senior Government energy official from Pakistan and lecturers from Cyprus and Brazil. Part-timers are from a hospital, a London borough, a county council, a large building firm, a large food retail chain, two consultancies, British Gas, British Rail and the Property Services Agency. Although each student presents a seminar on an energy topic of his choice, informal opportunities to share this wide range of experience occur each time the course meets.

So far most of the initiative to attend the course has come from the students themselves. Many employers will, even if under pressure, allow an enthusiastic member of staff to join the course but few will suggest it. Possibly this is right as only strong personal motivation sees someone through an advanced course after an absence from study - especially part-time. For those who come as full-time students without affiliation there is no shortage of offers of appointment at the end of the course. At a time when fees for overseas students have increased considerably it is worth noting that the number of applicants from other countries is increasing and so far students from 15 overseas countries have been enrolled.
5.0 OUTREACH
Surrey's involvement in continuing education in energy management has not been confined to those who have enrolled on this course. Specific connections with companies are maintained by members of the academic staff for consultancy and contract research work, sometimes involving research students as well. The results of this and other work are made more widely available through contributions to technical literature and conferences. As another example, in-house courses have been provided for a large industrial group so that practising energy managers can be given guidance in the first stages of a corporate energy management programme. All these activities feed back the live concerns of industry into lectures and case study material. A recent development has been arranged with the help of one of our graduates who set up a short course for industry in Portugal conducted by Surrey with a local university input. Lastly in this category mention should be made of the Guildford Energy Managers' Group set up at the initiative of the author in conjunction with the Government's Regional Energy Conservation Officer and based at the University. Students are welcome to attend the meetings where they meet local energy managers and have the opportunity of discussing the current concerns of their companies or institutions. This helps those without existing employment to be aware of the opportunities and challenges of some of the various types of work open to them on graduation.

6.0 CONCLUSION
The course appears to have met a real need among practising engineers for continuing education in this field. The proportion, among those enrolling, of experienced engineers seeking midcareer educational opportunities has been much higher than those who conceived the course imagined and the contribution made by these students to the University has been appreciable.

REFERENCES
Postgraduate education in energy management

A W E Henham
SUMMARY

This paper describes the development of a postgraduate course in the utilization, optimisation and management of energy. The course is closely related to industry in a number of ways. About half the students are released one day a week to participate in the course over two years. Most of the rest, completing the course full time in one year, have served for many years in industry or the public sector. UK students are mostly seconded from their employment and supported by the employer or receive a grant from the government or EEC. Students from other European countries, Asia, Africa and South America are often given assistance by their governments, employers or by the British Council (for certain countries only) or other agency.

The course seeks to provide a background in the sources of energy and in energy conversion processes but is primarily concerned with the efficient management of energy use in private and public sectors. Project work, whenever possible, is undertaken in conjunction with the student's employer or with an industry with which the University has research or consultancy links. A few students, however, contribute to one of the on-going energy research programmes of the University.

The paper describes the setting up and subsequent development of the course in conjunction with industry and emphasises the various forms of contribution made by industry to the course content, as well as that made by the course to the application of concepts of energy management in industry and the institutions. The course programme is outlined and examples of case study and project work presented.
1.0 INTRODUCTION

Education and training in energy management may be undertaken in many different and complementary ways. This variety was outlined by the author in an earlier paper(1). Most of the provision of energy education in the U.K. revealed in a survey in 1980(2) was either at undergraduate level, usually as an option or modification of an existing science or engineering course, or a short course aimed at postgraduate or general audiences. The latter may be better described as training rather than as education and covers the range of those involved in energy utilization from caretakers to directors(3). Universities and similar establishments have much to contribute in the field of energy management not only in teaching but also in promoting interest in the subject and providing a back-up of advisory and research services(4). Most of the people responsible for energy matters in industry, commerce and the public services are mature engineers. In the United Kingdom there are estimated to be about 27,000 postgraduate students over 25 years of age(5) and it is largely into this 'market' that the University of Surrey moved with the introduction of its Master of Science Energy Engineering course in 1978.

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recorded in Section 4.0. These students can begin to apply the course content from their first day of attendance. This does not imply that others are not right in providing other levels and lengths of course, but for Surrey, at that time it still seems that the right decision was made.

2.2 Consultation
Having made the decision to opt for the postgraduate course a brochure was produced and circulated to those outside the University thought most likely to be able to comment. Representatives of process and manufacturing industries, government departments, local authorities and the professional bodies were sent the proposals with an invitation to an afternoon consultation at the University. After an introduction to the proposal, members of the working party chaired small groups of the visitors and recorded their comments and suggestions. Questionnaires for the same purpose were sent to those unable to accept the invitation.

As a result of all these reactions a final form of the course brochure was produced and circulated to external contacts which were likely to have suitable candidates. At the same time the technical and educational press was notified.

2.3 Pattern
Figure 1 shows how full-time and part-time patterns of study co-exist.

Figure 1. Pattern of part-time and full-time courses.
Partly in order not to take on too large a step increase in teaching load in one year and partly to assess the requirements of the representative actual students who joined the first intake, only the part-time course was given in year 1. The second year saw the beginning of the full-time course joining the first and second part-time intakes and broadening the range of potential students able to apply.

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The course is divided into a number of subjects, each of which constitutes a series of lectures reinforced, where appropriate, by tutorials and practical demonstrations. In some subjects all the lectures are given by one member of staff, in others by a team comprising University and external lecturers. The breakdown into subjects is:

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The choice of subject matter is influenced by the broad range of students admitted from all branches of engineering and from many backgrounds of experience in employment. Some review of the underlying engineering science is required in order to bring everyone to a common base from which to begin looking at applications in the field of energy engineering management. Here again the interaction between students is important as graduate mechanical engineers assist their electrical or civil counterparts.
in an understanding of thermodynamics while the reverse applies in the electrical distribution and building materials fields.

3.2.1 Energy Schemes
Taking a wider view than individual subjects, while drawing on their content, is an Energy Schemes component. This comprises a series of group case studies of typical situations encountered in energy management and an individual study in depth for the final project. In the group studies a progression is made from straightforward calculations of tightly specified problems through laboratory-based open-ended investigations to case studies based on site visits. Considerable scope for everyone to contribute is available in these sessions since the lecturer poses the problems and acts as chairman in the subsequent discussion.

3.2.2 Laboratory
The laboratory work is not an extension of undergraduate type set-piece experiments. Rather there is a specific intention to examine techniques of broad application in energy management. A two-day concentrated laboratory course on instrumentation is held in the Easter vacation. In the same week a two day "hands-on" microprocessor course is held in the Department of Mechanical Engineering's multi-station teaching laboratory, familiarising students with the working principles and programming of microprocessors. Teaching back-up in the form of preparatory courses is given during the second term in measurement and computing science.

3.2.3 Projects
The wide range of projects is illustrated by some examples in Figures 2 + 3.

Table 1 - University Based

<table>
<thead>
<tr>
<th>Electric motor control system</th>
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<tr>
<td>Horizontal axis wind turbine</td>
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<td>Solar energy and storage system</td>
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<tr>
<td>Small scale hydro-electric plant for Sri Lanka</td>
</tr>
<tr>
<td>Fuel policy for Turkey  Fuel policy for Malaysia  Fuel policy for Cyprus</td>
</tr>
<tr>
<td>Rotary cement kilns</td>
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<td>Combustion of municipal waste</td>
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<tr>
<td>Combustion of refuse derived fuels</td>
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<tr>
<td>Infra-red combustion control system</td>
</tr>
<tr>
<td>Combustion of heavy fuel oil</td>
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</tbody>
</table>
Energy applications for flow metering
Domestic oil-fired boilers
Performance of building control system in University
Energy recovery from ventilation systems in University
Communication: comparison of energy costs in moving and non-moving methods
Energy costs of electric vehicles
Fuel economy in private cars
High-compression, lean-burn, spark-ignition engine
Educational implications of energy
Energy audit documentation

Table 2 - Some typical 'Industry Based' projects
Estimation of plant capacity for building heating (PSA)
Computer control of building energy services (IBM)
Services design for new building (consultancy)
Low energy design for office block structure and services (Tuckey Ford)
Thermal performance of low thermal inertia buildings (East Sussex CC)
Thermal characteristics of intermittently-heated buildings
   (London Electricity Board)
Influence of thermal mass on energy requirements (Wimpey Laboratories)
Hotwater supply in commercial buildings (British Gas)
Performance of heating controls (PSA)
Lighting control in group space office (PSA)
Energy utilization at Slough College (Berkshire CC)
Energy recovery in hospital air-conditioning systems (Contair Ltd)
Energy survey on industrial site (Revlon Health Care (UK) Ltd)
Energy considerations of school buildings (Essex CC)
Energy use at Gatwick Airport (British Airports Authority)
Energy study of civic centre (London Borough of Hillingdon)
Study of hot water system for rebuilt hospital
   (SW Surrey Health District)
Energy survey of hospital (NW Surrey Health District)
Hospital energy utilization (Kingston & Esher Health Authority)
Energy use in liquid storage terminal (Unitank Storage Co Ltd)
Electric power use in a process plant (James Walker & Co Ltd)
Combined heat and power plant assessment (PSA)
Performance of large chiller plant
   (Royal Borough of Kensington & Chelsea)
Domestic heat pump with storage (PCL)
Performance of corrugated plates as rotary heat exchanger matrix (CEGB)
Total energy requirement of private cars (AA)
Energy sources for Pakistan
(Pakistan Ministry of Petroleum and Natural Resources)

The final project is of special importance in that it gives depth to an otherwise broadly-based course in one field of special interest to the student. Part-time and some full-time students will come with a fairly well-defined project title from their current or past industrial involvement. For others there are many on-going research topics in the University in the energy field into which MSc students can slot, making a specific contribution. It is also possible for a student to be allocated to an industrial concern for the investigation of a particular problem which he can do with the backing of a University supervisor. This is especially useful for those with limited experience of energy-related work in industry or the public sector.

4.0 EXPERIENCE
The background of students varies very considerably and this variation contributes greatly to the atmosphere of the group. Initially it was expected that full-time students would be young and relatively inexperienced whereas part-timers would be mature and wise in the ways of the big world. In the event the recognition of the course for awards for UK and overseas students and for sponsorship for employees has resulted in a more experienced full-time class. There is a difference in average age at entry - 38 years for part-time, 32 years for full-time, but the range of ages overlaps considerably. The first intakes demonstrated that experience in industry is necessary to get the most out of the course, and this is now a course requirement. Indeed experience is taken into account balancing academic achievement when considering candidates. Those with a broad experience of industry over a long period will be considered at the minimum level of qualification required for Chartered Engineer status, while recent graduates with the minimum of time in industry (usually a year) are required to have at least a degree with second class honours, lower division.

4.1 Student background
The spread of former and current employment is very wide indeed compared
with that for entrants to traditional MSc courses. Full time students have come from 15 overseas countries and this has been during the period when the fees were greatly increased for non-EEC members. Overseas students have included, for example, an industrial manager from a Brazilian ceramics factory, an Iraqi oil company control engineer, a Turkish chemical plant engineer, a Malaysian refinery engineer, a Nigerian electric power engineering director, officials of the Ministry of Petroleum and Natural Resources in Pakistan, a building services engineer from Hong Kong and lecturers from Brazil, Cyprus, Malaysia and the People's Republic of China.

UK full-time and part-time students have come from a wide range of employers as heavy and light industry, building and construction companies, consultancies, food companies, local government, hospitals, colleges and polytechnics, the armed services, the Property Services Agency, gas and electricity boards.

Opportunities are provided for students to share this experience formally by giving a seminar to their fellow students and any others who wish to attend. Informally they communicate with other members of the course and so are drawing on their background all the time for the benefit of the whole group.

4.2 Initiative

So far most of the initiative to attend the course has come from the students themselves. Many employers will, even if under pressure, allow an enthusiastic member of staff to join the course but few will suggest it. Possibly this is right as only strong personal motivation sees someone through an advanced course after an absence from study - especially part-time. For those who come as full-time students without affiliation there is no shortage of offers of appointment at the end of the course.

5.0 OUTREACH

Surrey's involvement in continuing education in energy management has not been confined to those who have enrolled on this course. Specific connections with companies are maintained by members of the academic staff for consultancy and contract research work, sometimes involving research students as well. The results of this and other work are made more widely available through contributions to technical literature and conferences. As another example, in-house courses have been provided for a large
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5.1 Engineering and Economics
In addition to the engineering involvement with the energy scene Surrey is very active in Energy Economics through the work of its Economics Department with its Surrey Energy Economics Centre. A parallel course provides studies for an MSc in Energy Economics and the two course teams contribute to the teaching of both courses. The interaction of these two interests on one campus is a broadening influence in understanding energy problems.

6.0 CONCLUSION
The course appears to have met a real need among practising engineers for continuing education in this field. The proportion, among those enrolling, of experienced engineers seeking mid-career educational opportunities has been much higher than those who conceived the course imagined and the contribution made by these students to the University has been appreciable.
REFERENCES


University-industry co-operation in postgraduate energy studies

A W E Henham
SUMMARY

From the planning stages onwards industry has been involved in the University of Surrey MSc Course in Energy Engineering. Part-time and some full-time students have been released and/or sponsored by their employers, who also allow them to pursue dissertation projects in conjunction with their employment.

Other industrial inputs include facilities for case study visits, literature on products and processes, visiting lecturers and provision of projects for University-based students. Industry and public sector establishments draw on the University for consulting work, energy surveys and contract research. The University provides the administration and a meeting place for the local Energy Management Group meeting the needs of those responsible for the efficient use of energy in industry, commerce hospitals and local government buildings. Many concerns participate in a number of these forms of co-operation.
1.0 INTRODUCTION

The Energy Engineering activity at the University of Surrey is based upon a Master of Science course. This is a taught course, including an individual study, lasting one calendar year full-time or two years part-time. The course initiated in 1978 has been described and its philosophy outlined elsewhere (Henham 1983, 1984). For the present purpose the important points are that the course was designed to meet the perceived needs of industry and the public sector both in the UK and overseas. The intention was that graduates of various engineering and applied science disciplines would be accepted and that experience in the applications of their subjects would have been obtained before entry. The proposals for the course were circulated to contacts in industry, government and professional institutions who were invited to come to the University and discuss these with the course team. So a foundation of industrial co-operation was laid before the first student registered. The post experience nature of the proposal has been justified by the applications received. Cambel and Madden (1985) draw attention to the short lifespan of content of engineering courses and this would seem to support the need for this pattern of mid-service education whether full or part-time.

2.0 SOURCES OF STUDENTS

2.1 Part-time students.

When the course opened the first intake was entirely of part-time students and, although energy managers and potential energy managers were the target group, the spread of job titles was wide. This has been the case for part-time students ever since. Some of these are listed in Table 1.
Chief Engineer, National Motoring Organisation.
Refrigeration Engineer, Frozen Food Processing Company.
Lecturers, Polytechnics and Technical Colleges.
Research Engineer, British Gas
Technical Consultancy Service Engineer, British Gas
Planning Engineer, British Gas
Sales Engineer, British Gas
Building Services Engineer, University
Technical Director, Heating & Ventilating Equipment Manufacturer.
Managing Director, Heating & Ventilating Consultancy.
Energy Conservation Engineers, Borough and County Councils
Group Energy Co-ordinator, Group of Timber Companies.
London Representative, Overseas Electricity Authority.
Building Management Engineer, Food Retailing Company.
Engineer Officer, Royal Navy
Regional Engineer, Government Department.
Regional Energy Conservation Officer, Government Department.
Hospital Engineer, Area Health Authority
Engineer, Regional Electricity Board.
Partners, Building Services Consultancies.
Engineer, Energy Management Company

TABLE 1. Part-time Students — Posts held in employment

Students from this wide range of backgrounds make an effective contribution to the course by sharing their varied experience with each other. In general employers pay fees (set at a modest level to encourage this type of involvement with the University) and, sometimes, provide travelling expenses.

2.2 Full-time Students

In the following year the course expanded to admit full-time students. There are various means by which these students are enabled to spend 12 months in full time education and these to some extent determine the sources from which graduates enter the course.

Young graduates coming straight from first degree courses, but having some industrial experience already, are able to receive fees and a small maintenance allowance through the Science and Engineering Research Council's Advanced Course Studentships. In general they do this because they are well qualified in one engineering or applied science discipline but wish to have a broader base of all the disciplines involved in Energy
Engineering. Consequently these students develop aptitudes which are appropriate to specific industrial needs. Older candidates, wanting to qualify for career development opportunities or finding their existing position is not leading to the type of work they would like, can apply for another government grant from the Training Opportunities Scheme (TOPS) of the Manpower Services Commission. This is especially appropriate for those working in declining industries although one of these, European Iron and Steel, has its own scheme for financing 'retaining' which has sponsored two members of the course so far. Secondment from employment full time is rather unusual as the costs of full salary plus fees and expenses are considerable but the public sector does offer this in special cases.

Overseas students from full-time employment are much more often seconded since the part-time alternative is obviously not available to them. Most, but not all, of these are also from the public sector which covers a wide range of activities in many countries from government energy departments to petroleum corporations.

Their employers often nominate these students for awards from their own governments, from regional trusts and from the British Council. Those coming from overseas are often from central decision-making bodies and will return to influential positions in them. Table 2 shows some of the overseas organisations from which students have joined the course. As for the UK they include higher education establishments.
Brazilian Ministry of Education (Pontifical University of Rio de Janeiro)
Cyprus Higher Technical Institute
Industria de Azulejos (Brazilian Ceramics Company)
Iraqi State Organisation for Oil Projects
Malaysian Ministry of Education (Universiti Teknologi Malaysia)
Anglo African Industries (Malawi)
National Electric Power Authority of Nigeria
Pakistan Ministry of Petroleum and Natural Resources
Sudan Ministry of Irrigation and Hydro-Electric Power
Directorate of Energy Conversion and Conservation, Indonesia
Sriwijaya University, Indonesia
MEI Project Engineering (Singapore Building Services Company)
Institute of Hydroresources and Electrification, Panama
Various universities of People's Republic of China
(through Commission of European Committees)
Ceylon Petroleum Company (Sri Lanka)
HMT Consort (HK) Ltd (Hong Hong Building Services Company)
Soares de Almeida & Ca (Portuguese Building Services Company)

TABLE 2. Full-time students — Overseas organisations from which students have been released to attend the course

3.0 COURSE CONTENT

Decisions about the course content were made after close consultation with industry and development of the content derives from the many forms of contact with industry discussed elsewhere in this paper.

3.1 Lecturers from Industry

An important part is played by visitors from industry who give one or two lectures each year and by associate lecturers who come in to give a series of lectures and who will also set and mark examination questions on their sections of the course. This participation ensures that up-to-date issues are presented, contemporary examples of practice and equipment included and that students have opportunities of discussion with people involved in the everyday realities of industrial life. As well as a cross-section of
industries these visiting lecturers represent a range of professional activities

architects, consultants, building services engineers
control engineers, planners, economists, fuel and combustion technologists, civil engineers, designers,
research workers and, of course, energy managers.

Industry has cooperated readily in this part of the programme and only very rarely does a company or government body refuse to allow a member of its staff to undertake this task in his or her working time. One would expect this in the case of organisations supplying forms of energy or energy equipment but it is equally true of those who have successfully initiated programmes of efficiency in energy utilization. A further contact with industry has been made by opening these special lectures to anyone from local industry who would like to attend by listing in the University's widely distributed list of events open to the public.

3.2 Seminars
Students each give a seminar during their course and these are most often based upon their experience in industry. By this means they share with each other, formally, the benefits of their varied backgrounds and the teaching staff gain an insight into these too. Many of the situations described are unfamiliar to their fellow students, especially where industries such as tea production, sugar cane processing or rubber growing are peculiar to certain limited regions of the world.
3.3 Energy Schemes

As well as the distinct academic subjects in the course, mainly dealt with by lectures, tutorials and private study, there is a series of case studies grouped under the title Energy Schemes. Starting with quite straightforward pencil and paper exercises to give confidence in manipulating data, the series progresses to practical situations. Some of these are based upon work undertaken for industry and described to the students. Visits to industrial sites are included so that real situations, for which sufficient data is available, can be assessed.

FIGURE 1. Case study visit: Sankey diagram for diesel-engined combined heat and power plant.

Several companies and one government establishment have made facilities available for this type of visit by supplying information and providing staff to act as guides and to answer questions. Figure 1 illustrates the energy flows in one plant visited.
4.0 PROJECTS

As in other UK taught courses for Masters' degrees, students are required to present a dissertation on an individual study. Topics for this can arise in various ways. Traditionally they are suggested by academics involved in the course who have suitable subjects within their research programme for the timescale available - the equivalent of about three months full-time work. Those which are appropriate to the theme of this conference, however, are related to industry and take two main forms.

4.1 Projects arising from students' employment.

Where a student attends part-time he has a very limited time available while on the University Campus to pursue his project. He has to use this to consult his academic supervisor so that the work is almost entirely conducted as part of his everyday position. Selection of a suitable topic depends very much on the current loading of the employer's programme but this has not been difficult to arrange. The student is encouraged to establish the project title early in his 2-year course so that he can collect data, carry out analyses and discuss fully with his supervisor over a longer period than if he were full time at the University. Although he would be engaged on the task for the benefit of his employer the analysis and assessment would be framed to meet the requirements for the dissertation.

One example of a part-time student's project shows how broad the scope can be compared with one confined to the University. As Chief Engineer of a national motoring organisation, data on every one of its 1800 roadside service vehicles was available. This enabled a detailed study to be made of the fuel consumption of statistically large samples of identical vehicles.
used in the differing conditions prevailing in the regions. Further studies were made on fuel consumption of a wide range of vehicles tested annually under different driving conditions and on energy requirements for car manufacture in the many countries in Europe (East and West), USA, Japan and SE Asia visited by the student in the course of his work. This has formed the basis of presentations to conferences and publications (e.g. Henham and Jacobson 1983 and Jacobson 1981).

![Graph](https://example.com/graph.png)

**FIGURE 2. Comparison of fuel consumption in private cars**

Full-time students seconded from industry in the UK will also carry out a project of specific interest to the employer, usually based on work in which the student had been involved before joining the course. He will normally return to his employer at various times during the year to continue liaison on this work. Although overseas students would have the University's support in similar arrangements, it is in practice much less likely to be possible to maintain the contact. They are still encouraged to choose projects of direct relevance to their employers' interests, or, at least, to their home countries' energy situations.
Confidentiality of projects can be arranged, usually for an agreed period, so that the dissertation is not available on open shelving in the library. Typical projects on this basis are listed in Table 3.

New plant design for building complex (City University)
Reduction in building temperature gradients (Colt International Ltd.)
Analysis of energy use in Airways complex (British Airways)
Analysis of energy use in Airways training centre (ITK Energen Ltd)
Energy saving in district heating system (Isherwood, Boyd & Atkinson)
Refrigeration systems study (Darace Ltd)
Estimation of plant capacity for building heating (PSA)
Services design for new building (consultancy)
Low energy design for office block structure and services (Tuckey Ford)
Thermal performance of low thermal inertia buildings (East Sussex CC)
Thermal characteristics of intermittently-heated buildings (London Electricity Board)
Influence of thermal mass on energy requirements (Wimpey Laboratories)
Hotwater supply in commercial buildings (British Gas)
Performance of heating controls (PSA)
Lighting control in group space offices (PSA)
Energy utilization at Slough College (Berkshire CC)
Energy recovery in hospital air-conditioning systems (Contair Ltd)
Energy considerations of school buildings (Essex CC)
Energy study of civic centre (London Borough of Hillingdon)
Energy use in liquid storage terminal (Unitank Storage Co Ltd)
Combined heat and power for freezing plant (Birds Eye Walls Ltd)
Combined heat and power plant assessment (PSA)
Performance of large chiller plant (Royal Borough of Kensington & Chelsea)
Total energy requirement of private cars (AA)
Energy sources for Pakistan (Pakistan Ministry of Petroleum and Natural Resources)
Development of Group Energy Monitoring System (Harrison & Crosfield PLC)
Energy Analysis of Community Centre (CHP Energy Systems Ltd)

TABLE 3. Typical employment-based projects

4.2 Industrial projects for University-based students.

Often students with no specific affiliation will opt to undertake a project in conjunction with industry. These projects will sometimes be the result
of enquiries from industry and the public sector, also items forming part of a longer-term contract or consultancy undertaken by academics.

Additionally certain local concerns have been contacted to arrange an attachment to satisfy a particular interest shown by a student. Naturally these arise where a co-operative relationship already exists between the external organisation and a member of the course staff. Some examples of this type of project are given in Table 4. As there are many mature students the company often obtains considerable expertise at relatively small cost.

- Computer control of building energy services (IBM)
- Energy use at Gatwick Airport (British Airports Authority)
- Study of hot water system for rebuilt hospital (SW Surrey Health District)
- Electric power use in a process plant (James Walker & Co.Ltd)
- Domestic heat pump with storage (PCL)
- Performance of corrugated plates as rotary heat exchanger matrix (CEGB)
- Control of large industrial oven (Gates Energy Products)
- Control strategy for frozen food refrigeration (Birds Eye Walls Ltd.)
- CHP feasibility study for hospital (SW Surrey Health District)
- Energy survey of industrial site (Revlon Health Care (UK) Ltd)

**TABLE 4. Examples of industrial projects carried out by University-based students.**

To expand one of the topics in this list a student undertook a complete survey of energy use in a pharmaceuticals plant. Although its energy manager was a qualified engineer he had another mainstream management position to fulfil and had not sufficient time to spend on a full survey. Only the total incoming energy (in the form of gas and electricity) was metered and no knowledge of the ultimate use had been established. As a result of the survey the major uses of energy were listed with estimates of annual use and diagrams produced showing proportions for various purposes (Figure 3).
FIGURE 3. Flow chart and pie charts showing energy use in a pharmaceutical factory.

Equipment for such a survey is held by the University and is available for short-term use on the sites of these projects. This includes a flue gas analyser, a clamp-on ammeter, thermometers for various specialised applications, a humidity meter, an air flow meter and a computer-readable recording device.

5.0 CONTRACTS AND CONSULTANCY

5.1 Contracts

Naturally members of the academic staff have specialisations on which they undertake research contracts for industrial organisations as well as those arising from government sponsored bodies such as the Science and Engineering Research Council. In most cases the contract is placed with the University with a named principal investigator and may involve the employment of a research assistant and the use of the facilities of the University. These contracts are relatively long term - as a rule from one to three years. Co-operative schemes between industry and the research councils encourage closer links with industrial needs.
5.2 Consultancy

Other shorter term projects arise on which a much quicker solution is required and depending upon existing knowledge rather than newly-researched areas. In such cases staff will act as consultants for the time required visiting the industrial situation and working partly there and partly on their own.

An example of this is the energy conservation programme for a large printing and publishing organisation. Plants were visited and surveyed to produce energy audits. Priorities for action were drawn up as opportunities for energy efficient measures were identified. Thermodynamic analysis of plant was conducted to determine heat recovery prospects from various processes. Throughout contact was maintained, not only with the Group Director responsible for energy, but with the Energy Manager at each of the many plants throughout the country. Seminars were arranged to help these corporation employees to fulfil the requirements of their new posts.

One example to illustrate this consultancy is the analysis of a solvent recovery plant as a result of which insulation and heat recovery were recommended and installed (Figure 4).

In this category also comes the Department of Energy's Survey Scheme by which a client can recover half the cost of a survey of his energy use. Recently one such survey led to the detailed examination of a very energy-intensive process by an MSc student with the result that errors in the original equipment were detected and a control strategy proposed.
5.3 Research Students in industry

The University has a scheme whereby a candidate can pursue studies for a higher degree while continuing his regular employment. His project has to be of a suitable standard to enable an academic thesis to result and his employer has to agree to make time available for the relationship with the University to be maintained. Additionally there must be a supervisor within the organisation to share with the academic supervisor in controlling and assessing the work. Such collaborative schemes build further bridges between industry and the University.

FIGURE 4. Solvent recovery plant
6.0 COMMUNITY LINKS

The university is well placed to provide a meeting placed to publicise the efficient utilization of energy in the local community.

6.1 Energy Management Group

A Guildford Energy Management Group was set up at a time when there were few such groups in the UK and it continues to meet regularly on the Campus with the Course Director as its Chairman. Members from a wide variety of industry, commerce, local authorities, hospitals and the energy industries meet and discuss matters of mutual interest and hear specialist speakers. During their course MSc students are encouraged to sit in on these events and this gives them another insight into the energy manager's role and an opportunity to meet others working in this area. In Industry Year '86 Energy will be featured in one of the displays for an open day to which the local community is invited.

6.2 Local organisations

Co-operation with local schools has included exhibitions, conferences and lectures on general studies courses. Talks on energy efficiency have been given to the local Managing Directors' Club, Productivity Association and Personnel Managers' Group.

6.3 Research Park

A recent development is the University Research Park which houses a number of industrial research organisations in large and small units on part of the Campus. Energy projects under investigation or proposals being
considered are referred to academic staff for advice and, if pursued, more continuous assistance through the Surrey Network for Industrial Collaboration (SUNET).

7.0 EMPLOYMENT

The last link in the chain of university co-operation with the industrial world is that of employment of graduates. Apart from the central careers service operated by the University, the close relationships established by the various means described in this paper enable prospective employers to enquire directly about their possibility of filling vacancies from the graduating group. The only problem here is that the number of graduates not already committed to an employer is far too small for the jobs available.

8.0 ALUMNI

An important contact with industry is through past students of the course. It is, after all, one method by which staff can know whether the course is relevant to present day requirements. To encourage this graduates are sent an annual newsletter about the course, staff, past and present students, and special events. A directory listing all past students with home address, telephone numbers, jobs and employers is circulated with this. By sending or telephoning in their updated information past students make personal contact with staff.

There is known to be professional contact maintained between many of the former students who can also meet once a year at an annual dinner at Guildford for past and present students and staff.
9.0 CONCLUSION

While many university courses, especially for undergraduates where industrial training is an integral part, have good liaison with industry in this course it is seen as essential to its existence.

REFERENCES


Lessons from experience in energy management courses

A W E Henham & R A Johns

Summary
The authors' experience in organising and participating in the teaching of energy management courses extends over more than ten years. The courses involved have ranged from a full one year leading to the Master of Science degree in Energy Engineering to one day on a specialised topic. Courses have been held at the University, in house for company and public sector clients and at a centre abroad for industrial participants in that country.

The technical aspects of energy utilization leading to greater plant efficiency and to reductions in building energy demands are, of course, fundamentally important. Experience of situations from which many short course participants come shows, however, that motivation and the raising of staff awareness are key issues in the achievement of success. The establishment of a successful energy management programme depends upon the right attitude at all levels in the organisation from the boardroom to the shopfloor.

Methods of encouraging this attitude through the content of short courses are discussed. There is an emphasis in this content upon active participation by all those attending and upon the communication of recommendations. The latter includes making a case for investment on one hand and encouragement of operatives to employ efficient working practices on the other.

Introduction
Over the period since the early seventies interest in energy efficiency has been closely linked with the price of crude oil programmes which were initiated by Government and its encouragement of voluntary and independent action were designed to raise the consciousness of industry and other consumers concerning energy efficiency. University courses in engineering have always been concerned
with the efficient use of energy in its various forms. In Mechanical Engineering courses this has been made explicit in studies in Applied Thermodynamics with its analysis of power plant, steam generation, air compressors, refrigeration and air conditioning systems. Electrical Engineering courses have included topics concerned with generation, distribution, motors, transformers, power factor correction, etc. Chemical and Process engineering courses have usually involved a study of fuels and combustion as well as the optimisation of processes. Since in this field one process can consume large amounts of energy, this component is always an essential consideration.

**Energy Engineering as a Postgraduate Study.**

The University of Surrey offered a Master's degree in Energy Engineering from 1978. The philosophy at that time was to cut across the traditional single discipline courses at undergraduate level which were often further narrowed at postgraduate level by taking one topic and exploring this at great depth. In place of this a broadening course was offered enabling entrants from all the fields of engineering to pursue a common interest in energy although starting from different viewpoints. Economic, environmental, political and human factors were considered when the course was established. A list of subjects covered is given in table 1 and a fuller description of the structure and philosophy is to be found in references 1 to 5.

This course has always been arranged in conjunction with local and national industry. This has been achieved through visiting lecturers from industry, course material provided by industry, site visits and industry-based student projects. In addition, since the course is also available part-time, there is continuous contact between all students and engineers working in industrial energy management. Also most full-time students have had extensive industrial experience before enrolling and so the sharing of these varied backgrounds between course members contributes to their understanding of the wide range of energy engineering applications.

Academic staff from four departments in the Faculty of Engineering - Chemical & Process, Civil, Electronic and Electrical and Mechanical - as well as from the Department of Economics are involved in the course. Many of these staff members are engaged in consultancy or contract research for industry and the public sector.
and in supervising projects arranged collaboratively with industry. The University of Surrey has for many years acted as the base for the Guildford Energy Management Group. All these contacts serve to keep the academics in touch with the reality of industrial energy utilization (6).

| Resources and Energy Engineering |
| Energy Management               |
| Economics and Management Studies|
| Energy Utilization I (Energy in Building and Processes, Electrical Energy) |
| Energy Utilization II (Direct use of fuels) |
| Systems Engineering            |
| Energy Conversion and Prime Movers|
| Heat Transfer                  |
| Energy Conversion and Distribution|
| Energy Schemes (case studies)   |
| Seminars                       |
| Visits                         |
| Laboratory                     |
| Site Investigations            |
| Individual Project.            |

Table 1. Subjects of University of Surrey Postgraduate Course in Energy Engineering.

In-Service Training of Energy Managers.
Soon after the beginning of the postgraduate course described above a demand appeared for the provision of short courses. The special needs of small groups of industrial energy managers have been met by purpose-built courses rather than by off-the-peg selections of more general material. The latter type is especially appropriate for a first taste of what energy management is about or for an isolated energy manager whose company would not find it possible to arrange more specific training. In-house courses have the great advantage of being focussed on the special needs of one company or of the companies in one group. Where co-
operation between companies in one industry exists this can also be a means of providing a course aimed at a particular sector.

Courses take various forms according to the requirements established after discussion with the clients and visits to typical situations with which the participants have to deal. This approach avoids unnecessary coverage of irrelevant detail, for example the generation and distribution of steam in a company which only uses hot water. It is also important when considering the financial aspects of project appraisal to be aware of the investment criteria of the particular company or organisation.

**Introductory Courses**

Most newly appointed energy managers have no special training or directly related qualification. They are expected to pick the job up as they go along, often carrying the responsibility in parallel with other tasks. Sometimes these are more pressing and involve dealing with crises as they arise so detracting from the more methodical, long-term application needed for energy management. Neither are all the holders of posts as energy managers engineers so it cannot be assumed that basic concepts of chemical, mechanical, thermal and electrical energy are well understood. It has been found that units are often a stumbling block and simple conversion tables are always distributed to participants in these courses and some explanation given. These contain only units commonly encountered in energy management - temperature, pressure, energy, power, etc. All-embracing conversion books make it difficult for the uninitiated to find the few units of significance to the energy manager.

What are the main issues that all energy managers want to know about? A survey conducted in one part of the country by the Energy Efficiency Office (7) revealed that general topics of a management nature - Monitoring and Targeting, Employee Awareness - are most in demand. It is possible that energy managers feel that they can obtain detailed help on their actual type and make of plant items from manufacturers, energy suppliers or consultants.
Energy Management Seminar

In a series of seminars for a public sector organisation the approach described was employed. The stages in constructing and executing the course may be summarised as follows:-

(i) Initial draft based on client's written request;
(ii) Discussion with representative of client organisation to elucidate points in (i);
(iii) Visit to site of first seminar which was also a site typical of those from which participants would come (including photography to illustrate seminar);
(iv) Discussion with permanent staff on that site about arrangements for seminars and suitable buildings for exercise in energy survey;
(v) Revision of draft programme for seminar in the light of (iii) and (iv);
(vi) Preparation of audio-visual aids;
(vii) Conduct of seminar;
(viii) Evaluation and revision of programme for further seminars, then repeating items (iii) to (viii).

The programme for a typical seminar of this type would include the following elements:-

(i) Introduction by Senior Official of client organisation;
(ii) Introduction of team;
(iii) Aims and objectives of organisation's energy efficiency programme
(iv) Introduction of concept of Energy Management Group exercise, presentation and evaluation;
(v) Energy in Buildings - introduction to survey format, energy units;
(vi) Evaluation in groups of sample energy survey
(vii) Energy survey - slides illustrating things to look for in typical situations in the organisation;
(viii) Groups using techniques on buildings on host site, preparation of survey report;
(ix) Presentation of reports on buildings to 'Establishment Energy Efficiency Committee' comprising one member of each group;

(x) Energy committees, energy wardens, organisation - the strength of working together, terms of reference, management tools;

(xi) Action plan for the future (each participant completing a list of key points to be tackled on home site);

(xii) Sources of help and support for energy managers;

(xiii) Questions and summing up.

Conclusions

The importance of participation by all attending is recognised in the construction of the seminar. Each topic is broken down into sections introduced by the team, exercises in groups by the participants, presentation of group findings, evaluation of these by other participants as well as by the team and discussion of any new points arising. Participants completing questionnaires found the practical exercises enabled them to experience techniques and to acquire confidence in working without supervision on return to their home sites. In terms of motivating energy managers to take a firm grasp of the task in hand the involvement with others, equally new to the job, in doing these realistic exercises on a small scale and with help at hand is a major factor. It is, of course, necessary to give some stimulation before expecting an effective response in group practical work but participants must not be inhibited by having every eventuality covered in advance. Participants in energy efficiency courses aimed at the energy managers level will return to their own sites and will try to involve other employees in the energy efficiency programme. To motivate others they need themselves to have confidence in the ideas they are promoting. The approach described encourages the acquisition of the attitude.
References


Industrial energy management - some case studies

A W E Henham

ABSTRACT

The University offers courses in Energy Engineering and project work for industry is undertaken in conjunction with these. Additionally, contract and consultancy work is carried out for industry. A range of different industrial applications is considered. In most of these, overall energy audits of the site and of the activities of the company were conducted. By this means, the appropriate level of priority could be decided for each potential energy-saving measure.

Advantages of looking at an establishment's operation from an independent viewpoint are illustrated. Examples are taken from a pharmaceuticals factory, a frozen food manufacturer, a large printing works, and a small computer imaging plant.

This review refers to the building structure and possible improvement to this, only where this interacts with the process. The relative merits of investing in different sectors of energy conservation are considered.

KEYWORDS

Energy management; energy conservation, process efficiency.

INTRODUCTION

The MSc course in Energy Engineering at the University of Surrey (described elsewhere by the author, 1983) seeks to provide industrial, commercial, institutional and governmental bodies with graduates educated in the utilisation and management of energy. Opportunities are given to those already involved in energy management by a part-time pattern of study alongside the full-time course.
There are many points of contact between these bodies and the University including:

a) secondment of employees for full-time study,
b) encouragement of employees to study part-time,
c) provision of projects for employees and for university-based students,
d) placing contracts for energy management,
e) placing contracts for research in specific areas,
f) employment of university staff as consultants,
g) presentation of case studies by visiting lecturers from industry,
h) arrangement of courses given by university staff in-house for a company or at local centres,
i) organisation by the university of an Energy Manager's Group for the locality.

The case studies described arise from activities (c), (d) and (f).

ENERGY SURVEY

When it is suggested that a particular process needs to be investigated, it is always desirable that this is seen against the background of the whole operation on the site. The pattern of energy use, comprising diurnal demand variation, plant loading, mix of energy sources, ratio of process:space heating energy, needs to be taken into account when decisions are made in one area. Examination of the historic energy use and some estimates of loading and, hence, consumption indicate the relative importance of various items in the energy picture of the site. Potential savings from the proposed change in process, plant or mode of operation can then be evaluated and compared with the capital outlay. Simple payback or, for more expensive changes, discounted cash flow calculations can be used to demonstrate the potential advantage.

CASE STUDIES

Pharmaceutical Works

The object of this project, described by Beacon, 1983, was to quantify, as completely as possible the use of energy in a small pharmaceuticals works, the total of which was about 12.7 TJ/year, 23% as electricity and the rest as gas. Diagrams in fig. 1 show estimated end uses as proportions of each source. In primary energy and cost terms, however, the use of each source is similar.

The diagram clearly shows that building services, comprising space heating, hot water, lighting, electrical space cooling and most of the absorption unit's load, account for about 80% (including its proportion of losses). The production processes are numerous and each is fairly small, showing that these are not the first points to begin an energy saving programme. A characteristic of all the premises was a uniform level of lighting irrespective of occupation by employees or the presence of outside light from windows. Similarly large unoccupied areas were heated in winter and cooled in summer.
Frozen Food Manufacturer

Additional activity was envisaged in a frozen food plant in which cooking and freezing processes take place in close proximity. Existing provision of heating was by low pressure (7 bar) boilers and of refrigeration by 360kW electric motor driven compressors. Investigation by Palmer, 1980, of the total energy requirements shows that the existing arrangement used 14% more energy than the proposed combined heat and power arrangement. This has a higher pressure (35 bar) boiler to supply a steam turbine, the exhaust steam from which (at 7 bar) is used in the cooking process.

Fig. 1. Annual energy proportions by end use

Fig. 2. Comparison of Schemes
There are two major advantages over many traditional CHP applications. The loads of process heat and refrigeration are directly proportional to each other and there is no intermediate loss in alternator and motor. The system is also compatible with the existing boilers which may be linked into the same 7 bar steam line as the turbine exhaust. Flexibility results from this and from the ability of the turbine to run at 3600 rev/min compared with the 3000 rev/min maximum of the electric motor. Fig. 2 shows the energy flow for both types of plant.

Discounted cash flow calculations at the time (1980) showed this scheme to offer advantages over the existing method and other possible CHP patterns. The payback, compared with installing another plant of the existing type, was 2.1 years.

Large Colour Printing Works

In the rotogravure process large volume flowrates of air are drawn over the heated drums round which the paper passes between successive colours. This air contains solvent which is removed for recycling and to minimise pollution of the atmosphere. Examination of the process during a complete audit of the works demonstrated that the recovery plant should be a major source of savings. Solvent is absorbed as the air passes through towers containing activated carbon. Each tower is taken off stream in turn and steam is passed through it. The resulting vapour mixture is condensed to recover the solvent and the separated impure water is discharged to waste. There were clearly opportunities here for heat recovery since the amount of condensate produced is proportional to the boiler make up water requirement. The most straightforward arrangement appeared to be an indirect heating of the boiler feed water by the condensing solvent and steam (fig. 3). For each kg of solvent recovered 3.5 kg steam is used so the energy available during condensing is over 8 MJ/kg solvent.

Fig. 3 Energy conservation in solvent recovery process
A fuel saving of over £90,000 each year gives a payback for the scheme of about 2 years. Additional scope for savings would result from the regulation of extraction air flow to match pressroom activity. This would also reduce heating and cooling of the replacement air fed to the room for the comfort and health of employees.

Small Computer Imaging Plant

A small building, floor area 380m$^2$, previously used as an office, was converted into a plant using computer imaging to produce originals for printing. A study of the building envelope (McEwan, 1982) was a pre-requisite here as there was an opportunity for upgrading this. Fabric loss during heating or gain during cooling was reduced to 18% of the original value. This enabled the initial and running costs of the new cooling and heating plant to be considerably reduced. Energy gains from equipment were expected to exceed energy loss at any winter condition so heating was for preheating mainly after weekends or holidays. Heat recovery from air conditioning was not recommended by the author in this case as there was no nearby building able to use the recovered energy, the only use for which was heating water for processing film. Independent means would be required for rapid start up and reliability so only running costs would be saved. The payback appeared too large for commercial justification compared with other measures.

This project is an example of the necessity to examine each site carefully, making a personal visit wherever possible. Installation of a similar process was in progress elsewhere in the same group at the same time. Quite different considerations applied there since that was on the ground floor of a two-storey building, the upper floor of which was an ordinary office. There was, therefore, an excellent and nearby use for energy recovered from cooling system condensers during the winter period. There still needed to be external dumping of energy in summer, of course, but the close location of the source of heating and demand for it changes the economics recovery entirely.

ACKNOWLEDGEMENTS

The author is grateful to the management and staff of the companies involved in the work described for their ready co-operation in providing data and making arrangements for the author's visits and investigations. The contribution made by the postgraduate students whose work is listed below is appreciated. One of these, M.A. Palmer, was the engineer responsible for the project within the company concerned while the others came to be involved through their course projects.

REFERENCES

Energy management case studies in co-operation between industry and university

A W E Henham
ENERGY MANAGEMENT
CASE STUDIES IN CO-OPERATION BETWEEN
INDUSTRY AND UNIVERSITY

A.W.E. HENHAM
University of Surrey
Department of Mechanical Engineering
GUILDFORD-UNITED KINGDOM

CONTRIBUTED PAPER
SUMMARY

The University of Surrey has for many years offered a postgraduate course for the Master of Science in Energy Engineering. This inter-disciplinary course is closely based on the requirements of industrial and commercial concerns and the public sector. Through this has developed a complex pattern of links with industry, especially in the field of energy management.

University staff undertake consultancy work, feasibility studies, energy surveys and the organisation of specialised in-house courses. The University acts as a focal point for meetings of local energy managers. Postgraduate students tackle projects in their own company where appropriate or in a location arranged through the network of contacts arising from the other activities listed. The University-Industry relationship often provides a fresh approach which is valued as an independent contribution to the solution of energy problems.

1. INTRODUCTION

The University of Surrey’s involvement in energy management in industry, commerce and the public sector is based on its postgraduate course in Energy Engineering. Subtitled the Optimisation, Utilization and Management of Energy, this course has been offered since 1978 and has been fully described in the literature. (Henham, 1979 and Henham, 1986).

1.1. Energy Engineering Course

The course is available on full-time (12 months) or part-time (24 months) patterns to make it available to a wider range of potential students. The part-time is undertaken by those holding various positions in industry, commerce and the public sector. The full-time course generally comprises an international group having considerably varied backgrounds and wide-ranging experience. Many overseas students are from government agencies, research centres and higher education. So far members registered on the course have come from 23 countries in Europe, Asia, Africa, Central and Southern America. The variation in discipline of first qualification — chemical, civil, electrical, mechanical and building services engineering are typical — is thus combined with practical experience in industry, commerce, local and national government, energy suppliers, research and educational establishments. The result is a very lively, interactive group in which members share their specific talents with each other. There is no part of the syllabus which is new to everyone on a course, neither does anyone find all of it familiar. The course is offered by the Faculty of Engineering, comprising five departments, with the co-operation of the Department of Economics.

1.2. Connections between Course and Industry

Involvement with employers of energy-related staff is inherent in the parttime pattern where project work is undertaken by the student in his own everyday situation. There is
always an unsatisfied demand for the graduates for whose placing companies and university also maintain close contact. Some employers are also involved with the university in the placing of undergraduates for the industrial year which forms part of Surrey Engineering courses.

Table I. Part-time Students - Posts held in employment

<table>
<thead>
<tr>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chief Engineer, National Motoring Organisation.</td>
</tr>
<tr>
<td>Refrigeration Engineer, Frozen Food Processing Company.</td>
</tr>
<tr>
<td>Lecturers, Polytechnics and Technical Colleges.</td>
</tr>
<tr>
<td>Research Engineers, British Gas.</td>
</tr>
<tr>
<td>Technical Consultancy Service Engineer, British Gas.</td>
</tr>
<tr>
<td>Planning Engineer, British Gas.</td>
</tr>
<tr>
<td>Sales Engineer, British Gas.</td>
</tr>
<tr>
<td>Building Services Engineer, University.</td>
</tr>
<tr>
<td>Technical Director, Heating &amp; Equipment Manufacturer.</td>
</tr>
<tr>
<td>Managing Director, Heating &amp; Ventilating Consultancy.</td>
</tr>
<tr>
<td>Energy Conservation Engineers, Borough and Country Councils.</td>
</tr>
<tr>
<td>Group Energy Coordinator, Group of Timber Companies.</td>
</tr>
<tr>
<td>London Representative, Overseas Electricity Authority.</td>
</tr>
<tr>
<td>Building Management Engineer, Food Retailing Company.</td>
</tr>
<tr>
<td>Engineer Officer, Royal Navy.</td>
</tr>
<tr>
<td>Regional Engineer, Government Department.</td>
</tr>
<tr>
<td>Regional Energy Conservation Officer, Government Department.</td>
</tr>
<tr>
<td>Hospital Engineer, Area Health Authority.</td>
</tr>
<tr>
<td>Engineer, Regional Electricity Board.</td>
</tr>
<tr>
<td>Partners, Building Services Consultancies.</td>
</tr>
<tr>
<td>Engineer, Contract Energy Management Company.</td>
</tr>
<tr>
<td>Engineers, Energy Consultancies.</td>
</tr>
</tbody>
</table>

Table II. Full-time students - Overseas organisations from which students have been released to attend the course

<table>
<thead>
<tr>
<th>Organisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazilian Ministry of Education (Pontifical University of Rio de Janeiro).</td>
</tr>
<tr>
<td>Cyprus Higher Technical Institute.</td>
</tr>
<tr>
<td>Industria de Azulejos (Brazilian Ceramics Company).</td>
</tr>
<tr>
<td>Iraqi State Organisation for Oil Projects.</td>
</tr>
<tr>
<td>Malaysian Ministry of Education (Universiti Teknologi Malaysia).</td>
</tr>
<tr>
<td>Anglo African Industries (Malawi).</td>
</tr>
<tr>
<td>National Electric Power Authority of Nigeria.</td>
</tr>
<tr>
<td>Pakistan Ministry of Petroleum and Natural Resources.</td>
</tr>
<tr>
<td>Sudan Ministry of Irrigation and Hydro-Electric Power.</td>
</tr>
<tr>
<td>Directorate of Energy Conversion and Conservation, Indonesia Sriwijaya University, Indonesia.</td>
</tr>
<tr>
<td>MEI Project Engineering (Singapore Building Services Company).</td>
</tr>
<tr>
<td>Institute of Hydroresources and Electrification, Panama.</td>
</tr>
<tr>
<td>Various universities of People's Republic of China (through Commission of European Communities).</td>
</tr>
<tr>
<td>Ceylon Petroleum Company (Sri Lanka).</td>
</tr>
<tr>
<td>HMT Consort (HK) Ltd (Hong Kong Building Services Company).</td>
</tr>
<tr>
<td>Soares de Almeida &amp; Ca (Portuguese Building Services Company).</td>
</tr>
<tr>
<td>Khon Kaen University, Thailand.</td>
</tr>
<tr>
<td>Ministry of Mines and Power, Cameroon.</td>
</tr>
<tr>
<td>Bureau of Energy Utilisation, Phillipines.</td>
</tr>
</tbody>
</table>
Tables I and II show respectively the employment form which home part-time and overseas full-time students have come. Some UK full-time students come straight from studies for first degrees at Universities and Polytechnics (and which usually involve industrial experience, in addition) while most have been working in a professional capacity for some years. Separate government grants apply to those who are young, recent graduates and to those with many years in industry who are seeking a new field into which their career may develop. In other cases government departments or educational establishments have seconded members of staff for a year to follow the course full time.

Further links with industry are maintained through the course content itself. Specialised applications are often covered by visiting lecturers from industry providing up-to-date experience of rapidly-moving technology. Visits are held to establishments where new energy utilization methods have been initiated. These have included hotels, hospitals and military establishments where combined heat and power plant are employed; a swimming pool complex using heat pump dehumidification; a research centre with large scale refrigeration plant; manufacturers of seals and packings and of pharmaceuticals as well as traditional power stations and an oil refinery.

2. THE UNIVERSITY IN ENERGY MANAGEMENT

With the background explained above it is apparent that the University has expertise in the areas required for effective energy management in industry, commerce and the public sector. Some reasons why industry may involve the university and its staff are outlined below.

a) Expertise is available to establishments with no suitably trained employees.

b) Expertise is available to supplement that of employees to tackle a task for which the latter would not have time in addition to their regular duties.

c) Advice is required which is impartial and free of:

(i) External commercial pressures (e.g. from the supplier of one form of energy or of one type of equipment);

(ii) Existing practice in the particular industry or site;

(iii) Connection with one section of a company or one company in a group where the performance of sections or member companies will be compared.

d) A wide range of back-up ability is available in specialist areas through the constituent departments of the university.

e) Facilities are available for metering, computing etc.

f) The possibility exists of further study of particular processes or possible future solutions based on an analytical or experimental research programme.

g) Where a general programme of energy efficiency is to be initiated by an organisation, this can be supported by tailor-made courses for employee awareness training and motivation.

h) In the UK for certain government grants towards projects an independent organisation must be employed to carry out a survey or feasibility study.
There are various methods by which members of the University interact with industry and other external organisations to achieve improvements in energy efficiency. Examples of these will be described later.

2.1. Student projects

As in other UK taught courses for Masters’ degrees, Surrey Energy Engineering students are required to present a dissertation on an individual study. Topics for this can arise in various ways.

Traditionally they are suggested by academics involved in the course who have suitable subjects within their research programme for the timescale available —the equivalent of about three months full-time work. Those which are appropriate to the theme of this paper, however, are related to industry and take two main forms.

2.1.1. Projects arising from students’ employment

Where a student attends part-time he has a very limited time available while on the University Campus to pursue his project. He has to use this to consult his academic supervisor so that the work is almost entirely conducted as part of his everyday position. Selection of a suitable topic depends very much on the current loading of the employer’s programme but this has not been too difficult to arrange in practice. The student is encouraged to establish the project title early in his 2-year course so that he can collect data, carry out analyses and discuss fully with his supervisor over a longer period than if he were full time at the University. Although he would be engaged on the benefit of his employer the analysis, presentation and assessment would be framed to meet the requirements for the dissertation.

Full-time students seconded from industry in the UK will also carry out a project of specific interest to the employer, usually based on work in which the students had been involved before joining the course. They will normally return to their employers at various times during the year to continue liaison on this work. Although overseas would have the University’s support in similar arrangements, it is in practice much less frequently possible to maintain the contact. They are still encouraged to choose projects of direct relevance to their employers’ interests or, at least, to their home countries’ energy situations.

Confidentiality of projects can be arranged, usually for an agreed period, so that the dissertation is not available on open shelving in the library. Typical projects on this basis are listed in Table III.

2.1.2. Industrial projects for University-based students

Often students with no specific affiliation will opt to undertake a project in conjunction with industry. These projects will sometimes be the result of enquiries from industry and the public sector while others are items forming part of a longer-term contract or consultancy undertaken by academics. Additionally certain local concerns have been contacted to arrange an attachment to satisfy a particular interest shown by a student. Naturally these arise where a co-operative relationship already exists between the external organisation and a member of the course staff. Some examples of this type of project are given in Table IV. As there are many mature students the company often obtains considerable expertise at relatively small cost.
Table III. Typical employment-based projects

New plant design for building complex (City University).
Reduction in building temperature gradients (Colt International Ltd.).
Analysis of energy use in Airways complex (British Airways).
Analysis of energy use in Airways training centre (ITK Energen Ltd).
Energy saving in district heating system (Isherwood, Boy & Atkinson).
Refrigeration systems study (Darace Ltd).
Estimation of plant capacity for building heating (PSA).
Services design for new building (consultancy).
Low energy design for office block structure and services (Tuckey Ford).
Thermal performance of low thermal inertia buildings (East Sussex CC).
Thermal characteristics of intermittently-heated buildings (London Electricity Board).
Influence of thermal mass on energy requirements (Wimpey Laboratories).
Hotwater supply in commercial buildings (British Gas).
Performance of heating controls (PSA).
Lighting control in group space offices (PSA).
Energy utilization at Slough College (Berkshire CC).
Energy recovery in hospital air-conditioning systems (Contair Ltd).
Energy considerations of school buildings (Essex CC).
Energy study of civic centre (London Borough of Hillingdon).
Energy use in liquid storage terminal (Unitank Storage Co Ltd).
Combined heat and power for freezing plant (Birds Eye Walls Ltd).
Combined heat and power plant assessment (PSA).
Performance of large chiller plant (Royal Borough of Kensington & Chelsea).
Total energy requirement of private cars (AA).
Energy sources for Pakistan (Pakistan Ministry of Petroleum and Natural Resources).
Development of Group Energy Monitoring y System (Harrison & Crosfield PLC).
Energy Analysis of Community Centre (CHP Energy Systems Ltd).
Electrical Generation Planning Methods (Instituto de Recursos Hidráulicos y Electrificación, Panamá).
Swimming Pool Energy Saving (Emstar Ltd).
Condensing boilers (British Gas).

Table IV. Examples of industrial projects carried out by University-based students.

Computer control of building energy services (IBM).
Energy use at Gatwick Airport (British Airports Authority).
Study of hot water system for rebuilt hospital (SW Surrey Health District).
Electric power use in a process plant (James Walker & Co Ltd).
Domestic heat pump with storage (PCL).
Performance of corrugated plates as rotary heat exchanger matrix (CEGB).
Control of large industrial oven (Gates Energy Products).
Control strategy for frozen food refrigeration (Birds Eye Walls Ltd.).
CHP feasibility study for hospital (SW Surrey Health District).
Energy survey of industrial site (Revlon Health Care (UK) Ltd).
Energy survey of hospital (Atkins Planning).

2.2. Consultancy

Consultancy work is normally arranged in one of two ways:

a) An individual member of staff acts as a consultant to a company or organisation mainly working on site and carrying out studies, analyses, etc. as an independent expert.
b) A contract is placed with the University, naming one or more individual members of staff as principal investigators but enabling the project to involve other staff and all the facilities of the University.

Generally smaller projects only requiring a small proportion of the time of a member of staff are more easily dealt with by the first approach. Longer term and more time-consuming projects are usually arranged by the second method. As this involves more formality it takes longer to set up.

2.3. Energy surveys

The first stage in considering improvements in energy utilization in any building, service, process or complete plant is an energy survey. This takes account of the historic use of all forms of energy and seeks to determine the distribution of this energy within the site so that the major items of consumption can be identified. Following this the opportunities for improving energy efficiency and reducing energy used per unit of production (or other appropriate measure according to function) can be investigated. The resulting report lists, in order of priority, measures which the client is recommended to undertake. Half the cost of the first such survey done on a site is met in the UK by the Government Department of Energy. Where further investigation is required application can be made for a similar contribution to a much larger and more detailed survey.

2.4. Feasibility studies

Where a new process or plant is envisaged in order to use energy more efficiently a thermodynamic and economic analysis is often required in advance. The University is well placed to conduct this type of study on an impartial basis. Most companies do not have the need to employ full-time staff capable of this level of analysis.

2.5. Contract research

A wide range of facilities, including workshops, laboratories, computing and instrumentation are available within a university. In conjunction with the expertise of academic staff and the ability to appoint short-term contract research assistants this enables contracts to be undertaken on various timescales usually up to three years maximum. As for some types of consultancy, contracts are placed by industry with the university with named permanent staff as principal investigators.

2.6. Short courses

There are many short courses offered in the general area of energy management and in certain specialised areas. Some of these are provided annually or, in different regions, on a travelling basis.

Surrey Energy Engineering staff, being involved with a full-time course, are readily able to organise special courses for groups of people involved in various aspects of energy management. These courses, which may take place on the client's premises or at the University, are individually tailored to meet the needs of participants. No two courses are the same as the levels of knowledge, experience and qualifications of the participants and the demands of their working situations will differ considerably.
2.7. Focal point

The University of Surrey places emphasis in its Charter on the establishment and maintenance of links with the community, especially with the industrial concerns in its Country and in neighbouring districts. One means by which this is done is by acting as a base for meetings of those involved in the business community in the Managing Directors’ Club.

The Energy Engineering group hosts the Guildford Energy Management Group comprising representatives of companies, local government, hospitals, etc. The Group’s expenses are met by the Government Department of Energy but all the work is done voluntarily. The University provides a neutral and central meeting place and one to which the members can easily come for talks, discussions and demonstrations of equipment. Proper facilities are available for all these activities. Incidentally these meetings provide a helpful opportunity for full-time students to meet practicing energy managers as well as finding out more about technical aspects relevant to their course.

3. Examples of co-operation

Many of the forms of co-operation described above overlap in that some companies have been involved in a number of ways with the University. For example, projects have been undertaken by university-based (as opposed to sponsored) students on the premises of members of the Energy Management Group while short courses have been arranged for the energy managers of a group for which an energy efficiency contract has also been undertaken.

3.1. Student projects

From the lists in Tables III and IV only one or two can be picked out as illustration.

One part-time student’s project shows how broad the scope can be compared with one confined to the University. As Chief Engineer of a national motoring organisation, data on every one of its 1800 roadside service, vehicles were available to him. This enabled a detailed study to be made of the fuel consumption of statistically large samples of identical vehicles used in the differing conditions prevailing in the regions for which typical results are shown in Table V. Further studies were made on fuel consumption of a wide range of vehicles tested annually under different driving conditions and on energy requirements for car manufacture in the many countries in Europe (East and West), USA, Japan and SE Asia visited by the student in the course of his work. More detailed description of this work can be found in presentations to conferences and publications (e. g. Henham and Jacobson 1983 and Jacobson 1981).

Table V. Fleet regional fuel consumption programme

<table>
<thead>
<tr>
<th>Region</th>
<th>Hourly distance</th>
<th>Road type</th>
<th>Fuel consumption/1/100 km</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>km</td>
<td></td>
<td>actual</td>
</tr>
<tr>
<td>Northampton</td>
<td>80-88</td>
<td>Motorway</td>
<td>10.8</td>
</tr>
<tr>
<td>West ana Wales</td>
<td>26-27</td>
<td>Cross-country</td>
<td>10.5</td>
</tr>
<tr>
<td>Cambridge</td>
<td>77-88</td>
<td>Trunk, flat</td>
<td>10.7</td>
</tr>
<tr>
<td>Scotland and North Ireland</td>
<td>26-36</td>
<td>Mostly cross-country</td>
<td>10.9</td>
</tr>
<tr>
<td>North</td>
<td>21-32</td>
<td>Trunk, urban</td>
<td>12.8</td>
</tr>
<tr>
<td>Midlands</td>
<td>21-29</td>
<td>Urban, motorway</td>
<td>14.1</td>
</tr>
<tr>
<td>South East</td>
<td>21-34</td>
<td>Cross-country, urban</td>
<td>12.6</td>
</tr>
<tr>
<td>Greater London</td>
<td>19-29</td>
<td>Urban, suburban</td>
<td>14.9</td>
</tr>
</tbody>
</table>
A part time student in the public sector was responsible for energy management in a recently built civic centre (Figure 1). He examined the ways in which energy was supplied to the building, and used within it. This included both energy unit and cost analyses, breaking them down into components (Fig. 2) (e.g. standing charge, maximum demand charge and unit charge for electricity). The specification and operation of all items of structure and plant were examined and a thorough investigation of possible improvements made. In some cases the original design criteria were found to be valid at the time but not 8 years later when the ratio of energy cost to capital cost had increased considerably.

Potential major improvements identified included:

a) Specific insulation upgrading of the roof and of the exposed first floor slab.

b) Revised operation of the ventilation system to allow more recirculation for cold and free cooling for warm ambient temperatures.

c) Step control of hot water system.

d) Revised operating pattern for chiller plant.

e) Lighting control to allow for ambient levels and occupancy patterns.
3.2. Consultancy

The University has various means of maintaining contact with local industry. Through these, enquiries are routed to the member of staff most likely to be able to advise on the problem raised. An additional source of such enquiries is the recently established Research Park on the Campus. Companies having their own research staff and facilities in this park will, nevertheless, occasionally need specialised assistance. The proximity of the academic departments encourages them to use this as a first resort when needing help. There is also a building in which joint venture facilities are available to innovators and proposals for this method are referred to staff for an opinion and report on viability.

Projects under this heading are often at an early stage commercially and most are the subject of confidentiality agreements. Subjects dealt with have included small-scale combined heat and power, a gas generator for automotive power and a variable valve timing system for internal-combustion engines.

3.3. Energy surveys

An example of this type of work in which one of the postgraduate energy engineering students took part was a complete survey of energy use in a pharmaceuticals plant. Although its energy manager was a qualified engineer he had another mainstream management position to fulfil and had not sufficient time to spend on a full survey. Only the total incoming energy (in the form of gas and electricity) was metered and no knowledge of the ultimate use had been established. As a result of the survey the major uses of energy were listed with estimates of annual use and diagrams produced showing proportions for various purposes (Fig. 3). This produced some results quite unexpected by the staff of the company. It can be seen, for example that more electricity is used in lighting than directly for...
production. This was less surprising to the independent visitor who noticed that on bright sunny days in a sparsely-populated workspace every lamp of a very generous lighting provision was on. Equipment for such a survey is held by the University and is available for short-term use on the sites of these surveys. This includes a flue gas analyser, a clamp-on ammeter, thermometers for various specialised applications, a humidity meter, an air flow meter and a computer-readable recording device which can be left in place over a period of hours or days.

<table>
<thead>
<tr>
<th>Energy form</th>
<th>metering</th>
<th>place used</th>
<th>medium</th>
<th>final use</th>
</tr>
</thead>
</table>

Electricity — principal meter

Rotating m/cs
(mainly ac induction motors)

Production m/cs

Other machines

Air handling

Transport

‘Direct use’

Lighting

Hot water

Space cooling

Production m/cs

Office equipment and others

All other plant 7.9%

Absorption Unit 7.1%

Boiler plant 4.9%

Production 24.6%

Air handling 13.2%

Space cooling 14.8%

Lighting 27.5%

Figure 3. Sample of analysis of end uses of each energy form - pharmaceutical plant.
Armed with the report of such an independent survey, a company’s engineer can more easily obtain finance for capital work needed to reduce his annual energy requirement. Similar work has been done in various industries and, in each case, the first requirement is to discover the essentials of the particular processes and working practices of that particular site. A typical survey identified means of saving 10% of the energy bill with an average payback on capital spent of 8 months.

As well as process industries surveys have included public buildings such as boarding schools, colleges, hospitals, airports and a civic centre.

3.4. Feasibility studies and research

Sometimes the need will arise from a general survey, on other occasions independently, for a more detailed analysis of a process to be attempted.

![Diagram](image)

**Figure 4.** Thermodynamic analysis - solvent recovery plant.

This may be where:

a) One process uses a large proportion of the energy involved in a product.

b) A plant is identified in a survey as being inefficient.

c) Alternative methods are available and future investment in plant is anticipated.

d) Energy use is higher than in similar processes in the same or other factories.
An example of this comes from the energy conservation program for a large printing and publishing organisation. Plants were visited and surveyed to produce energy audits. Priorities for action were drawn up as opportunities for energy efficient measures were identified. Thermodynamic analysis of plant was conducted to determine heat recovery prospects from various processes. Throughout contact was maintained, not only with the Group Director responsible for energy, but with the Energy Manager at each of the many plants throughout the country.

A solvent recovery plant uses a highest proportion of steam generated on the site for any single operation. A thermodynamic analysis of this was undertaken and insulation of high temperature outdoor towers and energy recovery from condensing steam introduced. These changes are illustrated in Fig. 4.

Other examples have included an on-site study of a large electric drying oven during which wasteful operating practices were identified and a new control strategy suggested. Research into the operation of energy-saving devices for induction motors has been carried out in the University (Marshall and Johns 1985).

3.5. Short courses

The national printing and publishing organisation mentioned in 3.4 comprises a large number of individual works ranging from large printers of weekly colour magazines through high quality printing of glossy monthly and annual publications to the printing and binding of scientific books.

Energy managers were appointed in all these varied establishments as one phase in the overall efficiency drive. A special course was held at the company’s headquarters enabling them to have specific training in their job in their industry. Incidentally many of them had already solved the problems currently experienced by others and merely bringing them together was extremely useful. New confidence was certainly acquired by those who were new to the task.

A course, which had to be less specialised, was organised in Portugal covering a number of different industrial organisations. Mutual participation of all those attending was again an important feature.

More recently seminars have been held in different locations for officers, senior ratings and civilian staff responsible for shore stations of the Royal Navy. This was part of an overall energy efficiency drive organised in this case by the Ministry of Defence. In leading these courses special attention was given to the features common to most naval establishments. Participants were encouraged not only by showing them how to tackle their own ‘good housekeeping’ surveys but by letting them try the techniques out in small groups each allocated a building in the host establishment.

Despite the disciplines of service life not normally available in industry, the motivation of everyone using energy to achieve savings was still an important feature of these courses as in others conducted by the University.

4. CONCLUSION

There are many ways in which the industrial community (in the widest sense) can benefit from links with a University.
Over the past ten years many of these have been explored specifically in the field of energy engineering by the University of Surrey. The contacts made are of mutual benefit to industry and to the University in keeping its courses relevant to current needs. Postgraduate students, already with experience of industry, are able to take part in this two way exchange.

Technology transfer is a fashionable expression but it has been clearly demonstrated as feasible by this paper.
BIBLIOGRAPHY


Utilization of hospital waste - a feasibility study

A W E Henham & R A Johns
A feasibility study into the utilization of energy from the incineration of hospital waste is described. The plant on which the study is based takes waste from the hospital at which it is situated and other nearby sources. The energy obtained from incineration is used to generate steam for the hospital supply. The problem investigated arises from the oversupply of steam when there is no space heating requirement. The analysis of historic data for a year's operation of the plant is used in conjunction with an on-site trial to enable a thermodynamic and economic analysis of potential solutions to be undertaken.

INTRODUCTION

Clinical waste from hospitals and community health establishments in the East Surrey District, together with some domestic waste, is disposed of by incineration at the East Surrey Hospital. The quantity burnt each week varies from 4 to 10 tonnes. The waste has a high water content and is consequently slow burning. The incinerator is operated for 12 hours each weekday and for a half day on Saturdays. At the end of each day the remaining charge burns down for about four hours. The ash is removed at the beginning of the next working day.

The heat generated from incineration is recovered in a waste heat boiler. Steam is generated at about 7 bar, with the waste heat boiler set as the lead boiler. The steam is used in sterilisers, kitchens, humidifiers and hot water calorifiers at the hospital. During the summer months the demand for steam is not sufficient to recover all of the energy available from the incinerator system. Excess heat is "dumped" to atmosphere through the chimney and clinical waste which cannot then be burned is taken away for incineration by a contractor. This is necessary as there is a limit to the rate at which burning can be undertaken when the flue gas enters the chimney without passing through the boiler as it is too hot to pass through the induced draught fan.

This study was commissioned to examine the feasibility of using the steam generated in a boiler supplied with hot combustion gases by a waste incinerator for power generation in order to give year round utilization of the energy reclaimed.

METHODS

To achieve this aim the programme was:
(a) to determine the historic data in terms of the supply of waste, its quantity and quality, and of the total steam and electricity use in the hospital;
(b) to estimate by experiment, using the plant, the average calorific value of the waste;

* Department of Mechanical Engineering, University of Surrey.
(c) to investigate by experiment the conversion of waste to energy in the furnace, combustion efficiency, flue gas analysis and flowrate;
(d) to investigate by experiment the production of steam, the heat transfer to the surroundings, the boiler efficiency and, subsequently, the whole plant efficiency;
(e) to study potential power plant options, cycles and components required and to analyse the resulting system efficiency;
(f) to carry out an economic appraisal of these plants;
(g) to consider alternative uses for the steam raised;
(h) to make recommendations for future actions.

EXISTING PLANT

Incineration plant

The waste in the plant investigated is burnt in a Consumat incinerator manufactured by Robert Jenkins Systems Ltd, Rotherham. The incinerator, shown schematically in Figure 1 comprises a refractory lined main combustion chamber into which the waste is introduced by an automatic hydraulic loader. The air supplied to the main chamber is restricted to about 70% of that required for stoichiometric conditions and so combustion is incomplete. The products of combustion leaving the main chamber contain a high proportion of partially burnt and unburnt components such as carbon monoxide, hydrogen and carbon particles. These pass into the upper chamber where excess air is supplied by a separate fan to complete combustion. The waste decomposes in the main chamber under quiescent conditions and carry-over of particulates, which would eventually be emitted from the chimney, is minimised.

![Figure 1 Schematic diagram of incinerator](image)

Figure 1 Schematic diagram of incinerator

Both main and upper chambers are fitted with gas-fired burners. With normal wastes the reaction in the main chamber is autothermic once the operating temperature has been achieved and the main chamber burners are then turned off automatically. With clinical wastes, however, which are substantially wet, the burners remain on throughout. The burner in the upper chamber remains on whilst the incinerator is in operation to maintain the gas temperature above 800 °C to ensure complete combustion. Temperature controllers are fitted to ensure stable conditions in both chambers and to minimise gas consumption. In the event of a sudden rise in temperature in the main chamber the temperature controller activates a waterspray
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to reduce the temperature and to protect the chamber lining. The flue gas temperature can be reduced at discharge by the addition of secondary excess air to protect the mild steel flues especially when gases are dumped directly to the external flue. Water sprays are also fitted into the discharge ducting to reduce gas temperatures further when excessively high at entry to the duct. Flue gases then exhaust through mild steel ducting either to a waste heat boiler in the plant room above the incinerator or directly to a dump stack.

Sealed bags of waste are loaded by hand into the charging system at one end of the incinerator main chamber. The lid is closed and the waste is fed into the chamber by the action of an hydraulic ram. Each charge is about 16 kg. The makers recommend a charging rate about 190 kg/h for a period of 8 hours during the working day. The waste remaining in the main chamber at the end of the working day burns down overnight under the action of a programmed controller. The waste has a high but variable ash content and the incinerator needs to be cleaned out at the start of each working day. Loads are recorded against time by the operators.

BOILERS

Waste Heat Boiler

When the dampers are set to pass combustion gases from the incinerator to the waste heat boiler they pass through a vertical duct 550mm diameter which passes through the 1st floor on which the boiler house is situated. This feeds through an elbow into a horizontal duct entering the boiler fire tubes by a chest on one side. The fire tubes pass through the shell to a chest at the far end and return on the other side to an induced draft fan and vertical flue.

The boiler data are as follows:

Make: Agaheat
Rating: 882 kg/h from and at 100°C (553kW)
Blowdown: manual

A feedwater meter is fitted.

Other boilers

Three other boilers are installed in the same boiler house, all direct gas fired. They all feed into the same supply main as the waste heat boiler and the pressure regulators are set such that the waste heat boilers are used.

Data for each of the three identical direct gas fired shell boilers are:

Make: Hartley & Sugden, Halifax
Type: COS 6000
Rating: 2720 kg/h from and at 100°C (1.7MW)
Max pressure: 10 bar

A control panel for all boilers is fitted in the boiler house, including feedwater meters for these boilers.

HISTORIC DATA

Availability of waste

Records of waste arising from various sources were available on a weekly basis for a period just over one year. The number of bags taken away by the contractor,
regarded as exported, were also listed. The total numbers of bags incinerated were available from separate records and these were added to the numbers exported to give the total available. The masses of material incinerated and available were also tabulated.

The information for 1987 was abstracted on a calendar month basis and is presented in Table I. The significance of the columns and means of calculating the figures are given below.

A. Calendar month
B. Exported waste/kg: derives from weekly figures
C. Exported waste/GJ: based on 15 MJ/kg as derived from trial
D. Gas required/GJ: gas required in same ratio as for trial period (2.39C)
E. Steam potential/GJ: produced by 0.43(C + D)
F. Steam potential/tonne: assuming 2.368 GJ/tonne
G. Steam demand/tonne: steam demand for same period based upon feedwater
H. WHB steam delivered/tonne: steam delivered based on WHB feedwater
I. Excess steam/tonne: steam potentially available from all waste, used and exported, less steam demand, ie steam available for CHP.
J. Additional gas cost/£: based on 29.6 p/therm (105.5 MJ = 1 therm)
K. Collection and incineration cost/£: based on contractor’s charge of £236/tonne.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
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<td>350.43</td>
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<td>90.26</td>
<td>159</td>
<td>88.2</td>
<td>19.16</td>
<td>983</td>
<td>2307</td>
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<td>1269</td>
<td>3034</td>
<td>1850</td>
<td>781</td>
<td>1647</td>
<td>1046</td>
<td>410</td>
<td>8511</td>
<td>19970</td>
</tr>
</tbody>
</table>

Table I Historic data analysis

Alternative disposal costs

Collection, transport and incineration costs were analysed for the waste exported in 1987 and the average charges were £147/tonne for collection and transport and £89/tonne for incineration. There did not appear to be a cheaper alternative to this method of disposal where the plant was unable to employ all the waste.

Steam generation

The waste heat boiler is set up to be the lead boiler when on stream so is used in preference to the three standard boilers. Figure 2 shows plots of the weekly steam demand and the steam supplied by the waste heat boiler, the difference being that supplied by the other three boilers.
The maximum weekly steam consumption measured in 1987 was 60 tonne. Rated at 1.7 MW, each standard boiler is capable of supplying 2.6 tonne/hour at the feed and stop valve conditions used. The rated weekly potential of the three standard boilers is, thus, 1310 tonne. This is equivalent to approximately 5616 tonne in a month or 23 times the highest monthly consumption recorded in 1987. Clearly the daily load profile is not constant and one boiler must be allowed to be idle for maintenance at any time. It would be difficult to justify the use of more than one main boiler however, in view of the storage inherent in the shell type of boiler.

The steam demand and waste heat boiler supply is replotted on a monthly basis as a histogram in Figure 3. The excess steam, available if all the waste were to be utilized, is shown alongside demand in Figure 4. The basis of this plot is that used for the data of Table I.
Figure 3 Monthly steam generation

Figure 4 Potential excess steam generation
ELECTRICITY CONSUMPTION

The overall energy consumption (i.e., gas and electricity) is shown in Table II for the whole site. It shows the maximum and average electricity demand for each month. The highest values of maximum demand are seen to be in July and August, suggesting that the air conditioning load is responsible for this. The average demand does not follow a similar pattern, the lowest value being in September and the highest February. There may be slight changes in meter reading days so it is not possible to be definite about the average demand variations.

<table>
<thead>
<tr>
<th>month</th>
<th>gas/therm</th>
<th>gas/GJ</th>
<th>elec/kWh</th>
<th>elec/GJ</th>
<th>MD/kW</th>
<th>average/kW</th>
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<td>4007</td>
<td>262610</td>
<td>945</td>
<td>520</td>
<td>353</td>
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<td>3854</td>
<td>282360</td>
<td>1016</td>
<td>540</td>
<td>420</td>
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<td>Mar-87</td>
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<td>267120</td>
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Table II Energy consumption overall

PERFORMANCE TRIALS

The performance of the incinerator and waste heat boiler was monitored closely over a three-week period to determine the quantity of waste incinerated, gas and electricity consumption, steam generation and the associated overall efficiency. Additionally a comprehensive trial was undertaken from 0800 to 2000 on one day to obtain sufficient data to determine, inter alia, the convection and radiation losses, the combustion chemistry, calorific value of the waste, flue gas analysis, the daily incinerator and waste heat boiler performance profiles and the site electricity consumption.

Convection and Radiation Losses

The heat losses from the incinerator, waste heat boiler and associated ducts were calculated from surface temperatures, ambient temperatures and air velocities using the ASME Power Test Code for Steam Generating Units (1).

Convection losses are specified by

\[ Q_c = A_s \cdot 1.946 \cdot (T_S - T_o)^{0.25} \cdot (1 + \frac{v}{0.35})^{0.5} \cdot \frac{W}{m^2K^{1.25}} \]

Radiation losses are specified by

\[ Q_r = A_s \cdot \varepsilon \cdot (T_S^4 - T_o^4) \]

where

- \( Q_c \) = convective heat transfer rate
- \( Q_r \) = radiation heat transfer rate
The emissivity was taken as 0.5 for metallic pigment painted surfaces. The heat transfer losses were calculated using the mean surface temperatures recorded during one hour in the day's trial when combustion conditions were steady. The calculated losses are:

- **radiation:** 31.7 kW
- **convection:** 37.2 kW
- **total:** 68.9 kW

Whilst this heat loss could be reduced substantially by the installation of suitable lagging on the ducting system (which accounts for over half the total loss), this would result in metal temperatures greater than the limit for mild steel.

**Sample calculation of combustion chemistry**

An estimate of flue gas losses and calorific value had to be made since no way of sampling such a heterogeneous collection of waste was possible. Results were taken for the same hour during the one day's trial as for the heat transfer calculation. In order to estimate the approximate composition of flue gases from the dry gas analysis readings, some assumptions need to be made about carbon: hydrogen: oxygen ratio of the fuel. It is not then necessary to make assumptions about its water content which would be difficult to justify. It is assumed that dry waste approximates to cellulose \((C_6H_{10}O_5)\). The equation is set up for the known quantity of natural gas used, taking this as CH\(_4\). For simplicity the oxygen requirements for each component is first evaluated separately and the equations are written in kmol:

\[
\begin{align*}
1.39 \text{CH}_4 + 2.78 \text{O}_2 & \rightarrow 1.39 \text{CO}_2 + 2.78 \text{H}_2\text{O} \\
b \text{C}_6\text{H}_{10}\text{O}_5 + 6b\text{O}_2 & \rightarrow 6b\text{CO}_2 + 5b\text{H}_2\text{O} \\
c \text{H}_2\text{O} & \rightarrow c\text{H}_2\text{O} \\
\text{from excess air:} & \quad z\text{O}_2 \rightarrow \\
1.39\text{CH}_4 + b\text{C}_6\text{H}_{10}\text{O}_5 + (2.78 + 6b + z)\text{O}_2 & + \frac{79}{21}(2.78 + 6b + z)\text{N}_2 \\
& \rightarrow (1.39 + 6b)\text{CO}_2 + (2.78 + 5b + c)\text{H}_2\text{O} \\
& \quad + z\text{O}_2 + \frac{79}{21}(2.78 + 6b + z)\text{N}_2
\end{align*}
\]

Corrected mass of waste used in this time 89.24 kg and hence

\[
b(6 \times 12) + 10 + (5 \times 16) + 18c = 89.24
\]

i.e. \(9b + c = 4.96\)
Various ratios of b to c will give possible solutions and these are tested against the dry gas analysis obtained to produce compatible values of z (excess O\textsubscript{2}) and y (total N\textsubscript{2}) in flue gas. In this case the values z = 17.0, y = 81.8 correspond to the trial readings of flue gas analysis.

Energy in flue gas for this one hour period using values from Rogers and Mayhew (2) is given by:

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<thead>
<tr>
<th>const</th>
<th>H\textsubscript{i}</th>
<th>n\textsubscript{i}</th>
<th>n\textsubscript{i}H\textsubscript{i}</th>
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<tr>
<td></td>
<td>kJ/kmol</td>
<td>kmol</td>
<td>MJ</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>5920</td>
<td>17.00</td>
<td>100.6</td>
</tr>
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<td>CO\textsubscript{2}</td>
<td>8150</td>
<td>3.35</td>
<td>27.3</td>
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<td>H\textsubscript{2}O</td>
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<td>Σn\textsubscript{i}H\textsubscript{i}</td>
<td></td>
<td></td>
<td>694.7</td>
</tr>
</tbody>
</table>

\[ H = \frac{\Sigma n_i H_i}{3600} = 193 \text{ kW} \]

Energy to steam is obtained from the mass flowrate, inlet water and outlet steam conditions to be 459 kW.

The energy from natural gas supplied is 344.4 kW

Thus the overall energy balance is:

- Heat transfer loss = 69 kW
- Energy to steam = 459 kW
- Flue gas loss = 193 kW
- Energy generated = 721 kW
- Energy from gas supplied = 344 kW
- Energy from waste by difference = 377 kW

Thus the waste energy equivalent to calorific value

\[ \frac{377 \times 3600}{89.24} = 15208 \text{ kJ/kg} \]

This corresponds closely to value obtained by Wallington and Kerset (3), 15MJ/kg, for NHS hospital waste. In view of the estimated accuracy the rounded figure 15 MJ/kg has been used in calculations.

Steam generator efficiency

During a three-week period in February 1988 hospital staff took additional readings on forms supplied by the authors throughout each working day so that the overall efficiency of the incinerator and waste heat boiler could be determined. The performance derived from these readings was calculated on a daily basis. The average performance throughout this period is summarised in Table III, and the energy flows are shown on the Sankey diagram of Figure 5.

The duration of incinerator operation each working day, including the burn down period, was measured from the chart recorder fitted to measure the boiler water feed temperature. The mass of steam generated was calculated from the feedwater flow meter after making due allowance for blowdown. This allowance was calculated from the average blowdown time of 6 minutes each day at 6.2 bar gauge, for a 20mm
diameter pipe using Energy Efficiency Office data (4). This indicated a loss of 306 kg/day.

The efficiency varied from 26.4% to 53.2% and the waste burned from 283 to 907 kg/day.

Table III  Performance of the incinerator and waste heat boiler system for the three-week period

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<th>Running time (including burndown)</th>
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<td></td>
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<tr>
<td>Waste</td>
<td>tonne</td>
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<tr>
<td>Calorific value</td>
<td>MJ/kg</td>
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<td>Gas consumption</td>
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<td>Feedwater</td>
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<td><strong>Energy output in steam</strong></td>
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<td>Overall efficiency</td>
<td>%</td>
<td>42.5%</td>
</tr>
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</table>

Typical flue gas (from 17 Feb 1988)

| Mass flow rate | kg/s | 0.92 |
| Energy loss    | kW   | 204  |
| Analysis by volume | | |
| CO₂             | %   | 5.0  |
| CO              | ppm | 49   |
| O₂              | %   | 13.0 |
| H₂O             | %   | 7.8  |

Typical surface heat transfer loss rates

| Convection | kW | 31.7 |
| Radiation  | kW | 37.2 |
Energy Management

Convection & radiation loss
69.8 GJ
10.9 %

Blow-down
13.6 GJ
2.1 %

Flue gas loss
20.6 GJ
32.3 %

Burn-down ash removal & other losses
78.4 GJ
12.2 %

Gas
439.6 GJ
68.7 %

Waste
182.2 GJ
28.5 %

Electricity
18.1 GJ
2.8 %

Steam generation
271.6 GJ
42.5 %

Figure 5 Sankey diagram for three-week test period of waste unit

Steam Generation Efficiency at steady load

From readings for the one hour chosen in earlier calculations, the steady-state efficiency of steam generation was calculated.

Temperature of gases entering boiler = 750°C
leaving boiler = 220°C

Energy change in gases passing through boiler

<table>
<thead>
<tr>
<th></th>
<th>( \text{H}_{\text{in}} ) (kJ/kmol)</th>
<th>( \text{H}_{\text{out}} ) (kJ/kmol)</th>
<th>( n_i ) (kmol)</th>
<th>( n_i \Delta H_i ) (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{O}_2 )</td>
<td>23519</td>
<td>5920</td>
<td>17.00</td>
<td>-299.2</td>
</tr>
<tr>
<td>( \text{CO}_2 )</td>
<td>34679</td>
<td>8150</td>
<td>3.35</td>
<td>-88.9</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>22225</td>
<td>5723</td>
<td>91.49</td>
<td>-1509.7</td>
</tr>
<tr>
<td>( \text{H}_2\text{O} )</td>
<td>26955</td>
<td>6728</td>
<td>6.42</td>
<td>-129.9</td>
</tr>
</tbody>
</table>

\[ \Sigma n_i \Delta H_i = -2028 \]

Rate at which energy is available to boiler:

\[ \frac{2028 \times 1000}{3600} = 563 \text{ kW} \]

Energy to steam = 459 kW

Efficiency of energy conversion in boiler

\[ \frac{459}{563} \times 100 = 82\% \]
Overall efficiency of incinerator and boiler system

\[
\frac{459}{721} \times 100 = 64\%
\]

Electricity

The main electricity meters for the hospital were read hourly during the one-day test and an hourly load profile plotted. The variations on the average load were quite small with the exception of the hour from 1100 to 1200 when it was about 100kW above the average. The lowest was only about 55kW below the average.

PLANT OPTIONS

During the period when the space heating load is low the demand for low pressure steam, for use in humidifiers, kitchen equipment and for domestic hot water, can be met entirely from the combustion of waste material in the incinerator and waste heat boiler system. Currently, waste in excess of that required for steam production during this period, is exported from the hospital site for separate disposal by the contractor. The alternative disposal cost is a financial loss to the Health Authority which is compounded by the additional loss represented by the disposal of a potential fuel. In the year examined some additional 410 tonnes of low pressure steam could have been generated from the waste exported for alternative disposal. The financial loss and disposal of potential fuel could be recovered provided that an economically justified use can be made of the excess low pressure steam generation. The total waste available in that year would provide a load factor of 0.8 based on the rated consumption of the incinerator: 190kg/h, 8h/day, 6 day/week.

In the summer months the air-conditioning load at the Hospital is high. Two units each with 3 vapour compressors have been installed to provide chilled water at 6.5 °C. The steam generation profile throughout the year could, therefore, be harmonized to meet the winter space heating load and summer air-conditioning requirement either by:

a. installing a low pressure steam turbo-generator unit to produce electricity for use in the vapour-compression units,

or, b. installing an absorption cold generator unit to provide chilled water from the excess steam.

The possible plant options are described below.

Turbo-generator units

Option 1 - Back pressure turbo-generator with steam supplied from the waste heat boiler.

This is shown schematically in Figure 6. The unit capacity was selected to accommodate the maximum flow rate available during steady state trial operation of the incinerator. The design conditions were, thus, specified as

6.2 bar gauge; 0.95 dry; 700 kg/h.

Two types of alternator are available. The synchronous machine, which is self excited and can thus be used also as a stand-alone or emergency generator, and the induction alternator which requires separate excitation from an alternative source, usually the mains supply. The price of the latter type is substantially less. It is not envisaged that the turbo-generator would be run as an emergency set and the induction type
alternator would, therefore, recommended in this case. Quotations were obtained from manufacturers although one regarded the flowrate as insufficient.

A maker's design chart was used to evaluate the power output and overall efficiency of a turbine for option 1. The steam conditions at the waste heat boiler stop valve are 7.2 bar, 0.95 dry (assumed) with a flow of 700 kg/h. The turbine exhausts to the existing calorifiers at 1 bar.

\[
\begin{array}{ll}
\text{isentropic enthalpy drop} & 320 \text{ kJ/kg} \\
\text{power output} & 18 \text{ kW} \\
\text{turbo-generator efficiency} & 28.9 \% \\
\end{array}
\]

Small backpressure turbines of this type are normally designed to operate with medium pressure, superheated steam with the exhaust passed-out above atmospheric pressure to process equipment.

![Diagram of the power system with incinerator, waste heat boiler, and alternator.](#)

**Figure 6** Back-pressure turbo-generator and waste heat boiler

**Option 2 - Condensing turbo-generator with steam supplied from the wasteheat boiler**

The power of the turbo-generator could be increased by exhausting to a condenser under vacuum, Figure 7. Assuming a typical exhaust pressure of 0.2 bar then for the turbine used in option 1:

\[
\begin{array}{ll}
\text{isentropic enthalpy drop} & 530 \text{ kJ/kg} \\
\text{power output} & 21 \text{ kW} \\
\text{turbo-generator efficiency} & 20.4 \% \\
\end{array}
\]

The power may be increased marginally the exhaust steam is at 0.2 bar, 60 °C and is, therefore, no longer available for hot water heating in the calorifiers. Additionally a cooling tower will be required with option 2 to dissipate 450kW.
Figure 7 Condensing turbo-generator and waste heat boiler

Option 3 - Back pressure turbo-generator with steam from the waste heat boiler supplemented from the main boilers.

The third option includes the supplementation of the steam generator in the incinerator and waste heat boiler unit with steam from the main gas-fired boilers. This option is shown schematically in Figure 8. A separate dump condenser would be required as the calorifier capacity would be insufficient for most of the year.

The same design chart for a single stage turbine indicates

- isentropic enthalpy drop: 320 kJ/kg
- plant output: 100 kW_e
- steam flow rate: 2808 kg/h
- turbo-generator efficiency: 40%

In this instance the overall efficiency may be calculated as 43%.

Figure 8 Turbo-generator supplemented by main boilers
Chiller plant

Existing chiller plant

The chiller plant installed close to the incinerator plant, comprises two identical chiller units each providing 377 kW of cooling load with 117 kW electrical input. They supply seven air handling units.

Absorption Chiller Unit

Option 4. Absorption chiller unit with steam from the waste heat boiler to provide chilled water at 6.5°C.

Steam from the waste heat boiler may be used in the lithium bromide and water absorption refrigeration cycle to chill water for air conditioning, as shown schematically in Figure 9. These units only require power to operate a multistage pump and power for a cooling tower to provide cooling water to the absorber condenser. The latter will not be greater than that required for vapour compression plant auxiliary load displaced.

A single stage unit type, having a nominal capacity of 355 kW of cooling, was selected.

![Diagram of absorption chiller and waste heat boiler](image)

Figure 9 Absorption chiller and waste heat boiler

Option 5 Back pressure turbo-generator, absorption chiller and waste heat boiler

As a further energy recovery opportunity a plant comprising a waste heat boiler supplying steam to a turbine which exhausts to an absorption chiller was investigated. The turbine is as in option 1 and the chiller as in option 4. Hence the power output is 18 kWe but the chiller cooling rate is reduced to 75 kW since inlet steam pressure is lower than when the chiller alone is connected. The plant configuration is shown in Figure 10
Figure 10 Waste heat boiler with back pressure turbo-generator exhausting into absorption chiller

ECONOMIC APPRAISAL

Turbo-generators

The estimated annual saving is based upon the price—currently paid for the electricity which is displaced by that generated internally plus the saving through not having to dispose of some waste commercially (£19,970 for the year concerned) less the cost of the extra gas used in the incinerator. In the case of option 3, using steam from the main boilers to supplement the flow and thus provide 100 kW for 10 hours a day, 350 days a year, the extra gas required is subtracted as well. Only in this case is a saving in maximum demand charge for electricity realised since the waste heat boiler only produces excess energy in the summer when there is a zero MD rate. For option 3 a dump condenser is required because the calorifier load is insufficient to provide the cooling needed.

Chillers

The net electrical saving for existing chillers is added to the saving in waste disposal costs and the extra incinerator gas cost is subtracted. For option 5 the electrical savings arise from power generation as well as chilling.

The results of the appraisal are summarised in table IV
### Table IV Summary of options

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Estimated Capital Cost</th>
<th>Estimated Annual Saving</th>
<th>Simple payback period years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Back pressure turbo-generator with synchronous alternator</td>
<td>£40 745</td>
<td>£12 050</td>
<td>3.38</td>
</tr>
<tr>
<td>1b</td>
<td>Back pressure turbo-generator with induction alternator</td>
<td>£19 340</td>
<td>£12 050</td>
<td>1.60</td>
</tr>
<tr>
<td>2a</td>
<td>Condensing turbo-generator with synchronous alternator</td>
<td>£43 245</td>
<td>£12 447</td>
<td>3.47</td>
</tr>
<tr>
<td>2b</td>
<td>Condensing turbo-generator with induction alternator</td>
<td>£21 840</td>
<td>£12 447</td>
<td>1.75</td>
</tr>
<tr>
<td>3</td>
<td>Back pressure turbo-generator with steam supplementation</td>
<td>(£17 858)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Absorption chiller</td>
<td>£31 000</td>
<td>£16 062</td>
<td>1.93</td>
</tr>
<tr>
<td>5</td>
<td>Absorption chiller with back pressure turbine</td>
<td>£50 340</td>
<td>£15 627</td>
<td>3.22</td>
</tr>
</tbody>
</table>

The cost saving through avoidance of commercial waste disposal outweighs other terms in the equations for cost saving. For option 3 there is a negative payback because of the low thermal efficiency of the cycle using low pressure saturated steam generated burning mostly a premium fuel (natural gas). The extra cost in 1a and 2a of a synchronous alternator is not justified as the hospital has diesel stand-by power plant.

**CONCLUSIONS**

It is apparent from the work described that the economics of providing plant to recover the optimum savings from the combustion of hospital waste depends essentially on local circumstances. No two cases will give the same result. In the system investigated the benefit of burning all the waste in-house outweighed the other factors, the cheapest plant which would achieve this would be the preferred option. Within the usual range of variation this could be either option 1b or option 4. The latter has virtues of directness and seasonal matching and the absence of additional machinery could offer maintenance savings over the former. As the payback is fairly close, the longer term higher savings would prove a bonus after the first two years. No allowance has been made for differences in operator costs since operators are employed throughout the summer when low flowrates of waste are currently handled. There could be increased maintenance costs from some of the
plant options and these have not been quantified in this analysis. It would not be expected to change the relative merit of the options examined.

The efficiency of incineration plant operated under different conditions was found to vary considerably. A careful control of operation of this type of plant needs to be maintained to realise the optimum savings. In particular monitoring and control to minimise the added gas to the incinerator could offer significant savings.

ACKNOWLEDGEMENTS

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REFERENCES