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STUDY AND DEVELOPMENT OF TECHNIQUES
IN COMPUTERISED NEUTRON TOMOGRAPHY

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A THESIS SUBMITTED TO THE DEPARTMENT OF PHYSICS
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DECEMBER 1986.
dedicated to
my wife Prabawati
with love
ABSTRACT.

Since the construction of the first commercial scanner for routine medical diagnosis implementing the principles of computerised tomography by Hounsfield in 1973 and its worldwide adoption, the use of various types of ionising and non-ionising radiations for tomographic imaging and other applications has been under continuous study.

In this work a neutron beam has been used as the probe in order to obtain tomographic images, in transmission and emission modes, of the internal structure and elemental composition of test objects respectively. Various methods of neutron transmission tomography were studied and developed. A collimated He-3 proportional counter, a conventional combination of film/Gd-converter in a single cassette and a 35mm camera were employed as the detecting systems. A computerised video camera-based microdensitometer was used to digitise the radiographs obtained and a method to improve image noise was developed and tested.

The technique of computerised tomography has also been applied to image elemental distributions, in the section of interest, employing delayed gamma-rays emitted by the object following neutron irradiation. The technique is not suitable in the case when very long-lived, very short-lived or stable isotopes are produced therefore a technique novel employing prompt gamma-rays emitted by the object during irradiation was developed and tested in this work. This technique has been termed Neutron Capture Prompt Gamma-ray Emission Tomography.
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INTRODUCTION.

1.1 Reconstructive tomography.

After the discovery of X-rays by Roentgen in 1895, the application of physics to medical diagnosis and therapy has been under continuous examination. In medical diagnosis X-rays have been used to image a three dimensional body in a two-dimensional X-radiograph with a great deal of information therefore irretrievably lost.

Tomography is a technique in which a selected layer of an object is clearly imaged and the overlying and underlying structures are seen either in only a blurred form or not at all. The intention of tomography is to remove the confusion of superimposed images that occurs in a normal projection radiograph so that individual attention can be given to the particular section of interest.

The earliest tomographic imaging was introduced by Bocage in 1921 (Bro-76) employing X-ray transmission. The technique is referred to as focal-plane tomography. The X-ray tube and film are moved in special trajectories such that only the desired layer is maintained in focus while other layers are blurred out. The technique is illustrated in Figure I.1. The object is radiographed...
by a moving radiation source, and the image is recorded on a moving film-screen detector system. In the most commonly used arrangement the source and the detector motions are confined to a horizontal plane in opposite directions to each other. The advantage of this technique is that it does not require reconstruction, but is limited by the blurring effect caused by the neighbouring sections and it only gives qualitative tomographic images.

![Diagram of focal plane tomography](image)

**Figure I.1. Basic principles of focal plane tomography.** The X-ray tube and film move in synchrony and in opposite directions.

In reconstructive tomography, the pencil beam of radiations used for imaging does not enter other sections of the object, but traverses only the section under examination, so that unwanted sections are completely avoided. If sufficient projections are obtained, the distribution of the physical quantity within the section may be determined quantitatively. The reconstruction of the image from its projections is a mathematical process and
usually performed using a computer therefore the technique is referred to as computerised tomography (CT). The principles of reconstructive tomography are discussed in chapter IV.

The concept of CT has had a major impact on diagnostic radiology with X-rays, since the introduction of the first commercial CT scanner by Hounsfield (Hou-73). The possibility of tomography with other forms of radiation in place of X-rays has been studied, including the used of charged particle beams, neutrons, and gamma-rays from positron annihilation. The use of very low energy photons has been explored by radiofrequency absorption in nuclear magnetic resonance (NMR) imaging.

More recently, as the technique of CT has become more widely appreciated, the range of applications in non-medical fields, particularly in industrial non-destructive testing, has expanded (Gil-82, McQ-85, Rei-84.)

1.2 Neutron transmission tomography.

In gamma and X-ray transmission tomography, the photon linear attenuation coefficient is the physical quantity of interest. For a particular energy of photon, the linear attenuation coefficient varies slowly with atomic number so that image contrast between materials of similar atomic number is small whereas the macroscopic cross-section for thermal neutrons differs by a factor of a hundred for neighbouring elements or isotopes. Neutron radiography, as a
useful complementary method to X and gamma-radiography, has been extensively used in industrial areas (Bar-83), so why not neutron tomography? Three novel different methods were suggested (Spy-84), neutron transmission tomography which is the subject in chapter V, neutron scattering tomography and neutron induced gamma-ray emission tomography.

Experiments in neutron transmission tomography have been reported by several workers. Barton (Bar-77) conducted a preliminary investigation of computerised neutron tomography. An experiment, employing multiple neutron radiographs was carried out to examine an array of fuels pins in a geometry similar to a section of a fast flux test facility subassembly. Zakaib et al (Zak-78) used mathematical reconstruction methods in neutron transmission, adapted specifically for two phase flow problems. A standard BF-3 proportional counter was used by Schlapper et al (Sch-81) in neutron transmission tomography to evaluate a 37-pin fuel assembly phantom employing a filtered neutron beam. Koeppe et al (Koe-81) showed in their experiments that interaction of an oxygen filtered beam of 2.35 MeV neutrons with samples simulating biological materials was more sensitive than X-rays to variations in the content of the material, thus providing the ability to produce high quality images. The capability of Argonne's Hot Fuel Examination Facility in performing neutron transmission tomography of nuclear fuel bundles, again using multiple neutron radiographs was reported by Richards et al (Ric-82). The technique of epithermal neutron radiography for tomography was tested at the Transient Reactor Test Facility by De Volpi et al (DeV-82).
Overley (Ove-83) demonstrated that energy-sensitive neutron transmission measurements can be used in conjunction with computerised tomography. Pulsed beam time-of-flight techniques were used to measure neutrons transmitted through the sample. Tow (Tow-83) developed a non-destructive three-dimensional imaging technique using reconstructive tomography from multiple neutron radiographs. Intended applications included the inspection of light water reactor and FBR fuel bundles in physical conditions ranging from pretest undisturbed to severely damaged. Yamamoto et al (Yam-84) applied time-of-flight and iron-filtered neutrons to computerised tomography in order to examine metallic objects.

Neutron transmission tomography is useful for imaging of neutron absorbing and neutron transparent material, whereas neutron scattering tomography is suitable for materials with high scattering cross-section. Only Beynon and his co-worker (Bey-80, Bey-86), known to the author, reported the work in neutron scattering tomography. They called their work neutron holography. The object of interest was placed in a beam of neutrons which would be scattered not only at the surface but throughout the volume, because neutrons can penetrate matter (Figure 1.2). To form the hologram they used a Fresnel zone plate as an encoding device placed between the object and a neutron-sensitive recording film. Every point in the object is uniquely mapped onto the film. The lateral position of a point in the object is represented by the lateral position of the corresponding zone plate pattern on the film, whilst the distance of a point from the zone plate is represented by the linear dimensions of the corresponding zone plate.
image. The source strength of a point is represented by the density on the film of those parts of the zone plate pattern which correspond to the zones transmitting neutrons. A computer code was used to decode the hologram. The image could be reconstructed at any desired plane. This technique is outside the scope of this work therefore it will not be discussed further.

![Diagram of neutron beam and object](image)

Figure 1.2. A typical arrangement for encoding an object in neutron holography.

1.3 Neutron induced gamma-ray emission tomography.

There has been a development of a CT technique where mapping of the elements present in the object is required. Davis et al (Dav-86) examined a simulated reactor fuel element employing delayed gamma-rays in conjunction with reconstructive tomography. Neutron emission tomography following neutron irradiation of biological samples was reported by Spyrou (Spy-85) and Balogun (Bal-86).

A problem arises in neutron induced gamma-ray emission
tomography in the case when very short-lived isotopes, very long-lived isotopes or stable isotopes are produced, therefore a new technique has been developed employing prompt gamma-rays emitted by the object during neutron irradiations, this is referred to as neutron capture prompt gamma-ray emission tomography (Kus-86), and is discussed in chapter V.
CHAPTER II.
INTERACTION OF NEUTRONS WITH MATTER.

2.1 Introduction.

The behaviour of neutrons in matter is quite different from that of either charged particles or gamma-rays. Since the neutrons are uncharged, no Coulomb forces come into play with either the orbital electrons or the nuclei. Therefore neutrons can travel through many centimeters of matter without any type of interaction. Thus, for neutrons to affect matter, they must either enter the nucleus or come sufficiently close to it for the nuclear forces to act.

The mechanisms by which neutrons interact with matter are:

1. Elastic scattering \((n,n')\).

The initial kinetic energy of the neutron is shared with the nucleus. The nucleus is not left in an excited state. The closer the mass of the nucleus is to the neutron mass, the greater the fraction of the kinetic energy taken by the nucleus.

2. Inelastic scattering , \((n,n')\), \((n,n'\gamma)\), or \((n,2n)\).

This process is energetically possible only for fast neutrons. In the \((n,n'\gamma)\) reaction the excitation energy is released in the form of a gamma-ray emission. In the \((n,n')\) process the nucleus remains in a metastable state. For incident neutron energies of 10MeV or
higher, the \((n,2n)\) processes can occur.

3. Neutron capture, \((n,T)\).
This reaction is also known as radiative capture and is the most common of all reactions, since thermal neutrons induce this reaction in nearly all nuclides. It also occurs with a very high probability for a number of nuclides at particular energies in the epithermal range. This latter phenomenon is known as resonance capture.

4. Ejection of charged particles, \((n,p), (n,d), (n,\alpha), (n,t)\) etc.
Since the charged particles must overcome the Coulomb barrier before escaping the nucleus, this type of reaction is most probable for light nuclei and fast neutrons. Important exceptions are those \((n,\alpha)\) reactions which are sufficiently exothermic to allow escape from the Coulomb barrier even with thermal neutrons. Examples of these thermal reactions are \(^{6}\text{Li}(n,\alpha)\) and the \(^{10}\text{B}(n,\alpha)\).

5. Fission, \((n,f)\).
The compound nucleus splits into two fission fragments and one or more neutrons. Fission occurs with thermal neutrons in \(^{235}\text{U},^{233}\text{U},\) and \(^{239}\text{Pu}\) and with fast neutrons in many heavy nuclides.

6. High-energy processes.
The capture in a nucleus of neutrons with energies around 100MeV or higher may cause the emission of shower of many different types of particles (spallation reactions).

It is interesting to note that a similar attitude can be
adopted towards photons. X-rays and low energy photons tend to interact via the photoelectric absorption process while higher energy photons are affected mainly by the Compton scattering interaction.

2.2 Interaction cross-section.

A quantitative description of the interaction of neutrons with nuclei can be made through the use of the concept of nuclear cross-sections. The cross-section is defined as an area whose magnitude is proportional to the interaction probability. It can be imagined to be an effective area surrounding the target particle, normal to the direction of incidence of radiations or as the cross-sectional area of an interactive, spherical volume centered on the target particle. An interaction takes place if, and only if, the incident radiation arrives within this area.

This is a classical model and is not entirely accurate, but it can be extended to a more abstract, mathematical representation that is quite compatible with quantum theory. This can be done by considering, a small, elemental thickness of matter, $dx$, containing $n$ target particles per unit volume, each with cross-section $\sigma$. The cross-section $\sigma$ is known as the microscopic cross-section since it refers to a single nucleus. The elemental thickness $dx$ is small enough to ensure that none of these cross-sectional areas overlap, so that, if radiations are incident normally on this matter, then over an exposed area $A$ the total interactive area is $n\sigma A dx$ (Figure
II.1). A may be the area of a beam or flux of radiation or it may be chosen to be a unit area within a beam. In either case, the fraction of radiations which undergo an interaction, that is the interaction probability, $P$, is given by

$$P = \frac{\text{interactive area}}{\text{exposed area}}$$

$$= \frac{n \sigma A \, dx}{A} = n \sigma \, dx$$

Although $\sigma$ still has the dimension of an area, this is a model-independent definition in which it is related to a probability in equation II.1. It can be visualised as a probability rather than a physical area. It includes energy effects and has zero value for incident energies less than the threshold energy of nuclear
reaction. In general, it is a property of the radiation as much as of the target matter. For example, the same target material will generally have different cross-sections for different types of energies of incident radiation. It also has different cross-section for different types of interaction, but these are additive, so that the total probability is measured by a total cross-section, \( \sigma_t \) and which is the sum of the absorption cross-section \( \sigma_a \) and the scattering cross-sections \( \sigma_s \), thus

\[
\sigma_t = \sigma_a + \sigma_s
\]

As mentioned above that the microscopic cross-section depends on the neutron energy and the nature of the target nuclide, at or near the thermal energy, the reaction cross-section is proportional to the time spent by a neutron passing a nucleus. Thus, it is inversely proportional to the neutron velocity and also to the square root of its energy, i.e

\[
\sigma \sim \frac{1}{v} \quad \text{or} \quad \sim \frac{1}{E^{1/2}}
\]

in addition, most absorbers, such as indium and cadmium, show resonance capture effects which are superimposed on the \( \sigma-E \) graph as sharp peaks, usually in the epithermal region (Figure II.2). Neutrons with these energies exactly match the nuclear shell levels and are more easily captured.

Because neutron absorption is a nuclear effect it is extremely sensitive to nuclear structure. An important result of this
dependence on nuclear structure is the fact that $\sigma$ varies considerably from one isotope to another of the same element. One consequence of this feature is that neutron radiography/tomography can pick out different isotopes of the same element, or element with adjacent atomic numbers, X-radiography/photon tomography shows a gradual change in absorption with atomic number, $Z$. The effect is described by the absorption coefficients shown in Figure II.3.
Attenuation coefficient comparison between neutrons and photons for different atomic numbers.

**Figure II.3.** Attenuation coefficient comparison between neutrons and photons for different atomic numbers.
2.3 Attenuation, macroscopic cross-section.

As radiation penetrates matter, neutrons may be removed from the incident beam either by absorption interactions or by those scattering interactions which deflect the neutrons out of the beam. The radiation intensity decreases with distance, \( x \), into an interactive material. The decrease is referred to as attenuation. Intensity is defined to be the number of neutrons arriving at a given point per unit area, across the beam, per unit time, and is referred to as neutron flux \( \phi \). The number of interactions which take place at a given point in a material per unit time may be described as the reaction rate, \( R \). As a fraction of incident flux, this is the interaction probability used above. It depends upon the interaction cross-section and also depends upon the flux.

\[
R = n \sigma \phi
\]

where \( n \) is the number of nuclei per unit volume. The interaction rate decreases with distance \( x \) into an interactive material. In fact, the number of interactions, \( d\phi \), which occur in a small element of radiation path length, \( dx \), is given by equation II-1, which can be rewritten as

\[
\frac{d\phi}{\phi} = n \sigma dx
\]

where \( \phi \) is the neutron flux entering the element \( dx \). The attenuation function can be obtained by solving equation II-4. If the flux at \( x=0 \) is \( \phi_0 \) and the cross-section, \( \sigma \), is a constant and all other affective parameters are constant, the solution of the
equation II-4 is given by

$$\phi = \phi_0 \exp (-n \sigma x) \quad \text{II-5}$$

In practice, it is convenient to replace $n \sigma$ by a single parameter, called the macroscopic cross-section. If the distance, $x$, is measured in units of length, the macroscopic cross-section, $\Sigma$, is defined by

$$\Sigma = n \sigma = \frac{A_o \rho \sigma}{A_w} \quad \text{II-6}$$

where $A_o$ is Avogadro's number, $\rho$ is the density of the material and $A_w$ is the atomic weight of the material. Equation II-5 becomes

$$\phi = \phi_0 \exp (-\Sigma x) \quad \text{II-7}$$

For a compound material, the macroscopic cross-section can be calculated as a mixture macroscopic cross-section which is the summation of the macroscopic cross-sections of each nuclear species, provided that the property of the nuclear species is unaffected by considerations of the molecular or crystal structure in which it resides.

$$\Sigma_c = \sum_i n_i \sigma_i \quad \text{II-8}$$
where $\Sigma_c$ is the macroscopic cross-section of compound, $n_i$ is the number of nuclei per unit volume in $i$th nuclear species and $\sigma_i$ is the microscopic cross-section of the $i$th nuclear species. This equation can also be written as

$$\Sigma_c = \sum_i \left( \frac{A_o \rho_i}{A_i} \right) \sigma_i$$

II-9

$$= \sum_i \left( \frac{A_o \rho_i}{A_i} \right) \sum_i \sigma_i$$

therefore

$$\Sigma_c = \frac{A_o \rho_c}{A_c} \sum_i \sigma_i$$

II-10

where $\rho_c$ is the density of the compound and $A_c$ is the atomic weight of the compound.

2.4 Neutron capture prompt gamma-ray emission.

The topic of radiative neutron capture is virtually as old as the discovery of the neutron itself. Within a year after Chadwick's discovery (1932) one of his students had observed gamma-rays resulting from the bombardment of paraffin from a polonium-beryllium neutron source. These were attributed to the capture of neutron by protons.
In recent years the usefulness of neutron capture gamma-ray spectroscopy has been established in a wide range of applications to rapid materials analysis.

The term "prompt" is to be understood as the observation of the characteristic electromagnetic radiation generated by the neutron radiative capture. This radiation is prompt in the sense that the nuclear decay time is of the order of $10^{-15}$ second and thus strongly contrasts with the time delay of seconds or longer.

The reaction of a neutron with a nucleus $^{A}X_{Z}$ can be represented as

$$^{A}X_{Z} + {}^{1}n \rightarrow [^{A+1}X^*_{Z}] \rightarrow ^{A+1}X_{Z} + \gamma \text{(prompt)}$$

if unstable.

$$^{A+1}Y_{Z+1} \rightarrow ^{A+1}Y_{Z+1} + \gamma \text{(delayed)}.$$  

where $(^{A}X^*)_Z$ represents the compound nucleus in an excited state, only for a short time, from $10^{-12}$ to $10^{-20}$ second. These processes are illustrated diagrammatically in Figure III.4. The excess energy is released by emitting gamma-rays (prompt). The compound nucleus $^{A+1}X^*_Z$, may be radioactive. If this is the case, the compound nucleus decay in this example, by emitting $\beta$ particles to become $Y$ which is still in an excited state and subsequently releases its excess energy by emitting gamma-rays (delayed). Prompt gamma-rays are also emitted in inelastic neutron scattering where the incident neutrons have energy higher than the threshold energy.
Figure II.4. Diagramatical illustration of neutron capture and inelastic scattering reactions producing prompt gamma-rays.
In the case when neutron radiative capture is observed, the number of prompt gamma-rays of a particular energy emitted per unit time is proportional to the neutron capture cross-section $\sigma$, the number of target nuclei $n$, the neutron flux incident on the target $\phi$ and finally the branching ratio or the yield of the prompt gamma-rays $Y$. Thus

$$C = \sigma n \phi Y$$  \hspace{1cm} \text{(II-11)}$$

$$C = \frac{\sigma \phi Y m f A_o}{A_w}$$  \hspace{1cm} \text{(II-12)}$$

where $m$ is mass of the element, $f$ is the fractional abundance of the isotope, $A_w$ is the atomic number and $A_o$ is Avogadro's number. The number of the prompt gamma-rays of interest detected is expressed as

$$D = \frac{\varepsilon t_c \sigma \phi Y m f A_o}{A_w}$$  \hspace{1cm} \text{(II-13)}$$

where $\varepsilon$ is the efficiency of the gamma-ray detector for this particular energy and $t_c$ is the time of counting.

The detection of prompt gamma-rays is frequently complementary to the detection of delayed gamma-rays. This has advantages, especially in the situations where:

- very short-lived isotopes are produced (e.g. $^{11}$B($n,\gamma$)$^{12}$B, 0.2s and $^{206}$Pb($n,\gamma$)$^{207}$Pb$^m$, 0.75s)
- very long-lived isotopes are produced \((^{10}\text{Be}(n,\gamma)^{11}\text{Be}, \ 1.6 \times 10^6 \text{yr})\)
- a stable isotope is the resultant product.
- lack of appropriate gamma-rays \((^{32}\text{P},^{35}\text{S},^{45}\text{Ca},^{55}\text{Cr},^{89}\text{Sr})\)

The other advantages are that it is instantaneous, non-destructive, and produces negligible residual activity. Since it is instantaneous, it can be used for on-line analysis.

On the other hand, sensitivities are not high unless very high flux thermal neutron beams are employed. Good shielding of the gamma-ray detector against neutron irradiation is also required so that the detector can be placed close to the sample in order to achieve better detector efficiency.
CHAPTER III

NEUTRON AND GAMMA-RAY DETECTORS FOR NEUTRON TOMOGRAPHY.

3.1 Introduction

In this work, neutron detectors as well as gamma-ray detectors are required to record the neutrons transmitted and the gamma-rays emitted by the object, respectively.

Neutron detectors being used must be insensitive to gamma radiations or at least allow discrimination of gamma-rays from neutrons such as in proportional counters. A combination of metal foil or scintillator-film emulsion still maintains its favour and more recently a neutron scintillator was coupled to a TV/video camera for dynamic neutron radiography imaging (Fuj-84).

For detection of gamma-rays, a spectroscopy detector is required. There is a compromise between the resolution and the efficiency of the detector. If a gamma-ray spectrum is to be observed, a high resolution detector, such as a Ge(Li) or hyper pure intrinsic germanium (HPGe) detector, is required. A scintillation detector is suitable for detection of a single energy or multienergy gamma-rays provided that there is no overlapping peaks of interest. Only those types of detector mentioned above are discussed in this chapter.
3.2 Proportional counter neutron detector

3.2.1 General principles

The operation of a gas-filled chamber in the voltage region where gas multiplication is present but a strong dependence on the particle energy is still maintained has resulted in a very useful detector.

In principle, the proportional counter is an extension of the ion chamber in which a higher electric field strength is used and internal pulse amplification takes place. The field is strong enough to accelerate electrons, between collisions with gas atoms, to give them enough energy to produce secondary ion pairs. The net result is that the primary electrons finally generate a large number of electrons. The original charge deposited by the ionising radiation is multiplied by a factor called gas multiplication factor and may be as large as $10^6$. Consequently, a large signal pulse of the order of 100 mV may be obtained. Clearly the pulse height is proportional to the number of ion pairs generated and, therefore, to the energy deposited. An important class of application for proportional counters is to neutron detection.

In order to detect neutrons, it is necessary to incorporate within the chamber a material from which charged particles will
be released as a result of nuclear reactions which the neutrons cause. The ability of proportional counters to discriminate between particle types which produce different output pulses is particularly useful in neutron counting. Neutrons often appear along with a large background of gamma radiation. However, the gamma-rays can usually be rejected since the secondary electrons which they produce cause less ionisation than do the charged particles which are released by the neutron reactions.

The most commonly used reactions for conversion of thermal neutrons into directly detectable particles are the $^{10}\text{B}(n,\alpha)$, $^3\text{He}(n,p)$ and fission reactions.

3.2.2 The boron trifluoride proportional counter.

The $^{10}\text{B}(n,\alpha)$ reaction is widely used for thermal neutron detection. A number of factor makes it highly satisfactory for this purpose. The cross section of the reaction is large (3840 barns). The reaction is easy to detect even in the presence of comparatively large gamma intensities because of the large energy of the particles which are released. Boron is available in its isotopic form, and its chemical properties are such that it can be incorporated successfully in the detector. The reaction may be written as

\[
Q\text{-value} \\
^{10}\text{B} + ^1\text{n} \rightarrow ^7\text{Li} + ^4\alpha \quad 2.792 \text{ MeV (ground state), 6.4%} \\
^7\text{Li}^* + ^4\alpha \quad 2.310 \text{ MeV (excited state), 93.6%}
\]
The reaction is exothermic, with energy release (Q-value) of 2.792 MeV. The ground state of Li product nucleus may be formed directly, with the entire energy released being shared by $^7\text{Li}$ and the alpha particle; alternatively, an intermediate excited state of $^7\text{Li}$ may be formed, followed by the emission of a 0.482 MeV gamma-ray. The probability of reaching the ground state directly is only 6.4 percent for reactions induced by thermal neutrons.

In this detector, the BF-3 gas acts both as the target for thermal neutron conversion into secondary particles as well as a proportional gas. Figure III.1. shows a typical pulse height spectrum from a large BF-3 proportional counter of 25.4 mm diameter and 203.2 mm long. Nearly all the reactions occur sufficiently far from the wall of the detector to deposit the full energy of the products within the proportional gas. Two peaks appear at high energies due to the branching of the reaction between the excited state and ground state of the $^7\text{Li}$ product nucleus. Whereas the peak at low energy is due to gamma-rays emitted by the excited $^7\text{Li}$ nucleus. In the case where the detector size is not large compared with the range of alpha particles and the recoil lithium produced in the reaction, some events deposit the full energy in the wall material when either particle strikes the detector wall and produce a small pulse. This process is known as "the wall effect". 
3.2.3 He-3 proportional counter.

The availability of He-3, a decay product of tritium, has made possible an important method of neutron detection, the reaction being

\[
^3\text{He} + ^1\text{n} \rightarrow ^3\text{H} + ^1\text{p} + 765 \text{ KeV}
\]

This reaction has ideal properties for neutron detection. Its cross-section for thermal neutrons is 5400 barn, this makes the neutron detection efficient. There are no excited daughter products and so the reaction products, the triton and proton, contain the entire energy in each reaction and should therefore
produces single energy peaks. Again, the wall-effect also appears, even more significantly than in BF-3 counters because the reaction products have lower atomic mass and so a longer range. Another disadvantage of a He-3 proportional counter is that the lower Q-value of the He-3 reaction makes gamma-ray discrimination more difficult. A typical energy spectrum obtained using an He-3 proportional counter of 25.4mm diameter and 101.6mm long is shown in Figure III.2.

![Figure III.2. A typical pulse height spectrum taken using a small He-3 proportional counter (25.4mm diameter, 101.6mm length).](image)

3.2.4 Position sensitive proportional counter.

The determination of radiation source positions as well as their strength is the main goal in imaging systems. A position sensitive proportional counter is one of the devices which
fulfils these requirement. The detection mechanism is the same as in an ordinary proportional counter. It differs in that its anode is a plane array of many wires instead of a single wire, it is therefore also called a multiwire proportional counter. The location of an ionising interaction is recorded as the position of the affected wire.

A typical multiwire proportional counter is illustrated in Figure III.3. It has two cathodes, each comprising a set of parallel wires and these are mutually orthogonal so that one measures the $x$ coordinate and the other $y$ coordinate of an ionising event. Between these two, and usually oriented at 45 degrees to each cathode, is an array of anode wires. The anode wire collects electrons and measures pulse height whereas both cathodes collect positive ions and record position coordinates of the discharge.

A method of extracting position information is illustrated in Figure III.4. In this method, a prompt or START pulse is derived from the anode. The pulses are passed along a continuous delay line, so that the total delay line represents the position of the activated wire. Each ionising event in the counter generates one prompt, anode pulse and two delayed, cathode pulses. All three pulses are passed on to time-to-amplitude converter (TAC) units after being amplified. Each TAC unit converts the time interval between the anode START and a cathode STOP pulse into a single voltage pulse whose height is proportional to the time interval, therefore, to the $x$
or $y$ coordinate of the event. If required a time-to-digital converter (TDC) can replace TAC units to digitise the data for storage and analysis in an on-line computer.

The spatial resolution of a multiwire proportional counter is affected by oblique incidence of radiation, the range of secondary radiations produced and also the wires spacing. This can be improved by employing high density gas mixture in a high pressure counter and small spacing wires. A spatial resolution of 0.2 mm has been achieved (Abd-83).
3.3 Neutron Radiography.

The film or photographic emulsion is one of the most widely used types of radiation detector, with major application in X- and gamma-radiography, crystallography, radiation dosimetry, autoradiography, and in the last two to three decades in neutron radiography.

It is almost the oldest form of detector, in view of the fact that it was the fogging of film by the emissions from uranium ore which led to the discovery of radioactivity by Becquerel, in 1896.

A typical film consists of a layer of emulsion, usually
between 10 and 25 μm thick, coated onto one or both sides of a transparent plastic base. The base provides structural support for the emulsion, which is the sensitive volume of the film. The active ingredients of the emulsion are crystalline grains of silver bromide, each containing about $10^6$ silverbromide atoms and held in suspension in a colloidal gelatine medium. The grains are closely packed and their diameter ranges from about 0.3 μm in slow, or insensitive film, to about 2 μm in the faster, more sensitive film used for imaging ionising radiations.

Films are extremely sensitive to visible light except at the red end of the visible spectrum and are sensitive to gamma-, X-rays and also electron and other charged particles but unfortunately they are insensitive to neutrons unless the emulsion is loaded with material with large neutron capture cross-section such as boron, producing charged particles for detection in emulsion. Therefore in order to detect neutrons, a neutron converter has to be used to convert neutrons into film detectable secondary radiations. There are two methods of neutron radiography using film emulsion: the direct method and the transfer method, depending on the type of the converter being used. Table 1 in Appendix 1 gives the characteristics of some converter foil materials.

a. Direct method

In this method, the converter foil is placed in contact with the film in a light tight cassette directly into the neutron beam (Figure III.5). Atoms in the foil absorb neutrons and 'promptly' emit secondary radiations. These secondary radiations then produce a latent image on the film. When for
example a gadolinium foil is used, the induced radiation is an electron. If a scintillator screen containing a mixture of lithium-6 or boron-10 and zinc sulphide is used (see section 3.5.5), on absorbing a neutron a lithium or boron atom emits an alpha particle and this then strikes the zinc sulphide, which in turn emits a light photon. Despite the disadvantage that the gamma-ray background may produce gamma-ray fogging of the film, this method is used because it is faster than the second method.

![Diagram of neutron radiography](image)

**Figure III.5. Direct method of neutron radiography.**

b. Transfer method.

In this method, an activation image is formed in the foil, and this is subsequently transferred to a film in a dark-room by placing the foil and film in contact and allowing the radiation emitted from the foil to produce the latent image in
the film (Figure III.6).

With this method the decay process starts during the neutron exposure in the beam and so some of the emitted radiation is lost. The transfer method is obviously slower than the direct method but this disadvantage is compensated by the fact that since the foil is insensitive to gamma-ray activation (assuming the gamma-ray energies are below the threshold for inducing activation of the nucleus) the method can be used in high gamma-ray backgrounds.

The response of a film is usually described in terms of degree of blackening, or optical density, $d$. The common method of representing film response is by its sensitivity. This specifies a quantity of radiation required to produce a given optical density.
Optical density can be measured by means of a microdensitometer in which the film is illuminated by visible light of intensity $I_o$ photons per unit area and transmits an intensity $I$ photons per unit area. The optical density is expressed as

$$d = \log\left(\frac{I_o}{I}\right)$$

The major advantage over other imaging systems is its excellent intrinsic spatial resolution. The position of an incident particle or photon is recorded as being somewhere within the silverbromide grain rendered developable, so it is defined to within the diameter of one grain. The resolution is somewhat larger for neutron radiography, due to the secondary radiations emitted isotropically at the point of interaction. Unlike an electronic device, however it does not record all the interactions that take place at the same point, in other words it has position-coincidence losses. A silverbromide grain, having recorded one count, becomes insensitive to further interactions so that the number of sensitive grains decreases with continued exposure to radiations, until the film becomes saturated. A typical film response against exposure curve is shown in Figure III.7. The linear part of the characteristic curve determines the dynamic range of the film.
3.4 Dynamic Image Detector.

In industrial applications of neutron radiography, the motions of an object are sometimes recorded for further examination. For example, the performance of an engine while it is running is examined using a dynamic imaging method. For neutron tomography purposes, the image recording and the scanning mechanism are synchronised. The method is illustrated in Figure III.8. A neutron scintillator is used to convert the neutron beam into visible light. Lithium containing neutron scintillators have achieved some popularity and are commercially available as e.g. NE421 (Nuclear Enterprises Ltd.). This consists of a lithium compound dispersed in a matrix of ZnS(Ag) with thickness of about 0.6 mm. Thin layer combinations of LiF and ZnS can also be used. Because of their small thickness, gamma discrimination is very effective since a large fraction of all secondary electrons created
by gamma-ray interactions will escape without depositing their full energy.

The image produced on the scintillator is then reflected using a mirror placed at 45 degrees with respect to the neutron beam and subsequently recorded by a video camera coupled with a computer for image storage as well as scanning control.

This technique is clearly faster than one employing a film emulsion detector and the statistical noise can be improved by averaging several picture frames, typically more than 250 frames (Fuj-84, Yon-86). However a very high neutron flux \(10^{10} \text{n m}^{-2} \text{s}^{-1}\) is required to produce a reasonable image unless an image intensifier is employed a neutron flux of \(10^8 \text{n m}^{-2} \text{s}^{-1}\) may be used (Von-81).
3.5 Scintillation detector.

3.5.1 General principles.

The principle of a scintillation detector is based on the fact that in any material, an incident particle or photon leaves a number of electrons in excited energy states from which they tend to deexcite, emitting photons of ultra-violet or visible light in the form of a light flash (scintillation). In practice, a number of conditions must be satisfied if the material is to be used as a radiation detector i.e.

1. The materials must fluoresce rather than phosphoresce; thus, the scintillation process must be immediate and not delayed until after the triggering event.

2. The de-excitation process must tend to be radiative, so that a large fraction of the available energy is converted into light rather than heat.

3. The material must be transparent to its own scintillations.

For these reasons, not all materials are useful scintillators. The scintillation detector can be classified into two groups: inorganic scintillators, such as certain
alkali halide crystals, glasses and noble gases, and organic scintillators, such as anthracene and plastics.

The scintillation mechanism in intrinsic inorganic crystals can be described by reference to the band structure diagrams for solid-state materials as shown in Figure III.9. A pure inorganic crystal such as an alkali-halide crystal is represented by a valence band of energies which is normally completely filled with electrons and a conduction band of energies which is normally empty. The latter lies above the former and is separated by a forbidden band of energies in which electrons cannot exist.

![Figure III.9. Scintillation process in intrinsic inorganic crystals.](image)

Incident radiations with sufficient energy can move electrons from their lattice site to the conduction band by leaving electron vacancies called holes in the valence band.
This process is known as ionisation. The electron in the conduction band and hole in the valence band are free to move independently through the crystal. An alternative process, referred to as excitation, forms a weakly coupled electron-hole pair known as an exciton. This pair is bound together, forming a hydrogen like 'atom' whose electron energy state is just below the conduction band. The ionised electrons lose their energy in thermal collisions, moving down the energy level. These electrons are easily recaptured by positive ions. This is the electron-hole recombination process from which a photon radiation is emitted. It leaves the electron in a vibrational, phonon state, from which it eventually decays, by thermal energy loss, to the valence band. The recombination and the de-excitation energies released are less than the ionisation energy, therefore the crystal is transparent to its own scintillations. However, the scintillation energy is high enough in the U.V. region which requires special optical system coupling. Furthermore, the electrons ionised into the conduction band are able to lose their energy through collisions only if the crystal is cooled. At room temperature they are inefficient because the emission and absorption spectra are similar.

Extrinsic inorganic crystals are formed by doping intrinsic materials with small quantities of heavy metal impurities, such as thalium (Tl), known as activators. The energy level structure is illustrated in Figure III.10. There is an activator ground state in the lower half of the forbidden energy
gap and an activator excited state in the top half. The scintillation process begins, as it does in the intrinsic crystal, with production of ion pairs and excitons, some of which decay, emitting U.V. photons, but at this stage, the process is strongly affected by the presence of activator impurities. An electron in the activator ground state is easily captured by a positive ion. This attracts and captures electrons moving freely in the conduction band. It also tends to capture excitons. In all cases, the result is an excited activator atom which subsequently de-excites to the ground state, emitting a photon in the visible light wavelength. It can be concluded that the activators perform two major functions. First, they capture and utilise electrons with excess thermal energy in the conduction band, so the crystal can be operated at room temperature. Secondly, they act as wavelength shifters, converting U.V. light into visible light. Because both functions have efficiency less than 100 percent, therefore the overall scintillation is much less than that of the intrinsic crystal at liquid nitrogen temperature. In addition, the extra stage in the scintillation process makes it longer.

Crystal scintillators may contain other types of impurity ions which form energy levels just below the conduction band. These tend to capture electrons from the conduction band and delay the scintillation process. They are known as trapping centres.

Glass is an amorphous material. The scintillation process
Figure III.10. Scintillation process in extrinsic inorganic crystals.

is similar to that in a crystal except that the more random structure attenuates the scintillation pulse, and the scintillation efficiency is not very high. Because of the lower density and atomic number than the crystal, glass is a less efficient photon detector. On the other hand, it can be made to a wide range of sizes, shapes and composition. At present for example cerium-activated lithium silicate glass, loaded with a few percent of enriched Li-6 is used for neutron detection and neutron radiography.

The scintillation process in gases is direct atomic excitation and de-excitation, so the emission spectra match the absorption spectra, and therefore the scintillation efficiency is very low. In practice, a wavelength shifter is added usually in the form of solid evaporated onto the internal surface of the gas container.
The scintillation process in organic crystals is a molecular process and can best be described in terms of a potential-energy diagram for the molecule shown in Figure III.11. The passage of ionising radiation can result in the transfer of the molecules from the electronic ground state to an electronic excited state. According to the Franck-Condon principle (Bra-83), the transition takes place at a fixed interatomic spacing (line AA', Figure III.11). The point A' represents a highly excited state. This extra energy is quickly dissipated as heat from the lattice vibrations, with perhaps the level B being reached. The molecules at this state will ultimately return to the ground state along path BB', emitting a photon. It can be seen in Figure III.10 that organic crystal scintillators are transparent to their own scintillation. To date, the most useful organic crystals are anthracene and
trans-stilbene.

The light produced in the scintillation process is then converted into electronic signals using a photomultiplier tube (PMT) attached to the scintillator material through an optical coupling system.

3.5.2 Sodium Iodide.

Sodium Iodide (NaI) intrinsic crystal is not popular because it requires liquid nitrogen for operation and the light output is in U.V. region. By doping the NaI crystal with thalium (Tl) as an activator, NaI (Tl), it can be operated at room temperatures and produces visible light output. This is the most common scintillator for gamma detection and is the standard with which other detectors are compared. Because of its relatively high density and atomic number, NaI(Tl) detector has a very high detection efficiency. This is one of the reasons why it is widely employed in imaging systems such as gamma cameras and CT scanners. The high efficiency helps to minimise radiation dose to the patient while generating satisfactory image statistics. It can be manufactured from small to very large sizes and therefore can detect a wide range of photon energies.
3.5.3 Caesium iodide.

Caesium iodide has become more popular recently. It has higher atomic number than sodium iodide and so its detection efficiency per unit volume. However, its scintillation efficiency is smaller. Caesium iodide is more suitable for gamma-ray imaging systems where an array of detectors is employed because of its compactness. Thalium and sodium are usually used as the activator materials.

3.5.4 Lithium iodide.

Lithium-containing scintillators are quite common as slow neutron detectors. If LiI(Au) crystal is prepared using lithium enriched in $^6\text{Li}$, this will give a high detection efficiency for slow energy neutrons through the $^6\text{Li}(n,\alpha)$ reaction. Because of the high density of the lithium iodide material, crystal sizes need not be large for very efficient slow neutron detection. For example, a 10 mm thick highly enriched LiI crystal is nearly 100 percent efficient for neutrons with energy from thermal through the cadmium cutoff of 0.5 eV (Tai-80). Furthermore, this detector is free of the wall effect, since the crystals of lithium iodide are generally large compared with the ranges of either of the reaction products from a neutron interaction. The only disadvantage is that gamma-ray discrimination is more difficult than that in typical gas-filled neutron detectors.
3.5.5 Zinc sulphide

Silver-activated zinc sulphide (ZnS(Ag)) has very high scintillation efficiency. Whereas, its gamma detection efficiency is very poor, since it is available only as a polycrystalline powder and is therefore limited to very thin layers. When this crystal is mixed with boron containing plastic it becomes an efficient detector for neutrons. A 1.2 mm thickness of molded plastic disc consisting of two parts of ZnS(Ag) and one part of a boron plastic has achieved 33 percent efficiency for counting of thermal neutrons (Pri-1964) and its ability to discriminate against gamma-rays was fair.

3.5.6 Bismuth germanate.

The high spatial resolution and gamma-ray detection efficiency of bismuth germanate (BiGeO) have resulted in its wide application in medical imaging replacing NaI(Tl) in positron tomography (Cho-77, Nah-80). The high atomic number of bismuth leads to a high detection of gamma-rays, despite the low light output.
3.6 Solid state detectors.

3.6.1 General principles.

The original idea behind the solid-state detector was, simply to replace the gas of a gas-filled counter with a solid. It has two major advantages. First, the stopping power of a solid is much greater than that of a gas, so the detection efficiency should be improved. Secondly, the energy to create electron-holes is determined by the energy gap between conduction band and valence band which is much smaller than the ionisation potential of a gas atom. Typically, the ionisation energy is about 3 eV compared with about 30 eV required to create an ion pair in typical gas-filled detectors. The increased number of charge carriers per unit energy gives much better energy resolution.

A material is classified as a conductor, a semiconductor or an insulator by the size of its energy band gap. Thermal energy can cause electrons move from the valence band to the conduction band, leaving positive holes in the valence band. Materials with a large band gap will have low probability of thermal excitation and therefore a very small number of free electrons is produced. Consequently these materials have very low electrical conductivity which is characteristic of insulators. For materials with band gaps only several electron volts,
sufficient thermal excitation will give a high electrical conductivity and the materials are classified as semiconductors. Conductor materials, such as metals, have almost overlapping bands of energies, therefore their electrical conductivity is very high at room temperature.

In the absence of thermal excitation, by cooling down the materials to liquid nitrogen temperature, semiconductors would have no free electrons, and would not show any electrical conductivity. The passage of ionising radiation raises electrons from the valence band to the conduction band, leaving positive holes in the conduction band. If an electric field is applied, the electrons and the holes are drifted towards the positive and negative electrodes, respectively. As a result a pulse is induced in the external circuit, and radiation detection is possible.

Semiconductor materials always contain impurities. There are two types of impurity, namely, pentavalent and trivalent atoms. If pentavalent atoms of, for example, phosphorus (P), arsenic (As) or antimony (Sb) replace the tetravalent atom of silicon or germanium, each atom provides one extra electron which does not form a covalent bond. Instead, these electrons occupy energy levels just below the conduction band and therefore are easily thermally excited to the conduction band and free to move through the crystal, even at low temperatures. This type of impurity is known as a donor. If trivalent atoms, such as boron (B), aluminium (Al), gallium (Ga) or indium (In)
replace the tetravalent host atoms, then a number of covalent bonds are missing. These vacancies easily attract valence electrons and generate positive holes. This type of impurity is known as an acceptor. Materials tend to have equal numbers of each type of impurity but they can be doped with one particular type of impurity to create a larger majority of that type. Crystals doped with pentavalent impurities are known as n-type, whereas crystals doped with trivalent impurities are known as p-type.

3.6.2 Lithium drifted detector.

An alternative method to produce 'intrinsic like' crystals is by compensation. In this process, impurity ions of the opposite type to those already present are introduced. The charge carriers of each type annihilate and the electric field of the two ion types cancel out to produce the equivalent of an intrinsic material.

If lithium ions are drifted into the lattice of a p-type crystal of silicon or germanium, under a reverse bias, they are attracted deep into the p-type material and tend to form neutral pairs with negative acceptor ions, creating a very thick and uniformly compensated depletion layer. These type of detectors are known as Si(Li) and Ge(Li).

The Ge(Li) detector has some fundamental advantages over
the Si(Li) detector. The higher atomic number makes a Ge(Li) detector more efficient for a larger range of gamma-ray energies. Because of the considerably lower energy band gap (0.67 eV), and so lower energy required to produce an electron-hole pair, the Ge(Li) detector has better energy resolution than the Si(Li) detector (energy gap of 1.12 eV). Finally, the higher charge-carrier mobility leads to a faster charge collection time.

3.6.3 Intrinsic germanium detector.

A major practical disadvantage of Ge(Li) detectors is that the lithium ions diffuse through the crystal at room temperature, resulting in a loss of compensation within the intrinsic region, therefore they must be operated and continuously stored at liquid nitrogen temperature.

At present a large volume high purity germanium (HPGe) with a level of impurity as low as $10^7$/mm$^3$ can be achieved. The absence of lithium compensation allows HPGe detectors to be stored at room temperature. The small energy band gap still suggests the operation of HPGe detectors at the liquid nitrogen temperature.
3.6.4 Gallium arsenide and cadmium telluride.

Besides silicon and germanium, there are several semiconductors which could produce useful radiation detectors. The most promising are the covalently bonded binary compounds of Group III-V and Group II-VI elements. These include gallium arsenide (GaAs) and cadmium telluride (CdTe).

The energy gaps of GaAs and CdTe are 1.43 eV and 1.5 eV, respectively. These allow the operation of these detectors at room temperature. But the large energy gap and the purity achievable combine to give poor energy resolution. The small sizes of the crystals make this type of detector suitable for constructing arrays of detectors of imaging systems for the detection of low energy photons in the region of several keV.

3.7 Conclusions.

From the discussion above, it can be concluded that there is no perfect detector for either neutrons or gamma-rays for the purpose of this work.

BF-3 proportional counter neutron detectors have the advantages that the discrimination of gamma-rays is easy and have smaller 'wall effect' compared with He-3 proportional counters. On the other hand, He-3 proportional counters have greater detection efficiency. Furthermore, as in the case of the neutron detector
employed in this work which was collimated to 1 mm diameter, the neutron always fell on the centre of the detector window, and this effectively reduced the 'wall effect'.

Examination of several sections of interest of the objects in neutron transmission tomography sometimes is necessary. For this purpose, the use of a collimated neutron detector is time consuming, unless an array of such detectors is used. Position sensitive detectors, such as multiwire proportional counters and film-emulsions are more suitable. The spatial resolution of the multiwire proportional counter limits its applications to large objects where details and quantitative results are not important. The data obtained are in digital form therefore they are readily reconstructed. This makes the process faster. A combination of converter foils and film-emulsions gives better spatial resolution but the reconstruction process becomes longer since digitisation of the film density is required. The limited dynamic range of film makes the technique not suitable to image objects containing materials which are largely different in macroscopic cross-section. More advanced techniques use a scintillation screen, such as NE421 and a combination of LiF and ZnS, coupled with a video camera and a dedicated computer. The automation process of the projection data acquisition is paid by the high cost of the system.

The choice in a given application of gamma-ray detectors most often revolves about trade off between detection efficiency and energy resolution. Sodium iodide scintillators have the advantage of availability in large sizes, which together with the high
density of the material, can result in very high detection efficiency. The energy resolution of scintillators is poor compared with that of germanium detectors. The smaller sizes available and lower atomic number of germanium give low detection efficiency.

Germanium detectors are clearly preferred for the detection of multienergy gamma-ray spectra. The choice is less obvious when only a few gamma-ray energies are involved, particularly if measurement of the intensity rather than an accurate energy determination is the prime objective. Then the greater efficiency, larger photofraction and lower cost of sodium iodide may well tip the balance in its favour. Nowadays HPGe detectors can be made in sizes approaching those achieved by Ge(Li) detectors. The only difference between Ge(Li) and HPGe in the practical consideration is that HPGe can be stored at room temperature.

If an array of gamma-ray detectors is required (see another possibility of performing NCPGET in Chapter VI), small sizes of detectors, such as CdTe, BGO and GaAs, are more suitable. Because of the small size of the detectors, they are efficient for the detection of low energy photons only.

In this work an He-3 proportional counter and an HPGe detector were employed for the detection of neutrons and gamma-rays, respectively.
Chapter IV
PRINCIPLES OF RECONSTRUCTIVE TOMOGRAPHY
AND IMAGE ANALYSIS

The aim of tomography is to view a section or layer of an object clearly, without interference from underlying or overlying regions. This can be achieved by a technique known as Reconstructive or Computerised Tomography. In this section the principles of reconstructive tomography are discussed briefly.

4.1 Basic principle.

The principle of reconstructive tomography is illustrated in Figure IV.1. The object a) is made up of multiple square blocks. The values of blocks are 1 and 0 for the white and the black respectively. Projections can be obtained by passing a beam of ionising radiation through the blocks and measuring the transmitted radiation. For simplicity, the projections are represented by the number of blocks in each row. The horizontal sums (called raysums) are shown on the right, while the vertical raysums are shown below the object. A set of raysums is called a projection. If the horizontal and vertical projections are added, a numerical reconstruction of the object is produced (Figure IV.1.b). A gray or colour scale value is then assigned to the numerical reconstruction to produce an image (Figure IV.1.c).
4.2 Mathematical representation of the reconstruction problem.

An (X,Y) coordinate system is used to describe a distribution of a physical quantity of interest on the plane under investigation. Let \( f(X,Y) \) be the density function which represents the value of the physical quantity at any point in the reconstruction region (Figure IV.2). The integral of \( f(x,y) \) along a line \( L(r,\theta) \) is called the raysum and is given by

\[
p(r,\theta) = \int_{L(r,\theta)} f(x,y) \, ds
\]

The problem is now to solve the equation for \( f(x,y) \) with a prior knowledge of \( p(r,\theta) \) from physical measurements. The data may be
obtained for transmission imaging, that is transmission of a beam through the object, or for emission imaging when radiation emitted by the object is detected externally. Ideally \( f(x,y) \) must be a continuous two-dimensional function and an infinite number of projections would be required for perfect reconstruction. In practice, \( f(x,y) \) is calculated at a finite number of points from a finite number of projections.

![Figure IV.2. Projection-measurement geometry. The raysum \( p(r,\theta) \) is the line integral of the physical quantity of interest along a line \( L(r,\theta) \).](image)

4.3 Image reconstruction algorithms.

Many mathematical approaches have been used. The mathematics of these algorithms have been reported by several authors elsewhere (Bro-76, Bar-81, Her-80, Kou-82). They can be classified into three groups: Simple back-projection, Iterative methods and
Analytical methods.

4.3.1 Simple back-projection.

Simple back-projection is the earliest method of image reconstruction, sometimes called the summation method. The method is illustrated in Figure IV.3. A circular object is scanned (projected) at five different angles (a), in practice many more would be required. The reconstruction is performed by smearing or back-projecting each profile across the reconstruction plane (b).

![Diagram](image)

Figure IV.3. Diagramatical approach to the simple back-projection method.

a) Projections are taken. b) Projections are back-projected, the image shows 'star' artefact.

The process may be described by the equation

\[ f(x,y) = \sum_{j} p(r, \theta_j) \Delta \theta \]

VI-2
where $\Theta_j$ is the $j^{th}$ projection angle, $\Delta \Theta$ is the angular distance between projections and the summation extends over all $m$ projections.

The technique does not produce a good reconstruction. This is due to the fact that each raysum is applied to all points along the ray, therefore that points outside the original object receive some contribution from the raysum and give rise to the 'star' artifact around a point of high density. In addition, points within the object receive contributions from the neighbouring points so that the density values obtained in equation IV-2 are not the true densities indicated in equation IV-1.

4.3.2 Iterative reconstruction.

In this method, the reconstruction area is broken up into an $n$ by $n$ array of cells or pixels with density values $f_i(x,y)$. Each projection is made up of $n$ raysums whose widths is usually chosen as equal to that of the pixel (Figure IV.4). The raysums are made up of the contributions of pixels intersected by the ray, i.e. for the $j^{th}$ ray, the raysum $P_j$ is expressed by

$$P_j = w_{1j}f_1 + w_{2j}f_2 + \cdots + w_{Nj}f_N$$
Figure IV.4. Diagramatical illustration of the Iterative reconstruction method.

\[ p_j = \sum_i w_{ij} f_i \]  \hspace{1cm} \text{IV-3}

where \( w_{ij} \) is the weighting factor that represents the contribution of the \( i \)th pixel to the \( j \)th raysum \( p_j \). Equation IV-3 is another form of equation IV-1 which has to be solved for \( f_i \) if \( p_j \) is measured in the experiment. The basic principle of solving equation IV-3 by the iterative method is to apply corrections to arbitrary initial pixel densities in order to match the measured raysums. The procedure is as follows, first, a uniform density distribution is assumed and projections are calculated from this starting density value. When, for example, a calculated raysum is too small compared with the measured value, the density value of each pixel that contributes to this raysum is increased by an appropriate amount, according to the formula being used. When this has been done for all pixels and
raysums, the first iteration is complete. This procedure is then repeated until the calculated raysums agree with the measured raysums within the desired accuracy. If the starting density value is zero everywhere, the first iteration is equivalent to a simple back-projection.

The iterative methods can be grouped into three groups according to the sequence in which corrections are made and incorporated during an iteration: the Iteration Least Square Technique (ILST), the Algebraic Reconstruction Technique (ART) and the Simultaneous Reconstruction Technique (SIRT).

4.3.2.1 ILST

This technique is also known as the Simultaneous Correction technique. In this technique all projections are calculated at the beginning of the iteration, and all pixels are corrected simultaneously. This, however, leads to an overcorrection, as each pixel is recorrection for every raysum passing through it, the result is an oscillation about the correct value. A damping factor can be applied to all corrections so as to produce the best least squares fit after each iteration. The technique is illustrated in Appendix 2 for the simple case of a four pixels object.
4.3.2.2 ART.

This technique is similar to ILTS but with a difference approach. At the beginning of each iteration, one raysum is calculated and corrections are applied to all pixels that contribute to the ray. This procedure is repeated for a second ray, a third and so on, always embodying previous corrections in each new calculation, until all raysums in all projections have been treated, thus completing one iteration. An example of this method is illustrated in Appendix 3. Since the corrections are performed ray by ray, this method is also called the ray by ray correction method.

4.3.2.3 SIRT.

The technique begins with a particular pixel for all raysums that contribute to this pixel. Other pixels are then treated the same way except that corrections made during the iteration are embodied in succeeding calculations. Each pixel receives a correction in proportion to its current density. This is performed by multiplying the current density by the ratio of the measured to the calculated raysum. This technique is also known as the point by point correction method.
4.3.3 Analytical methods.

The methods are based on the direct solution of equation IV-1 for the density function \( f(x,y) \). Because the number of raysums, the number of projections and the image reconstruction plane, in practice, are limited therefore the spatial resolution of the image is also limited. If projections are sampled at the same interval \( d \), then the image produced will contain no spatial frequencies (wave numbers) greater than \( k_m = 1/2d \). The density function \( f(x,y) \) should always be zero outside the reconstruction plane. All analytical methods are basically equivalent. They can be categorised into two groups: Two dimensional Fourier reconstruction and Filtered back-projection.

4.3.3.1 Two dimensional Fourier reconstruction.

The density function \( f(x,y) \) can be expressed as a superposition of sinusoidal waves by taking its two dimensional Fourier integral.

\[
f(x,y) = \iint \mathcal{F}(k_x, k_y) \exp[2\pi i (k_x x + k_y y)] \, dk_x \, dk_y \quad \text{IV-4}
\]

The parameter \( k_x \) and \( k_y \) are the wave numbers in the \( x \) and \( y \) directions, respectively. The inverse Fourier transform of equation IV-4 gives the Fourier coefficient \( \mathcal{F}(k_x, k_y) \).
By rotating the \((X, Y)\) axis to the new axis \((R, S)\) (Figure IV.5) by an angle of rotation \(\theta = \tan^{-1}(k_x/k_y)\) and defining \(k = (k_x^2 + k_y^2)^{1/2}\) the equation IV-5 can be simplified as

\[
F(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \exp[-2\pi i (k_x x + k_y y)] dx \, dy \quad \text{IV-5}
\]

Note that the integral of \(f(x, y)\) is just the raysum \(p(r, \theta)\), as given by equation IV-1, so that

\[
F(k_x, k_y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \exp(-2\pi i k r) dr \, ds \quad \text{IV-6}
\]

The Fourier transform of \(p(r, \theta)\) with respect to \(r\) is given by

\[
P(k, \theta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(r, \theta) \exp(-2\pi i k r) dr \quad \text{IV-8}
\]
It means that each Fourier coefficient or wave amplitude $F(k_x,k_y)$ of the density function is equal to a corresponding Fourier coefficient of the projection taken at the same angle as the Fourier wave

$$F(k_x,k_y)=p(k,\theta) \quad \text{IV-9}$$

From the derivation above, the procedure of image reconstruction in this method can be summarised as follows: first, take the one-dimensional Fourier transform of projections (equation IV-8) then interpolate to provide a two-dimensional array of Fourier coefficient (equation IV-9) and finally take the inverse two-dimensional Fourier transform of the Fourier coefficient (equation IV-4) to get the density function $f(x,y)$. This procedure is shown diagramatically in Figure IV.6.

4.3.3.2 Filtered back-projection.

Filtered back-projection is also known as the convolution method. It is similar to that of simple back-projection. In this method, all projection data are filtered or convolved (using suitable filtering formulae) before they are back-projected, to produce an image free of 'star' artifacts. The formulae are of various types and have been reported elsewhere (Bro-76,Bar-81,Her-80,Kou-82) Basically these can
be classified into three variations according to which mathematically equivalent filtering formula is used: Fourier filtering, Radon filtering, and Convolution filtering.

4.3.3.2.1 Fourier filtering.

The Fourier integral in equation IV–4 can be expressed in polar coordinates

$$f(x,y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(k_x,k_y) \exp[2\pi ik(x \cos\theta + y \sin\theta)] k \, dk \, d\theta$$ IV–10

By replacing $F(k_x,k_y)$ with $P(k,\theta)$ as in equation IV–9 and $(x \cos\theta + y \sin\theta)$ with $r$, equation IV–10 can be written as
\[ f(x,y) = \int_0^1 p^*(r,\theta) \, d\theta \quad \text{IV-11} \]

where

\[ p^*(r,\theta) = \int_{-\infty}^{\infty} \delta_{k1} P(k,\theta) \exp(2\pi ikr) \, dk \quad \text{IV-12} \]

In practice, equation IV-11 is replaced in its discrete form, since the projection data are obtained at discrete intervals imposed by the physical size of the detectors, the collimators and the finite number of projections.

\[ f(x,y) = \sum_{j=1}^{m} p^*(r_j,\theta_j) \, d\theta \quad \text{IV-13} \]

where \( m \) is the number of projections and \( d\theta \) is the angular interval between each projection. It is interesting to note that essentially equation IV-13 is similar to the equation IV-1 of simple back-projection method, except that the filtered projection \( p^* \) is back-projected.

This method can be summarised as follows: a Fourier transform of a projection is taken (equation IV-8) then each coefficient, \( P(k,\theta) \), multiplied by the magnitude of the spatial frequencies \( |k| \); its inverse Fourier transform, \( p^*(r,\theta) \) is taken (equation IV-12) and this is finally back-projected onto image plane using interpolation (equation IV-13) and those steps are repeated for all projections. The procedure is also explained diagrammatically in Figure IV.7. The aim of
filtering is to increase the high frequency components in accordance with their spatial frequency and this produces a biphasic function with average value zero (Bro-76).

Figure IV.7. Principles of the filtered back-projection algorithm.

4.3.3.2.2 Radon filtering.

The convolution theorem states that the Fourier transform of a product is equal to the convolution of the individual Fourier transform. It can be seen that equation IV-12 represents the Fourier transform of the product of two functions, /k/ and P(k,θ). The Fourier transform of P(k,θ) is p(r,θ) (equation IV-8), and the Fourier transform of /k/ is -1/2πr (Bro-1976). Applying the convolution theorem to equation IV-12 should therefore
Integration by part of this equation produces

\[
\frac{d^2}{\partial r^2} p^*(r, \theta) = \frac{1}{2 \pi^2} \int_{-\infty}^{\infty} \frac{dp(r', \theta)}{(r-r')^2} dr'
\]

The reconstruction procedure is exactly as that for the Fourier filtering, except that a different filter is now used.

4.3.3.2.3 Convolution filtering.

The singularity at \( r=r' \) in equation IV-14 leads to the inaccuracy of the result in the computer implementation. Effectively, this is caused by the factor \( k/\) of which the Fourier transform contains factor \( 1/r \). As mentionned in the beginning of this discussion \( k/\) is equal to zero for \( k=0 \), therefore if this is applied to the Fourier transform of \( k/\) this will result in

\[
\int_{-K_m}^{K_m} |k| \exp(2\pi ikr) \, dk = K_m \sin(2\pi K_m \cdot) - \frac{\sin^2(K_m r)}{\pi^2 r^2}
\]

IV-15
Using the convolution theorem as before, we get
\[ p^*(r, \theta) = \int_{-\infty}^{\infty} p(r', \theta) \left[ \frac{k_m \sin[2\pi k_m (r-r')]}{\pi (r-r')} - \frac{\sin^2[\pi k_m (r-r')]}{\pi^2 (r-r')^2} \right] dr' \] \hspace{1cm} \text{IV-16}

Various approaches have been used to solve this integration (Bra-1967, Ram-1971, Led-1974). The equation can be simplified as
\[ p^*(r, \theta) = k_m p(r, \theta) - \int_{-\infty}^{\infty} p(r', \theta) \frac{\sin^2[\pi k_m (r-r')]}{\pi^2 (r-r')^2} dr' \] \hspace{1cm} \text{IV-17}

In the implementation:

\[ k_m = \frac{1}{2d} \]

where \( d \) is the sampling interval

\[ \frac{\sin^2[\pi k_m (r-r')]}{(r-r')} = 0 \quad \text{for} \quad (r-r') \text{ even multiple of } d \]

\[ = 1 \quad \text{for} \quad (r-r') \text{ odd multiple of } d \]

Thus in its discrete form, equation IV-17 becomes
\[ p^*(r_i, \theta) = \frac{p(r_i, \theta)}{4d} - \frac{1}{\pi^2 d} \sum_{\substack{j=\text{odd}}}^{n} \frac{p(r_j, \theta)}{(i-j)^2} \] \hspace{1cm} \text{IV-18}

The procedure can be summarised as follows: First, filter a projection (equation IV-18) then this filtered
projection is back-projected (equation IV-13), and finally repeat for all projections.

4.3.4 Conclusions.

There is no single algorithm that is perfect in all conditions. The choice of reconstruction algorithm is usually based on the speed, accuracy and the simplicity of its implementation. In general, iterative methods are better suited to high contrast objects than analytical methods (Her-73). This is particularly so when the number of projections is small in relation to the number of raysums per projection. Bracewell and Riddle (Bra-71) suggested that the minimum number of projections, \( m \), required to fully determine the density values is

\[
m = n \frac{\pi}{4} \tag{IV-19}
\]

where \( n \) is the number of raysums per projection. The iterative methods are expected to be superior to the analytical methods when the input data are noisy.

The analytical methods are simple in their computer implementation, and are faster than the iterative methods. The data from each projection can be processed independently of the other projections. This makes the whole process of the reconstruction even faster when an on-line processing is
employed.

ART is the most efficient method among the iteration methods, because it incorporates corrections during the iteration, whereas convolution filtering is the simplest and fastest method of the analytical methods.

In this work, convolution filtering was employed because of its simplicity, particularly when implemented on a microcomputer.

4.4 PSF, LSF and MTF.

The spatial resolution of an imaging system is determined by its ability to resolve two adjacent point objects. One of the criteria to measure the spatial resolution of a system is by determining the full-width-at-half-maximum (fwhm) of an image produced from a small point object. The image response against distance is called the point spread function (PSF). If the object is a straight line instead, the image response is known as a line spread function (LSF). Basically, LSF is equivalent to the PSF integrated along one direction. Thus, mathematically the LSF can be expressed as

\[ L(x) = \int_{y} P(x,y) \, dy \]
where \( P(x,y) \) is the PSF in the \((x,y)\) plane.

![Diagram](image)

Figure IV.8. a) Experimental ESF. b) Fitted ESF. c) PSF derived from the ESF.

The LSF is one dimensional, therefore it is easily treated mathematically and graphically. The LSF can be obtained by imaging a narrow slit but this is impractical since it is impossible to obtain an infinitely thin line source or narrow slit. However, if one part of the slit is removed, then an indirect determination of the line spread function can be undertaken. In practice the LSF is obtained by imaging a sharp, opaque, knife-edge object. The image response across the edge is referred to as the unsharpness curve or the edge spread function (ESF). If \( E(x) \) is the ESF of the system, it has been shown that the slope of the ESF at a point \( x \) gives the value of the LSF, \( L(x) \), at that point (Lam-58)
The LSF can therefore be obtained in three steps (Figure IV.8.)

a. Experimental determination of ESF.
b. Mathematical representation of ESF, i.e. by fitting the experimental curve with a function

\[ \text{ESF}(x) = \frac{1}{2} + \frac{1}{\eta} \tan^{-1} u(x-x_0) \]  

where \( u \) is determined in the fitting process.
c. Differentiation of it with respect to \( x \) gives

\[ \frac{dE(x)}{dx} \]

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a. Experimental determination of ESF.
b. Mathematical representation of ESF, i.e. by fitting the experimental curve with a function

\[ \text{ESF}(x) = \frac{1}{2} + \frac{1}{\eta} \tan^{-1} u(x-x_0) \]  

where \( u \) is determined in the fitting process.
c. Differentiation of it with respect to \( x \) gives

\[ \text{LSF}(x) = \frac{u/\eta}{1 + u^2(x-x_0)^2} \]  

Another way to describe the performance of an imaging system is by its spatial frequency response, known as modulation transfer function (MTF). An ideal imaging system is one which has a constant MTF for the entire spatial frequency spectrum. In other words, an ideal imaging system reproduces images from objects without any loss of informational content. The MTF can be evaluated experimentally with a test object in which the distribution of the physical quantity of interest varies
sinusoidally with known spatial frequency $f$. MTF is then calculated as the ratio of the output modulation to the input modulation.

$$\text{MTF}(f) = \frac{M_o}{M_i}$$  \hspace{1cm} \text{IV-24}

where $M_i$ and $M_o$ are the input and output modulation respectively.

$$M_i = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$  \hspace{1cm} \text{IV-25}

and

$$M_o = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$  \hspace{1cm} \text{IV-26}

where $I_{\text{max}}$ and $I_{\text{min}}$ are the maximum and minimum intensity of the response.

The MTF can also be calculated analytically. It has been shown mathematically (Oze-75) that the MTF is the Fourier transform of the LSF.

$$\text{MTF}(f) = \int_{-\infty}^{\infty} \text{LSF}(x) \exp(-2\pi i f x) \, dx$$  \hspace{1cm} \text{IV-27}

By substituting LSF($x$) as given in equation IV-11, the MTF is found to be...
\[ \text{MTF}(f) = \exp(-2 \pi f u) \]  

The important feature of the MTF is its cascading property; if an imaging system is a linear system and can be separated into several subsystems of individual \( \text{MTF}_i \) \((i=1, \ldots, N)\) the total MTF is given by (Kou-82)

\[ \text{MTF} = \text{MTF}_1 \cdots \text{MTF}_i \cdots \text{MTF}_N \]  

4.5 Image contrast.

Brightness is the psychological concept associated with the amount of light stimulus. Due to the great adaptive ability of the eye, absolute brightness cannot be accurately judged by the human eye. Two images of equal intensity do not appear equally bright, but depend on the immediate surround which gives different contrast, therefore a quantitative measure of contrast is necessary in image analysis. The term contrast is to emphasize the difference in intensity of images.

Several definitions of contrast have been given by Hall (Hal-79). In psychology, contrast \( C \) refers to the ratio of the difference in intensity of an object \( I_o \) and the immediate surround \( I \)
A contrast measurement commonly used in optics describes the contrast $C$ of a spatial frequency grating as

$$
C = \frac{I_0 - I}{I} \quad \text{IV-30}
$$

where $I_{\text{max}}$ and $I_{\text{min}}$ are the maximum and minimum intensities of the profile. In imaging systems, this contrast is also known as contrast range or contrast ratio. A definition of image contrast which is equivalent to signal to noise ratio is given by Sanders (San-84) as

$$
C = \frac{I_{\text{max}} - I_{\text{min}}}{(I_{\text{max}} + I_{\text{min}})^{1/2}} \quad \text{IV-32}
$$

again $I_{\text{max}}$ and $I_{\text{min}}$ are the maximum and minimum intensities of the profile.
CHAPTER V.
NEUTRON TRANSMISSION TOMOGRAPHY
AND
NEUTRON CAPTURE PROMPT GAMMA-RAY EMISSION TOMOGRAPHY.

5.1 Introduction.

Experiments in neutron transmission tomography and neutron capture prompt gamma-ray emission tomography were carried out using a horizontal neutron beam of a high flux reactor during a period of two weeks on two occasions in July 1984 and January 1986.

The high flux reactor (HFR) at the Institut Laue-Langevin, Grenoble, France operates at a thermal power of 57 MW and provides a high intensity neutron beam predominantly for neutron scattering and diffraction instruments. In order to extend the experimental facilities available on the HFR, nine neutron beams are carried by internal reflection within curved neutron guides into an adjacent experimental hall. The guides have differing radii of curvature which determine the maximum neutron energies propagated along each guide.

The experiments described here were performed at the end position of a thermal neutron guide (H22) with a radius of curvature of 27 km. The curved guide ends at a distance of
approximately 110m from the reactor core after which the neutron beam travels a further 4m through a straight evacuated beam tube to the end experimental position. The schematic plan view of the experimental arrangement is shown in Figure V.1 and the photograph of this arrangement is shown in Figure V.2. The neutron beam emerges from an up stream experiment and LiF collimators reduce the beam dimension to 20 mm high x 12.5 mm wide. An evacuated beam tube surrounded by 30 mm of paraffin wax loaded with 50 percent \( \text{Li}_2\text{CO}_3 \) extends to the scanning rig position. The thermal neutron flux at this position was \( 1.8 \times 10^{12} \text{ n/m}^2/\text{s} \).

![Figure V.1. The schematic plan view of the experimental arrangement.](image)
5.2 Neutron transmission tomography.

Neutron tomography, based on the CT technique has been studied by several workers and reviewed in chapter I. Most of the studies were intended for the purpose of nuclear fuel examination.

The only basic difference between gamma-ray transmission tomography and neutron transmission tomography is that in gamma-ray transmission tomography the image is a representation of the distribution of the photon linear attenuation coefficient in the slice of interest, whereas in neutron transmission tomography the distribution of the total macroscopic cross-section of elements is the physical quantity being imaged.

The purpose of this study is to produce tomographic images.
using neutrons in transmission, where various modes of detection and recording of data for reconstruction of images are compared. A gamma-ray transmission tomography scan of the same object was also performed for comparison. In this section, the basic principles of neutron transmission tomography are also discussed.

5.2.1 Formation of raysum in neutron transmission tomography.

The principles of neutron transmission tomography are similar to that of X- and gamma-ray transmission tomography. Consider a well collimated thermal neutron beam of flux $\phi_0$ which traverses an object as shown in Figure V.3. The transmitted flux, $\phi$, is measured using a collimated neutron detector. This can be expressed using equation II-7 where the total macroscopic
cross-section in this case is a function of position since the object is inhomogeneous, therefore

\[ \Phi(r,\theta) = \Phi_o \exp(-\int \Sigma(x,y) \, ds) \quad \text{V-1} \]

by taking the natural logarithm of both sides we get

\[ \ln \frac{\Phi(r,\theta)}{\Phi_o} = -\int \Sigma(x,y) \, ds \quad \text{V-2} \]

Substituting \( \Sigma \) for \( f \) in equation IV-1, the raysum is given by

\[ p(r,\theta) = -\ln \frac{\Phi(r,\theta)}{\Phi_o} \quad \text{V-3} \]

The neutron flux is proportional to the counts recorded by the detector i.e. for proportional counters, the flux is given by (Far-83)

\[ \Phi = \frac{1.128 \, I}{\sigma N \, V \, t} \quad \text{V-4} \]

\[ = k \, I \]

(assuming Maxwell Boltzmann statistics and for neutron energies less than 30keV)

where \( I \) : detector counts

\( t \) : time of counting (s)
\( \Phi \) : neutron flux \((n \text{ mm}^{-2} \text{s}^{-1})\)

\( \sigma \) : microscopic cross-section of filling gas (barn)

\( N \) : density of filling gas (atoms/mm\(^3\))

\( V \) : sensitive volume of the counter (mm\(^3\))

Thus

\[
\Phi_0 = k I_0
\]

and

\[
\Phi(r, \theta) = k I(r, \theta)
\]

where \( I(r, \theta) \) and \( I_0 \) are the detector counts with and without the object, respectively. Hence equation V-3 becomes

\[
p(r, \theta) = -\ln \frac{I(r, \theta)}{I_0} \tag{V-5}
\]

The measurement of \( I \) and \( I_0 \) can be performed in various ways as will be discussed in the next sections.
5.2.2 Experiments in neutron transmission tomography.

5.2.2.1 Instrumentation.

Three ways of recording the projections of the test object were employed; in the first, a single collimated He-3 proportional counter recorded neutrons transmitted through the object at each position and for each angle of projection. In the second case, a conventional converter/film combination in a single cassette was employed to produce radiographs and thus obtain projections of the test object. Finally, a 35mm camera was modified to incorporate a neutron converter so that sequential radiographs of the object could be obtained more rapidly. Figure V.4 shows the experimental setup.

In the case where the projection data are obtained using a converter/film combination, a digitiser is required to convert the projection data into digital form so that reconstruction of the images can be performed. In this study, a computerised video camera-based microdensitometer was employed with a spatial resolution of 12 pixels per millimeter and a 256 gray/colour scale. The photograph of the microdensitometer system is shown in Figure V.5.

The system consists of a light box, a Philips 50 video camera, a Pluto frame grabber, a colour monitor, and a
computer. The film to be digitized is placed on the light box, the picture of this film is grabbed by the video camera and stored into the computer memory in digital form of 256 by 256 pixels. The selected line on the picture can be scanned and the data obtained are stored in a separate file for reconstruction. The pictures are stored in a negative images therefore a conversion has to be carried out before reconstruction.

In the preliminary experiments, the system was tested to produce a tomographic image of a sparkplug. The projection data were recorded on Fuji RX films in direct mode employing a gadolinium foil of 0.025 mm thickness placed in contact with the film in a light tight cassette. Thirty projections
Figure V.5. Photograph of the microdensitometer system.

of the sparkplug were obtained for every 6 degrees of rotation. Figure V.6 shows the projection obtained at 0 degrees (a) and the photograph of the cross-section of the sparkplug (b). The tomographic image of the section shown by an arrow in Figure V.6 was then reconstructed and displayed in 16 by 16 pixel in Figure V.7.

In the next experiments the test object, a cylinder of 10mm diameter, was made of teflon. Two holes of 5 mm diameter each, were drilled perpendicularly to the axis of the cylinder. In one hole brass and copper rods were placed, separated at the centre by a cadmium foil of 0.1mm thickness, with foils of 0.05mm thickness of silver and 0.24mm thickness of indium fixed at the outer ends of the rods. The other
Figure V.6. a) A projection of the sparkplug object obtained at 0 degrees; the section shown by the arrow was reconstructed. b) The photograph of the cross-section being reconstructed.
hole was filled with copper and perspex rods only with no foils at the ends or the centre. The photograph of the object and the cross-section of the section of interest are shown in Figure V.8.
Figure V.8. a). Photograph of the test object for neutron transmission tomography experiments. b). The diagram of the section of interest.
5.2.2.2 Neutron transmission tomography using a well collimated He-3 detector.

In neutron transmission tomography experiments, ideally, both the neutron beam and the neutron detector are collimated. However, in these experiments the beam was open, covering an area of 12.5 mm by 20.0 mm, in order to compare with the case when radiographs were taken (Figure V.9). Furthermore, there is a difficulty of accurate alignment if the neutron beam and the neutron detector are collimated. An He-3 proportional counter, 25.4 mm diameter, active length of 101.6 mm, was collimated to 1 mm diameter using enriched Li-6 in a Li$_2$CO$_3$ plate of 2 mm thickness. A cadmium knife-edge object of 0.5 mm thickness was scanned to examine the spatial resolution of the system. The Edge Spread Function (ESF), Point Spread Function (PSF) and the Modulation Transfer Function (MTF) are shown in Figure V.10.

The neutrons transmitted through the object were recorded at each position and for each projection angle for a counting time of 40 s. Fifteen projections of the section (i.e. for every 12 degrees of angle of rotation) were obtained, each projection being made up of nineteen raysums. The image, reconstructed using a filtered back-projection algorithm, is shown in Figure V.11.

The detector count rate was quite high, therefore a correction for the dead time was necessary. In order to do
Figure V.9. The collimated He-3 detector scans the object, then the object is rotated through a small angle and the detector scans the object again; this is repeated until the object has rotated through 180 degrees.

so, the dead time was measured in a separate experiment.

Consider a beam of neutrons passing through a material of thickness $x$ and total macroscopic cross-section $\Sigma$, and let $I_0$ be the uncorrected detector counts without absorber, $I_0'$ be the corrected detector counts without absorber, $I$ be the uncorrected detector counts with absorber, $I'$ be the corrected detector counts with absorber.

Therefore we have the relation

$$I' = I_0' \exp(-\Sigma x)$$

or
Figure V.10. The ESF a), PSF b) and the MTF c) of the collimated Be-3 detector.
Figure V.11. The reconstructed image obtained using the Re-3 detector.

\[ \ln\left( \frac{I'}{I_{o}'} \right) = -\Sigma x \]  \hspace{1cm} V-6

Assuming the nonparalysable model (Kno-79), the corrected count-rates are given by

\[ I' = \frac{I}{1-tI} \] \hspace{1cm} V-7

and

\[ I_{o}' = \frac{I_{o}}{1-tI_{o}} \] \hspace{1cm} V-8
where \( t \) is the dead time of the detector. By substituting equations V-7 and V-8 into equation V-6, the dead time \( t \) is given by

\[
t = \frac{I - I_0 \exp(-\Sigma x)}{I_0 \Sigma [1 - \exp(-\Sigma x)]}
\]

The experiment was carried out for different thicknesses of several materials. Thin foils of gadolinium, silver, dysprosium, and indium were used and the dead time \( t \) was found to be \((25\pm1)\mu s\).

5.2.2.3 Neutron transmission tomography using a conventional converter/film combination.

The conventional converter/film combination technique still maintains its favour in neutron transmission tomography. The advantage over the collimated proportional counter is that it records the projection of the whole object instead of a single section of the object. The disadvantage of this technique is that it requires an open beam which increases the contribution of the scattered neutrons to the projection being recorded.

In this experiment, a single film/converter combination was placed in a light tight cassette. Fuji RX film and a
0.025mm thick foil of gadolinium as the direct converter were employed.

A knife-edge object, made of cadmium plate 0.5mm thick, was radiographed to examine the geometrical unsharpness of the system. The graphs of the ESF, PSF and MTF are shown in Figure V.12, V.13, and V.14, respectively.

Thirty projections of the test object for 10 second exposures per projection over 180 degrees of rotation of the object were obtained by replacing the exposed film with unexposed film for each projection. The radiographs obtained were then digitised using the computerised video camera-based microdensitometer. Forty four raysums per projection were used to reconstruct the section of interest.

5.2.2.4 Neutron transmission tomography using a modified 35mm camera.

The conventional film/converter combination technique is time consuming unless a set of film/converter combinations in separate cassettes is used. The system becomes very expensive, therefore a 35mm camera was considered and modified to incorporate a neutron converter so that sequential radiographs of the object could be obtained more rapidly without disturbing the geometrical arrangement between beam, object and recording medium. The modified
Figure V.12. ESF of the converter/film system.

Figure V.13. PSF of the converter/film system.

Figure V.14. MTF of the converter/film system.
camera is shown diagramatically in Figure V-15. The neutron beam was incident on the back of the camera (the lens system was not used) and the gadolinium converter foil of 0.025mm thickness was placed in contact with the light sensitive part of the film, the exposed and unexposed film not directly in

Figure V.15. A diagram a) and photograph b) of the modified 35mm camera.
the neutron beam area was shielded from background gamma-rays using lead blocks. Ilford HP5, ASA 600, 35mm film was used and developed using a fast developer ('microphen') in order to increase the film speed. Thirty projections of the same object were obtained for a 10 second exposure per projection. Again, the radiographs obtained were digitised using the microdensitometer. The same section of interest as in the experiment using the conventional converter/film combination was reconstructed.

5.2.2.5 Gamma-ray transmission tomography.

A gamma-ray transmission tomography experiment of the same section of the same object as in neutron transmission tomography experiments was also performed. An 241Am source, 21Bq (200mCi) activity, was collimated to 1mm diameter using a lead collimator. The full energy peak of the 60 keV line was recorded using a 50.8mm by 50.8mm NaI(Tl), again collimated to 1mm diameter. Thirty projections of the object were obtained being made up of 44 raysums per projection.
5.2.2.6 Discussion and conclusion.

The three regions in the section of interest of the sparkplug test object are clearly distinguished in the tomographic image as shown in Figure V.7. The outer cylinder was made of nickel (Ni), the inner cylinder was made of iron (Fe) and in between was a ceramic material (Al$_{203}$Si$_{13}$). These three regions also can be distinguished by examining the variation of the macroscopic cross-section through the tomographic image. When the macroscopic cross-section was calculated from reconstructed data and compared with the expected value of the total macroscopic cross-section there was severe disagreement. However when the macroscopic absorption cross-section was used for comparison instead, agreement with experimental values was found to be within 10 percent.

The reconstructed image obtained using the collimated He-3 detector is shown in Figure V-11. This represents the distribution of the total macroscopic cross-section in the section. It is displayed on a matrix of 19 by 19 pixels. The right hand side of Figure V-11 represents a line scan taken from the top to the bottom of the image, and shows the variation of the macroscopic cross-section along the line. The three materials, indium, cadmium and silver can be distinguished in the image as well as in the line scan, however the values of the calculated total macroscopic cross-section obtained do not agree with tabulated ones (Von-81). This is mainly due to the partial volume effect.
since the foil thicknesses are 0.24, 0.1 and 0.05 mm for indium, cadmium and silver, respectively whereas the pixel size is 1 mm by 1 mm. Teflon, brass and copper could not be differentiated in the image. The system was not sensitive enough to detect differences between their total macroscopic cross-section (3, 5 and 9 mm\(^{-1}\), respectively). Furthermore, the solid angle subtended by the collimated He-3 proportional counter was large (0.628 steradian) so that a significant fraction of scattered neutrons was also recorded. This in turn degrades the image. The effect becomes more apparent in the case where photographic emulsion is used since the film/converter combination acts as an open, bare and unshielded detector which receives information from both scattered and transmitted neutrons.

The counting statistics of the data obtained from the digitisation of the radiographs is poor. This is due to the maximum gray level available being only 256. To overcome this problem, a number of adjacent sections could be added together for reconstruction, alternatively many picture frames, typically more than 250 frames, could be grabbed (Fuj-84, Yon-86). The latter is better because the reconstruction involves a single section only so that the effect of blurring caused by the overlying and underlying sections can be avoided. However the digitiser system used has not been programmed to do so. The images reconstructed using a single section and seven sections are shown in Figure V.16 and Figure V.17 for the Fuji RX and Ilford HP5 films,
respectively. It can be seen that the image reconstructed using seven sections is less noisy. This improvement can be explained as follows; The variance on the image reconstructed using the filtered back-projection algorithm is proportional to the variance of the raysums (Kou-82)

$$\sigma_i^2 = \sigma_r^2 \left( \frac{\pi}{12} d_1^2 M \right)$$

where $\sigma_r^2$ is the variance of the raysums, $d_1$ is the spatial sampling interval and $M$ is the number of projections. For the same number of projections and the same spatial sampling interval, the statistical error of the reconstructed image can be improved by reducing the statistical error of the raysums. This can be done by increasing the number of counts in the raysums (i.e., by increasing the counting time). This cannot be applied for the case when the film/converter combination is used because the dynamic range of the film is limited. However, the error in this can ideally be improved by taking the observation of each raysum several times. It has been shown in error analysis that as the number of observations increases, the estimation of the true value becomes more accurate (Bev-69). It can also be shown that the relative error of the sum of the observed values equals relative error of the mean of the observed values. Let $S_i$ be the $i$th observed value with an error $dS_i$, therefore for $N$ observations the sum $S$ is given by
Figure V.16. The images reconstructed using single section a) and seven sections b) for the Fuji RX film.
The mean value is

\[ S = \sum_{i=1}^{N} S_i \]  

\[ V-11 \]

with an error

\[ dS = \left( \sum_{i=1}^{N} dS_i^2 \right)^{\frac{1}{2}} \]  

\[ V-12 \]

and the relative error is

\[ \frac{dS}{S} = \frac{\left( \sum_{i=1}^{N} dS_i^2 \right)^{\frac{1}{2}}}{\sum_{i=1}^{N} S_i} \]  

\[ V-13 \]

The mean value is

\[ \bar{S} = \frac{1}{N} \sum_{i=1}^{N} S_i \]  

\[ V-14 \]

and its standard deviation is given by

\[ d\bar{S} = \frac{1}{N} \left( \sum_{i=1}^{N} dS_i^2 \right)^{\frac{1}{2}} \]  

\[ V-15 \]

Hence, the relative error is found to be

\[ \frac{d\bar{S}}{\bar{S}} = \frac{\left( \sum_{i=1}^{N} dS_i^2 \right)^{\frac{1}{2}}}{\sum_{i=1}^{N} S_i} \]  

\[ V-16 \]
Figure V.17. The images reconstructed for the Ilford HP5 film.
   a) using a single section b) using seven sections.
which is the relative error of the sum as given in equation V-14. For 7 measurements, the relative error was found to be \(1/\sqrt{7}\) better than that of single measurement.

The image reconstructed from the gamma-ray transmission tomography experiment is shown in Figure V.18. This represents the linear attenuation coefficient distribution in the section for the gamma-ray of energy 60 keV. The result does not show the structure of the object. This can be explained as follows. The minimum detectable length \(l\) of a material with a linear attenuation coefficient \(\mu_c\) in a matrix with a linear attenuation coefficient \(\mu_r\) of length \(L\) is determined by (Kou-82)

\[
\frac{1}{L} = \frac{\mu_r}{\mu_c - \mu_r} \cdot f
\]

where \(f\) is the expected contrast or the expected fractional change in the raysum. In this experiment, the minimum detectable length of cadmium, indium and silver was found to be for all three elements 2mm for a ten percent change in the linear attenuation coefficient of the teflon matrix (i.e. \(f=0.1\)) whereas the thicknesses of the foils used were considerably less than the minimum detectable length found.
5.3 Neutron capture prompt gamma-ray emission tomography (NCPGET).

The technique of gamma-ray emission tomography has been applied to objects following irradiation by neutrons in order to image the distribution of isotopes and therefore elements within the object employing the characteristics of the radionuclides produced on irradiation (Dav-1985, Spy-1985, Bal-1986). In the case when very short-lived, very long-lived or stable isotopes are produced, this technique is not suitable. In considering that prompt gamma-rays
are emitted by the object on neutron capture during irradiation, as discussed in chapter (II), a new technique of tomography has been studied and developed in this work. Principles, experiments and problems are presented in this section.

5.3.1 Formation of raysums in NCPGET.

The technique is based on the principles underlying gamma-ray emission tomography where gamma-rays emitted by the object are detected and their distributions are imaged.

Consider a well collimated thermal neutron beam of flux $\Phi_0$ which traverses an object and induces through neutron capture prompt gamma-rays within it (Figure V.19). Assuming that a
narrow-beam geometry is maintained along the line $L(r, \theta)$ and using equation (II-13), the number of prompt gamma-rays of interest induced along this line per unit time is given by

$$N(r, \theta) = \int_{L(r, \theta)} \Phi_o Y f A_o \sigma m(x, y) \frac{ds}{A}$$  \hspace{1cm} \text{(V-17)}

provided that the neutron flux does not vary along its length, otherwise the flux is also a function of position i.e. $\Phi_o(x, y)$. In the equation:

- $y$: yield of prompt gamma-rays of interest.
- $f$: fractional abundance of the isotope.
- $m(x, y)$: mass of element at point $(x, y)$ in the plane.
- $A_o$: Avogadro's number.
- $\sigma$: microscopic capture cross-section of the nucleus.
- $A$: atomic weight of the element of interest.

The number of gamma-rays detected is:

$$D(r, \theta) = \epsilon N(r, \theta) t$$ \hspace{1cm} \text{(V-18)}

where $\epsilon$ is the efficiency of the gamma-ray detector and $t$ is the time of counting and equal to the time of irradiation. By substituting equation V-17 into V-18, we get

$$D(r, \theta) = \int_{L(r, \theta)} \frac{\epsilon \Phi_o Y f A_o \sigma m(x, y) t}{A} ds$$ \hspace{1cm} \text{(V-19)}
and this can be written as

\[ \frac{D(r,\theta) A}{\varepsilon \phi_0 t \sigma A_0 f Y} = \int m(x,y) \, ds \]  

Using equation (IV-1) and substituting \( m \) for \( f \), the raysum is given by

\[ p(r,\theta) = \frac{D(r,\theta) A}{\varepsilon \phi_0 t \sigma A_0 f Y} \]

5.3.2 Correction for flux depression.

Equation (V-21) is derived by assuming that the neutron flux is constant along its path length. As neutrons traverse the object, they undergo interactions with the nuclei along the path length and the flux will change accordingly.

![Figure V.20. A one-dimensional representation of neutron flux depression.](image)
Consider a one dimensional coordinate, \( x \) (Figure V.20).
Let \( N \) be the number of nuclei per unit volume. The neutron flux at a point \( x \) is given by

\[
\phi(x) = \phi_0 \exp(-\Sigma x)
\]

where \( \phi_0 \) is the neutron flux at \( x=0 \) and \( \Sigma \) is the mixture total macroscopic cross-section. Using equation (II-3) the reaction rate in element \( dx \) is

\[
dR = N A \, dx \, \sigma \, \phi(x)
\]

where \( A \) is the beam area

\[
dR = N A \, \sigma \, dx \, \phi_0 \exp(-\Sigma x) \, dx
\]

Integration of equation V-23 above over total length \( L \) gives the total reaction rate

\[
R = N A \, \sigma \phi_0 \frac{1 - \exp(-\Sigma L)}{\Sigma}
\]

whereas the true total reaction rate, where the neutron flux is expected to be constant, is given by

\[
R_{true} = N A \, L \, \sigma \phi_0
\]
From equation V-24 and equation V-25, the correction factor \( R_{\text{true}}/R \) is expressed as:

\[
\text{CF} = \frac{\sum L}{1-\exp(-\sum L)} \quad V-26
\]

The correction is applied to every raysum before reconstruction where the value of \( \sum L \) can be found from the measurement of the transmitted neutrons.

A more accurate correction can be applied to each pixel, by considering equation V-19 and replacing \( \phi_0 \) with \( \phi(x,y) \) as a function of position

\[
D(r,\theta) = \frac{\mathcal{E} \phi(x,y) \int A \sigma m(x,y) \, ds}{\mathcal{J}(r,\theta)} \quad V-27
\]

By separating all the constants to the left hand side we get

\[
\frac{D(r,\theta)}{\mathcal{E} \sigma A \int Y \mathcal{J}(r,\theta)} = \int \phi(x,y) m(x,y) \, ds \quad V-28
\]

It can be seen in this equation that what has been reconstructed is the distribution of the product of the neutron flux \( \phi(x,y) \) and the mass of element \( m(x,y) \). The flux \( \phi(x,y) \) can be calculated if the distribution of the total macroscopic cross-section \( \Sigma(x,y) \) is known. In this case, the flux is the sum of fluxes derived from raysums passing through the pixel to
be corrected. Thus, the neutron flux at pixel \((x,y)\) is given by

\[
\phi(x,y) = \sum_i \phi_0 \exp \left( -\sum_j S_{ij} \right)
\]

where \(S_{ij}\) is the weighting factor. The correction is applied after reconstruction of both neutron transmission and neutron capture prompt gamma-ray emission data and therefore needs a considerable amount of extra computer memory. This type of correction was considered unsuitable for implementation in a microcomputer with very limited memory.

5.3.3 Correction for gamma-ray attenuation.

The problem of photon attenuation always occurs in emission tomography, especially for low energy photons in a high density material. The effect of photon attenuation is loss of the information content. This is due to the fact that the intensity of gamma-ray detected is not the true intensity emitted by the object. Various methods of photon attenuation compensation in single photon emission tomography have been suggested by several authors. Budinger et al (Bud-79) suggested a least squares method for variable and constant attenuation. In this method, the raysums are discretely expressed as the summation of pixel activity concentration multiplied by attenuation factor between the pixel and the edge of the object. The distribution of the linear attenuation coefficient is determined from a transmission
experiment or may be assumed constant. They also suggested the geometric means method. The corrected raysums is the square root of the product of the raysum and its conjugate. Sorenson (Sor-74) applied a correction technique called the hyperbolic sine correction. It involves correcting the conjugate means of raysums by a factor that assumes a constant attenuation coefficient. Kay and Keyes (Kay-75) suggested that the summation of two opposing raysums can be written as

\[ p(r,0) + p(-r,0 + \pi) = \int_{0}^{L} f(r,\theta,1)[\exp(-\mu l) + \exp(-\mu(L-1))]dl \tag{V-30} \]

where \( L \) is the total length of the path of the photon through the attenuating medium along the conjugate point and \( l \) is the distance between the pixel being corrected to the surface of the gamma-ray detector. Again assuming constant attenuation, the minimum value of the exponential factor is \( 2\exp(-\mu L/2) \) and its maximum value is \( (1+\exp(-\mu L)) \). By averaging these two values, the corrected raysum is given by

\[ p'(r,\theta) = \frac{2[p(r,0) + p(-r,0 + \pi)]}{1 + \exp(-\mu L) + 2 \exp(-\mu L/2)} \tag{V-31} \]

Budinger (Bud-79) took the average value of the factor \( [\exp(-\mu L) + \exp(\mu(L-1))] \) in equation V-30 which gives the corrected raysum as
Walters et al (Wal-76) proposed an algorithm for constant and variable attenuation in an iterative convolution method. First, the projection data are modified by convolving them with a convolver. Then the modified data are back projected. The resulting image is then re-projected with a compensation factor. The difference between the original measured projection data and the attenuated projections are evaluated and convolved with the same convolver as before and then back projected giving the correction factors of activity concentration. Finally, these correction factors are subtracted from the previously reconstructed image giving a new approximation of the intensity distribution. The procedures are repeated until a certain value of the correction factors has been reached. Gullberg et al (Gul-85) used a similar approach with attenuation factors calculated for each pixel during the projection and back projection operations instead of using precalculated values.

Attenuation compensation in single photon emission tomography remains a complex subject. It is even more complicated in the case of neutron capture prompt gamma-ray emission tomography. None of the methods of attenuation compensation suggested is applicable in neutron capture prompt gamma-ray emission tomography, because the nature of raysum formation is different (see Figure V.1). A simple approach to attenuation compensation is suggested here. After the
reconstruction, each pixel on the image plane contains the intensity attenuated by a factor that is a function of the attenuation coefficient between the pixel and the detector. To simplify the problem, the attenuation factor is calculated along the line that connects the pixel and the centre of the detector surface. Thus the attenuation factor for the ith pixel at the mth projection is given by (see Figure V.21)

\[ A_i^m = \exp \left( \sum_{i,j} L_{i,j}^m \mu_{i,j} \right) \]

where \( L_{i,j}^m \) is the length of that portion of the line mentioned above for projection m. All pixels are corrected at each angle of projection. The attenuation coefficient \( \mu_{i,j} \) can be determined from a transmission experiment or may be assumed.
constant.

5.3.4 Experiment in NCPGET

In this experiment the neutron beam discussed in section 5.1. was further collimated to 1 mm diameter using 12 mm thick LiF, in order to act as a probe to induce prompt gamma-rays in a section of the object. Gamma-rays emitted by nuclei of interest along this probing beam were then recorded using a high resolution HPGe detector positioned at 90 degrees to the neutron beam and on the central axis of rotation of the object. The detector has 23 percent efficiency, resolution of 1.75 keV and a peak to Compton ratio of 60:1 for gamma-rays of 1.332 MeV. The detector was protected from scattered neutrons by 4 mm of LiF at the end face of the detector and apart from the aperture which allows the detector to 'view' the object, the detector was surrounded by 30 mm Li$_2$CO$_3$/wax and 50mm lead.

It is possible to acquire the gamma-ray spectra and to store them on a magnetic tape using a Canberra Series 80 MCA. Hence the distribution of elements present in the object can be imaged. In most of these experiments, only one photopeak of interest and its scattering region were selected by using two SCA windows and their output was fed into counters and subsequently stored onto floppy disk through a BBC-B microcomputer, 32K memory, interfaced with the counter using an
IEEE interface. An He-3 proportional neutron detector was employed to measure the transmitted neutrons. This detector was collimated to 1 mm diameter using 12 mm thickness of 'flex/boron'. It is also possible to measure the transmitted neutrons and emitted gamma-rays simultaneously as shown in Figure V.22. The scanning movements as well as the data acquisition were controlled by the BBC microcomputer under one package computer program written in a combination of BASIC and assembly languages.

5.3.5 Measurements.

In the preliminary experiment the test object was made up of two
Cylinders, an inner cylinder of 5 mm diameter and 0.5 mm thickness made of cadmium and an outer cylinder of 14 mm diameter and 1.5 mm thickness made of polyethylene. Both cylinders were completely filled with lead shot of 3 mm diameter. The cross-section of the test object is shown in Figure V.23.

![Figure V.23. The cross-section of the test object.](image)

Cadmium has a high radiative neutron capture cross-section in the neutron energy range 0 to 0.5 eV due to $^{113}$Cd ($12.3\%$ isotopic abundance). The effective cadmium microscopic cross-section for thermal neutron is about 2450 barns. The capture of thermal neutrons by the nucleus of $^{113}$Cd is followed by prompt emission of a cascade of gamma-rays in which the strongest intensity is that of the transition 559 keV from the first excited state of Cd to the ground state. The yield of these gamma-rays is about 80 per 100 neutrons captured in natural cadmium. The prompt gamma-ray spectrum, resulting from neutron capture and including the 559 keV gamma-ray line of
cadmium was recorded for a counting time of 500s per raysum. A complete projection of the object comprising 21 raysums was obtained by translating the object in front of the probing beam in 1 mm step intervals, maintaining fixed geometry between beam and gamma-ray detector. The spectra were then analysed by using a computer program to determine full energy photopeak areas and the 559 keV gamma-ray line was used to image the distribution of cadmium in the slice of interest of the object. In this case, the transmitted neutrons were not recorded, and the correction of the neutron flux depression was performed using literature values of the macroscopic cross-sections of the matrix (Von-83).

In the second stage of the experiment, the characteristics of the system were examined. The point spread function of the collimated neutron beam was measured by scanning a pellet of CdCl2 of diameter 7 mm at positions 70, 100 and 140mm away from the collimator and the 559 keV prompt gamma-ray line of cadmium was again recorded. The detector response against position for various distances of the pellet is shown in Figure V.24. It can be seen from this graph that the point spread function of the collimated neutron beam is the same at the various distances used. The full width at half maximum of these responses was found to be 7.0±0.8mm which is equal to the diameter of the pellet. This shows that the beam collimation was very effective and the beam was parallel.

The spatial resolution of the collimated He-3 proportional counter was also examined by measuring its step-edge function.
A cadmium plate, 1mm thickness, was scanned across the neutron beam. The detector response against the position of the cadmium plate was plotted and it is shown in Figure V.25. The spatial
resolution or unsharpness of the system was calculated using 'Klasens' method (Kla-56) in which a straight line is drawn to cut the 'S' shaped detector response curve at 0.16 times the range of detector response. The projection of this line on the maximum and minimum plateau lines of the density curve gives the unsharpness value of the system as 0.40±0.05 mm (see Figure V.25).

At this stage of the work, it was intended to test the spatial resolution of the tomographic system and also the effect of the attenuation of the gamma-rays by the matrix material on the tomographic image produced. Two cylindrical test objects were used, one of lead and one of aluminium each of diameter 40mm, containing pellets of cadmium chloride of 7mm diameter. The pellets were placed along the diameter of the cylinder, one at the centre and the other two on either side with axis to axis distances of 9 and 14mm respectively. The photograph and the diagram of the cross-section of the test objects are shown in Figure V.26. The test objects were scanned in tomographic mode (translation and rotation) in order to obtain 45 projections of a section through the object over 360 degrees angle of rotation, each comprising of 45 raysums counted for 30 seconds per raysum. Two energy windows of equal size were set. One at the photopeak (559 keV) prompt gamma-ray line of cadmium and the other at an energy just below, in order to estimate the contribution of the dynamic background as well as that due to scattered photons (San-83) from higher energies. Figure V.27 and V.28 show the projections of the test objects made of Al and Pb respectively,
Figure V.26. a) The cross-section of the test object for NCFGET and b) the photograph of the test objects.

which were obtained at 0 and 180 degrees.

Neutron transmission tomography of the same slice through the objects was also performed in order to obtain the distribution of the macroscopic cross-section of the objects in the slice. This information was subsequently used for neutron
Figure V.27. Projections of the test objects taken at 0 and 180 degrees for Al matrix.
flux depression correction. It is desirable in these experiments to have both the neutron beam and the neutron detector collimated maintaining narrow beam geometry, however, in order to overcome the problem of alignment the neutron beam was opened and the collimated neutron detector was placed as close as possible (65mm) to the object so as to improve the solid angle subtended between the collimated detector and the object plane.

5.3.6 Discussion and conclusion.

As the aim of this work is to study and develop the technique of neutron capture prompt gamma-ray emission tomography, evaluation of the results is based on comparison of the images produced with those expected (i.e. the test objects) both qualitatively and quantitatively.

The first test object was scanned to obtain one projection only and by assuming that the object was symmetrical (cylindrical shape) 36 such projections were used representing projections of the object at every 10 degrees of rotation. The reconstructed image is shown as a 21x21 matrix of pixels in Figure V.29. This represents the distribution of cadmium in the section being imaged. The variation of the cadmium
Figure V.28. Projections of the test objects taken at 0 and 180 degrees for Pb matrix.
concentration along a diameter is also shown in the same figure. The red spot at the centre of the image is an artifact due to a build up error; an error accumulated during the reconstruction since exactly the same projections were used. From the image produced, the diameter of the cadmium cylinder was found to be 5.7±1.0mm. The effect of using the same projections is also reflected in the regularity of the image produced due to the
lack of statistical fluctuation from projection to projection.

The images of the second test object shown in Figure V.26, were reconstructed with and without flux depression corrections and shown in Figure V.30 and Figure V.31 for lead and aluminium matrices, respectively. The top left hand corners are reconstructed images of the raw data without any correction and the bottom left hand corners are images corrected for background and by a neutron flux depression factor. The right hand columns in Figure V.30 and Figure V.31 are their corresponding line scans across the images found in the left hand columns. The line scan represents the variation of the concentration of the element of interest, cadmium in this case, along the line drawn. The three CdCl₂ pellets are not well resolved, however, when the flux depression correction is applied, these three pellets can be distinguished clearly. This can also be observed in the line scan where the diameter of the pellets is found to be 7mm and their separation is 2mm and 5mm (Figure V.30 and Figure V.31 bottom right hand corners).

The image contrast was calculated with respect to the central pellet using equations IV-31 and IV-32. The results are listed in Table V.1. for the aluminium and lead objects, corrected and uncorrected for neutron flux depression, for expected and experimental values.
Table V.1. The expected and experimental image contrast for Al and Pb objects.

<table>
<thead>
<tr>
<th>Image contrast</th>
<th>Expected</th>
<th>Experiment</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncorrected</td>
<td>Corrected</td>
<td></td>
</tr>
<tr>
<td>Al  Pb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a.</td>
<td>0.012 0.027</td>
<td>0.036 1.6</td>
<td>0.12 2.5</td>
</tr>
<tr>
<td>b.</td>
<td>0.028 0.042</td>
<td>0.042 0.2</td>
<td>0.08 6.8</td>
</tr>
<tr>
<td>a.</td>
<td>0.2 0.7</td>
<td>0.17 0.31</td>
<td>0.7 0.3</td>
</tr>
<tr>
<td>b.</td>
<td>0.6 1.1</td>
<td>0.13 0.03</td>
<td>0.5 0.9</td>
</tr>
</tbody>
</table>

a: central to farther pellet contrast  
b: central to closer pellet contrast

There is severe disagreement between the expected and experimental contrast especially when equation IV.32 was used. However, when the contrasts were calculated using equation IV.31, they agreed within an order of magnitude with the expected values, particularly for the contrasts calculated from the corrected images.
Figure V.30. Tomographic images of cadmium distribution in Pb object with and without flux depression corrections.

Figure V.31. Tomographic images of cadmium distribution in Al object with and without flux depression corrections.
CHAPTER VI

CONCLUSION AND SUGGESTIONS FOR FURTHER WORK.

It has been shown that tomographic images obtained in transmission mode using the collimated He-3 proportional counter are better than those obtained using either the conventional combination of film/converter in a single cassette or the 35 mm camera. This is due to the better quantum noise of the He-3 detector system and reduction of the effects of neutron scattering by collimation.

In neutron transmission tomography employing a He-3 proportional counter, the use of a good collimation system is necessary. A precision positioning device e.g. a rail system used in optics, should overcome the problem of alignment between beam and detector. Additional collimation of the neutron beam and neutron detector will further reduce the effects of neutron scattering and will in turn improve the contrast and spatial resolution of the system.

Redesign of the 35mm camera system to give better contact between converter and film thus diminishing scattering of the emitted radiation should be possible; it has been shown that the best unsharpness of a converter/film combination is achieved at zero separation (Oze-75). The experiment time can be further reduced by controlling the film winding mechanism using the microcomputer and synchronising it with the rotation of the object as well as the beam shutter. Such a system would then be preferable to the single cassette converter/film combination.
It has been shown that the tomographic image produced using film emulsion is noisy unless several adjacent sections are added together for reconstruction. This means that the section being imaged becomes thicker and overlying and underlying sections may cause a blurring of the image produced. The method of reducing image noise by grabbing several picture frames is considered as the best solution. The software of the microdensitometer system needs to be upgraded for future work.

Problems involving inspections such as complete, irradiated reactor fuel assemblies provide strong motivation for the practical development and use of neutron transmission tomography.

The experiments have shown that the technique of neutron capture prompt gamma-ray emission tomography can be used to image the distribution of an element of interest in the section being imaged. The spatial resolution of the system is good as shown in Figure V.30 and V.31. However the technique is unsuitable to image an object containing very thick neutron absorber material as it would severely attenuate the beam. This is a common problem not only for neutron but also for photon transmission tomography.

The sensitivity or the minimum detectable limit of the system has not been investigated. The minimum detectable limit in this case would vary from element to element. It depends on the capture cross-section of the element, neutron flux and also the matrix material. The minimum detectable limit can be evaluated in the experiment by varying the concentration of the element of interest and
measuring the image contrast produced. Plot of concentration against image contrast should give an indication of the detection limit of the system.

It can be seen in Figure V.27 and Figure V.28 that photon attenuation affects the projection data and consequently the images produced do not represent the actual elemental concentration. In this work photon attenuation compensation has not been carried out. The compensation method suggested should be tested and a more accurate method of photon attenuation compensation still needs to be developed. Again this problem arises in all applications of photon tomography, whether in the medical field or elsewhere.

There is also the possibility of performing neutron capture prompt gamma-ray emission tomography in other modes. The gamma-ray detector, neutron detector and neutron beam are collimated. The data collection can be performed in two ways. In the first, the data are collected by linear stepping of the object followed by a linear stepping of the gamma-ray detector or in the second, by raster motion of the object (Figure VI.1). The advantages of both modes are that they do not require a reconstruction algorithm to produce a tomographic image and the photon attenuation compensation as well as flux depression corrections become simpler. The only disadvantage is that since the gamma-ray detector is collimated, its total detection efficiency becomes small. This in turn increases the counting time required per pixel and so the total experiment time. Unless an array of detectors or a position sensitive detector is employed, the total time may become prohibitively long.
Figure VI.1. The other possible modes of performing neutron capture prompt gamma-ray emission tomography.

It may be possible to acquire and store the whole gamma-ray energy spectra rather than regions of interest onto a magnetic tape using a Canberra series 80MCA or onto a floppy disk of the BBC B microcomputer by incorporating for example an ADC buffer Ortec ADCAM system. Hence, the distribution of isotopes (elements) present in the section of interest can be evaluated in a single experiment.

An example of application of neutron capture prompt gamma-ray emission is diffusion studies for materials such as boron and lithium in either metals or semiconductors.
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### APPENDIX 1

Table 1. The characteristics of some possible Neutron Radiography Converter Material (Von-81).

<table>
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<tbody>
<tr>
<td>Abundance %</td>
<td>of Active isotope</td>
<td>section life section</td>
<td>Type</td>
<td>Max. energy, Mev.</td>
<td></td>
</tr>
<tr>
<td>D Lithium</td>
<td>7.4</td>
<td>Li(n,a)H</td>
<td>935</td>
<td>stable</td>
<td>4.7</td>
</tr>
<tr>
<td>D Boron</td>
<td>19.5</td>
<td>B(n,a)Li</td>
<td>3837</td>
<td>stable</td>
<td>2.3</td>
</tr>
<tr>
<td>D Rhodium</td>
<td>100</td>
<td>Rh(n,7)Rh</td>
<td>144</td>
<td>43 s</td>
<td>2.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rh(n,n)Rh</td>
<td></td>
<td>57 min X-ray</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rh(n,7)Rh</td>
<td>11</td>
<td>4.4 min</td>
<td>0.5</td>
</tr>
<tr>
<td>D Silver</td>
<td>51.4</td>
<td>Ag(n,7)Ag</td>
<td>44</td>
<td>2.4 min</td>
<td>1.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ag(n,7)Ag</td>
<td></td>
<td>B</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ag(n,7)Ag</td>
<td>110</td>
<td>24.5 s</td>
<td>2.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ag(n,7)Ag</td>
<td>3</td>
<td>254 d</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ag(n,7)Ag</td>
<td></td>
<td>B</td>
<td>0.66</td>
</tr>
<tr>
<td>D Cadmium</td>
<td>12.3</td>
<td>Cd(n,7)Cd</td>
<td>20000</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td>T Indium</td>
<td>95.7</td>
<td>In(n,γ)In</td>
<td>45</td>
<td>14 s</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In(n,γ)In</td>
<td></td>
<td>B</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In(n,γ)In</td>
<td>154</td>
<td>54min</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In(n,γ)In</td>
<td></td>
<td>B</td>
<td>0.42</td>
</tr>
<tr>
<td>D Samarium</td>
<td>13.9</td>
<td>Sm(n,γ)Sm</td>
<td>41500</td>
<td>stable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>26.6</td>
<td>Sm(n,γ)Sm</td>
<td>210</td>
<td>46.7 h</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sm(n,γ)Sm</td>
<td></td>
<td>B</td>
<td>0.1</td>
</tr>
<tr>
<td>D Gadolinium</td>
<td>14.7</td>
<td>Gd(n,γ)Gd</td>
<td>58000</td>
<td>stable</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>15.7</td>
<td>Gd(n,γ)Gd</td>
<td>240000</td>
<td>stable</td>
<td>0.13</td>
</tr>
<tr>
<td>T Dysprosium</td>
<td>28.1</td>
<td>Dy(n,γ)Dy</td>
<td>800</td>
<td>2.3 h</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dy(n,γ)Dy</td>
<td>2000</td>
<td>1.26min</td>
<td>1.04</td>
</tr>
<tr>
<td>T Gold</td>
<td>100</td>
<td>$^{197}\text{Au}(n,\gamma)^{198}\text{Au}$</td>
<td>98.8</td>
<td>2.69 d B</td>
<td>0.962</td>
</tr>
<tr>
<td>--------</td>
<td>-----</td>
<td>---------------------------------</td>
<td>------</td>
<td>---------</td>
<td>-------</td>
</tr>
</tbody>
</table>

D = direct method  
T = transfer method
APPENDIX 2

A numerical illustration of the ILST algorithm.

a.

\[
\begin{array}{cc}
5 & 7 \\
6 & 2 \\
\end{array}
\]

\[
\begin{array}{cc}
13 & 11 \\
9 & 7 \\
\end{array}
\]

\[
\begin{array}{cc}
0 & 0 \\
0 & 0 \\
\end{array}
\]

b.

c.

\[
\begin{array}{cc}
5.0 & 5.6 \\
5.3 & 4.0 \\
\end{array}
\]

\[
\begin{array}{cc}
13-0 & 11-0 \\
9-0 & 7-2 \\
\end{array}
\]

\[
\begin{array}{cc}
10.9 & 10.3 \\
9.6 & 9 \\
\end{array}
\]

d.

e.

\[
\begin{array}{cc}
5.0 & 6.1 \\
5.5 & 3.3 \\
\end{array}
\]

\[
\begin{array}{cc}
13-10.9 & 11-10.3 \\
9-9.6 & 7-9 \\
\end{array}
\]

\[
\begin{array}{cc}
5.0 & 6.9 \\
5.9 & 2.0 \\
\end{array}
\]

f.
a). Original object. The original horizontal raysums are 12 and 8 and the original vertical raysums are 11 and 9 whereas the original diagonal raysums are 7 and 13. These raysums are obtained from the measurements.

b). The first estimate of the object. This can be given any value. In this example zero is chosen.

c). The first correction for error. The corrections are performed simultaneously for all the raysums in all projections. The new estimate is calculated from all the raysums passing through the pixel being corrected. When this has been done for all pixels, the first iteration is completed.

d). The second estimate of the object. The new horizontal raysums are 10.6 and 9.3 and the vertical raysums are 10.3 and 9.6 whereas the diagonal raysums are 9 and 10.9.

e). The second correction for error. It is performed in the same way as in c).

f). The image found at the end of the 9th iteration. The original distribution is still not recovered.
APPENDIX 3

A numerical illustration of the ART algorithm.

a. 

2.5 -1.0 2.5 -1.0
2.5 +1.0 2.5 +1.0

b. 

1.5 1.5
3.5 3.5

c. 

d. 

1.5 -0.5 1.5 +0.5
3.5 -0.5 3.5 +0.5

e. 

1 2
3 4

f.
a). The original object. The original horizontal raysums are 3 and 7 whereas the original vertical raysums are 4 and 6. These raysums are obtained in the measurement.

b). The initial estimate of the object. This may be given any value. It is usually zero or the average of pixel values in the original data i.e. the summation of raysums in a projection divided by the total number of pixels, in this example

\[
\frac{3+7}{4} = 2.5 \text{ or } \frac{4+6}{4} = 2.5
\]

c). The first correction for error. The horizontal projection is corrected. The correction factor are calculated as the original horizontal raysums minus the new horizontal raysums divided by two i.e.

\[
\frac{3-5}{2} = -1.0
\]

and

\[
\frac{7-5}{2} = 1.0
\]

d). The second estimate of the object. The vertical raysums of this
image are 5 and 5.

e). The second correction for error. It is done as in e) but this time the vertical raysums are corrected. The corrections are

\[ \frac{4-5}{2} = -0.5 \]

and

\[ \frac{6-5}{2} = 0.5 \]

f). The final image which is equal to the original object.