CHAPTER 1
NON-DESTRUCTIVE TESTING

In today’s rapidly growing world, the requirement of reliability is increasing day by day because new modern techniques (based upon advanced technology) are being introduced on a large scale. Non-destructive testing is the process used to examine the condition of an object without damaging it, so that the usefulness and integrity of object are not affected by investigation process. The term "non-destructive examination" (NDE) also refer to various evaluation, testing, monitoring, or inspection techniques that are performed to "examine" materials or components in ways that do not impair future usefulness and serviceability in order to detect, locate, measure and evaluate discontinuities, defects and other imperfections; to assess integrity, properties and composition; and to measure geometric characteristics [1]. In other words, Non-destructive testing (NDT) or Non-destructive Inspection (NDI), as the name imply, is technology of assessing soundness and acceptability of a material, component or structure without impairing its functional properties or ‘Worth’. NDT techniques are used in practically every engineering industry, space applications, nuclear establishments, power plants, chemical/fertilizer plants and medical field etc.

To meet these requirements, NDE can be performed using different technical methods that rely on acoustic, optical, electric, magnetic, and electromagnetic or various other properties. Acoustic techniques encompass ultrasonic testing and passive monitoring of acoustic emission. Electric and magnetic methods involve eddy currents and magnetic flux leakage methods respectively, as well as techniques involving direct measurement of electric
parameters like resistance, capacitance or inductance. Electromagnetic waves, including X-rays, gamma rays, microwaves, infra radiation, laser and natural light are also employed in NDE.

Although nuclear and atomic radiations require careful handling during their use (due to risk of exposure or contamination by potentially harmful radioactivity) even then gamma radiation based techniques are well acceptable in NDE as it is a non-intrusive, non-invasive and non-destructive examination method. Radiation can provide intrinsic properties that are not directly given by other methods, such as density and elemental composition. It can be used in harsh environments (high temperature, high pressure, corrosive, caustic, explosive, viscous media etc.), since radiation examination dose not require direct contact with inspected object. Radiation can be used with any type of medium regardless of its nature; i.e. the material can be in the form of a gas, liquid or solid, it can be conductive or insulating of heat or electricity; it can be ferromagnetic or non-magnetic, ceramic or metal, porous or impermeable, sealed or open, etc.

1.1 Need for Non-destructive testing

Material scientists and material engineers know that no material can be categorized as absolutely perfect (i.e. having zero defect). One can only minimize the amount of defect or may reduce defect size by proper selection of manufacturing processes or by improving production processes. As one has to live with the defects present in any material, component, product, system or plant without impairing their future usefulness. To meet this requirement, various NDT techniques are used [2].

Akin to medical field, where NDT is used as a diagnostic tool right from
inception of a child (ultrasonogram of child in the womb) to old age, NDT today is an inseparable part in industrial world being used from cradle to tomb of a component i.e. right from raw material stage through fabrication, during service and also to determine remaining life of component. Also, it becomes necessary to characterize the defect and obtain quantitative information about its size, shape and location so that this could serve as an input to fracture mechanics calculations for predicting remaining life of component. This need was particularly strong in nuclear, defense and space industries. This led to emergence of Non Destructive Evaluation (NDE) as a new discipline. NDE refers to quantitative inspection in which the defect is not only detected, but also characterized with respect to its size, shape and orientation. Today, a number of research programs have evolved all over world in field of NDE [3].

1.2 Benefits of NDT

The main advantage of applying NDT for material inspection, during manufacturing process and for in-service inspection is that it:

1. ensures product quality, reliability and safety
2. controls manufacturing process to within specified tolerances
3. aids in optimum product design
4. ensures uniform quality levels
5. ensures customer satisfaction
6. predicts impending failures, thus preventing costly shutdowns and aids in plant life extension

A wide range of industries/professions use NDT methods. To name a few: Nuclear, Aerospace, Automotive, Chemical, Defence, Electronics, Electrical, Fabrication, Fertilizers, Food Processing, Marine, Medical, Metal & Non-metals,
Petrochemical, Power, Security, etc. Indeed, progress of human civilization in many industrial activities would not have been possible without diagnostic NDT. The success of NDT depends on combination of Qualified Personnel, Calibrated Equipment, Documental practices and Standard Procedure and Codified Acceptance Criteria.

Efforts are currently being made by various industrial houses and research organizations to develop on-line monitoring NDT techniques i.e. NDT techniques which can inspect components/products etc. during manufacturing/service. On-line monitoring of machines, engines, turbines, railways etc. would avoid shut-downs for routine inspection and thus overhauls would become less frequent.

1.3 Types of NDT techniques

There are a number of NDT techniques which are used in various industries/organizations for NDI. Some of these NDT techniques are for certain specific applications only to suit requirement of particular industry/organizations, whereas other NDT techniques are more broad based and may be used for varied applications. The common NDT techniques [1, 2 and 3] are discussed below in brief:

1.3.1 Visual Examination (VE)

Visual examination – first stage in examination of a component is one of the simplest methods used for inspection of defects/discontinuities open to surface. The method finds wide applications for inspection of materials during various stages of manufacture. For many non-critical parts, integrity is verified principally by visual inspection. Even when other NDT methods are used, visual inspection still constitutes an important part of practical quality control. VE can
and should be performed before, during and after manufacturing process. A variety of aids are available to enhance the capabilities of visual inspection. These range from simple aids such as magnifying glass, optical microscope to fiberscopes, videoimagescopes and robotic based remote inspection systems for closely inspecting the internal of tubes, pipes and areas with limited access.

Surface lighting and angle of inspection are two of the important factors to be considered during visual inspection. The surface should be inspected at an angle which is preferably at 90° to the surface of inspection. Adequate lighting should be available on the inspection surface.

This method is low cost and can be applied while work is in progress. But is applicable to surface defects only and provides no permanent record.

1.3.2 Liquid Penetrant Testing (LPT)

LPT is one of the simplest, but highly sensitive NDT methods used for detection of defects open to the surface. The method is applicable to almost any component, large or small, of simple or complex configuration, and it is employed for inspection of wrought and cast products in both ferrous and non-ferrous metals and alloys, ceramics, glassware and some polymer components.

The principle of liquid penetrant inspection technique is based on phenomenon of capillary action. If a component is dipped into a liquid or a liquid is sprayed over the component’s surface, a part of liquid penetrates into the crack by capillary action. The part of liquid which has penetrated into the crack remains there till it is brought back to the surface by capillary action again (i.e. if one wipes-off liquid gently from component’s surface; only the liquid on component’s surface shall be wiped-off and the liquid which has penetrated into the crack, shall remain at its place).
LPT is well suited for detection of all types of cracks, laps, porosity, shrinkage areas, laminations and other similar defects open to the surface. It can be applied to any material regardless of size, shape, thickness and composition. It is highly sensitive and cost effective. But, it can not detect sub-surface defects and it is difficult to apply on rough and porous surfaces. It can not be used effectively on hot assemblies. One must also ensure that chemistry of penetrant material does not affect the inspected object. If penetrant can not reach the flaw, one can not see it.

1.3.3 Magnetic Particle Testing (MPT)

MPT is a sensitive test method used for detection of surface and sub-surface defects in ferromagnetic materials and components. It is based on the principle that when a ferromagnetic material is placed in a magnetic field, it gets magnetised. The lines of force through the material are continuous from one pole to another. When any surface or sub-surface defect is present, the magnetic field and associated lines of force get deflected and form a leakage field. This leakage field is present at and above the surface of magnetised component. Its presence can be visibly detected by utilization of finely divided magnetic particles. Dusting the surface with iron particles either dry or suspended in liquid results in the collection of magnetic particles at the discontinuity. The ‘magnetic indication’ so formed can be clearly seen and reveals the location, size and shape of the discontinuity. Magnetization of a component is accomplished using alternating current (AC), direct current (DC), Half Wave DC (HWDC), permanent magnet or electromagnets.

MPT is very effective for detection of sub-surface cracks, grinding cracks, heat treatment cracks, stinger type non-metallic inclusions, porosities, laps and
folds. The method can be applied to finished articles, billets, hot rolled bars, casting and forgings. But, it can be used only for ferromagnetic materials. Magnetic fields must be perpendicular to the plane of discontinuity. Two or more sequential inspections are required to cover all orientations of defects. Demagnetization and post cleaning following inspection is often necessary. Exceedingly large currents are required for very large parts. Thus, care is necessary to avoid local heating and burning of finished parts or surface at the points of electrical contact.

1.3.4 Radiographic Testing (RT)

Radiography is one of the oldest and most widely used NDT methods. In this method, a source of penetrating radiation such as X-rays or gamma rays is used. When these radiations pass through an object, they are differentially absorbed. The amount of radiation absorbed depends on nature of object, its composition (density) and thickness. Variations in the beam intensity are detected, normally with a sheet of photographic film. On processing the film, a permanent image is formed. The developed film is called radiograph. Possible imperfections are indicated on the film as density changes in the same manner as a medical X-ray film shows broken bones or stones in kidney. Thus during material testing, a void would appear darker since more radiation will pass through while an inclusion, because it is of higher density, will appear to be white since lesser radiation will pass through.

Radiography is widely used for inspection of welds, casting, assemblies and adhesively bonded structures, plastics, wood, composite materials and electronic components. A visual image is formed which makes interpretation easy and provides a permanent record. But, the radiography requires access
from both sides of the sample. Linear flaws (cracks) are difficult to detect. Compared with other (NDT) methods of inspection, radiography is expensive. Since radiations are hazardous, proper safety precautions are to be taken while carrying out radiography.

### 1.3.5 Ultrasonic Testing (UT)

In this inspection method, high frequency sound waves strike the object under test. During their path of travel through the material they suffer loss of energy and are reflected at interfaces. A receiver probe picks up the reflected wave, and an analysis of this signal is done to locate flaws in the object under inspection. Most of the ultrasonic inspection is done at frequencies between 0.5 and 25 MHz which is well above the audible range.

Ultrasonic can detect defects such as cracks, laminations, shrinkage, cavities, flakes, pores and other discontinuities, inclusions etc. in plates, pipes, welds, casting and forgings reliably. The technique is widely used for quality control and material inspection in all major industries. It is used very extensively for in-service inspection in nuclear and processing industries. But, manual operation requires careful attention by experienced technicians. Unfavorable geometries, parts that are rough or irregular in shape or very small are difficult to examine.

### 1.3.6 Eddy Current Testing (ECT)

Eddy current testing is based on well known phenomenon of electromagnetic induction and is applicable for non-destructive evaluation of all electrically conducting materials. When a coil carrying current is brought near an electrically conducting material, eddy-currents are induced in the material by electromagnetic induction. Magnitude of induced eddy-currents depends upon
the magnitude and frequency of alternating current; distance between current carrying coil and material under test; presence of defects or inhomogeneities in material and physical properties of material. The induced eddy-currents modulate the impedance of exciting coil or any secondary coil situated in vicinity of test material. The difference between original coil impedance and modulated coil impedance (due to presence of eddy-current) is monitored to obtain meaningful information regarding the presence of defects or changes in physical, chemical or micro structural properties.

Eddy current testing is used to measure or identify properties such as electrical conductivity, magnetic permeability, grain size, heat treatment conditions and physical dimensions. It is used to detect seam, laps, cracks, voids and inclusions (and other surface discontinuities in non-ferromagnetic material) and to measure thickness of a non-conductive coating on a conductive metal. The main limitation is its low penetration in parts being limited to thin walls or near surface flaws. The technique is difficult to use on ferromagnetic materials. Extensive technical knowledge is required for development of inspection techniques; design of specific probes and to interpret the inspection data.

**1.3.7 Computed Tomography (CT)**

The computed tomography is a radiographic inspection method that uses a computer to reconstruct an image of a cross-sectional plane of an object. It is able to reconstruct images of an object by measuring attenuation along the path of rays from X-ray source. Computed tomography (CT) techniques enable two and three dimensional external and internal visualizations of an object. The X-ray and gamma ray computed tomography is capable of providing information about the spatial distribution of mass density, atomic number and chemical species
within objects down to the micron level.

The goal of tomographic imaging in its simplest terms, is to reconstruct a two dimensional array of linear attenuation coefficients from a series of one-dimensional transmission profiles. The initial data, which is acquired in the form of intensity measurements, must be converted to projection data, which approximate the line integral of linear attenuation coefficients characterizing the material within the object. The main factors that determine imaging capabilities of a CT scanner used in engineering applications are the spatial, temporal and density resolution. Spatial resolution is the minimal distance separating two high-contrast point objects; temporal resolution refers to frequency with which the images can be obtained and density resolution refers to smallest difference in mass attenuation coefficients that the system is able to distinguish.

Gamma ray CT has many advantages over X-ray CT or ultrasonic CT in the diagnosis of large scale industrial process units. CT with a high energy gamma ray can produce a good contrast for a large-scale system. Furthermore, a sealed gamma ray source can be easily handled, installed and moved in various local plant environments.

In nuclear medicine, CT is also used to reconstruct from projected images the distribution of injected radio nuclides, emitting gamma rays. The method is called single-photon emission computed tomography (SPECT). Instrumentation usually consists of gamma cameras, which can be rotated round the patient and so generate the required set of projections for the body organ. But in positron emission tomography (PET), a compound labeled with a positron-emitting radioisotope is injected into the patient in a manner similar to that used for SPECT imaging. However, in this case, the detectors are not collimated, which
increases the overall detection efficiency and, thereby, reduce the radiation exposure to the patient.

1.3.8 Electrical impedance tomography (EIT)

Electrical impedance tomography [4] is a medical imaging technique in which an image of conductivity or permittivity of part of the body is inferred from surface electrical measurements. Typically, conducting electrodes are attached to the skin of the subject and small alternating currents are applied to some or all of electrodes. The resulting electrical potentials are measured, and the process may be repeated for numerous different configurations of applied current.

EIT is useful for monitoring patient lungs because the air has a large conductivity contrast to other tissues in the thorax. It is also being investigated in field of breast imaging as an alternative/complementary technique to Mammography and MRI for breast cancer detection. Moreover, electrical impedance tomography can reliably determine regional ventilation in healthy lungs and various models of induced lung injury when compared with CT, electron beam CT, and single photon emission CT. Medical EIT systems are not being widely used till now due to medical safety legislation but several medical equipment manufactures have started to supply commercial versions of systems developed by university research groups.

1.4 Gamma rays interaction with matter

The objective of present work is to study gamma ray techniques for non-destructive testing, so it becomes essential to have knowledge of various processes that occur during gamma rays interaction with matter. All interactions of radiation with matter occur at fundamental level of atoms or their more elementary constituents such as electrons and nuclei. There are a number of
processes which can cause the gamma rays to be scattered or absorbed in a material. Fano [5] and Siegbahn [6] provided a systematic form of these interactions. Combining the kind of interaction with their effects produced in a material, there are twelve processes by which gamma rays can be absorbed or scattered. In intermediate energy range from 10 keV to 10 MeV, the most significant processes are:

1) Photoelectric effect
2) Compton scattering
3) Rayleigh scattering
4) Pair Production

Gamma ray interaction processes (like photoelectric effect, pair production, Compton effect, coherent scattering in the intermediate energy range are taken into consideration) can be categories on the basis of absorption and scattering as shown in Fig. 1.1.

![Diagram](image)

**Fig. 1.1:** Gamma ray interaction in energy of nuclear domain.

The probability of occurrence of a particular type of process depends upon following factors:

i) energy of the incident photon
ii) scattering material

iii) scattering angle

iv) experimental conditions

The relative importance \[7\] of three major gamma ray interactions (Photoelectric effect, Compton scattering and Pair production) are shown in Fig. 1.2, which also indicates that for low-Z elements, Compton scattering dominates the other two over entire energy domain.

![Fig.1.2: Relative importance of three major gamma ray interactions.](image)

Photoelectric absorption, Compton scattering and Rayleigh scattering are the main processes to be taken into account for energy range of photons used in biomedical and industrial applications. To have more insight into these three processes, the details are given below:

**1.4.1 Photoelectric effect**

The photoelectric process (Fig.1.3-a) occurs when the incident photon (primarily of low energy) interacts with an inner orbital electron. When this
process occurs, energy of incident photon is transferred to orbital electron and the photon is completely absorbed. Since the electron is bound to atom, part of energy of photon is used for overcoming this binding energy. The balance appears as kinetic energy of ejected electron, from atom. This electron is also referred to as photoelectron. Since a vacancy now exists in one of the electron shells, an outer orbital electron will fall into that vacancy with a subsequent emission of characteristic X-rays. Photoelectric effect predominates for low incident energies (upto about 150 keV) and high atomic number materials. The atomic cross section, $\sigma_{\text{photoelectric}}$, provides absolute probability of a photoelectric interaction, and is given by

$$\sigma_{\text{photoelectric}} \propto \frac{Z^{4.5}}{\hbar \nu^{7/2}}$$  \hspace{1cm} (1.1)

The $Z^{4.5}$ dependence means that for a given photon energy this process is more pronounced in high atomic number absorbers. Also its probability increases sharply with decrease in incident photon energy.
1.4.2 Compton scattering

Compton scattering, also called incoherent scattering, is a second order process in which an incident photon having energy $h\nu$ (and wavelength $\lambda$) interacts with an electron, which is considered as free and at rest. The photon, after interaction, is scattered in a direction making an angle $\theta$ with the direction of incident photon with reduced energy $h\nu'$ (and increased wavelength $\lambda'$). The electron on the other hand, recoils at an angle $\phi$ as shown in Fig. 1.3-c. The wavelength shift for a given scattering angle is given by

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0c}(1-\cos\theta) \quad (1.2)$$

Where $m_0$ is rest mass of electron, $c$ is velocity of light and $h$ is Planck’s constant. The quantity $h/m_0c$, is known as Compton wavelength ($\Delta\lambda$) which is regarded as the wavelength of a photon whose energy is equal to rest mass energy of the electron. Eqn. (1.2) also indicates that Compton shift in wavelength increases with increase in scattering angle, but is independent of incident gamma photon energy. In sharp contrast, Compton shift in energy is strongly dependent on incident photon energy. The low energy photons are scattered with only a small energy change, but higher energy gamma photons are scattered with large energy change in Compton interactions of incident gamma photons with free electrons of scattering material. Compton scattering is predominant in the medium energy range from about 150 keV to about 1 MeV.

Applying laws of conservation of energy and momentum for photon-electron interaction in relativistic case, the energy of scattered photon is given by

$$k' = \frac{k_0}{1 + k_0(1-\cos\theta)} \quad (1.3)$$
Where \( k_0 \) and \( k' \) are energies (in \( m_0c^2 \) units) of incident and scattered photons respectively. The kinetic energy \( T \) (in \( m_0c^2 \) units) imparted to recoil electron (assumed to be initially free and at rest) is given by

\[
T = k_0\cdot k' = \frac{k_0^2(1-\cos\theta)}{1+k_0(1-\cos\theta)}
\]  

(1.4)

The kinetic energy of recoil electron is maximum when \( \theta = 180^\circ \) i.e. the photon is backscattered. The maximum kinetic energy of recoil electron is

\[
T_{\text{max}} = \frac{2k_0^2}{1+2k_0}
\]  

(1.5)

This is referred as Compton edge in scintillation spectroscopy. The angular distribution of Compton recoil electron can be obtained from directional distribution of scattered photon by using the relation.

\[
\cot\varphi = (1+k_0)\tan\frac{\theta}{2}
\]  

(1.6)

This equation gives the probability per electron of the number of photons scattered into the solid angle \( d\Omega \) in direction of \( \theta \). From this equation, it is clear that the recoil electron is always emitted in forward hemisphere. Experiments have shown that both recoil electron and scattered photons are emitted simultaneously, and also both momentum and energy are conserved in each such collision.

The probability for occurrence of Compton scattering process has been provided by Klein and Nishina [8]. Their expression for collision differential cross-section per electron per unit solid angle in direction \( \theta \) as

\[
\frac{d\sigma_{\text{KN}}}{d\Omega} = \frac{r_0^2}{2} \left[ \frac{1}{1+k_0(1-\cos\theta)} \right]^2 \left[ 1+\cos^2\theta+\left[ \frac{k_0(1-\cos\theta)}{1+k_0(1-\cos\theta)} \right]^2 \right]
\]  

(1.7)
Where $r_0$ is classical electron radius ($r_0 = e^2/m_0c^2$) having value $2.817938 \times 10^{-15}$ m. For low energy incident photons i.e. $k_0 << 1$, the eqn. (1.7) reduces to well-known Thomson scattering cross-section as below.

$$\frac{d\sigma_{TH}}{d\Omega} = \frac{r_0^2}{2} (1+\cos^2 \theta)$$

(1.8)

In most of work on Compton scattering of gamma rays, electron binding effects have usually been neglected. The justification given for this is that, for high energy photons the inner shell binding energies in low atomic number elements are small, while for high atomic number elements with larger binding energies the K-shell electrons are a small fraction of total number of electrons in the atom. The Klein-Nishina formula is applicable only when the struck electron is initially free and stationary. It is possible only when the binding energy of struck electron is negligible as compared to incident gamma ray energy, i.e. for low atomic number elements or for valence electrons of high atomic number elements. For high atomic number elements and low energy gamma rays, binding energies of inner shell electrons are not negligible as compared to incident photon energy. When the photon is scattered from bound electrons, the whole atom suffers recoil and the process becomes three body problem.

The binding energy ($B$) of atomic electron can be used to represent electron’s momentum which non-relativistically can be approximated as $\sqrt{2m_eB}$. Now if struck electron has randomly directed momentum $\sqrt{2m_eB}$ and momentum transferred to the recoil electron, which is initially free and stationary is $\sqrt{2m_eT}$, the momentum $q$ with which this electron recoils out of atom after collision may be expected to be in domain of

$$q = \sqrt{2m_eT} \pm \sqrt{2m_eB}$$

(1.9)
and corresponding kinetic energy is
\[
\frac{q^2}{2m_q} = T \pm 2\sqrt{TB} = T \left(1 \pm 2\sqrt{\frac{B}{T}}\right)
\] (1.10)

From conservation of energy, the spread of the energy of the photons Compton scattered photon at an angle will be of order of \(2\sqrt{TB}\). When the effects of Coulomb forces (which bind electrons to its atomic nucleus) are considered, there is a small but experimentally well established defect \(\delta\lambda\) in the magnitude of most probable Compton shift, so that for bound electrons Compton shift in wavelength is to be replaced by
\[
\lambda'' - \lambda = \frac{h}{m_o c} (1 - \cos(\theta)) \lambda^2 D
\] (1.11)

where \(\lambda''\) is most probable shifted wavelength. Theoretically, the defect \(\delta\lambda = \lambda^2 D\), where \(D = \frac{bB}{hC}\), with \(b\) is numerical constant of the order of unity. Physically, the defect \(\delta\lambda\) in Compton shift originates in Coulomb binding between struck electron and its atomic nucleus. The recoil electron tends to drag nucleus along with it. The nucleus and hence entire atom, acquires some of recoil momentum. The effective electron mass is slightly increased and effective value of \(h/m_o c\) is decreased slightly by this nuclear drag. Hence wavelength shift and energy shift for a given energy and scattering angle are reduced slightly. Also direction of the recoil electron is slightly altered. Due to this fact, Klein-Nishina cross-section is modified as
\[
\frac{d\sigma_c(\theta)}{d\Omega} = \frac{d\sigma_{KN}(\theta)}{d\Omega} \cdot S(x,Z)
\] (1.12)

where \(\frac{d\sigma_c(\theta)}{d\Omega}\) is the probability that the photon be deflected at a certain angle
and transfer to the electron a corresponding amount of momentum as though the electron were free, and \( S(x,Z) \) (Incoherent scattering function) expresses the probability that the atom will be raised to an excited or ionised state when the photon imparts a recoil momentum to any of the atomic electrons. The values of \( S(x,Z) \) for various values of \( x \), which is a function of incident energy and scattering angle, are given by Hubbell et al. [9] and Wang et al. [10].

1.4.3 Rayleigh Scattering

It is a process, also known as unmodified or elastic scattering, [11, 12 and references therein] in which the scattered photon has same energy as that of incident photon (Fig. 1.3-b). Here the interaction of incident photon takes place with a bound atomic electron thus enabling the atom as a whole to take up the recoil. The atom being massive, ensures that interaction takes place without transfer of energy to electron, and thus outgoing photon has same energy as that of incoming photon. The physical description is given as an interaction of electrostatic field of electron with electric vector associated with incoming photon. The induced oscillations of bound electron absorb energy of incoming photon. The re-emission of electromagnetic radiation by the electron set in motion can be in any direction but the frequency will be that of induced oscillations. Thus, this creates a change of direction but no change in energy of scattered photon. Rayleigh scattering is dominant for small incident energies and high atomic number absorbers. The cross-section for this process varies approximately as square of atomic number for small scattering angles, and as cube of atomic number for large angles.

When a photon incident upon a free electron the oscillating transverse electric field will induce the electron into sympathetic oscillations at same
frequency as of incident wave. An accelerating electric charge will emit electromagnetic radiation and hence the electron will appear to scatter radiation of same phase and frequency as that of incident beam. This phenomenon is known as classical Thomson scattering from a free electron. If electron is not free but bound in an atom then the situation is more complicated. The scattered amplitude from an atom of atomic number $Z$ is not simply $Z$ times that from a single free electron because interference effects can now take place. In this process each of the electrons in the atom will scatter. Only in forward direction do the scattered amplitudes add up in phase. In all other directions, there will be, to a greater or lesser extent, destructive interference. At increasing scattering angles, the destructive interference will increase and hence coherent scattering from bound atomic electrons will occur and the process is known as Rayleigh scattering. The resultant wave generated by an atom from elastically scattered photons is due to the combined scattering from each of the atomic electrons and is not simply summation over all electrons of scattering from a single electron. Only in the zero angle scattering direction, the wave fronts from each electron be in phase and may therefore simply be summed. At all non-zero angles, the resultant wave fronts may be out of phase and destructive interference may ensue. Consequently, the resultant elastic scattering by an atom is defined as product of elastic scattering from free electron and a quantity, which is a function of atomic number and momentum transfer, $q$. This function is known as atomic form factor $f(q, Z)$, where the momentum transfer parameter $q$ is defined as

$$hq = 2k\sin(\theta/2)$$

(1.13)

Where $k$ is wave number, $\hbar$ is the Planck constant and $\theta$ is scattering angle. This is more commonly expressed in terms of a related parameter $x$ given as
\[
\sin \left( \frac{\theta}{2} \right) = \frac{x}{\lambda}
\]

(1.14)

Where \( \lambda \) is gamma photon's wavelength. Then this atomic form factor is expressed as \( F(x,Z) \). The free atom scattering cross-section (Thomson cross-section) is then replaced by Rayleigh scattering from bound electrons which is given by

\[
\frac{d\sigma_R(\theta)}{d\Omega} = \frac{d\sigma_{\text{TH}}(\theta)}{d\Omega} \left[ F(x,Z) \right]^2
\]

(1.15)

The atomic form factor \( F(x,Z) \) is a momentum space Fourier transform of charge distribution and corrects the point charge scattering function to account for the atomic charge distribution. That is, instead of treating the scattered amplitude from an atom of atomic number \( Z \) as simply scattering from a point charge it accounts for the fact that electron cloud is spread over a finite spatial range and thus interference effects may become apparent. The values of \( F(x,Z) \) are tabulated by Hubbell et al. [9, 13, and 14] and Wang et al. [10] covering a wide range of momentum transfers.

### 1.4.4 Rayleigh to Compton scattering ratio

The combined use of Rayleigh and Compton scatterings has been proven, in particular in relation to medical and industrial applications, quite useful. One of the major advantages of this method is that by taking ratio of Rayleigh to Compton detected photons, the attenuation effects due to surrounding material can be neglected. Attenuation corrections are not necessary because Rayleigh and Compton scattered photons are attenuated approximately to the same extent by overlying material due to small energy difference between them. The simultaneous detection of Rayleigh and Compton
scattering intensities, which is possible by semiconductor detector, has lead to measurement of Rayleigh to Compton (R/C) scattering intensity ratio. Rayleigh to Compton scattering cross-section ratio becomes (from eqns. 1.7, 1.8, 1.12 and 1.15)

\[
R = \frac{d\sigma_R}{d\sigma_C} = P(k,\theta) \frac{F(x,Z)^2}{S(x,Z)} \tag{1.16}
\]

where

\[
P(k,\theta) = \frac{\left[1+k(1-\cos \theta)^2\right] (1+\cos^2 \theta)}{(1+\cos^2 \theta)+\frac{k^2 (1-\cos \theta)^2}{1+k(1-\cos \theta)}} \tag{1.17}
\]

is a constant for a given incident photon energy and scattering angle. Rayleigh to Compton scattering ratio, R, has a power relation to Z (and hence to density also) and this power dependence is based upon the ratio \(F^2/S\). Rayleigh to Compton scattering cross-section ratio decreases with increase in incident photon energy and hence low photon energy is generally preferred for these types of measurements. But for low incident energy simultaneous detection of Rayleigh and Compton scattering intensities is possible only with high resolution semiconductor detectors.

Another major advantage of this technique is that by taking intensity ratio of Rayleigh to Compton scattered photons, a number of parameters such as absolute source strength, solid angles subtended by source and detector at the target are eliminated in the expression of ratio technique, otherwise these parameters introduce large amount of error in the final measured results.

1.5 Comparison of transmission and scattering imaging for NDT

Although there has been considerable technical development over the last century since Roentgen’s discovery of X-rays, the principle of transmission radiography has remained unchanged since then. This demonstrates the
robustness of transmission radiography, a formidable opponent against which scatter imaging has to compete. The most significant points of comparison between the two in non-medical radiography are defect contrast, measurement geometry and system complexity needed for tomographic imaging. Details [15] for these points are elaborated below:

1.5.1 Backscatter measurement geometry

Conventional radiography is based on rectilinear propagation of X-rays/gamma-rays from the radiation source to the detector where they are converted to a measurable signal. This is an example of an in-line imaging geometry, in which the object under investigation is inevitably located between source and detector. It is clear that such an imaging geometry, while being intuitively simple, can not be applied to objects of large spatial extent; as attenuation, radiations suffer in penetrating the object will prohibit measurement of transmitted radiation field. The possibility to place radiation source and detector on same side of object is without analogue in transmission radiography. It opens perspective for radiography of objects that would not otherwise be accessible to low energy transmission imaging.

1.5.2 Density sensitivity of transmission and Compton radiography

A second point of comparison between scattered imaging and transmission radiography refers to their sensitivity to small changes in density in low-density objects. Consider for simplicity a void (Fig. 1.4) or hole of diameter, \( w \), and zero attenuation coefficient in highly transparent material, such as a piece of fabric. The cloth material is assumed to have attenuation coefficient, \( \mu \), much less than that of, say, water. As illustrated in lower half of figure, the void will give rise to a change in number, \( N \), of transmitted photons (detector is assumed
to have perfect efficiency). Then, the absolute contrast, i.e. mean difference in number of photons reaching the detector along two ray paths shown is

$$|N_{\text{void}} - N| = N_0 \exp(-\mu L) w \mu$$  \hspace{1cm} (1.18)

where $N_0$ is number of photons in the primary beam and it is assumed that the hole is small enough to allow replacement of the exponential form by its linear expansion. The relative contrast of the hole, defined as $2|N_{\text{void}} - N|/(N_{\text{void}} + N)$, depends from eq. (1.18) on difference in attenuation coefficients between the material and air and is often small, e.g. $\mu$ at 60 keV for cotton fabric is $\sim 0.1$ cm$^{-1}$. Hence, 1 mm diameter air porosity at this energy produces a relative contrast of only 1%.

Fig.1.5 shows a schematic illustration of single-point Compton radiograph in which a beam of mono-energetic photons travels through an object of characteristic dimension, L, composed of material with attenuation coefficient $\mu$.
containing a void of width, \( w \). The radiation signal is recorded in a detector whose angular acceptance is limited by a mechanical collimator (e.g. pinhole aperture). The intersection region (also called scattering volume) of the primary photon beam with the acceptance region of detector is sensitive point of object. To evaluate accuracy of measurements on objects of variable size and shape, knowledge of internal structure of sensitive volume is important. If the attenuation coefficient, \( \mu \), is dominated by the Compton scatter component and cross-section is assumed to be isotropic (i.e. photon energy is assumed << \( m_e c^2 \)), signal, \( S \), from centre of object into a detector of solid angle \( \Delta \Omega \) is

\[
S \approx I_o \mu \exp\left(-\frac{\mu L}{2}\right) \exp\left(-\frac{\mu S L}{2}\right) \Delta \Omega + M
\]

(1.19)

where \( I_o \) is flux of photons in primary beam, \( w \) is length of beam that scatters into detector and \( \mu_s \) is attenuation coefficient of material at energy of scatter radiation. \( M \) represents multiple scatter component (two or more scatter events).
The energy difference between primary and secondary radiations will be small, following the assumption that photon energy is $<< m_e c^2$; hence $\mu_s$ will be approximated in this section by $\mu$. The relative contrast in this case is

$$2\left|S - S_{\text{void}} \over (S + S_{\text{void}})\right|$$

(1.20)

Eq. (1.20) implies that the relative contrast in the absence of multiple scatter for the arrangement of Fig. 1.5 is 100%, which is invariably much greater than in transmission imaging.

1.5.3 Tomography with transmitted and scattered radiation

The term “tomography” originally referred to a method of radiological imaging in which a certain 2-D layer of an object is rendered in focus, while non-focal layers are blurred through relative movement of radiation source and detector. Until the development of computed tomography (CT) this was only method of obtaining radiographs, which showed detail of interest free of disturbing effects of superimposed structures above or below the plane of interest. The phenomenon of superimposition is fundamental to conventional radiography, in which the degree of darkening at some point on radiograph is related to path integral of linear attenuation coefficient through object along the line joining the point to radiation source.

Computed tomography provides a way of solving a set of projection equations to reconstruct the spatial distribution of $\mu$ in some thin slice of material. It requires a radiation source and a linear or planar array of detectors, which together rotate around the object such that the reconstructed slice is generally perpendicular to axis of rotation. In order to avoid artifacts, all projections must relate to same object, which must therefore remain stationary during scan time. A further obvious consequence is that the object slice must be enclosed with in a
circular scan region; indeed CT works best when the object slice itself is circular. In contrast to CT, which is based on manipulation of projection information, Compton scatter imaging (CSI) registers scatter signal from a certain volume element (voxel), defined by intersection volumes of primary and scatter beams. The geometrical limitation of CT on shape of object, which requires that the object be bounded by a circle, is not present in scatter imaging. Hence CSI allows a much broader class of objects to be examined than CT and in many cases yields information, which is unavailable with transmission radiographic techniques. Compton scatter, excited by radiation whose energy is low relative to electron rest mass energy is emitted substantially in all directions. Hence the detector may be placed in any desired position relative to radiation source and scattering object. The free choice of measurement geometry in CSI leads to a possibility, excluded in CT, of monitoring the backscattered radiation from voluminous or strongly absorbing material. In this way, images of superficial regions of a bulky object may be obtained. On the basis of these points, Compton scatter offers an attractive alternative to transmission when tomographic information about scattering medium is required.

Attenuation of signal occurs (due to absorption of photons in material) for transmission as well as for scattering techniques. Other than this problem of multiple scattering also reduces quality of image for two techniques. These effects acts as inherent source of error for radiation based techniques. From experimental and theoretical survey of literature of absorption and scattering techniques, it is found that the scattering methods have advantages over the transmission methods. A comparison [16] of the two techniques is shown below in tabular form.
Table 1.1 Comparison of absorption/transmission and scattering methods for NDT

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Absorption Technique</th>
<th>Scattering Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>It provides 2-D information</td>
<td>It provides 3-D information</td>
</tr>
<tr>
<td>2.</td>
<td>With this method energy analysis has limited value</td>
<td>With this method energy analysis is possible</td>
</tr>
<tr>
<td>3.</td>
<td>Density of object is achievable by conversion from attenuation to density value</td>
<td>Density of object is achievable on absolute scale</td>
</tr>
<tr>
<td>4.</td>
<td>Imaging achieved indirectly by reconstruction from projections</td>
<td>Imaging achieved directly by scanning</td>
</tr>
<tr>
<td>5.</td>
<td>Here fractional contrast of defect structure in the object is low due to superposition effect</td>
<td>Here fractional contrast of defect structure in the object is high</td>
</tr>
<tr>
<td>6.</td>
<td>Requires two sides of sample for inspection</td>
<td>The object can be accessed from one side only using back scattering geometry</td>
</tr>
<tr>
<td>7.</td>
<td>No degrees of freedom</td>
<td>Measurements can be made using variable scattering geometry</td>
</tr>
<tr>
<td>8.</td>
<td>Scanning rate of the object is fast</td>
<td>Scanning rate of the object is slow</td>
</tr>
</tbody>
</table>

1.6 Review of literature

Several investigations have been made for ‘tomographic non-destructive testing’ of samples of medical and industrial interest by using various techniques as stated in section 1.3. This section includes survey of literature, for non-destructive inspection (NDI) of samples using X-rays or gamma rays as a radiation source.

Puimalainen et al. [17] presented a method based on measurement of intensity ratio of coherent to Compton scattered photons (in narrow beam geometry at scattering angles of 45° and 90°) for in-vivo determination of stable iodine content of tissues. A 100 mCi $^{241}$Am radioactive source (emitting gamma photons of energy 59.54 keV) having active diameter of 7.8 mm was collimated.
by a cylindrical collimator of length 38 mm and diameter 7 mm. A Ge(Li) semiconductor detector with active diameter of 16 mm and energy resolution of about 400 eV at 60 keV was used to detect scattered radiations with a measuring time of 300 s. The sample solutions were prepared from KI in a plastic vial (volume 100 ml and diameter 47 mm) whose iodine contents varied between 0 and 10 mg/cm$^3$. The authors concluded more suitability of this method for measurement of iodine content of tissues as compared to the X-ray fluorescence method.

Puumalainen et al. [18] further extended their measurements using Philips X-ray tube with 1 mA ac anode current at 59 kV$_\text{p}$ to determine the trabecular bone mineral contents using coherent to Compton scattering method. The X-ray beam of the tube was collimated with a 30 mm long, 5 mm diameter lead collimator and filtered to almost mono-energetic by a 400 mg/cm$^2$ CsCl filter. In the first measuring geometry, scattered radiation were detected with an HPGe detector (diameter 15 mm, thickness 5 mm) with an energy resolution of about 300 eV in the studied energy range at a scattering angle of 60º. In the second geometry the HPGe detector was replaced by two 2" x 1.75" NaI(Tl) detectors. The X-ray beam was shaped with a pallet of lanthanum oxide (600 mg/cm$^2$), which has the K-absorption edge at 38.9 keV. The scattered radiations were led through a thin CsCl target (100 mg/cm$^2$). The scattering angle of X-ray tube was selected so that only the coherently scattered radiation (38.9 keV) could excite the Cs K$_\alpha$ X-ray fluorescence radiation in the CsCl target (K-absorption edge at 36 keV) and the Compton scattered photons penetrated it without X-ray fluorescence interaction. The coherent NaI(Tl) detector was placed near the CsCl target to measure X-ray fluorescent counts and the Compton detector to
observe transmitted counts with energy 35.4 keV which is obtained at scattering angle of 107°. It was observed that the correlation coefficients between calcium hydroxyapatite content (weight %) and coherent/Compton ratio for semiconductor detector arrangement and for the two NaI detector were 0.96 and 0.90 respectively. The correlation coefficient between the trabecular bone mineral content and coherent/Compton ratio was found to be 0.97.

Ling et al. [19] described a photon scattering method for determination of trabecular bone mineral density (TBMD) in vitro that involves measurement of intensity ratio of coherent to Compton 90° scattered photons. A narrow beam geometry with $^{241}$Am point source (200 mCi) of energy 59.54 keV and HPGe detector (200 mm$^2$ and 7 mm thick) with an energy resolution of 400 eV at 60 keV was employed for this study. They have investigated the feasibility of using small scattering angles for better counting efficiency along with associated problems in their applications. Calibration of the system with fresh trabecular bone samples showed a linear relationship between the coherent to Compton intensity (R/C) ratio for detected counts. Their results showed that for a 10% increase in fat content in the interstices of trabecular bone there was a 2.5% decrease in R/C intensity ratio. The estimated absorbed dose to bone marrow was about 139 m Rad.

Raghunath et al. [20] measured backscattered gamma ray spectra using 1 mm thick x 50 mm diameter NaI(Tl) scintillator detector at 662 keV incident gamma photon energy (backscattered at an angle of 145°). They have used targets of concrete, dimensions 30 x 15 x 15 cm$^3$, with different amount of water soaked in it so that density varies in the range 2.4 - 4.0 g/cm$^3$. It was possible (from the calibration curves) to estimate the water content within 0.25% (by
weight) with help of this method for borated concrete, ordinary concrete and mortar bricks.

Holt and Cooper [21] suggested that in addition to the transmitted gamma flux through the object to be investigated, scattering techniques can also be used for non-destructive testing and imaging of medical and industrial samples. They pointed out some advantages of scattering over transmission measurements; like 3-dimensional information of the object rather than 2-dimensional, scattering method allows changes in composition to be monitored irrespective of attenuation of incident and scattered beam, scattering method only requires access from one side and this can be major advantage if object is part of larger structure etc. Authors outlined that coherent to Compton scattering intensity ratio method have many potential applications, in particular in detecting small density changes of tissues and organs, and could be used to provide good contrast and high resolution images.

Shukla et al. [22] used intensity ratio (coherent to incoherent scattering) technique to determine bone mineral density of calcaneum for 60-keV incident photons, obtained from $^{241}$Am (44.4 GBq), at scattered angle of 71° using HPGe detector. Bone mineral density is defined as mass of mineral present in unit volume in its normal morphological state. Total Nine Calcaneum were obtained from fresh cadavers stored at -10° C and cut into cubes each of size 15-26 cm$^3$. Volume of each calcaneum was measured by Archimedes water displaced volumetric method. These samples were put in an oven at 600° C for 70 hours and measurements were done for weight of ashed mineral. Directly measured bone mineral density (mass/volume) for each calcaneum was then compared with bone mineral densities determined by coherent to Compton scattering
technique. The coherent to incoherent intensity ratio technique has shown to be 5% accurate and 3% precision in vitro.

Wolf and Munro [23] performed lung density measurement with $^{241}$Am source and NaI(Tl) detector placed at scattering angle of 150°. Compton backscatter of 60 keV gamma radiations from a simple lung phantom had been used to measure changes in “lung” density. A phantom consisting of a 200 x 300 x 200 mm$^3$ perspex box of wall thickness 5 mm was filled with damp sawdust and placed in front of the detector, so that the crossover region lay within the box. Variations in lung density from 0.22 to 0.45 kg/L were simulated by varying the dampness of sawdust inside the box. Variations of chest wall thickness from 5 to 20 mm were simulated by putting Perspex sheets between the box and detector. A minimal chest wall was also simulated by using a smaller polythene container of wall thickness approximately 1 mm. It was shown how introduction of a small volume of air can increase as well decrease the count. Radiation scattered from the “chest wall” were prevented from entering the detector by careful choice of geometry. The residual count increased linearly with “lung” density. The relative increase of count rate with density was entirely independent of “chest wall thickness”. Authors claimed that, with their apparatus, a change of 0.01 kg/L in “lung” density produced a 2.2% change in count rate.

Loo and Goulding [24] employed a Compton densitometer for measuring pulmonary edema. A phantom consisting of a thin metal can 10 cm in diameter and 10 cm in length was used to represent a uniform volume of the lung. The effect of chest wall was simulated by a 6.5 mm plexiglas layer which intercepts the incident and exit beams. The density of “lung” within the can was varied from 0.19 – 1.0 g/ml by mixing an appropriate amount of sawdust and water. A narrow
beam of gamma-rays (from a $^{57}$Co source) was directed through centre of can at a 35° angle with respect to front of detector housing which was intended to be parallel to chest wall. The scattering volume along narrow beam was viewed by an HPGe detector (about 1 cm cube) whose effective center was about 9 cm from that of can. Preliminary test results indicate that with a radioactive source of under 30 GBq, it should be possible to make an accurate lung density measurement in one minute, with a risk of radiation exposure to the patient a thousand times smaller than that from a typical chest X-ray. The distributions of count rate per cm interval as a function of depth were plotted for different lung density phantoms. Results of a system calibration showed the linear relationship between empirical attenuation factor and target density values.

Tartari et al. [25] investigated a technique for characterisation of biological tissues, based on energy analysis of Compton scattered photons. The incident beam consists of 59.54 keV photons and backscatter geometry was employed for the study. The instrument was equipped with an HPGe planar detector (scattering angle 137°) with an active area of 200 mm$^2$ and 10 mm in thickness, the resolution of which was 350 eV at 59.54 keV. By the use of suitable collimators for both source and detector, it was possible to determine the angular divergence and volume of sample effectively irradiated. Two different experiments were performed using this apparatus. In the first one, bone phantoms were prepared by filling plexiglas tubes, 60 cm in diameter, with solution of various K$_2$HPO$_4$ concentrations in distilled water, in order to simulate the mineral content in bone. In the second one, the samples consisted of similar tubes filled with mixtures of liquefied pig fat and water with traces of surfactant material added so that, after resolidification by freezing, a stable uniform mixing
between water and fat fraction was obtained. Compared to the technique based on ratio of photons coherently scattered due to Rayleigh effect and those incoherently scattered due to the Compton effect, the technique provided similar results for mineral content evaluation, with an error lower than 1%. However it allowed the determination of fat content in a soft matrix – even in the case in which Rayleigh peak was not measurable – although the error rise up to 3%.

Mullin and Hussein [26] used the energy spectrum of Compton scattered photons for detecting collinear defects in aluminium blocks and in laminated composite materials. By relating the energy of scattered photons to their angle of scattering, indications of material density at different locations along the beam path were obtained. The difficulty of utilizing a detector of finite size to obtain point-to-point scattering information was overcome by viewing the physical detector as being composed of a number of virtual point detectors. Using equivalent point detectors, together with the energy-angle relationship of singly scattered photons, directional information was extracted from the energy spectrum of a high-purity germanium detector (HPGe). The results of tests of this technique were presented using a $^{60}$Co collimated photon beam and (HPGe) detector (energy resolution of 1.7 keV, full width half maximum, at 1.33 MeV). The test target was an aluminum block (size 190 x 50 x 37 mm$^3$) with 5 mm cylindrical drillings simulating defects. The indications for the presence of a flaw were reflected by peaks in the spectrum (obtained from energy spectrum of flawless reference target minus the energy spectrum of test target).

Zhu et al. [27] constructed an in-line density measurement system based on X-ray Compton scattering for detection of density variation between the cogs of rings. The measurement system consists of five elements; an X-ray source, a
detector unit, a source-detector collimator, an x-y-z micromanipulator and a PC computer as control unit. For all the measurements, the X-ray tube voltage was 160 kV, (and tube current was 18 mA) and detector unit consists of a 25.4 mm NaI(Tl) detector. For the purpose of density measurement, authors chose a scattering angle of 90°, in such a way to obtain a roughly cubic measurement volume. Intended to be installed on an industrial production line, this computer-controlled system measures automatically the local density (within a few mm³) of the middle products of power metallurgy (green state). The measurement is non-destructive and is made from a single side of the sample. An industrial X-ray tube and a multihole collimator allowed a measurement time of 40 sec with an accuracy of better than 1%, for products obtained after compression of iron powder and whose density ranges from 6 to 7.3 g/cm³.

Arendtsz and Hussein [28-29] described the theoretical and experimental technique for tomographic imaging of electron density using the energy spectrum of Compton scattered gamma rays. The energy-angle relationship for Compton scattering was utilized to determine the direction of scattered photons. Image reconstruction algorithms, based on a single-scatter model, were devised and tested using Monte Carlo simulations. The second part of the paper deals with experimental problems associated with the physical size of detector and intrinsic distortions in its response function. Authors employed ¹³⁷Cs radioactive source and high purity germanium (HPGe) detector for experimental measurements. Reconstructions of the electron-density images for several test objects from experimentally measured detector responses were presented to demonstrate the viability of the detector unfolding and image reconstruction methods.

Lopes et al. [30] utilized the Compton scattering technique (CST) in the
detection of the problem produced by the formation of paraffin (condensed petrol) inside the petrol draining pipeline in deep-water exploration off-shore. This study was made by using an inspection system consists of $^{137}$Cs and NaI(Tl) detector at scattering angle of $90^\circ$. Test objects were made with parts of the off-shore pipelines with a 10 cm inner diameter. Its wall were formed by four different materials arranged in the following order- the internal shell was made with flexible stainless rings covered with a resin compound, protected by a closed wire trellis and at the surface another part of the resin protects all the pipe. The total thickness of the tube used in this work was 20 mm. With the intention of determining what should be minimum and maximum amounts of paraffin that could be detected in the tube, authors assembled a test object with paraffin positioned in its inner wall in proportions of 0%, 20%, 30%, 50%, 80% and 100% of inner tube area, that represents thickness of approximately 2, 3, 5 and 8 cm of paraffin. The measurements were made with two types of beam, punctual and fan beam, by analyzing a pipeline cross-section or small elements of volume through a traversal line. The punctual system detected a minimum of 10% paraffin. This value was 20% with a fan-beam system. The results presented in this study showed that the gamma radiation Compton scattering technique was capable of identifying the presence of paraffin inside a pipeline used for oil flow at an off-shore exploration.

Shakeshaft et al. [31] reported the potential of in-vivo gamma ray photon backscatter technique to measure the percentage of fat in specific tissue volumes. $^{241}$Am gamma rays were used as source of radiation and the backscattered gamma rays were detected with a HPGe detector, with ethanol (approximately 80% fat, 20% muscle) and water (muscle) being used as tissue
substitutes. For measurements of the depth dependence, 300 mm$^2$ slabs of epoxy resin phantom of varying thickness were used. For other measurements a polythene walled tank was used (180 mm x 140 mm x 150 mm). The phantoms were placed at a set distance of 70 mm from the detector collimator. The angle between the two collimator axes (source and detector) was 30° (150° scatter angle). Three phantom material were used: epoxy resin slabs (Royal London Hospital formulation: H: 8.32%; C: 68.1%; N: 2.38%; O: 19.11%; Cl: 0.14%; Ca: 1.92%), water (H: 11%; O: 89%) and ethanol. The elemental composition of ethanol, C$_2$H$_5$OH (C: 52%; H: 13%; O: 35%) is approximately equivalent to 20% muscle (C: 14%; H: 10%; O: 71%; N: 3.4%) and 80% fat (C: 60%; H: 11% O: 28%). Two measurement techniques were used; the measurement of ratio of coherent to Compton scattering and the measurement of Compton scatter profile. Both shown to be sensitive to the composition difference between ethanol and water. For coherent/Compton scatter ratio, the measured difference between water and ethanol was 1.85:1, close to the value calculated (about 2:1). A similar difference in coherent/Compton ratios between muscle and fat was calculated (2.2:1). The FWHM of the Compton profile found to vary with tissue composition with a difference of 0.10 keV (5%) between ethanol and water profile widths.

Morgan et al. [32] extended their previous work [31] to assess regional body composition at selected sites using backscatter technique. Two measurement techniques were examined: the measurement of coherent to Compton scatter ratio and the measurement of Compton scatter profile. Two possible applications were considered: measurement of trabecular bone mineral density and measurement of the average fat/muscle ratio in a tissue volume. The
results presented indicated that the analysis of coherent and Compton backscattered gamma ray spectra from an $^{241}$Am source (recorded with 32 mm diameter 10 mm depth hyper pure germanium detector) has the potential for measuring both trabecular bone mineral density and average fat/muscle ratio in a tissue volume, with a low absorbed dose to the subject. Various phantom materials were used to simulate different tissues. Aqueous solutions of $\text{K}_2\text{HPO}_4$ in the concentration range 0-90 g/100 ml were used to simulate the density range of trabecular bone. The solutions were contained in thin-walled polythene bottles, 38 mm in diameter and 60 mm in height. Ethanol and water were used, respectively, as fat and muscle substitutes, and these were contained in large polythene tank. It was concluded that this ratio technique is a sensitive indicator of bone mineral density for peripheral bone locations.

Morgan et al. [33] further investigated the feasibility of using gamma ray scattering technique to estimate the mandibular bone density. They used 7.4 GBq $^{241}$Am radioactive source (5 mm diameter sphere) with 5 mm diameter lead cylindrical collimator for the measurements. The scattered radiations were detected by an HPGe detector (32 mm diameter and 10 mm depth) collimated with 10 mm thick steel sleeve fitted over the detector housing with a central 40 mm diameter collimator at a scattering angle of 150°. To simulate the mandibular, a phantom was constructed of concentric thin walled polypropylene cylinders. The inner diameter of the cylinders were 54 mm, 74 mm and 90 mm, creating two concentric layers of 10 mm and 8 mm thickness surrounding the inner 54 mm diameter cylinder. The outer 8 mm layer (and the inner cylinder) were filled with water as a soft tissue substitute to a depth of 45 mm. Solutions of $\text{K}_2\text{HPO}_4$ were used as bone substitutes in the inner 10 mm layer to simulate the
mandibular bone. The phantom was irradiated with the inner 10 mm layer containing varying concentrations of $\text{K}_2\text{HPO}_4$ to a depth of 45 mm in the range 0-30 g $\text{K}_2\text{HPO}_4/100$ ml water simulating bone in the density range 1000-1200 kg/m$^3$. The coherent to Compton scatter ratio and Compton profile ratio were normalised to water values. The average uncertainty estimated in the ratio over density range 1000-1200 kg/m$^3$ was 2.5%.

Jama and Hussein [34] showed that with good source collimation and a well-confined detector's field-of-view the scattering angles can be directly determined, from the energy-calibrated pulse-height distribution (without numerical unfolding), for Compton scatter non-destructive testing. Factors affecting the technique were studied and system-design guidelines were outlined. The applications of this technique for detection of multiple collinear flaws, as well as to inspect a multilayered structure, were successfully demonstrated by employing $^{137}\text{Cs}$ source and an HPGe detector. The inspected object consisted of both small steel rods and aluminium blocks. The rod was used to represent small scatterers that provide a narrow range of scattering angles and was used to adjust system parameters. The aluminium blocks contained holes of different diameters drilled into it to represent flaws. These holes were also filled with higher-density materials to simulate inclusions. Objects consisting of a composite material adhesively joined with aluminium were also used as a demonstration of one of the applications of the technique for detecting flaws caused by joint debonding. The response function of the detector used in this work was calculated with the aid of Monte Carlo simulations using photon-electron particle transport code EGS4. It was also concluded that from shape of the distinct peak, or a dip, in the spectrum, one can estimate size (from...
width of the peak) or density of defect (from peak’s height).

Balogun [35] presented a numerical study of the variation of scattering angles and collimator sizes for Compton scattering tomography. The calculations were performed for various collimator sizes and configurations on scanning rig. A symmetry was observed between the scattering volume at forward and back scattering within the scattering angle range of $90\degree \pm 30\degree$ with small diameter collimators, while asymmetry effect was observed in large holed collimators. It was proposed that the best volume spatial resolution in Compton scattering densitometry tomography is obtainable within the above stated scattering angle range.

Ho and Hussein [36] also presented a method for quantifying information obtained from the indications of a Compton scattering nondestructive testing technique. This was achieved by formulating a measurement model, which provides a numerical estimate of the detector response for a given anomaly. Using the measured response function, the location of an anomaly, its size and density were obtained with the aid of their model. The process was demonstrated by quantifying indications obtained from experimental measurements, for flaws artificially created in an aluminium block (size $60 \times 50 \times 50$ mm$^3$), by employing a collimated $^{137}$Cs gamma-ray source and an HPGe detector.

Duvauchelle et al. [37] performed the experiment for the detection of X-ray photons scattered from a sample by the Rayleigh and Compton processes which was used for tomographic images. The work has been carried out at European Synchrotron Radiation Facility (ESRF) in Grenoble in France on the beam line 1D15B to obtain monochromatic beam of 60 keV with a fluence rate of
about $10^{12}$ photons/mm$^2$/s. The sample was a polyethylene cylinder whose diameter was 20 mm and was placed at a scattering angle of 35° relative to the incident beam. Inside this cylinder, three holes of 6 mm in diameter were machined and filled up with aqueous solution diluted with water to obtain three different concentrations corresponding to 0.5, 10 and 50 g/l of iodine. A little hole of 2 mm diameter filled with air at atmospheric pressure was also machined. The input collimator consists of a set of adjustable horizontal and vertical tungsten slits. A simple scanning method was used to reconstruct the images of the sample with voxel size of 1 x 1 mm$^2$ in the plane of the slice and 0.3 mm in the third direction. A standard reconstruction algorithm provided two intermediate images, corresponding to the Compton and Rayleigh contributions. Quantitative comparison was made with the aim to explain the difference of sensitivity between each scattering process. On both images artifacts were present due to attenuation, but ratio between these two images produces the map free from artifacts which determine the effective atomic number of the sample. A good spatial resolution between polyethylene and an aqueous solution containing a low concentration of iodine (0.5 g/l) was easily performed as a result of very high photon flux and short measurement time.

Sharaf [38] described a technique for determining the physical density distribution within an object using Compton scattered radiation. The technique was based on measuring the scattered radiation flux, with varying sample depth from an external monoenergetic photon source, using a high-resolution Si(Li) detector at scattering angle of 90°. The radiation source was an X-ray generator fitted with Molybdenum anode industrial X-ray tube operating continuously at 55 kV and 35 mA. The X-ray beam of the tube was used to excite a secondary
stannum (Sn) target to produce almost monoenergetic (25.2 keV) fluorescent radiation. To test the system performance, measurements performed on some plastic and tissue substitute materials as well as distilled water performed using fixed geometry center of the source and detector arrangement. Water was used as a reference material and the attenuation of incident and scattered beams were not taken in consideration as the ratio of scatter signal eliminates these effects. The measurements were performed in air using plastic samples, water, saline solutions and a composite phantom. The water and saline solutions were contained within 12 mm diameter by 30 mm long, polyethylene tubes and the plastic samples consisted of rods of 10 mm diameter by 30 mm long. Each sample was scanned with its longest side placed parallel to direction of incident beam. The measured scattered signal from an isolated volume element of investigated object was found to be proportional to its electron density. The spatial resolution of the system, determined by its collimator width, was 2 mm. The mathematical aspects of this technique were presented and the experimental data obtained in line scans of representative tissue equivalent materials were also shown to demonstrate the validity of method.

Cesareo et al. [39] designed a simple apparatus consisting of a well-collimated photon beam from an X-ray tube, a CZT thermoelectrically cooled semiconductor detector and an (x, y, θ) translation-rotation table containing the object to be studied. Two X-ray tubes (working at 50 kV, 1 mA and 80 kV, 5 mA) with tungsten anode were employed to produce monoenergetic radiations. To detect both the incident spectrum and the Compton scattered spectrum for scattering angle 90°, a CdZnTe detector was employed, having 2 mm thickness and 9 mm² area. To test the scattering system for Compton tomography, a 3 x 3
voxel system composed of a 2 x 2 x 2 cm Lucite with 9 holes of 4 mm diameter were filled with various elements. Images were shown for Transmission and Compton tomography at 60 kV, 4 mA for a Lucite cylinder of 14 mm and 20 mm internal and external diameter respectively, with a graphite cylinder of 6 mm diameter at the interior.

Tartari et al. [40] proposed a Compton scattering technique for non-destructive testing in the inspection of fresco substrate. The aim of enhanced Compton Spectrometer proposal was to consider synergic effects of both physical design of apparatus and data processing management. The pixel imaging obtained by collecting total Compton scattered photons from a single layer was then examined in terms of a multivariate principle components analysis (PCA) approach. The apparatus consists of an axially symmetric backscattering spectrometer incorporating a 2 mm point source of $^{241}$Am which emits 59.54 keV photons and was placed in a cylindrical (12 mm diameter) shielding head at the center of a large-area NaI(Tl) detector of 40 mm diameter. The sample under test was a plexiglas sheet 10 mm thick of slightly variable density with a 6 mm diameter hole in central position. It was concluded, in terms of density evaluation, that single and multiple scattering contaminations in presence of non-homogeneous attenuation can be discriminated using PCA method.

Cesareo et al. [41] designed a first generation CT-scanner consisting of a 80 kV, 5 mA X-ray tube (with a collimator of 2 mm in diameter) and a NaI(Tl) detector (with no collimation) to collect Compton scattered photons from the whole irradiated sample (cylinder). The performance of this equipment was tested for contemporaneous transmission and Compton images. They compared
the transmission and Compton images for various test objects (a hollow Lucite cylinder, the same cylinder with a graphite cylinder at the interior, a Lucite box with nine holes, a walnut), along with a Compton tomography of a cork cylinder of 25 mm diameter with four bores (one void, three filled with a 0.8, 0.05 and 0.15 mm diameter Fe, Ag and Cu wires respectively). It was concluded that Compton tomography provides good results when low atomic number materials were investigated and reported that the quality of Compton images get impaired due to statistics of the processes, multiple Compton scattering, approximate auto attenuation etc.

Shivaramu et al. [42] determined the moisture contents in limestone concrete by gamma scattering method. The coherent, incoherent, coherent/incoherent intensity ratio and effective atomic number \( (Z_{\text{eff}}) \) of limestone concrete for 0%, 2%, 4%, 6%, and 8% of water were calculated at different scattering angles of 36.40°, 49.40°, 62.74°, 77.4°, 93.6° and 112.81° for 59.54 keV gamma energy and at two scattering angles of 21.6° and 43.6° for 661.6 keV. The experimental set up consisted of a collimated \(^{137}\text{Cs}\) radioactive source with a lead shielding mounted on a fixed arm of about 100 cm length which can be rotated at any desired angle and 90° scattered photons were detected by HPGe detector. The limestone concrete blocks of density 2.71 g/cc and dimensions 230 x 160 x 50 mm\(^3\) (comprised of ordinary Portland cement, limestone, limestone sand and water in the proportion of 1:3.121:1.830:0.484 respectively) were fabricated according to standard mix ratios and cured for 28 days. The concrete block was then subjected to uniform heating in an oven at 130° C for varying periods up to a maximum of 47 hours. The concrete blocks were then mounted on a mild steel target frame of dimensions 35.3 x 10.3 x 2.0
cm for the measurements. The scattered intensity and effective atomic number were found to vary linearly with the amount of water present in concrete specimen and the results had shown that the scattering method was highly sensitive to changes in moisture content in limestone concrete and < 1% change can be easily detected using this method.

Gouveia et al. [43] had analyzed the Compton scattering technique as a possible tool for the characterization of materials inside draining petroleum pipelines. The study was accomplished in laboratory scale, so the results should be analyzed to conclude if the system could be used in the field. The system used was composed of two NaI(Tl) detectors aligned by a $^{137}$Cs source forming an angle of 90° with the detectors line (662 keV- direct beam, and 288 keV-scattered beam). The collimator with squared opening of 4.7 and 150 mm length was employed to source. Detector collimators were 4.7 mm$^2$ in area and 100 mm in length. The other experimental parameters were as follows: scattering angle of 90°; distance between source and test body and between test body and detectors 200 mm; step between two sequential measurements, 4 mm. The results obtained show the capability of system for characterization of materials like sand, paraffin and water inside pipelines.

Balogun and Cruvinel [44] investigated the Compton scattering technique as a possible tool in soil density distribution mapping for agriculture purposes. A $^{137}$Cs radioactive source emitting photons at energy of 662 keV was employed. The counting system consists of a NaI(Tl) scintillation detector (at scattering angle of 120°), a spectroscopic amplifier, a single-channel analyser (SCA) and a dual timer counter. The objects examined consist of samples of soil at various compaction stages. Samples of soil were placed in a 50 mm x 50 mm x 80 mm
Perspex container with and without compaction. With a stepping of 2 mm, a horizontal length of 65 mm and vertical height of 85 mm were scanned. Images were also shown, of soil samples, at two closely related densities. Good contrast was recorded between the various inserts and their host matrix. Line scans through the images showed good contrast resolution, shape and edge definition. Spatial resolution could be enhanced by the use of a focusing collimator on detector. This will also serve to increase the solid angle subtended at detector by the scattering volume, with a possible reduction in counting time at the same precision level.

Bonifazzi et al. [45] presented a imaging technique based on the detection of Compton scattering photons and a further statistical analysis of the collected data. The photon detection was performed by enhanced Compton spectrometer (ECoSp) that allows to collect the backscattered photons by investigating tested sample from one side only. The ECoSp device consist of a cylindrical collimated $^{241}$Am gamma ray source (59.54 keV) coaxially associated with an annular collimator device and a large-area NaI(Tl) detector, that allows one to detect the Compton backscattered radiation coming from a cylindrical volume 3 mm wide and about as deep as overall thickness of tested sample. Photons collected during planar scanning of a given area were used to describe electron density of sample as a density image: afterwards, the principle component analysis (PCA) was applied to the image. As a case study, a non-destructive testing of plaster substrates supporting mural paintings was performed using this technique, searching for flaws, defects, fractures and so on. The principle component correlation analysis, performed over resulting data from all VOIs, then reveals each gap in his size, shape and position.
Achmad and Hussein [46] presented a method for non-intrusively determining the electron density at a point embedded within an object. An X-ray machine operating at 400 kV and 3 mA with a 4 mm focal spot size was employed for this work. The shielding in front of the machine had a hole 5 mm in diameter and 0.26 m in length that provided the source beam. CsI(Tl) scintillation detector was used for measuring the scattered photons. Advantage was taken of multi energetic nature of X-ray photons to devise a dual energy-group multiple-detector scattering scheme for density determination. A measurement model that relates the density of object to detector response was formulated, then inverted to determine electron density at monitored point. Normalization factors were calculated to compensate for wide energy distribution of X-ray photons, and account for other system parameters. In addition, the spread in source and detectors field-of-view was accommodated by calculating in advance the volume of inspection voxel. The method was experimentally applied to a variety of geometries and materials, showing that the electron density can be calculated with a reasonable uncertainty.

Harding [47] given an account of three explosive detection techniques based on X-ray scatter tomography i.e. coherent scatter computed tomography, energy-dispersive X-ray diffraction tomography and Compton backscatter imaging. A brief description was given of some of the parameters relevant to X-ray scatter system design and of optimization of these parameters relevant to X-ray scatter system design and of optimization of these parameters for target application. The above technique was applied to the problem of identifying and detecting explosive material in airport baggage and buried landmines. Decision criteria needed to limit the number of “false alarms” were discussed.
Representative results drawn from the fields of baggage inspection and mine clearance were given.

Tang and Hussein [48] employed isotopic gamma sources for identifying anti-personnel landmines. Experimental measurements verified the feasibility of proposed method and demonstrated the detectability of mockups of landmines as small as 45 mm in diameter buried near the soil surface, or mockups larger than 80 mm in diameter buried at a depth of 80 mm, in light soil (500 kg/m$^3$). In heavy soil, (1650 kg/m$^3$) targets 80 mm in diameter were detectable at a depth of 30 mm. A wooden box, 0.61 x 0.61 x 0.46 m$^3$, was used to hold soil. The well-known MCNP code for Monte Carlo simulation of particle transport was employed to conduct a parametric study to determine best source energy, and most suitable source/detector configuration. A single NaI(Tl) photon detector was employed, and was moved along both sides of the source to count backscattered photons. Materials used were sucrose, molasses and sand, to provide various target densities. Other mockup was filled with a mixture of chemicals, which consists of cyanuric acid, oxalic acid and graphite designed to imitate elemental composition of TNT. The use of low-energy (60 keV) $^{241}$Am source makes it possible to design a light-weight hand-held device that can augment other methods of detecting plastic landmines.

Castellano et al. [49] developed a mobile instrument for detection and mapping of detachments in frescos by using Compton back scattered photons. The instrument was mainly composed of a high energy X-ray tube working at 80 kV and 1 mA, a CdZnTe detector (effective area of 9 mm$^2$ and thickness of 1 mm) and a translation table. The instrument was first applied to samples simulating various detachment situations, and then transferred to the Vatican
Museum to detect detachments and inhomogeneities in the stanza di Eliodoro, one of the “Raphael’s stanze”. It was concluded that Compton scattering seems to be a suitable technique to detect detachments, fractures and inhomogeneities in frescos and, of course, in all situations related to low density samples in which variations occurs (wood, stone, marble, ceramics).

Rao et al. [50] evaluated the tomographic imaging based on scattered radiation from polyethylene ($C_5H_8O_2$) using 10, 15, 20, 25 and 30 keV synchrotron X-rays. The SYRMEP (Synchrotron Radiation for Medical Physics) facility at Elettra, Italy was used to detect the scattered radiation from the sample at an angle of $90^\circ$ using Si-Pin detector to a multi-channel analyzer. The contribution of transmitted, Compton and fluorescence photons was assessed from a test phantom of small dimensions with simple approximations. The samples that were investigated in this study were homogeneous cylinder samples of polyethylene. The optimum analysis was performed with the use of dimensions of sample by detecting radiation at various energies. The calculations reflect the data on tomographic imaging based on scattered radiation from biological materials.

Yuk et al. [51] described a continuously operating scanning X-ray image system developed for landmine detection based on a backscatter X-ray principle. The X-ray source operating at 120 kVp and 3 mA, sixteen-channel linear array detector module (fabricated by bonding $CdWO_4$ scintillator crystal block of 1.7 mm x 10 mm x 3.0 mm onto a silicon PIN photodiode) and a plastic and metal mine phantom of approximately 8 cm in diameter were used for the experiment. To study the physics of Compton X-ray backscattering, the photon transport factor (PTF), backscatter factor (BSF) and backscatter probability (BSP) were
simulated using Monte-Carlo calculations using the generalized transport program MCNP. Based on the Monte-Carlo analysis results, a mine detection system was designed with a low false alarm rate, a high detection probability and a direct imaging facility.

Cruvinel and Balogun [52] extended their previous measurements [42] for tomographic instrumentation for agricultural samples based on Compton scattering that allows for simultaneous measurements of density and moisture of soil samples. To calibrate soil bulk density measurements, a set of air-dried and sieved soil samples were placed in a number of 50 x 50 x 80 mm$^3$ plexiglas boxes. The experimental set-up consists of two radioactive source, one of $^{137}$Cs for soil bulk density measurements and the other of $^{241}$Am for water content measurements, emitting gamma ray energies of 662 keV and 60 keV with source strength of 600 mCi and 300 mCi respectively. The counting time employed for each energy was 50 seconds per sample point on the projection with a spatial resolution of 2 mm, a total of 30 sampled points per projection and a total 10 cm vertical displacement. The results showed that there is linear correlation based on this method and direct transmission tomography. For soil water contents, a coefficient of linear correlation better than 0.79 was found when compared with measurements obtained by time domain reflectrometry (TDR). In addition, a set of Compton scatter images (CSI) were presented to illustrate the efficacy of this imaging technique, which makes possible improved spatial variability analysis of pre-established planes.

Sharaf [53] proposed that photon scattering technique (PST) can be used to evaluate tissue density and a method for non-invasively generating profiles of density distribution within an object using Compton scattered X-rays. The
investigator for this study considered that scattered photon intensity produced by adipose tissue was similar to that produced by olive oil while the scattering behaviour of fibro-glandular tissue was similar to that of water. The purpose of the study was to examine the potential of using scatter information to evaluate tissue density at selected sites. The Compton scatter method was modified to scan longitudinal sections of composite phantoms and samples of tissue substitute materials. The scanning process performed by moving the sample along X-ray beam in equally spaced translation steps and count rate was recorded from a high resolution Si(Li) detector located at a scattering angle of 90°. The results showed that the technique was sufficiently sensitive to allow differentiation between materials like water, olive oil, polyethylene and glycerin of similar chemical properties but of slightly different densities.

Singh et al. [54-55] used Rayleigh to Compton scattered intensity ratio (a non-destructive technique) method for assigning effective atomic number to composite materials. They employed 145 keV (at scattering angle of 70°) and 279 keV (at scattering angle of 50°) gamma rays using a high resolution HPGe semiconductor. The intensity ratio of Rayleigh to Compton scattered peaks, corrected for photo-peak efficiency of the gamma detector and absorption of photons in the target and air column present between target and detector, was plotted as a function of atomic number and constituted a fit curve. From this fit curve, the respective effective atomic numbers of the composite materials were determined. The agreement of measured values of effective atomic number ($Z_{\text{eff}}$) with the theoretical calculations was found to be quite satisfactory.

Shivaramu et al. [56] demonstrated a non-destructive evaluation technique involving Compton backscattering with a PC controlled gamma
scattering scanning system. The experimental set-up consists of a $^{137}$Cs radioactive source and a HPGe planar detector providing high resolution energy dispersive analysis of the scattered spectrum. Two $15 \times 15 \times 15$ cm$^3$ cubical concrete blocks were scanned for the detection of voids. In one of the concrete blocks air cavities were created by insertion of two hollow cylindrical plastic voids each of volume $71.6$ cm$^3$. The two concrete blocks, one normal and another with air cavities were scanned by lateral and depth-wise motion in steps of $2.5$ cm. The results showed that the scattering method is highly sensitive to change in density of the volume element under study and hence the size and position of voids in concrete materials. The voids were detected with a statistical accuracy better than $0.1\%$ and their positions were determined with good spatial resolution.

1.7 Conclusion and scope of work

Non-destructive testing (NDT) are those evaluation methods in which the material under test is not destroyed or to say that future usefulness of material under test is not impaired. The ability of gamma rays to penetrate deep in matter makes it attractive for use in non-destructive testing applications. The objective of the present study is to examine the potential of using absorption and scattering of gamma rays to evaluate density variation in inspected objects.

Many investigators have already reported the theoretical as well as experimental work for tomographic (section-wise) non-destructive inspection of samples of medical and industrial interest. But the study reported here in present work is a fruitful extension to previous investigations (specially applying inverse matrix approach to obtain true spectra from observed pulse-height distribution in case of NaI(Tl) detector), so it is expected that experimental findings of present
study will be quite useful to other investigators in improving their experimental design for field/clinical instruments.

To explore the use of gamma photons for medical diagnosis, especially for measurements of mandibular bone density and pulmonary edema, scattering techniques for 59.54 keV and 662 keV (Rayleigh to Compton scattered ratio and Compton scattering) have been reported in the present work as a non-destructive methods. Also, the applicability of gamma photons to process diagnosis in various samples of industrial interest has been studied, by image reconstruction with Matlab, as a non-destructive tomographic technique. Industrial interest applications involve investigations for pipeline conditions (wall thickness measurements, blockage detection and type of liquid flowing etc.) and flaw/inclusion locations for metal blocks/concrete materials. Apart from this investigations for landmine detection have also been performed with the help of gamma photon based scanning system. Moreover, an experimental technique (based on inverse matrix approach) for construction of response function, to obtain true photon spectrum from observed pulse-height distribution, for NaI(Tl) detector have been reported. Spectra obtained from NaI(Tl) detector for various studies have been corrected, for multiple scattering, with the help of this response matrix.

Scope of gamma ray non-destructive techniques is not limited to few applications only, but can be successfully employed for detection of presence or absence of rebars, voids etc. in structural engineering, agricultural, medical and industrial samples. Not only absorption but scattering techniques are also capable of distinguishing between rebars and air voids. Moreover, position and estimating the size of bars in reinforced concrete can be estimated by these
methods. The density of some diseased parts of the human body, bones, lungs, tissue etc. can be evaluated by gamma ray scattering techniques. For any type of discontinuity (detection of flaws or presence of some inclusive materials) Compton scatter NDT can be employed for the detection. Images for any type of density variation can be obtained by using any appropriate software, which is one of the important features of non-destructive testing. Recent application of this technique is to detect the explosive in the baggage and land mines.