# Industrial Gamma Radiometry and Imaging Applications using Sealed Radioisotope Sources and Radiation

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**Abstract**

Conventional and emerging applications of radioisotopes and radiation in medicine, industry, agriculture and environment form an important part of non-power utilisation of nuclear energy for societal benefits in the country. Selected radioisotopes as sealed sources of penetrating and ionising radiation are employed for a variety of applications in industry. Gamma radiometry as an industrial diagnostic technique is used for troubleshooting, defect localisation and shielding integrity test of large-scale blocks and assemblies. Imaging modalities widely employed in industry using gamma rays and X-rays are conventional film-based radiography, computed radiography (CR), fluoroscopy, digital industrial radiography (DIR) and computed tomography (CT) in a variety of configurations. This article highlights industrial radio-diagnostic techniques using in-situ gamma radiometry and radiography of small components, structures and assemblies and in-house development activities in computational imaging by Industrial Tomography and Instrumentation Section (ITIS) of Bhabha Atomic Research Centre, Mumbai over the last couple of years.

**Keywords:** *Gamma radiometry, Film radiography, Computed radiography(CR), Digital industrial radiography(DIR), Computed tomography (CT)*

## 1. Introduction

Use of radioisotopes and radiation in their various forms in industry, healthcare, agriculture and life sciences constitute the broad spectrum of non-power applications of nuclear energy for the benefit of society and are primarily aimed at improving the quality of life. The use and popularity of non-destructive and non-invasive conventional diagnostic techniques using sealed radioisotope sources both in medical and non-medical domain have been phenomenal due to their simplicity, cost effectiveness and their suitability to be easily deployed. Selected radioisotopes as sealed sources of penetrating and ionising radiation are employed for a variety of applications in industry such as gamma radiometry, scanning of industrial process columns, control systems using nucleonic gauges for level, thickness, moisture and density measurements, voidage determination, analysis of mixers, well logging and elemental analysis in samples besides a host of other specialised applications [1]. Most of the conventional nucleonic methods using sealed radioisotopes and compact radiation sources (X-rays) are based on detection and measurement of transmitted radiation through a given object or scattered radiation from the test specimen [2-4]. Broadly speaking, a sealed radioisotope-based radiation source used in industry may be emitting narrow beams of gamma rays, beta rays or neutrons for a specific application. The other class of relatively high activity sealed radio-isotope sources and electrically-operated radiation generating devices are broad-beam imaging applications for Non-Destructive Testing and Evaluation (NDT&E) of industrial components and assemblies [5]. Due to the high penetrating power of X-rays, gamma rays and neutrons, these are preferred for conventional Industrial Radiography (IR) and computational imaging technologies e.g., Computed Radiography (CR), Digital Industrial Radiography (DIR) and Industrial Computed Tomography (ICT) [6-9].

Conventional and new applications of radioisotopes and radiation in industry form an important part of the Department of Atomic Energy (DAE) mandate of using nuclear technologies for industrial growth, enhanced productivity, self-reliance and societal benefits. With early realisation of the importance of isotopes and radiation technologies along with production of radioisotopes in the indigenous nuclear reactors, India has at present a fairly self-sustained programme and infrastructure for conventional and advanced applications of radioisotopes and radiation technology in multiple domains of national significance. Over the last few decades, Bhabha Atomic Research Centre (BARC) has made pioneering contributions to the development and promotion of applications of sealed radioisotope sources and X-ray equipment for NDT&E by making use of conventional methods as well as advanced and upcoming technologies. In addition to these, BARC has significantly contributed in generating a large number of trained and certified manpower from across the country in industrial applications of radioisotopes and radiation for quality control in manufacturing, testing and maintenance activities through Radiography Testing Level-1 and Level-2 training programmes. The scope of this article is limited to highlighting the specialised area of sealed radioisotopes and radiation applications in industry; especially in gamma radiometry of large and complex structures and assemblies and, computational imaging for advanced non-destructive testing and evaluation undertaken in recent years.

## 2. Gamma Radiometry Testing

For numerous problems in industrial structures and processes, many industries depend on penetrating radiation-based radiometric measurements for troubleshooting and defect localisation. Gamma radiometry is used where other measuring principles are excluded due to extreme process conditions or mechanical, geometric and / or design factors. In chemical, petrochemical and petroleum refining industries, optimum working of process columns such as distillation, extraction and stripper sections is very important as it affects the production efficiency and product quality. Under certain malfunction conditions, deviation in the product quality is observed. Sometimes, many dissimilar problems in the columns can produce almost similar manifestations. Such issues may be solved using conventional techniques including simulation studies based on mathematical models. Online tests like pressure drop, density and viscosity measurements may also be employed. Gamma scanning being a non-invasive technique is often employed in such situations to pin point the problems in process columns.

In addition, radiometry testing being a nucleonic technique is often used for detection of flaws present in the biological shield components in nuclear industry. Biological shield is made of mass of radiation attenuating materials placed around a reactor or radioactive source to reduce the intensity of radiation to an acceptable limit. These flaws may be sub-surface in nature and hence may not be visible to human eyes. The flaws can be in the form of voids, cracks, foreign material or even design faults. Presence of flaws may severely affect the efficiency of a shield component to attenuate radiation and may result in higher transmitted radiation. The purpose of shield is to attenuate the intensity of harmful radiation to a safe level as permitted by the regulatory body and hence its effectiveness during use is of utmost importance.

Most commonly used shielding material for transportation casks is Lead (Pb). Lead-based shield is usually made by casting process. The advantages of using Lead as shielding material are its high density, cost effectiveness and ease of fabrication by casting process as its melting point is relatively low. The problem is with its poor tensile strength and hardness. Sometimes, Antimony (Sb) is mixed in Lead to increase its hardness.. The other problem is failure due to creep. The long time-dependent deformation under a certain applied stress in metals and alloys is called creep. Mostly this problem is observed in Lead-sheets which are commonly used as shielding material in medical X-rays rooms. Gamma radiometry is commonly used for thickness qualification of blocks and assemblies for nuclear radiation shielding. Such blocks and assemblies are made of normal concrete, high-density concrete, Lead, steel, composite materials or a combination of different shielding materials, etc. The manufacturing process may lead to a variety of problems such as structural and dimensional variations or loss of material due to internal voidage or entrapment of foreign materials other than the specified ones. The sensitivity of the technique to detect thickness loss of the material depends on various factors such as selection of radiation detectors, radiation source (quality of radiation), collimator system, calibration method and counting statistics. The radiometry testing is an indirect measurement technique. The data recorded by the nucleonic instruments require very careful interpretation. Inferences drawn by such experiments depend on many factors such as a priori knowledge about the engineering details of the specimen and the sensitivity of the measuring system. The clear advantage of using radiometry testing is in specimens made up of composite materials where most of the other NDT techniques may fail to give satisfactory results.

### *2.1 Gamma Radiometric Measurement*

Gamma radiometric investigation relies on the principal of nucleonic measurement based on a simple yet sophisticated concept – the principle of attenuation [1]. A typical radiometric measurement consists of

- a radioactive sealed source that emits $\gamma$-radiation e.g., $^{60}$Co or $^{137}$Cs nuclide;
- an industrial component or assembly under investigation and
- a nucleonic detector and data acquisition system.

The process of radiometric measurement can be explained as follows:

A narrow beam of gamma rays emanating from the source container or beam generator and directed towards the test specimen undergoes preferential absorption as it travels through the material block. The transmitted intensity will undergo little or no attenuation if there is very less attenuation in the beam path either due to very low density or very less thickness of the material in between the detector probe and the source. The amount of radiation detected by the detector and data acquisition system can be used to estimate loss of equivalent material thickness in relation to expected degree of attenuation through a standard configuration of the test specimen. Techniques based on nucleonic measurement are in general highly reproducible. However, every measurement involves and comprises errors and radiometric measurements are no exception.

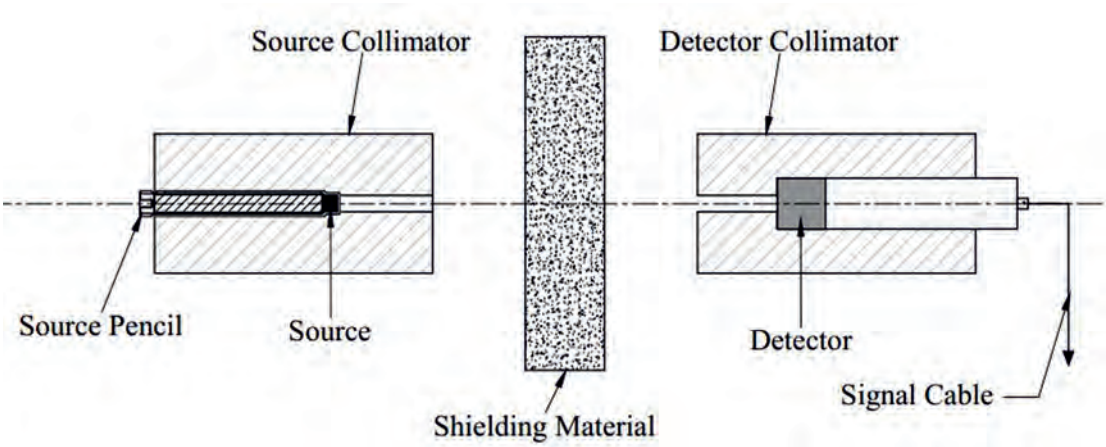


**Figure 1: Schematic block diagram of a typical gamma radiometry setup**

**Figure 2: Preparation for gamma radiometry testing of a high thickness cask**

Fig. 1 shows schematic block diagram of a typical gamma radiometry setup used to carry out shielding adequacy tests of large and heavy shielding blocks used in nuclear industry. Fig. 2 shows preparatory work for carrying out radiometry testing of a high thickness cask in actual field setup. Fig. 3 depicts another two gamma radiometry investigations being carried out on industrial scale shielding assemblies prior to their deployment in actual use.


**Figure 3: Shielding adequacy tests of typical industrial assemblies using gamma radiometry**

## 3. Industrial Radiography Testing

Industrial radiography is a non-destructive testing (NDT) modality, which has become the backbone of quality control protocols in general industrial manufacturing, power generation, automobile production and in-service inspections of plants and assemblies besides other uses. Gamma ray and X-ray-based industrial radiography plays an important role needed to ensure product quality and reliability in many industrial sectors.

In non-destructive testing, materials do not change in their size, shape, physical or chemical properties after testing / inspection. Radiography Testing (RT) being a volumetric NDT technique can reveal internal details of a specimen. With the discovery of X-rays in 1895 and radioactivity in 1896, the penetrating nature of radiation was experimentally observed. Radiographic testing uses either gamma rays from natural radioactivity or sealed radioisotopes or, X-rays generated using an electrical equipment to investigate the internal structure of objects (e.g., components, structures or assemblies) for identification and localisation of defects. The general transmission-type RT technique employs a near-point like radiation source, an object to be radiographed and a detection medium for recording the two-dimensional planar radiation intensity attenuated by the object placed in between the source and the detector. Conventional RT often employs silver halide films or phosphor plates for recording latent images. Fig. 4 shows general scheme of radiographic exposure for two-dimensional (2D) RT image. The schematic diagram also shows the basic difference between a radiographic image and a two dimensional tomographic image plane. Fig. 5 represents use of one-dimensional (1D) linear detector array (LDA) and 2D electronic detectors for imaging applications [10].

For technical reasons, industrial radiography is primarily carried out using Cobalt-60 ($^{60}Co$) or Iridium-192 ($^{192}Ir$) sealed radioisotope-based gamma exposure devices or industrial X-ray generators. In conventional radiography, by choosing a variety of source-film combinations, varying degree of flaws detection in different materials can be achieved. However, the existing techniques have their inherent limitations in flaw detection sensitivity for examination of thicker or thinner sections of materials. Using $^{192}Ir$ and $^{60}Co$-based radiographic cameras; steel equivalent thickness over the range of 15 to 175 mm can be satisfactorily inspected. For radiographic testing of thick concrete and composite materials made up of concrete, Lead and steel, use of high-energy X-rays from linear accelerators (LINACs) or betatron may be required. Use of micro-focus X-ray systems for examination of thin sections as well as for detecting very fine defects in low-density materials is now prevalent. Exposure devices using other radioactive sources e.g., $^{169}Yb$, $^{75}Se$ and $^{241}Am$ are also suitable for inspecting thin sections of specimen of light metals and composites. Gamma-ray back scatter NDT techniques are used for inspection of large components and assemblies with only one-side of physical access. Flash X-ray-based radiography is used to inspect fast dynamic systems, ballistic and shock-wave studies and recording extremely short-duration events.

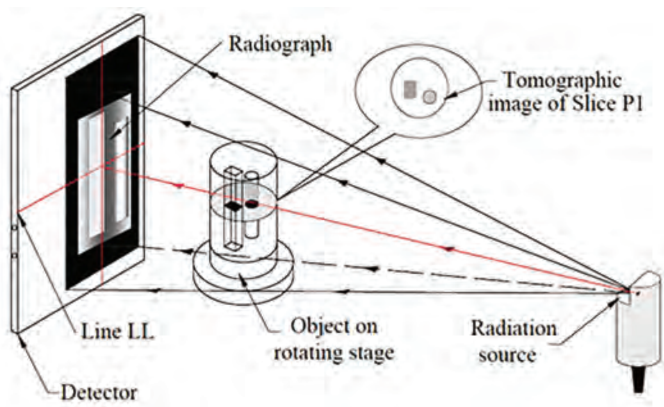


**Figure 4: Radiographic exposure scheme and difference between an RT image and a tomographic cross-section**

## 4. Industrial Imaging Modalities

The whole imaging modality may be off-line as in the case of conventional film radiography (FR) and computed radiography (CR), or online as in fluoroscopy or digital industrial radiography (DIR) employing high-resolution two-dimensional electronic image detectors. It may also be real-time where radiographic images may be seen instantly and in high frame rate so that possibly dynamic systems and processes may also be visualised. These are basically direct imaging methods employing none or minimum computations for generating an image for visual interpretation. There is another class of computational imaging methods which are capable of providing two and three dimensional representations of the objects and embedded defects, and can provide more accurate data on quality and geometric information of defects. Industrial computed tomography (ICT) makes use of different scanning modalities based on hardware and software as well as type of radiation source used.

### *4.1 Computed Radiography and Digital Industrial Radiography*

There are different techniques to produce digital radiographs e.g., high resolution scanning of RT films, fluoroscopy / image intensifier coupled with high resolution digital cameras having digital interface with a computer, use of phosphor image plates (IP) instead of chemical and light-sensitive films as in computed radiography and finally a 2D direct digital detector (DDR).

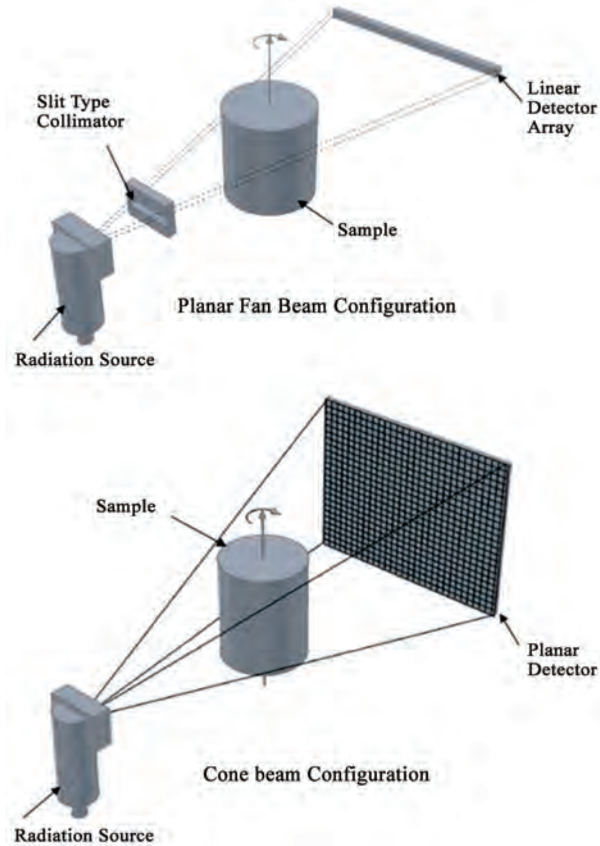


**Figure 5: Use of 1D and 2D arrays of electronic detectors for computation imaging**

Among these, most popular in routine industrial applications are computed radiography using image plates and flat panel detectors as they are portable and do not require addition chemical processing with dark room facility [7-9].

*Computed Radiography:* Computed radiography is a non-destructive evaluation technique where phosphor image plates are used as recording medium for the transmitted radiation beam after it passes through the object under investigation. Image Plates are exposed in a way similar to chemical-based films and latent image is created (matrix of trapped electrons in the plate) by absorption of X-ray quanta by the atoms without any visual effect. A typical image plate consists of a flexible polymer-based thin sheet covered with a photo-stimulable phosphor layer generally consisting of BaFBr mixture doped with Eu2+. A thin protection layer prevents the surface from mechanical damages.

The exposed plate is scanned using a He-Ne laser (red) during which the absorbed energy is released. The laser releases a quantity of blue light (photo-stimulable luminescence) which is detected by photo multiplier tube (PMT) or a solid-state detector. The intensity of blue light detected by PMT is a measure of radiographic density at a particular point. The signal intensity is electronically converted into digital values and stored as an image file for further processing. Typical pixel pitch is 50 to 150 µm. The latent image is erased subsequently scanning with white light and the plate is ready for next exposure. The image acquired in the connected personal computer is further processed and enhanced using image processing operations before evaluation and analysis. Thickness of phosphor determines sensitivity and spatial resolution. The quality of scanner and the laser beam focal spot also influence the image resolution. Normally scanning is optimized with 100 μm (typical value) spot side for fast IP whereas for standard IP it is 50 μm. High definition IP pixel size of 20 μm is used for applications requiring higher resolution [14]. A typical case study of RT investigation using high definition CR is described below.

Computed radiography-based investigation of 6 MeV LINAC-based X-ray source system developed for cargo inspection was carried out for its suitability for industrial NDT applications [15]. Experiments were conducted using 100 mm thick mild steel block as the specimen. A suitable Image Quality Indicator (IQI) was placed on source side. The pentameters used were of Wire-type ASTM set D:1-ISO-7; 6-ISO-12 and Hole type 80T & 100T IQIs.

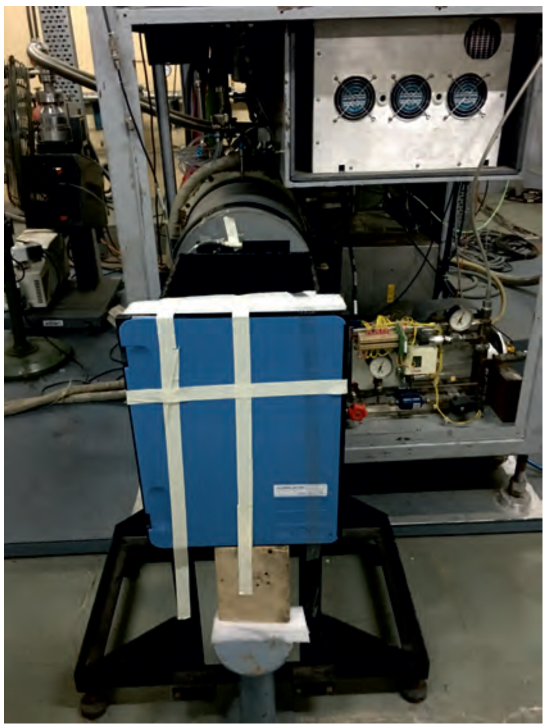

**Figure 6: LINAC assembly X-ray head with IP for CR exposure**

The LINAC (Fig. 6) was operated at 6 MeV, 160 mA peak current at 100 Hz pulse repetition rate to achieve a dose rate of approximately 2 Gy / min. at 1 m distance from the target. Exposure time was kept at seven minutes [16]. The exposure setup included CR BLUE IP of size 24 x 30 and HD-CR 35 NDT electronic scanner . Fig. 7 shows the radiograph obtained after reading on the scanner. Thickness sensitivity better than 2% was achieved during this experiment. Minimum Grey value achieved was 10000. Acceptable level of sensitivity and grey value could be achieved in this experiment. Results were in agreement with those obtained by experiments carried out by other Divisions of BARC [16, 17].

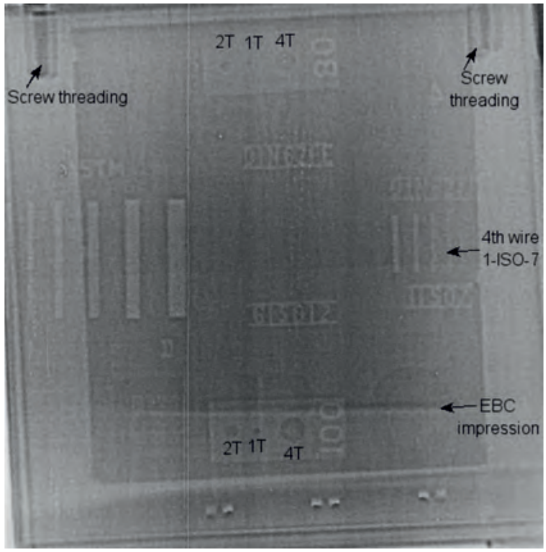


**Figure 7: Mega-voltage computed radiograph (CR) of 100 mm thick steel specimen with adequate IQI sensitivity. Image shows screw threading at the top and feature of EBC impression at the bottom**

Another example of CR for investigation of an archaeological sample is shown in Fig. 8(a). This study was carried out to evaluate internal structures using X-ray-based CR imaging. The machine-based X-ray source had an effective focal spot of 0.4 mm. HD-IP was used as detecting medium. Exposures were taken at 100 kV and 10 mA-min. Contrast sensitivity of about 2% was achieved and the internal details of specimen (Buddha statue) are clearly revealed by the radiograph shown in Fig. 8 (b).

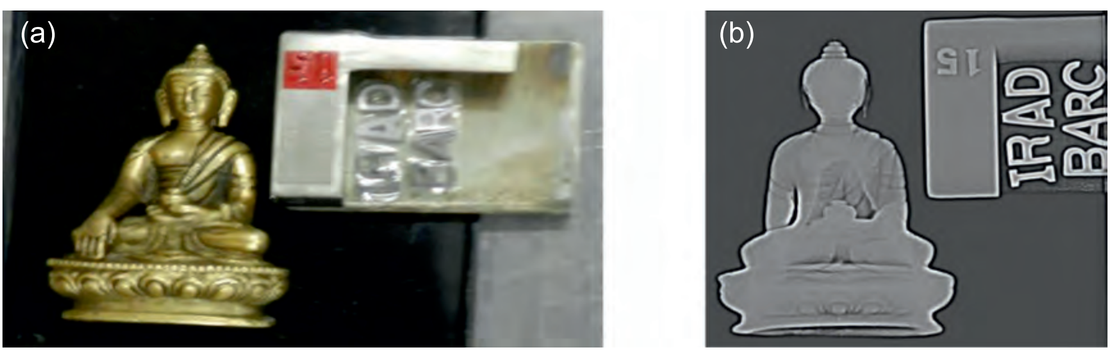


**Figure 8: Computed radiography investigation of an archaeological sample (a) Photograph of the specimen (Buddha statue) (b) X-ray computed radiograph**

*Digital Industrial Radiography :* Flat panel detectors (FPD) are two dimensional arrays of small solid-state detectors which converts the incoming X-ray / $\gamma$-ray photons into electronically measurable charge carriers. Entire structure is built on a glass substrate and is encased in a rigid metallic assembly to protect it from physical damage. Detectors' size in the array determines the final image resolution. Digital signal from the detector module is interfaced with a computer through a fast data acquisition system. Data proportional to the radiation exposure to the device is digitally acquired and the radiographic image is displayed almost instantly for interpretation. Two types of FPDs are commercially available- direct conversion and indirect conversion type [18, 19].

In direct type FPDs, X-ray photons absorbed by amorphous selenium are converted into charge carriers (electron-hole pair). No separate scintillator is required. Under application of bias, electron and hole travel to respective electrodes. Thin film transistors (TFT) and storage capacitor for each pixel are design elements of the integrated detector unit. Image resolution is governed by pixel geometry in addition to other factors. It has limited stopping power and hence practical applicability may be restricted up to 50 keV of X-ray energy.

Indirect type FPDs have a layer of scintillating material ($Gd_2O_2S$:Tb, CsI, etc.) as the first layer where X-ray or other ionizing radiation falls. This layer of scintillator converts the striking X-rays into visible light photons. These photons are coupled to an array of photodiode which converts them into electrical charge (electron-hole pair) that activates the TFT in a layer of amorphous silicon (a-Si). Each of the TFTs attached to the photodiode makes up individual pixel. Resolution is not governed by the pixel size but also the scintillating material used and the optical cross-talk in the scintillator medium. Generated signal strength (or intensity) is proportional to quanta of light produced by the scintillation layer.

A typical application of digital radiography is in inspection of welds. Radiographic inspection of welded plates (Stainless Steel, thickness 10 mm) with FPD has been carried out in our laboratory to evaluate weld integrity. Imaging has been performed using 40-450 kV constant potential X-ray equipment having 0.4 mm effective focal spot size and indirect FPD based on a-Si. Fig. 9 (a) shows photograph of plate weld used in the study. Digital radiograph of the plate weld as shown in Fig. 9 (b) was able to reveal lack of penetration (LOP) and spatter around weld and heat affected zone (HAZ) boundary. In order to improve the visibility of defects, sharpness filter was applied to process the image. Sharpness filter is an edge enhancement filter which improves the boundary of flaws i.e., high frequency components, in radiographic images.

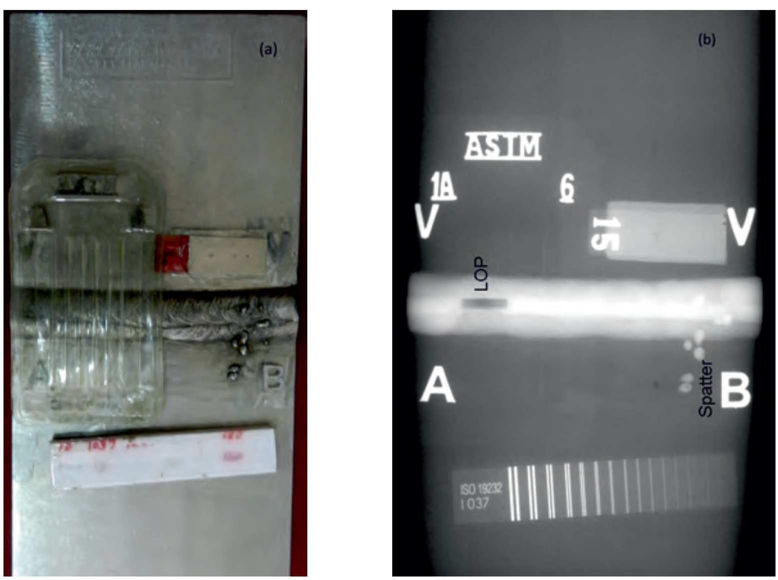


**Figure 9: (a) Photograph of plate weld (b) digital radiograph of plate weld using FPD after image enhancement revealing defects (LOP and spatter)**

Another application of DR for the study of opacity properties of polymer composites made of polyurethane (PU) and silicon rubber (SR) with different compositions (0%, 1%, 3%, 5%, 10%, 25% & 50%) is presented in Fig. 10.

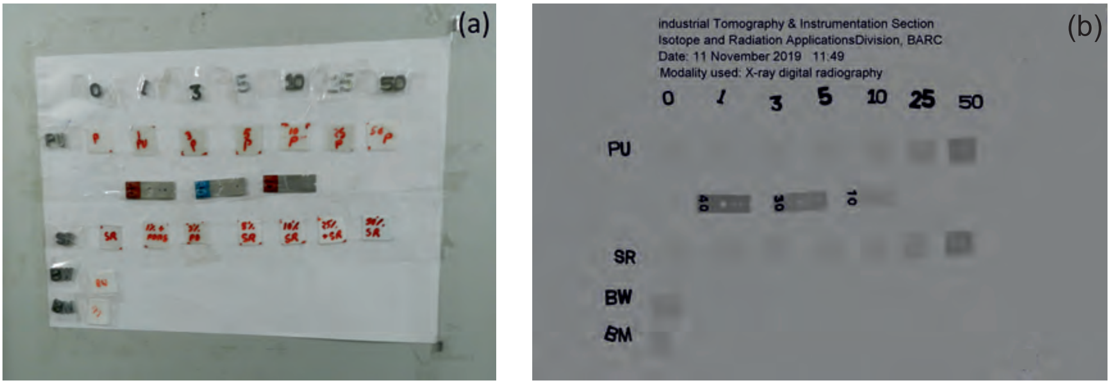


**Figure 10: Radiographic analysis of polymer samples:**
**(a) photograph of the samples, (b) corresponding digital radiograph**

### *4.2 Industrial Computed Tomography*

Unlike the simple projection radiography, industrial tomography is an indirect imaging technique. In its simplest form, tomography refers to reconstruction or recovery of cross-sectional images representing slices through a volumetric object under examination. The analytical method of reconstruction of parameter of interest in tomography involves large computational steps on directly measured external data. Even though computed tomography is often perceived as a medical imaging tool, it is now widely employed in many industrial applications due to its non-invasive nature of imaging. Industrial computed tomography is an advanced NDT&E imaging method used in physics, material science and other branches of science and engineering.

In case of transmission computed tomography, the reconstruction or generation of cross-sectional images is based on some mathematical procedure, which makes use of multiple projection data through the object at different angular positions. The mathematical procedure is specifically referred to as image reconstruction. Basically, there are two broad classes of reconstruction algorithms: analytical back projection methods and iterative reconstruction (IR) methods.

Projection data are mathematically represented by Radon transform. The Radon transform $R\,(f(\,t, \beta\,))$, or the projection '$P_\beta(t)$' of an object $f(x,y)$ is the line-integrals through the object in all angular directions in the scanning plane (Fig. 11). This means, a single Radon value is the integral of all points along a line at an angle '$\beta$' and perpendicular distance '$t$' from the origin. The Radon transform can be written as follows [10]:

$$P_\beta(t) = \mathrm{R}(f(t,\beta)) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y)\delta(x\cos\beta + y\sin\beta - t)\,dxdy \tag{1}$$

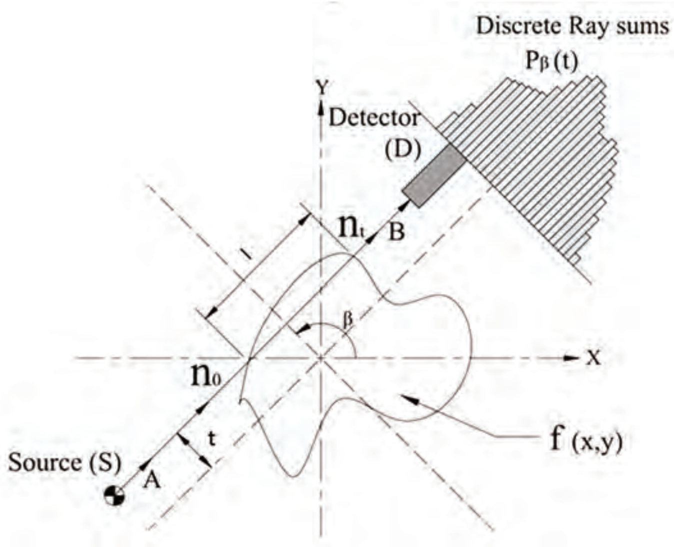


**Figure 11: Coordinate system to define projections**

Tomographic image is the sum of all back projections. In case of equiangular fan-beam geometry of source and detectors (Fig. 12), reconstructed image $\hat{f}(x, y)$ from its fan-beam projection data can be obtained using filtered back projection (FBP) method using the following formula:

$$\hat{f}(x,y) = \Delta\beta \sum_{i=1}^{M} \frac{1}{L^2(x,y,\beta_i)} p(\beta_i, \gamma') \qquad (2)$$

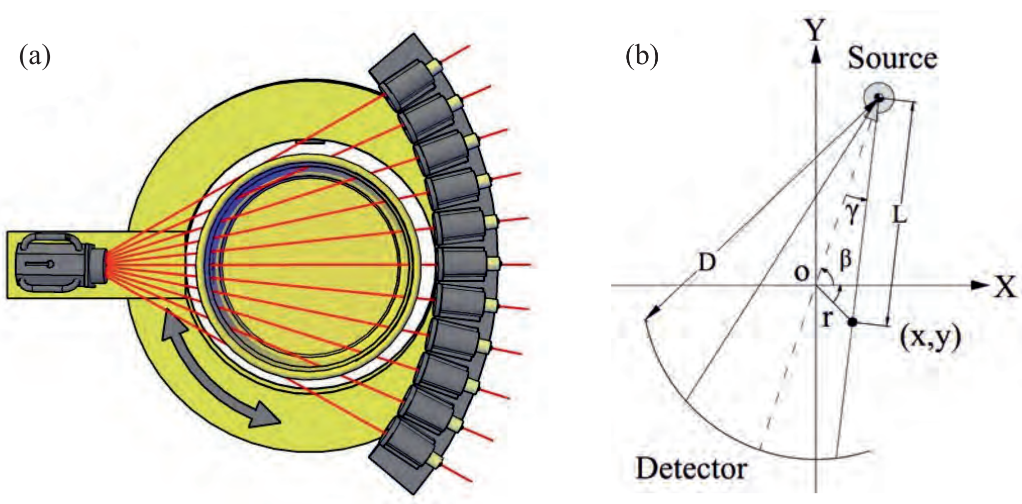


**Figure 12: (a) Schematic diagram of equiangular fan-beam geometry and (b) coordinate system for scanning geometry**

where, $p(\beta_i,\gamma')$ is the $i^{th}$ row of the sinogram acquired by equiangular fan-beam geometry, '$L$' refers to the distance from the source to pixel, '$M$' refers to total number of projections over 360 degrees with an angular interval $\Delta\beta=\frac{2\pi}{M}$, and γ' is the angle of a fan-beam ray that passes through the pixel ($x,y$) [10].

As can be seen, one dimensional detector array can be used to acquire projection data across a plane at a time. In case of two-dimensional detector array, a planar projection of a three dimensional object can be acquired. A set of these projections can be used to reconstruct volumetric tomography data. In an ideal situation, if parallel projection data are available, a plane integral may be obtained from the one dimensional integration of projection data along a line on the planar detector. However, the near-point radiation source produces a divergent cone-beam and a plane integral is not equal to a one-dimensional integral of divergent projection data. Feldkamp, Davis and Kress [11] describe an approximate reconstruction algorithm popularly known as FDK algorithm for circular cone-beam tomography. Further details on tomographic image reconstruction from projections are well reported [10-13]. It is to be noted that there are many variations and optimised implementations of fan-beam and cone beam algorithms.

Industrial Tomography and Instrumentation Section (ITIS) of Bhabha Atomic Research Centre (BARC), Mumbai has been actively involved in research and development (R&D) activities pertaining to industrial applications of X-ray and gamma-based radiography and tomography for more than two decades. Development programmes undertaken earlier resulted the setting up of an experimental facility for X-ray radiographic imaging and cone-beam computed tomography (DR&CT). Fig. 13 shows a schematic representation of X-ray DR&CT setup. It shows relative orientation and location of a 40-450 kV (variable anode voltage) constant potential X-ray generator having focal spot sizes of 0.4 mm and 1.0 mm, a flat panel detector (FPD) and a multi-axis precision manipulator for positioning source, detector and specimen. The detector is a medium resolution amorphous silicon (a-Si) based FPD with 2048 × 2048 pixel resolution (pixel pitch : 200 μm × 200 μm) providing maximum image size of 41 cm × 41 cm. This imaging system has been custom designed and used in several experiments for advanced Non-Destructive Evaluation (NDE) of industrial specimens. It is capable of scanning specimen having maximum dimension up to 400 mm in any orientation. Components and assemblies for scanning are selected based on their radiation attenuating capacities and physical shape and size. The system can generate data for three dimensional volume visualization and measurements. A computer-based workstation controls the machine software and is also used for computational requirement. The system can operate in specified DIR geometry and volume tomography mode within its designed capabilities (Fig. 14).

For illustration, photograph of a typical industrial specimen (fuel injector) and the corresponding cone beam computed tomography (CBCT) 3D reconstructions are shown in Fig. 15. For getting the mathematical reconstruction, digital radiographs of the sample, also termed as projections in the ICT terminology, have been acquired on the scanner set-up described above. Tomographic reconstruction was done using FBP algorithm to generate multiple ICT images. These images have been stacked together to form the three dimensional perspective view of the sample.

Another example is non-destructive examination of structural integrity of a PMT assembly. Fig. 16 shows photograph of the specimen (PMT assembly) and its digital radiographs. Fig. 17 illustrates 3D reconstructed volume, its cut-away view and cross-sectional images. These images clearly show different parts of the assembly such as dynode structure, joints and stainless steel cover.

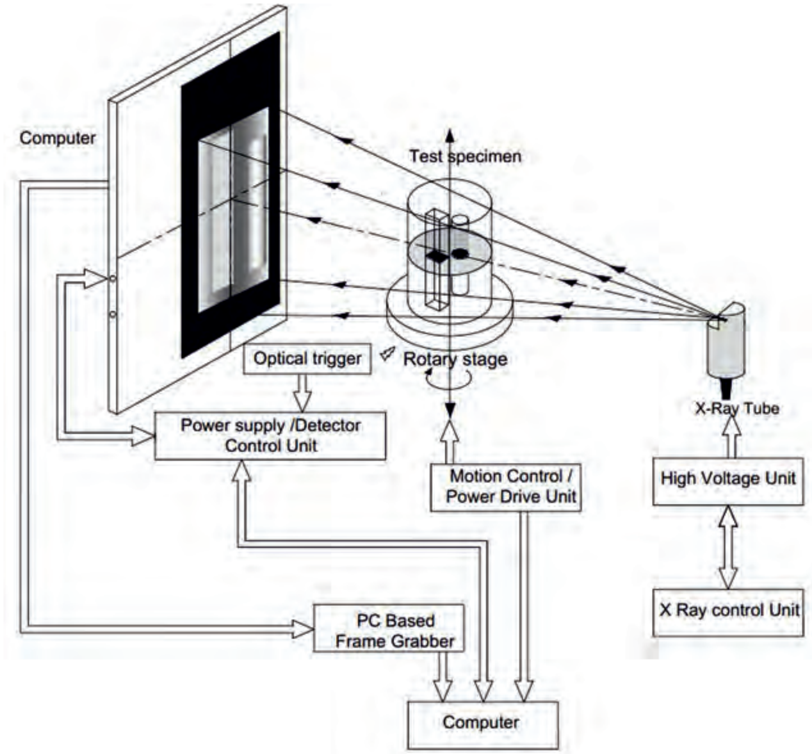


**Figure 13: Schematic representation of a typical X-ray based DR&CT setup**

**Figure 14: Photograph showing X-ray based DR&CT setup at BARC consisting of a 40-450 KV constant potential X-ray source, Flat Panel Detector (FPD) and a multi-axis computer-controlled mechanical manipulator**

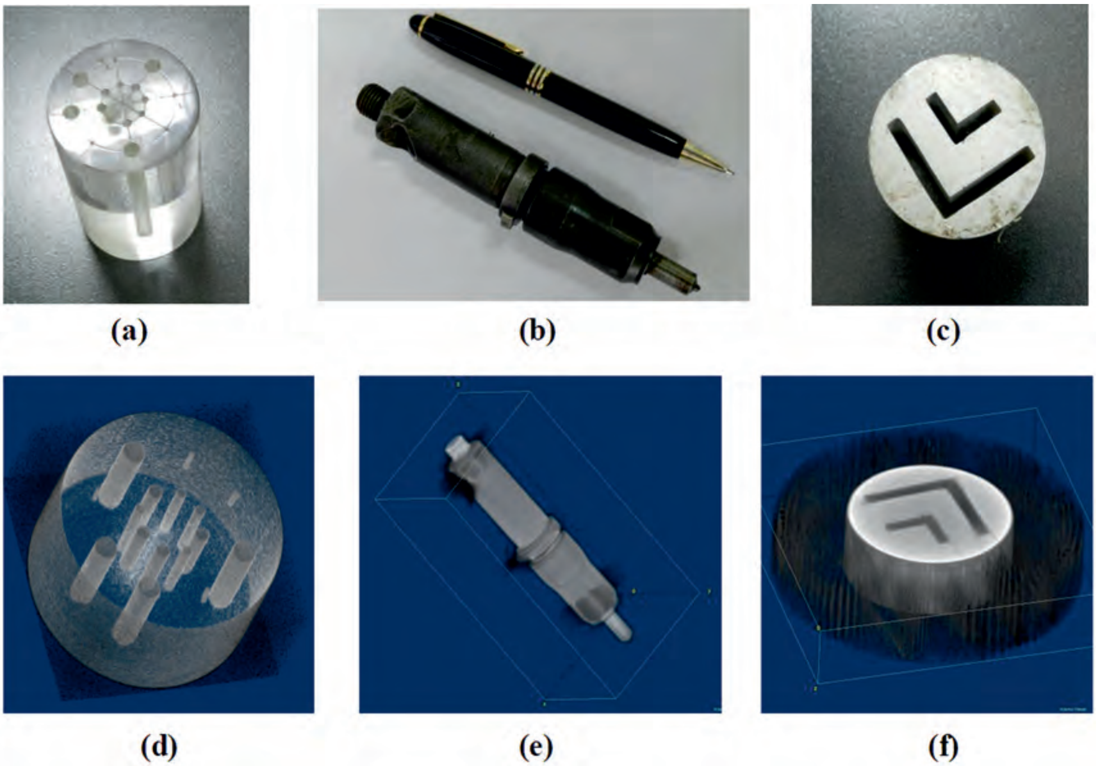


**Figure 15: Photographs of samples used for test CT scans (a) a perspex block with multidimensional holes (b) a diesel injector assembly (c) an aluminium block with 'L' sections cut into it and corresponding 3d reconstructed cone beam CT images as shown in (d) (e) (f) respectively.**

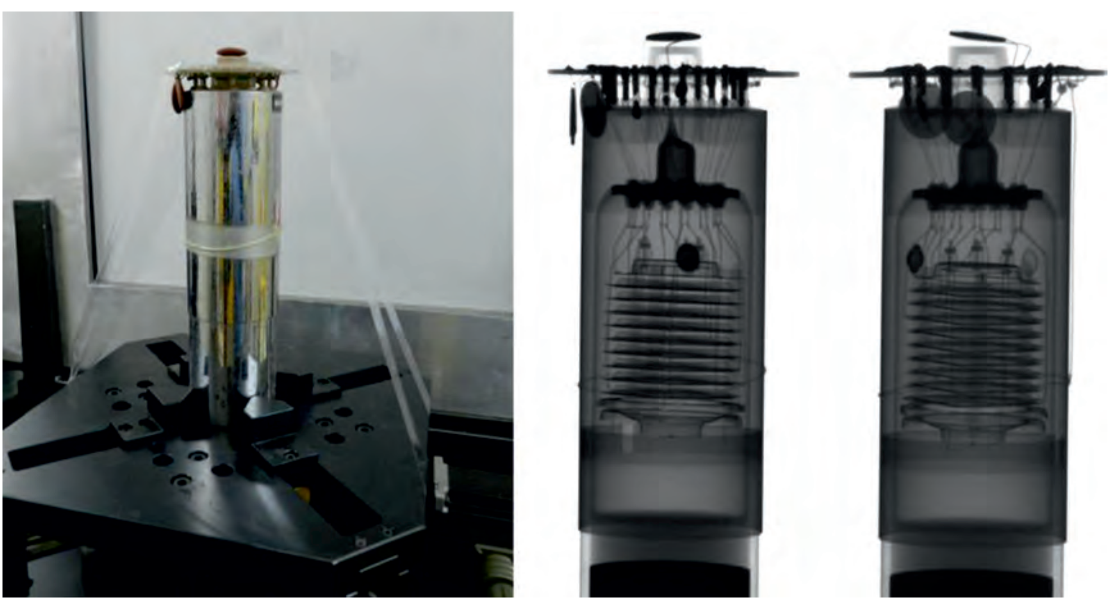

**Figure 16: Photograph of a PMT assembly and its digital radiographs**

**Figure 17: 3D reconstructed volume, cut-away view and cross-sectional images showing different parts of the PMT assembly such as dynode structure, joints and stainless steel cover**

### *4.3 Industrial Process Tomography*

Process Tomography (PT) is one of the ICT modalities generally useful in chemical and process industries. It is an advanced radio-diagnostic technique based on the principle of tomographic reconstruction using data acquired specifically with discrete detectors and a radioisotope-based beam generator for field applications. In a typical PT setup, the measurements represent steady-state approximate bulk density distribution of an industrial process column as a result of interaction with gamma rays. Process tomography can also be carried out on a test specimen using resistive or capacitive properties of the bulk material. However, transmission-type PT based on gamma radiation from sealed radioisotopes can be employed in many chemical and process industries in actual working conditions. This computational technique may as well be used for assessment of the variations in the quality of the end product [20-22].

Development work has been carried out earlier on software codes and hardware solution for a typical industrial process tomography requirement. An experimental facility for carrying out data generation, scanning parameter optimization and visualization of process related cross-sections up to 600 mm column diameter was setup in collaboration with the R&D Centre, IOCL, Faridabad. A 32-channel nucleonic data acquisition system with thirty two detector probes was used at the premises. The integrated system was capable of acquiring projection data under different experimental conditions. The data generated at the facility could also be sent back to laboratory for detailed analysis. The development work provided an entirely different experience to all the technical and scientific personnel involved in the proposed experimental setup during that time [23].

Fig. 18 shows general scanning modality in process tomography using transmission method. Fig. 19 shows the PT system installation in progress and also the test column structure in final configuration at the research and development facility of the collaborating organization. The figure also shows the multiple detector probes aligned across an arc on the scanning gantry. The experimental system made use of thirty two Bismuth Germanate ($Bi_4Ge_3O_{12}$) detectors along with other sub-systems. It provided the cross-sectional images of the column representing the approximate density distribution. The PT system validation and fluid flow distribution using tomography technique have been carried out. Fig. 20 shows results of PT images and flow distribution in test operating condition of scaled-down pilot plant [24].

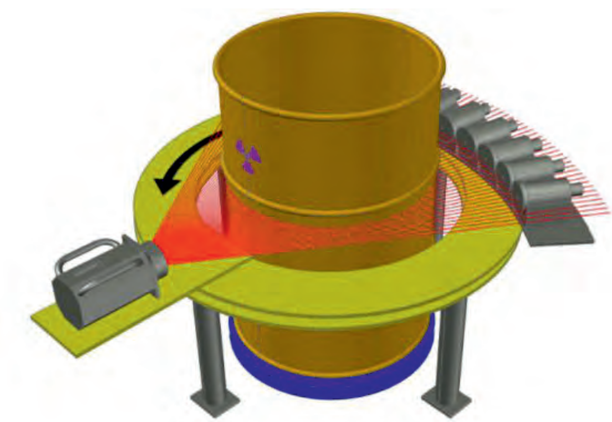

**Figure 18: General scanning modality in process tomography using transmission method**

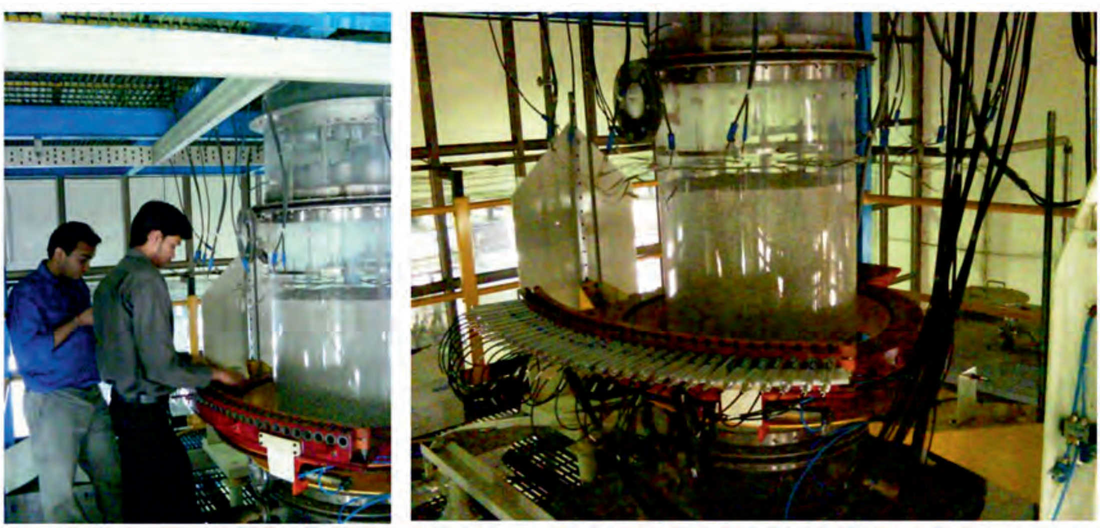

**Figure 19: Process Tomography setup by ITIS, BARC on a test catalytic column for at the IOCL R&D Centre during (i) installation and (ii) final view**

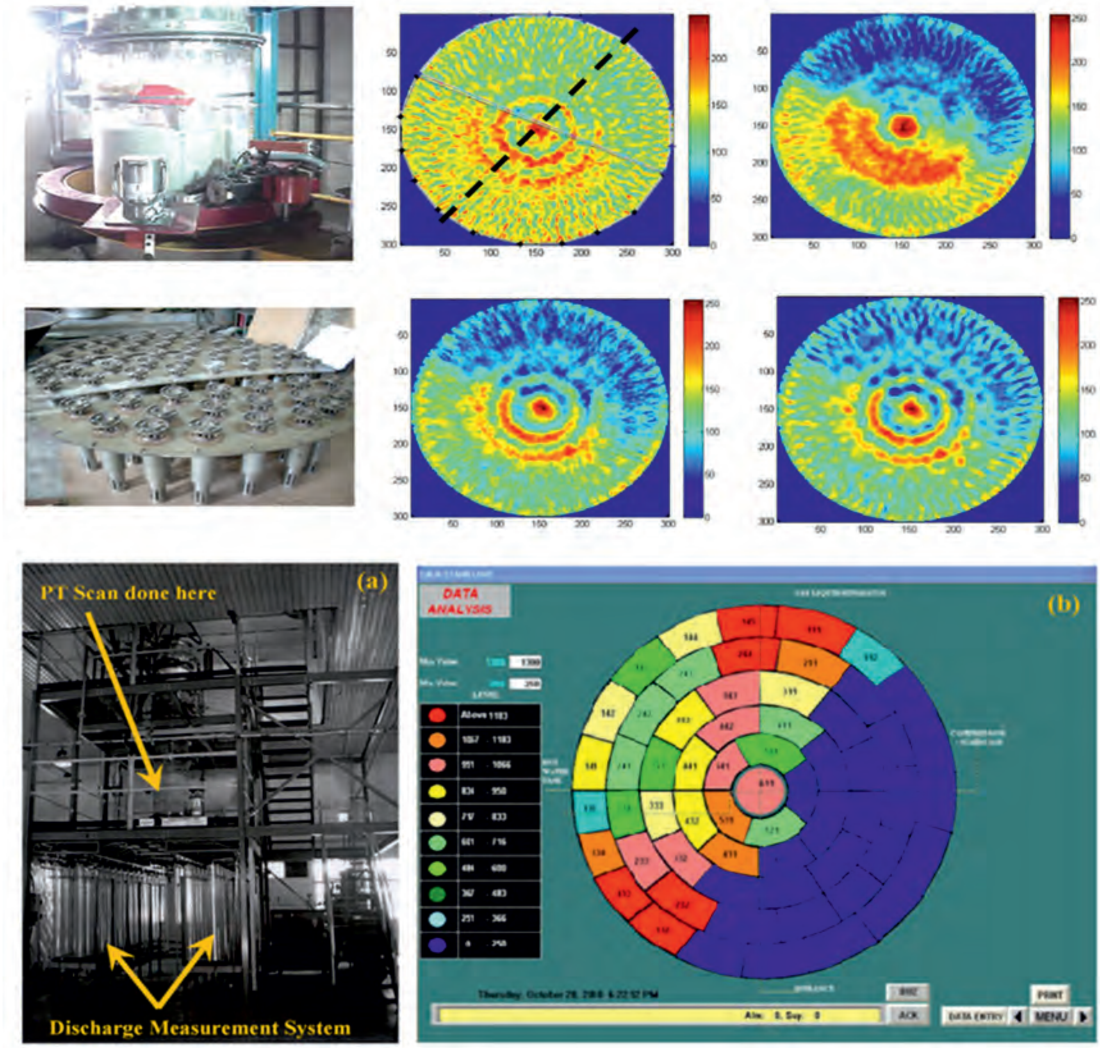


**Figure 20: Photographs showing some results obtained on PT system developed by ITIS and typical flow distribution in operating condition of the pilot-scale test column [24]**

## Conclusion

Besides conventional industrial radiography and radiometry techniques, computational imaging methods and especially industrial computed tomography as well as some of its adaptations for different problem areas in select manufacturing, process and in-service inspection domain are gaining importance as advanced non-destructive testing and evaluation techniques. These industrial diagnostic technologies often rely on penetrating and ionising radiation generated by sealed radioisotope sources in addition to other electrically-operated devices. Research and development is often an ongoing process in any sector of science and technology applications for the benefit of the society and radioisotope and radiation applications are no exception. However, the focus needs to be in the area of rapid adaptation of newer technologies in order to produce cost effective solutions locally in addition to building capabilities and infrastructure for sustaining these efforts in future.

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