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Industrial Applications of Sealed Radioactive Sources

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INDUSTRIAL APPLICATIONS OF SEALED RADIOACTIVE SOURCES

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INDUSTRIAL APPLICATIONS OF SEALED RADIOACTIVE SOURCES

INTERNATIONAL ATOMIC ENERGY AGENCY
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FOREWORD

Non-intrusive and non-destructive sealed radioactive source techniques are largely applied for troubleshooting and diagnosing industrial processes. The IAEA has been promoting these techniques in developing Member States for several years. Extensive experience has accumulated all over the world in the safe application of sealed source techniques, and there are many application groups in developing Member States that provide routine services to their local industries.

As processing vessels and pipelines in industry are not, and most likely never will be, transparent, it is useful to have a range of on-line non-intrusive techniques that can effectively 'look' through vessel and pipe walls to measure process parameters and identify problems. Radioisotopes that emit gamma and neutron radiation are ideally suited for this purpose and have been used for industrial applications for many years. For example, the gamma scanning technique provides the clearest picture of on-line conditions inside a process vessel. The gamma scanning technique is the most widely applied sealed source application worldwide, with tens of thousands of gamma scans carried out every year, and the economic benefits of column scanning in small and medium sized petroleum refineries exceed US $100 000 per year.

This publication describes various sealed source techniques, giving examples of their use in industrial applications, and demonstrates how they can be applied to improve process efficiency and save money. The focus is on two major sealed source techniques, gamma scanning and neutron backscatter, which are largely applied in diagnosing and troubleshooting processing vessels, columns and pipes.

The IAEA officer responsible for this publication was P. Brisset of the Division of Physical and Chemical Sciences.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Applications of sealed radioactive sources in industry began about fifty years ago, and since then, there has been continuous expansion in their usage. They have been widely used by various industries to improve the quality of product, optimize processes, save energy and materials [1, 2]. The economic benefits obtained from sealed source techniques have been amply demonstrated and recognized by industry. Looking at trends in the industrialization process in developing countries, there is evidence that these techniques will continue to play an important role in industry for many years to come; their success is primarily due to the advantage of online detection without shutting down processing vessels.

Radiation techniques for diagnosis and troubleshooting of industrial processes, columns and vessels are of two categories [3, 4]:

- Sealed radioactive source inspection techniques;
- Open radioactive source (radiotracer) techniques.

This publication is dealing with sealed radioactive source techniques for inspection of industrial processing vessels, columns, reservoirs and pipes. Two major techniques largely applied in diagnosing and troubleshooting industrial processing vessels and pipes are gamma scanning and neutron backscatter techniques [5].

The gamma ray transmission scanning technique is used to investigate column and pipe performance. The gamma scanning technique is the most applied in routine service to the industry worldwide, especially in petrochemical plants to identify process anomalies and malfunctions as well as to verify the integrity of columns' internals. In addition, it is also applicable to measure and quantify deposits and blockages in pipelines [6].

Another technique, named neutron backscatter, involves the use of a fast neutron emitting sealed source. Neutron has the same size as hydrogen. Neutrons penetrate lagging and steel, but if any hydrogenous liquid is present within a vessel or pipeline, the neutrons are rebounded (or scattered back) by the hydrogen out of the vessel as slow thermal neutrons and can be detected by a thermal neutron detector. The source and detector are located within a small portable instrument that can be moved up and down the vessel walls to quickly and accurately locate levels and interfaces. In addition to level measurements, the neutron backscatter technique can be used to accurately measure interfaces such as oil/water or oil/sludge, because of the different hydrogen contents between the two phases.

1.2. OBJECTIVE

The objective of this publication on Industrial Applications of Sealed Radioactive Sources Applications is to promote and sustain the routine application of sealed sources in industry, by providing its methodology aspects and illustrating with many case studies performed worldwide. It contains examples of good practices and know how in sealed source application for diagnosing and troubleshooting industrial processing vessels, columns and pipes.

1.3. SCOPE

The main scope of the publication on Industrial Applications of Sealed Radioactive Sources is to describe the methodology and technology of sealed sources as applied to diagnosing and troubleshooting of industrial processing plants.

1.4. STRUCTURE

This publication is organized into six sections. Section 1 contains the background, objective, scope and structure.

Sealed source methodology is covered in Section 2. Section two contains discussion of the two most known sealed source techniques, the gamma scanning and neutron backscatter techniques, which are largely employed in routine services in industry.

Sections 3 deals with case studies applying gamma scanning and neutron backscattering techniques.

Section 4 deals with laboratory modelling of gamma scanning technique. Miniature columns, vessels and pipes can be designed for laboratory tests to master the technique and scale it up.

Section 5 provides basic considerations about planning and execution of sealed source field work.

Section 6 gives some consideration about economic benefits of applying gamma scanning and backscattering techniques for troubleshooting and diagnosis various columns and vessels.

Section 7 provides basic information about ISO standards.

2. SEALED RADIOACTIVE SOURCE METHODOLOGY

2.1. BACKGROUND

Sealed radioactive sources can be used to scan vessels and pipelines to identify such things as integrity of internals, levels and interfaces, deposits build-up, and other process anomalies. Sealed source techniques are based in the principle of gamma and neutron transmission and scattering [1, 3].

Gamma rays are used for on line investigations because they penetrate and pass through matter, such as steel for example, and are attenuated to an extent that is directly proportional to the density and thickness of the material. By measuring the relative attenuation of the transmitted gamma rays, accurate information can be inferred on the material that they have passed through.

By simultaneously lowering the sealed source and detector down a column diametrically opposite each other and taking measurements of the count rate as they are lowered, a 'picture' (profile) can be formed showing what is happening within the column. This profile is effectively the mean density of material between the source and detector at each point, and hence internal structure of the vessel can be easily and quickly identified. No preparation of the column is needed, and lagging does not need to be removed.

Neutrons emitted from radioisotope sources are energetic particles, with energies up to several MeV, such energetic neutrons are referred to as 'fast neutrons'. Fast neutrons do not interact with the electric fields of atoms and molecules. In addition, because of the large mass of the neutron compared with that of the electron, neutrons are irrelevantly affected by electron collision. The only way in which a fast neutron passing through matter can lose its energy is by direct collision with an atomic nucleus. Therefore, fast neutrons are penetrating particles, capable of passing through substantial thickness of material and hence ideal for tank and vessel scanning.

Fast neutrons, in the range 0.5-11 Me V, lose their energy by scattering process. In elastic scattering, the neutron is slowed down in the collision and its direction of motion is changed. In the energy range 30 eV - 0.5 MeV, elastic scattering is essentially the only process by which a neutron can be slowed down. If the neutron energy before collision is denoted by E_1 and after collision by E_2, it is possible to show that in a head-on collision, the energy transferred to the nucleus of an atom is

$$E_2/E_1 = [(A-1)/(A+1)]^2$$

Where A is mass number of the nucleus. It is clear from the above equation that it is possible for a nucleus to lose all its kinetic energy in a head-on collision with a hydrogen nucleus. Hence, the presence of hydrogen is a major factor in the slowing down of fast neutrons. The concentration of thermal neutrons near the fast-neutron source is increased by the presence of hydrogen. This fact can be used to accurately measure interfaces such as oil/water or oil/sludge, because of the different hydrogen contents between the two phases.

2.2. SEALED RADIOACTIVE SOURCES

A sealed source is made with a radionuclide sealed in a double metallic capsule according to international regulations. Source capsule integrity is the main characteristic of a sealed source used in industry. Sealed sourced manufacturers specify a 10 - 15 years life for the source capsule integrity. There are many sealed sources used in industry, mostly for non-destructive testing. The major radioisotopes applied for scanning techniques are classified in gamma and neutron sources.

2.2.1. Gamma sources used for gamma scanning

The main gamma sources used routinely for field gamma scanning of columns and pipes are: ^{60}Co, ^{137}Cs and ^{192}Ir (Table 1) [5, 6].

TABLE 1. MAIN RADIOISOTOPES USED FOR GAMMA SCANNING

Radioisotope	$T_{1/2}$	Energy (MeV)	Gamma constant μSv/h/GBq at 1m
^{137}Cs	30.2 y	0.662 (89,9%)	105
^{60}Co	5.27 y	1.173 (100%) 1.332 (100%)	360
^{192}Ir	74.2 days	0.316 (86.1%) 0.468 (50.0%)	150

X ray generators are normally not used for field gamma scanning and cannot replace sealed source s in this application for the following reasons:

- An X ray generator needs a power supply;
- An X ray generator is less stable than a sealed source;
- X ray generators with high energy (order of 1 MeV) are very bulky or does not exist.

Figure 1 shows typical form of encapsulated gamma sealed sources.

FIG. 1. Typical gamma sealed source (Courtesy, Eckert & Ziegler).

2.2.2. Neutron sources used for neutron backscatter scanning

The two main neutron sources used for neutron backscatter scanning are ^{241}Am-Be ($T_{1/2}$ =432.7 y) and ^{252}Cf ($T_{1/2}$=2.645 y) (Table 2). ^{252}Cf and ^{241}Am-Be have wide range of applications in industries because of their high flux and reliable neutron spectrum. ^{241}Am-Be, in fact is a mixture of the radioisotope ^{241}Am, which decay with alpha particles packed in a low-Z elemental matrix of Beryllium. Neutrons are produced when alpha particles impinge upon the isotope of beryllium. Typical emission rates for this alpha reaction neutron source range from 1×10^6 to 1×10^8 neutrons per second [3].

TABLE 2. MAIN RADIOISOTOPES USED FOR NEUTRON BACKSCATTER SCANNING

Neutron source	$T_{1/2}$	Neutron mean energy (MeV)	Flux of fast neutrons
^{241}Am – Be	432.7 y	4,46	$2,6 \times 10^6$ n / Ci / s
^{252}Cf	2,645 y	2,12	$2,3 \times 10^6$ n / μg / s

The useful lifetime for this neutron source is depending upon the half-life of the radioisotope 241Am that emits the alpha particles. 241Am and Be produce neutrons at a rate of approximately 2200 neutrons/second per mCi of 241Am. 1Ci 241Am-Be neutron source is a typical source used in field work; it produces a flux of 2.6×106 n/s and contains an energy spectrum from 0.1 MeV to 11.2 MeV, with an average energy of approximately 4.5 MeV. Dose rate at 1 meter is 0.60 mSv/hr per Ci [5].

252Cf is another neutron radioisotope, which undergoes spontaneous fission with emission of neutrons. 252Cf neutron sources are typically 0.5–1.5 cm in diameter and 2.5–5 cm in length. One microgram of 252Cf emits 2.3 × 106 fast neutrons/s. 252Cf neutron source that are used for neutron backscatter scanning emits nearly 106 neutrons per second, that means in the quantity of few micrograms. 252Cf is reliable and cost-effective neutron source for neutron backscatter scanning.

252Cf and 241Am-Be sources generate not only neutrons, but also emit high-energy gamma rays that are useless when using neutron backscatter method. Gamma rays contribute 68% of the total activity from a 252Cf and 37.5% from a 241Am-Be.

Figure 2 presents a typical ^{241}Am-Be neutron source.

FIG. 2. Typical ^{241}Am-Be neutron source (Courtesy, J.Thereska).

Neutron generators are normally not used for field neutron backscatter scanning and cannot replace sealed source for the following reasons:

- A neutron generator needs a power supply;
- A neutron generator is less stable than a sealed source.

2.3. RADIATION DETECTION

The detection of radiation is based on their interaction with matter. The choice of gamma ray detector depends on several factors including their efficiency (determined in part by their density) and their peak resolution (determined in part by their light output). In addition, other detector material properties are important to consider such as whether the detector is rugged to thermal and mechanical shock and whether it is hygroscopic (absorbs water). Of course, price may also be a consideration in selecting a detector type.

2.3.1. Scintillation detectors

The most common type of radiation detecting instrument for field applications is the scintillation detector. A scintillator is a material that converts energy lost by ionizing radiation into pulses of light. Sodium iodide, NaI (Tl), cesium iodide, CsI, and bismuth germanate, BGO are all examples of scintillation detectors. The most common gamma-ray scintillator in use is NaI(Tl) single crystal [7].

The scintillation detector system consists of a scintillator coupled optically to a photomultiplier tube (PMT) (Fig.3). The light produced from the scintillation process is reflected through a clear window where it interacts with device called a photomultiplier tube. The photocathode of the PMT, which is situated on the backside of the entrance window, converts the light (photons) into so-called photoelectrons. The photoelectrons are then accelerated by an electric field towards the dynodes of the PMT where the multiplication process takes place. The result is that each light pulse (scintillation) produces a charge pulse on the anode of the PMT that can subsequently be detected by other electronic equipment, analyzed or counted with a scaler or a rate meter.

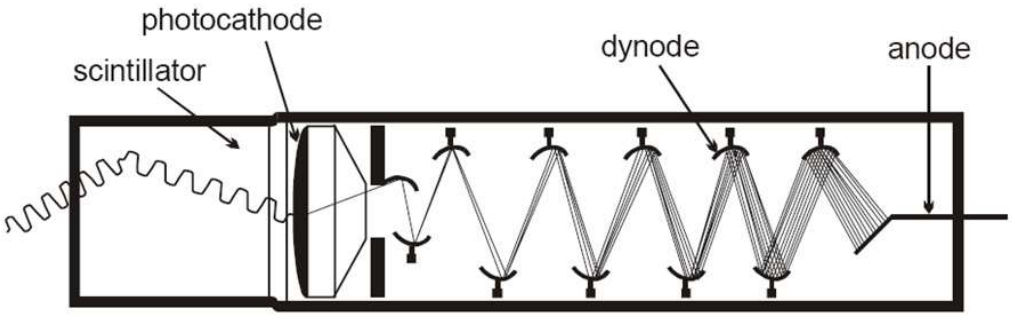

FIG. 3. Scintillation detector principle.

The thickness of the scintillator is an important factor that determines its detection efficiency. The thickness of a scintillator can be used to create a selected sensitivity of the detector for a distinct type or energy of radiation. Thin (e.g. 1 mm thick) scintillation crystals have a good sensitivity for low energy X rays but are almost insensitive to higher gamma ray energies. Large volume scintillation crystals with relatively thick entrance windows do not detect low energy X rays but measure high energy gamma rays efficiently. Scintillation detectors are very sensitive radiation instruments and are used in both portable and stationary systems.

The main drawback of scintillation detectors is their dependence on temperature; NaI(Tl) is the best among other scintillation detectors; NaI(Tl) detector has good performance from -20^0C till up to 80^oC.

2.3.2. Radiation detectors efficiency

More than any other part of the detection system the detector itself determines the overall response function and therefore the sensitivity and minimum detectable count rate of the system. For any detector two important parameters affect the overall efficiency of the system, the geometric efficiency and the intrinsic efficiency [1, 3, 7]. By multiplying these values, one can calculate the total efficiency:

$$\text{Total efficiency} = \text{Geometric efficiency} \times \text{Intrinsic efficiency} \quad (1)$$

In radiation measurements, the geometric efficiency is the ratio of the number of radiation particles or photons that hit the detector divided by the total number of radiation particles or photons emitted from the source in all directions. Geometric efficiency is the solid angle subtended by the detector's active area divided by the area of a sphere whose radius is the distance from the radiation source to the detector.

Numerically, the geometric efficiency is the ratio of radiation photons or particles incident on the detector divided by the number of photons or particles emitted from the source in all directions. For gamma rays, this is expressed as:

$$\varepsilon_{geometric} = \gamma_{incident} / \gamma_{emitted} \quad (2)$$

For example, if 10 000 gamma rays are emitted from a source and 100 hit the detector, then the geometric efficiency is 1%.

The geometric efficiency follows a $1/r^2$ relationship and it drops rapidly as distance increases. For every doubling of the distance, the geometric efficiency decreases by a factor of 4. For a NaI (Tl) 3"x3" detector, the geometric efficiency of 1% would be reached at about 20 cm from the source, while for a large 6"x30" plastic scintillator (Polyvinyl Toluene), 10% geometric efficiency occurs at about 95 cm.

The intrinsic efficiency is the ratio of counts detected to the number of photons or particles incident on the detector and is a measure of how many photons or particles result in a gross count:

$$\varepsilon_{intrinsic} = \gamma_{counts} / \gamma_{incident} \quad (3)$$

Some radiation is not energetic enough and does not reach the detector because it is attenuated or scattered before it can interact in the detector. Some radiation is so energetic it passes through the detector or is scattered out of the detector without depositing its energy. As a result, the actual count measured by the system is a fraction of the radiation emitted in the direction of the detector.

The intrinsic efficiency of various detectors may range from 100% to very small values such as 0.1%, but for NaI(Tl) detectors largely employed in field work, it is typically around 10 to 50%.

The product of these two efficiencies is the total efficiency, or the number of counts detected, relative to the total number of radiations emitted from the source:

$$\varepsilon_{total} = (\gamma_{counts} / \gamma_{incident}) / (\gamma_{incident} / \gamma_{emitted}) \quad (4)$$

$$\varepsilon_{total} = \gamma_{counts} / \gamma_{emitted} \quad (5)$$

2.3.3. Data acquisition system

Recently there has been a remarkable improvement in online detection and acquisition of data in field applications. The block diagram of a typical 12-channel DAS is shown in Figure 4. The commercial availability of such system makes possible to study fast industrial processes. A simple portable data logger can be used for gamma scanning as well.

FIG. 4. Gamma scan profile recorded by portable data logger in application site (Courtesy CEA)

The detection and data acquisition system has obviously to be prepared and tested before the preparation of the real experiment. This preparation includes:

- Appropriate setting of the detectors (high voltage, threshold) suitable with the energy of the radiation emitted by the radionuclide;
- Verification of accessories such as batteries or power supplies, cables, etc.…;
- Verification of the operational conditions of the full system.

2.3.4. Radiation counting statistics

2.3.4.1. Background

Radioactive decay is randomly occurring event, and therefore must be described quantitatively in statistical terms. Not only is there constant change in the activity of a specific sample due to the half-life of the radionuclide, but there is also a fluctuation in the decay rate of a particular sample from one instant to the next due to the random nature of radioactive decay.

The statistical nature of radioactive decay was recognized soon after the discovery of radioactivity. Hence, in any sample containing a large number of radioactive atoms, some average number will disintegrate per unit time. However, the exact number, which disintegrates in any given unit of time, fluctuates around the average value. In counting applications, it is important to estimate this fluctuation because it indicates the repeatability of results of a measurement.

2.3.4.2. Frequency distributions

If one plots the frequency of occurrence of values against the values themselves for a series of identical measurements of a statistical process, a curve will result, which is known as the frequency distribution curve. In nuclear counting statistics, frequency distributions of interest are the normal, the Poisson, and the chi-square distributions [7].

The normal distribution describes most statistical processes having a continuously varying magnitude. If one plots the frequency distribution curve for a large number of measurements on a quantity, which conforms to the normal distribution, a familiar bell-shaped curve (similar to the one shown in Fig. 5) will result. This is the normal distribution curve. It is characterized by two independent parameters: the mean (m) and the standard deviation (σ).

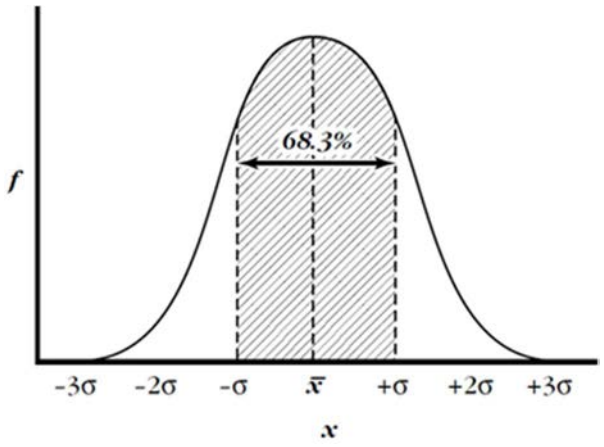

FIG. 5. Normal distribution curve.

The mean is the average value of the quantity under observation. For the standard normal distribution (i.e., symmetrical about the mean), the mean value is the one that occurs with the highest frequency. Since, in reality, only a portion of the population is observed, the estimation of the mean is done by a numerical average:

$$\bar{x} = \frac{\sum x_i}{n} \tag{6}$$

where x_i is the value of the i^{th} measurement, n is the total number of observations.

The standard deviation is defined as the square root of the average of the squares of the individual deviations from the mean. Expressed mathematically, this is:

$$\sigma = \sqrt{\frac{\sum (x_i - m)^2}{n}} \tag{7}$$

where m is the mean value, x_i is the value of the i^{th} measurement, and n is the total number of observations.

As with the mean, we must estimate σ from a finite number of observations. The best estimate of σ is called estimated standard deviation s_x, which is given by:

$$S_x = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}} \tag{8}$$

The use of (n-1) in the denominator results from the use of $\bar{x}$ instead of m in the numerator.

The smaller the standard deviation, the greater is the reproducibility of the measurements. Within one standard deviation on each side of the mean of a standard normal distribution curve, approximately 68% of the total area under the curve will be included (see Figure 6). Two standard deviations on each side of the mean include approximately 95% of the total area, while three standard deviation includes 99.7%.

The practical significance of this is that if one estimates the mean of a series of normally distributed measurements by $\bar{x}$, and estimate the standard deviation by s_x, it can be said with 95% confidence that the true mean is somewhere between:

$$\bar{x} \pm 2s_x \tag{9}$$

In fact, strictly speaking, the radioactive decay obeys the Poisson distribution law. If, however, the number of observed events is moderately large, say 30–50 or more, the Poisson distribution is adequately approximated by a special normal distribution for which:

$$\sigma = \sqrt{m} \tag{10}$$

Or, in terms of the estimates of these parameters:

$$S_x = \sqrt{\bar{x}} \tag{11}$$

The approximation is usually considered acceptable if the mean value is 30 or greater.

2.3.4.3. Application of statistics to radiation counting

The following symbols are used:

N = total counts
t = counting period
n = N/t = count rate

The subscript, *g*, refers to the sample plus background count (*gross count*), ***b*** refers to the *background* count alone, and *s* refers to the *net sample count*. Naturally, *s* must be obtained by subtraction, since it is impossible to observe directly the sample activity apart from the ever present background.

The standard deviation of the total sample plus background count, S_{Ng} is given by:

$$S_{N_g} = \sqrt{N_g} \tag{12}$$

and the standard deviation of the total background count, S_{Nb} is calculated from:

$$S_{N_b} = \sqrt{N_b} \tag{13}$$

To obtain the standard deviation of the gross count rate, divide both sides of Equation (12) by the counting period t_g. Then:

$$S_{\mathbf{n}_g} = \frac{S_{N_g}}{t_g} = \sqrt{\frac{N_g}{t_g^2}} = \sqrt{\frac{N_g}{t_g} \times \frac{1}{t_g}} \tag{14}$$

but, $N_g/t_g = n_g$, therefore, the standard deviation of the gross count rate s_{ng} is calculated as follows:

$$S_{\mathbf{n}_g} = \sqrt{\frac{n_g}{t_g}} \tag{15}$$

Similarly, the standard deviation of the background count rate S_{nb} is given by:

$$S_{\mathbf{n}_b} = \sqrt{\frac{n_b}{t_b}} \tag{16}$$

The net count rate n_s is given by:

$$n_s = n_g - n_b \tag{17}$$

The count rate is used because normally the counting interval is different for background and gross count.

By combining equations above, the standard deviation of the net count rate is calculated as follows:

$$S_{n_s} = \sqrt{\frac{N_g}{t_g^2} + \frac{N_b}{t_b^2}} = \sqrt{\frac{n_g}{t_g} + \frac{n_b}{t_b}} \quad (18)$$

Example:

During the measurement of a radioactive source, the following data were found:

- sample plus background count (gross count), Ng = 40000 counts for the measuring interval of tg = 10 minutes;
- background count only, N_b = 3600 counts for the measuring interval of t_b = 20 minutes.

Given the following data the net count rate was calculated: n_s = (3820 ± 40.6) cpm, at the 95% confidence level.

2.3.4.4. Statistical control chart

A statistical control chart permits a periodic check to see if the observed fluctuation in the counting rate from a constant source of radioactivity is consistent with that predicted from statistical considerations.

To construct such a chart, it is necessary first to make around 30 independent measurements of the same source, keeping the counting time constant. Once proper operation is established, the mean counting rate and the standard deviation are calculated from the data. Next, a graph is constructed, and daily counting rates are plotted. Individual deviations from the mean should not exceed one standard deviation more than 33% of the time, two standard deviations more than 5% of the time, etc. If a measurement falls outside the 95% (2 σ) line it should be repeated.

Since there is one chance in 20 that a single value will fall outside these limits by chance alone, the chances are one in 400 that such will be the case on two successive observations. Hence two successive measurements outside the 95% control limit is enough to suspect anomalous data. One should also watch for trends in the data, i.e., gradual but consistent changes in either direction.

One readily available source for constructing statistical control charts is the ever-present background radiation. It is important to measure background at least daily on a routinely used radiation detection instrument, since certain causes of erroneous data (e.g., contamination and external sources in the area) are reflected in changing background count rates.

2.4. METHODOLOGY OF GAMMA RAY SCANNING OF COLUMNS

2.4.1. Principle of gamma ray scanning

Gamma ray scan method uses the transmission or absorption principle (Fig.6). Transmission of a mono-energetic beam of collimated γ-ray photons through a simple absorption medium can be described by Lambert-Beer's equation [1, 3]:

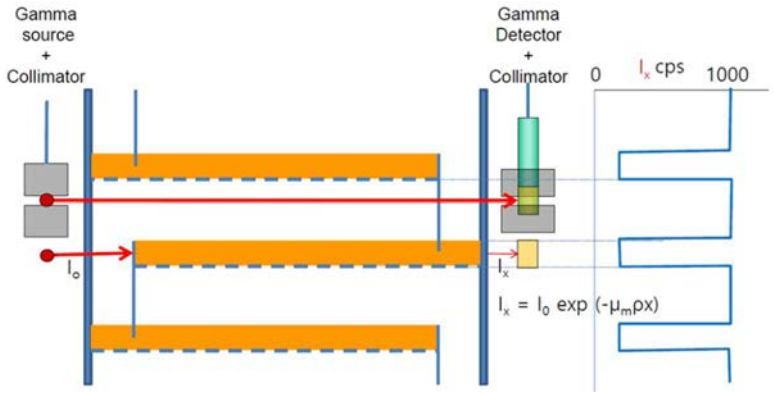

FIG. 6. Principle of gamma absorbtion method (Courtesy, J.Joon-Ha) .

The quantity of gamma radiation absorbed into the material between the sealed source and detector is described by transmission law:

$$I_x = I_0 \, e^{-\mu x} \tag{19}$$

where:

- μ is the linear absorption coefficient with dimension cm^{-1};
- x the sample thickness in cm.

Or,

$$I_x = I_0 \, e^{-\mu \rho x} \tag{20}$$

where:

I_x = transmitted radiation through material between the radioactive sealed source and scintillation detector (variable). This is a function of gamma-ray energy, absorber composition and absorber thickness;
I_o = incident radiation intensity without a medium to absorb radiation between radioactive sealed source and scintillation detector (constant);
μ = absorption coefficient of the inspected material between the sealed source used and scintillation detector (constant);
ρ = the density of absorbing material between the source and scintillation detector (variable);
x = is the thickness of material (radiation path length in cm^2/g) through which the radiation travels (i.e. distance between radioactive sealed source and scintillation detector) (constant).

The quantity of gamma radiation absorbed or transmitted is an indication of the actual quantity and nature of material in the path length between a radioactive sealed source and scintillation detector.

The ratio I/Io is called the gamma ray transmission. The equation describes an exponential attenuation, which is a function of the product properties, such as thickness (x) and density (ρ) (i.e. mass per unit area) of the absorbing medium. This criterion forms the basis of gamma-ray absorption techniques used for plant process investigation.

By applying this relation, an accurate relatively density profile of the process inside the distillation column can be obtained. The expression reveals that the radiation intensity (Ix) measured by the scintillation detector is inversely proportional to the material density (ρ) of the absorber; i.e. material medium between radioactive sealed source and scintillation detector.

Gamma-ray scanning is based upon the principle that when a gamma-ray passes through a column the intensity of the emerging beam is related to the path length and density of material through which the beam passes. An appropriate source and detector are aligned at the same elevation opposite each other on the column. This may be on a diameter or on a chord depending upon the requirements of the scan. By lowering the sealed source and detector down and taking measurements of mean density as they are lowered, a 'picture' can be formed showing what is happening within the column. Figure 7 gives the gamma ray scan principle [5].

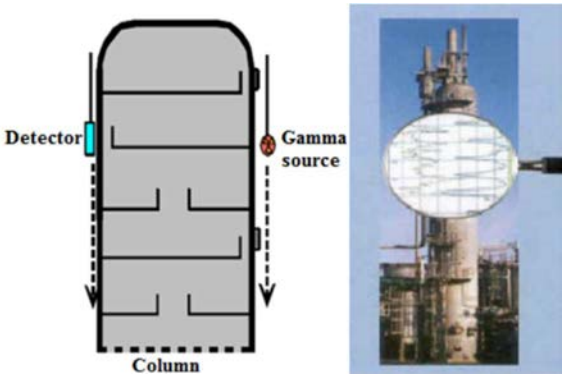

FIG. 7. Gamma scanning principle. (Courtesy, A.Hills).

The sealed source is moving inserted into a panoramic collimator (360 grades). The panoramic (or all sides open) collimator is important for ensuring the same detection geometry in various conditions of source torching or slight movement under wind conditions (Fig. 8).

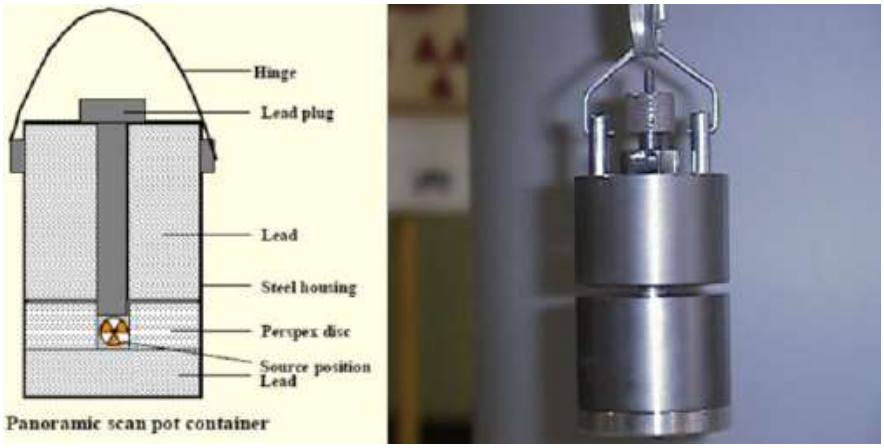

FIG. 8. Panoramic source for gamma scanning (Courtesy KAERI).

Figure 9 shows the practice of gamma scanning [5].

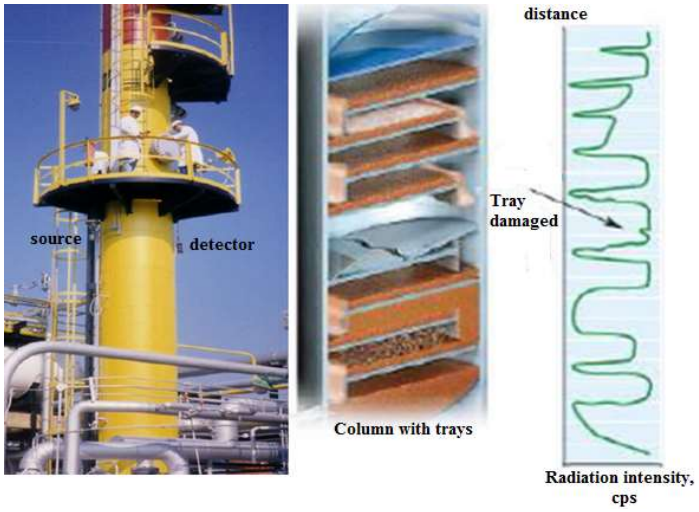

FIG. 9. Gamma scanning practice (Courtesy, A.Hills).

In fact, due to radiation scattering, the real gamma scan profile is not rectangular but in the form of peaks (Fig. 10).The experimental gamma scan profile obtained in counts per second in fact is mirror reflection of the density profile of materials along column inside; as seen in Figure 11, the high-density materials are represented with low count rates.

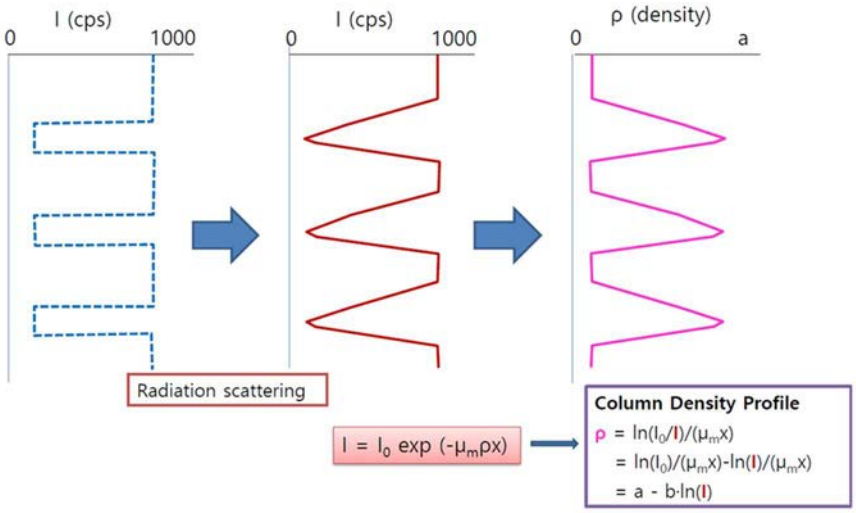

FIG. 10. Gamma scan profile (Courtesy, Joon-Ha Jin).

The gamma scan technique can be used for all columns, and for both major group of tray and packed bed columns [8, 9, 10]. It includes columns with different diameters, wall thicknesses, tray or packed bed configurations. Regions of high density, e.g. a tray plus liquid or a flooded region, will attenuate the signal to a greater extent than areas of low density, e.g. vapor regions. The same technique can be used for packed bed columns to establish the position of beds, and to identify any mal-distribution through the beds. Figure 11 shows typical gamma scan profiles obtained by gamma scanning in tray and packed bed columns [11].

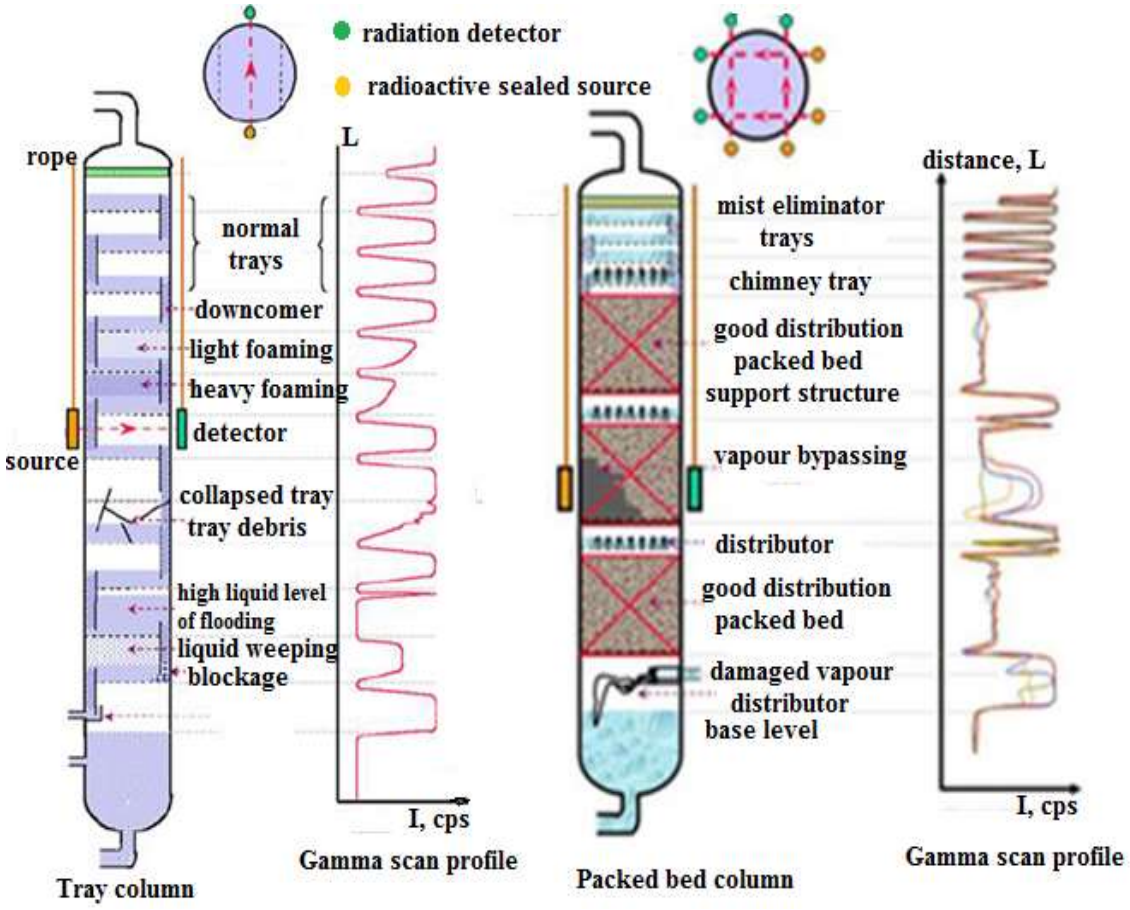

FIG. 11. Typical gamma scan profiles in trayed (left) and packed bad (right) columns (Courtesy, Jaafar Abdullah).

In order to facilitate interpretation of scan profiles it is recommended to keep a complete record of relevant distillation column data. It is suggested that the following scans be carried out on distillation columns in order to obtain:

- Scan profiles on 'empty' columns, not in operation but with all the necessary equipment in place;
- Scan profiles before a maintenance shutdown;
- Scan profiles after maintenance shutdown under normal operating conditions.

2.4.2. Selection of gamma source activity

Selection of the gamma source (^{60}Co, ^{137}Cs or ^{192}Ir) and its activity should be done based on the column diameter, internal configurations in relation to radiation absorption, and statistical limitations of radiation counting. All three factors are interrelated. The largest challenge is overcoming the large column diameters used in vacuum distillation in relation to radiation penetration through the tower.

The optimal radioactive source activity A required for the gamma scanning can be reasonably estimated using the following formula [5]:

$$Activity(mCi) = \frac{D\, d^2\, 2^{e/X_{1/2}}}{\Gamma} \quad (21)$$

where:

D = Dose rate required at the detector (practically accepted as 10μSv/h);
d = internal diameter of the column (m);
e = double wall thickness of the column (mm);
$X_{1/2}$ = half-value thickness (mm) for steel and the source (e.g. 22 mm for the steel and ^{60}Co);
Γ = gamma constant for the gamma source (e.g. 13.5 mSv/h in 1 m distance in air for ^{60}Co source of 3.7×10^{10} Bq - 1 Ci).

This empirical relation is used in fieldwork as a simple approach for rough calibration of radiation detectors. Approximately 200 mm needs to be added to the column diameter to take into account the distance of source and detector positions from the column.

The value of D mentioned in the above equation corresponds to the transmitted radiation intensity which will give 5000 -7000 cps (counts per second) in vapor space of the column (vapor base line); and will decrease to around 1000 -2000 cps in the tray level (liquid base line). This estimated count rate gives a good compromise between the contrast (between liquid & vapour phases) and the accuracy of counting.

The graphic presenting the relation gamma source activity (1 mCi = 3.7×10^7 Bq)) - column diameter (m), calculated based on the above formula - is given in Figure 12, for two common used gamma sources ^{137}Cs and ^{60}Co.

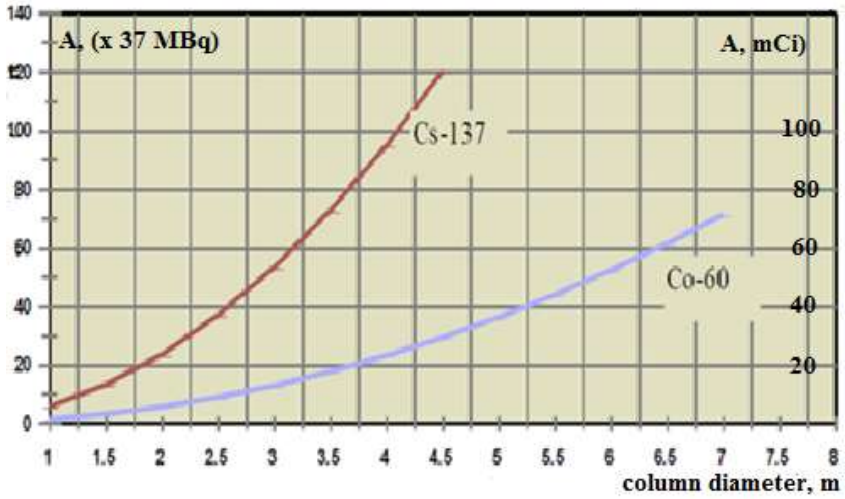

FIG. 12. Source activity versus column diameter for ^{137}Cs and ^{60}Co.

Table 3 gives the ^{60}Co activity (estimated, rounded off) in function of vacuum column diameter (wall thickness of 10 mm and the dose rate of 10 μSv/h):

TABLE 3. COLUMN DIAMETER AND ESTIMATED GAMMA SOURCE ACTIVITY FOR ^{60}CO

Column Diameter (m)	Source Activity (mCi)	Column Diameter (m)	Source Activity (mCi)
1.0	1	4.0	23
1.5	3	4.5	30
2.0	5	5.0	38
2.5	8	5.5	43
3.0	15	6.0	54

Theoretically, the values above are within reason, mostly for the vacuum column. In the case when columns have internals such as packing that will be of interest in scanning packed bed towers, the activity is higher. Penetrating the internals requires a separate calculation relating the diameter of the tower to the internals bulk density. If it is assumed that standard structured packing is used in a tower with a density of 0.23 g/cm^3, then the corresponding source sizes will be needed to get statistically correct data; the experience has shown that the gamma sealed sources used for packed bed columns have an activity nearly two times higher than gamma sources for try columns.

With these source sizes in mind, it is important to understand the statistics of radiation counting and how they relate to radiation intensity. The typical NaI (Tl) radiation detectors used in the industry have a high and low limit for effective radiation counting. The upper limit of radiation refers to the NaI crystal and photomultiplier tube ability to process the gamma particles as the crystal becomes saturated with gamma particles. This upper limit is called 'dead time' and has a sliding scale as to the effects to the count rates or radiation intensity increases on a detector. Naturally, the more intense the radiation the larger is the effect on the ratio of 'lost' counts. The effects of dead time can begin to be seen at approximately 18 μSv/h and above. The lower limit is self-explanatory as the few particles that contact the crystal are lost in the background noise of natural radiation and electronic noise.

The natural statistical variations that occur in radiation counting also become an issue as the radiation intensity increases or decreases. The substantial variations occur in the lower detectable limits of radiation counting. Figure 13 shows the effects of statistical variations (Srel., %) as a function of radiation dose rate (mSv/h) [11, 12].

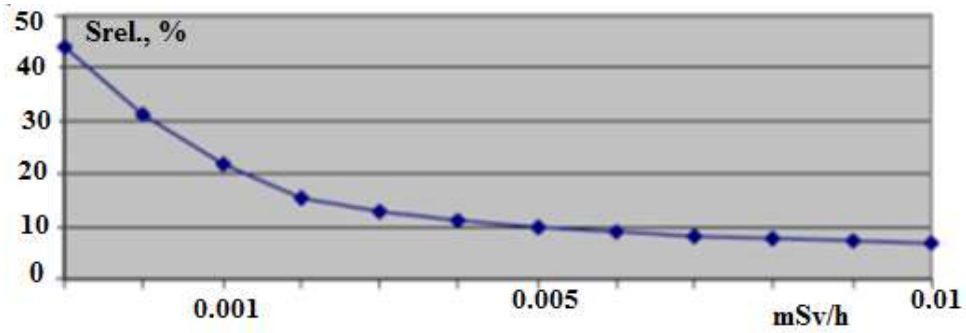

FIG. 13. Statistical variations versus dose rate.

This is the reason that the gamma source activity is estimated at dose rate level of D = 10μSv/h, where the relative standard deviation S_{rel} of a radiation measurement would be less than 10%.

2.4.3. Radiation dose rate in vicinity of a point source of gamma rays

There is an empirical relation between the radiation dose rate P in air and the activity A of an unshielded point source of gamma rays in a distance r (m) [2]:

$$P = \Gamma \times A/r^2 \quad (22)$$

where, dose rate factor Γ (gamma constant) is an empirical factor for the specific radioisotope.

The inverse-square law of gamma absorption in air is assumed as long as the source can be considered a point source. The absorption of gamma rays in air is also assumed to be negligible.

Γ factors are usually tabulated for unit of activity and distance of 1 meter. For example, the dose rates at 1 m from unshielded point source for two typical gamma sources used for gamma scanning are:

- ^{60}Co = 0.36 mSv/h/GBq (13.5 mSv/h/Ci),
- ^{137}Cs = 0.08 mSv/h/GBq (3 mSv/h/Ci)

2.4.4. Scan - line orientation

When a scan is carried out on a tray-column, the scan orientation or scan line (line between radioactive sealed source and detector) must be selected in such a way that it is carried out over the live area of the tray, i.e. avoid scanning through the downcomers. Typical scan-line orientations that are recommended for tray columns are indicated in Figure 14.

According to these scan lines it would be possible to detect certain process anomalies such as: tray foaming, tray weeping, jet flooding and entrainment from tray to tray. In some cases, the access to the column is not ideal as expected and scan line orientations have to be changed.

Once a scan line is designed, it should not be changed during scanning operation, otherwise the interpretation of the scan profile can mislead.

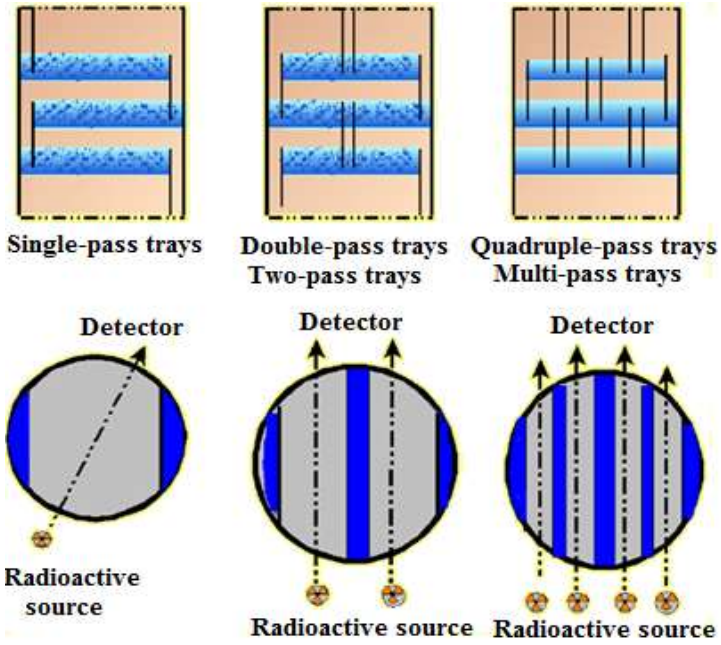

FIG. 14. Typical scan-line orientations for tray column (Courtesy, A.Hills)

2.4.4.1. Single-pass trays

Figure 15 shows the internal design of a single pass-trays column. Liquid from the downcomer flows across the life area of the tray and flow over the weir and down the downcomer to the next tray where it will mix with the vapour on that tray. Single pass trays are most commonly use in small diameter distillation columns.

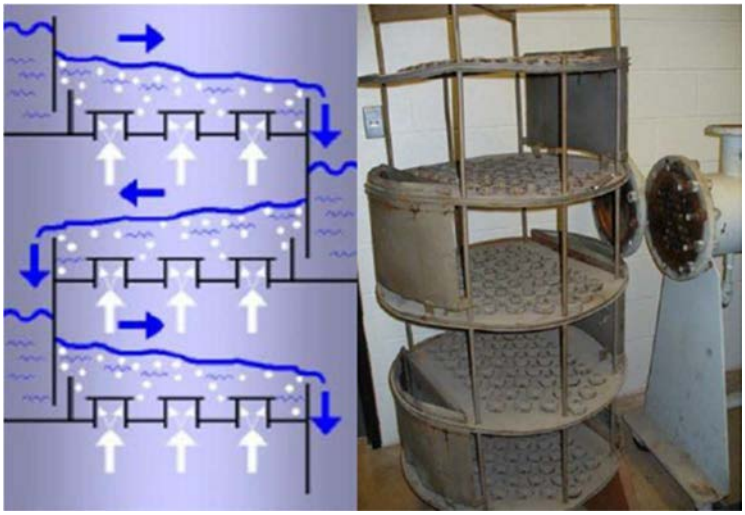

FIG. 15. Single pass tray (Courtesy, A.Hills)

2.4.4.2. Two-pass or double-pass trays

Two-pass or double-pass trays alternate between a center downcomer and two side-downcomers (Fig. 16). Therefore, on one tray, liquid flows from two side- downcomers to a centre downcomer, on to the next tray below.

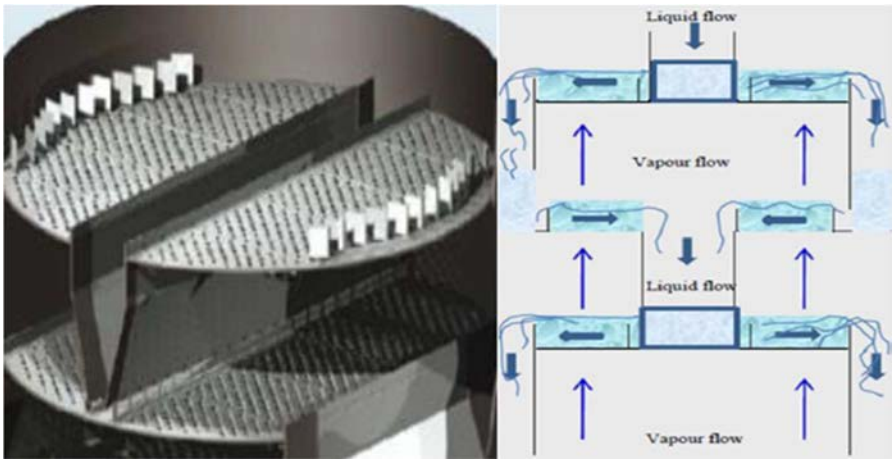

FIG. 16. Double-pass trays (Courtesy, A. Hills).

Liquid from the center downcomer again splits in two flows towards both side downcomers. This arrangement allows it to increase the outlet weir length, in order to reduce the liquid flow rate across the tray. This kind of tray configuration is occasionally used in vacuum columns to lower the tray pressure drop by reducing the height of the liquid crest over the outlet weir.

2.4.5. Spray and liquid heights on distillation trays

The amount of liquid on a try is reflected on the gamma scan profile [5]. Figure 17 presents the gamma profile between two trays; the amount of liquid on a tray can be calculated as shown in the figure.

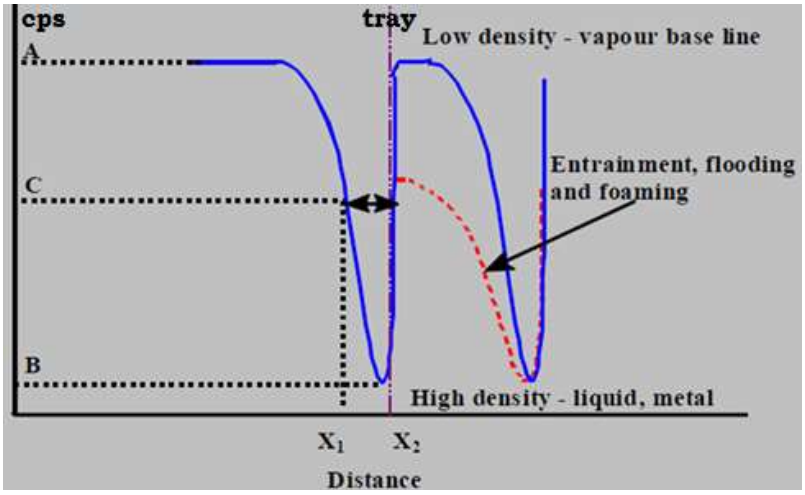

FIG. 17. The calculation of the amount of liquid on a try (Courtesy A.Hills).

Empirically, the liquid level on try is estimated as:

$$(X_2 - X_1)/2 = (\text{Maximum} - \text{minimum})/2$$

i.e. [maximum count rate elevation point (vapour) - minimum count rate elevation point – (liquid)]/2

where:

A: vapour base-line;
B: highest density (lower radiation intensity) of the tray, i.e. the tray itself (X_2);
C: midway between the vapour base-line and the highest density point of the tray (X_1).

2.4.6. Some characteristic gamma scan profiles in tray columns

A gamma scan of a vessel can detect and locate liquid and vapour regions within a column. It can discriminate between aeration of liquid and detect foam or spray heights in vapour regions. By measuring and analysing density changes, many parameters indicating column performance can be obtained. Each tray and the vapour space above it "tells the story" of its operating status. A properly operating tray has a reasonable level of aerated liquid showing a rapidly decreasing density gradient until it reaches a clear vapour space just under the next tray. To distinguish the above symptoms, experience is required.

Figures 18 - 23 present ideal gamma scan profiles in tray columns, which are characteristic of various pure phenomena. In the reality, the gamma scan profiles are more complicate, and several phenomena could happen in the same time.

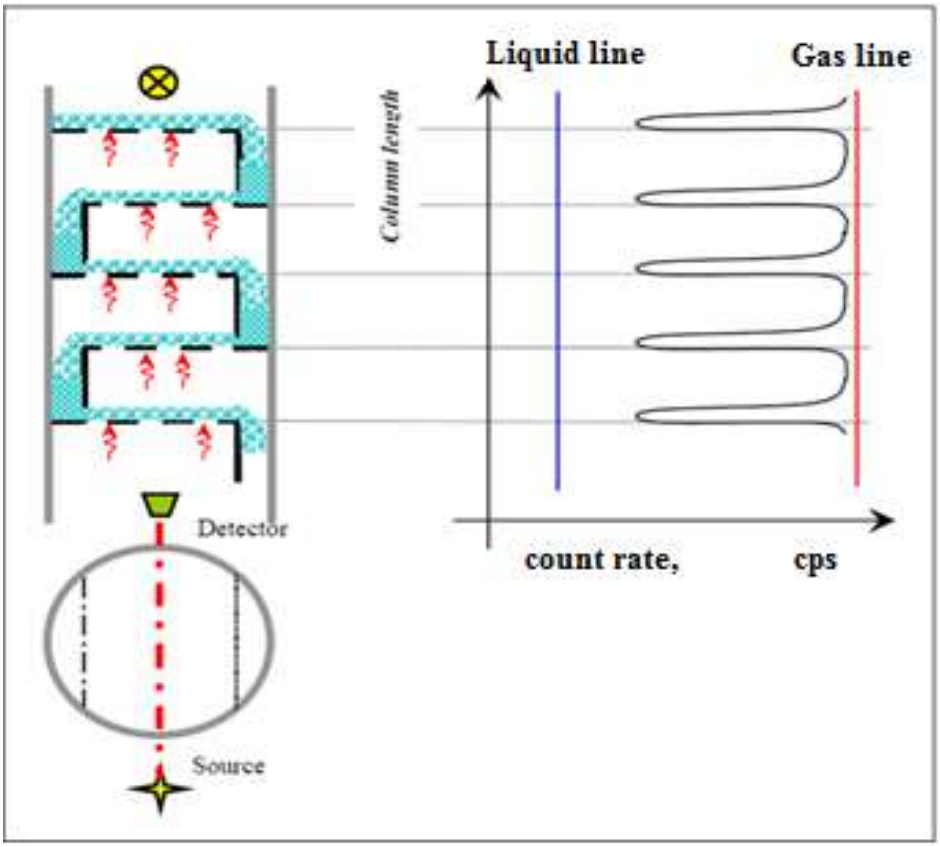

FIG. 18. Scanning profile of a normal distillation column (Courtesy A. Hills).

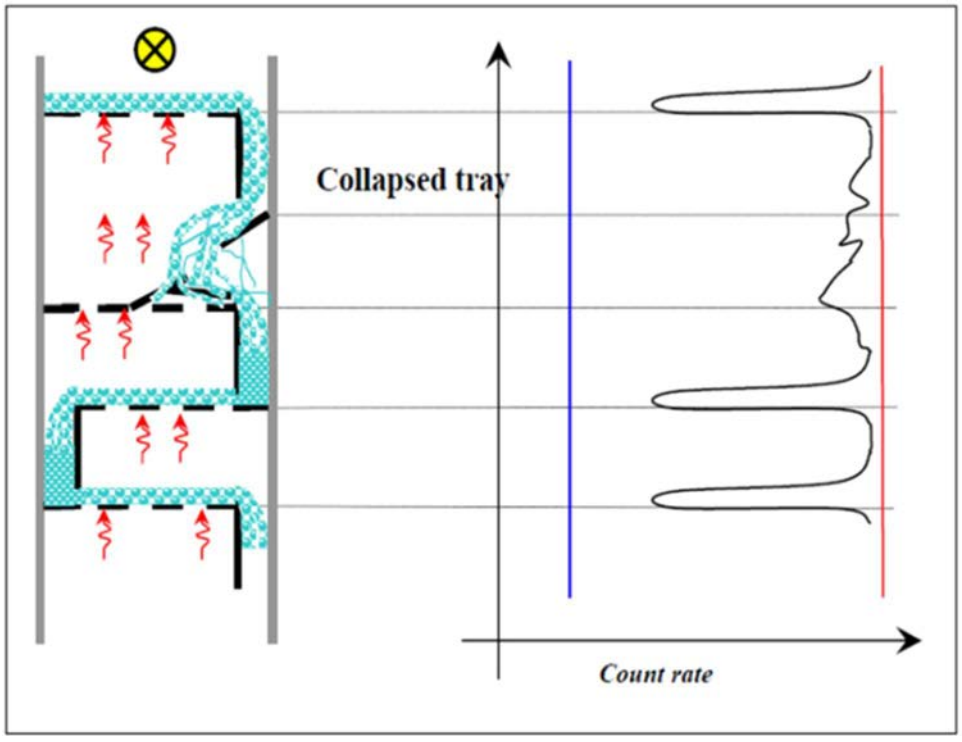

FIG. 19. Gamma profile of column part with collapsed tray (Courtesy A. Hills).

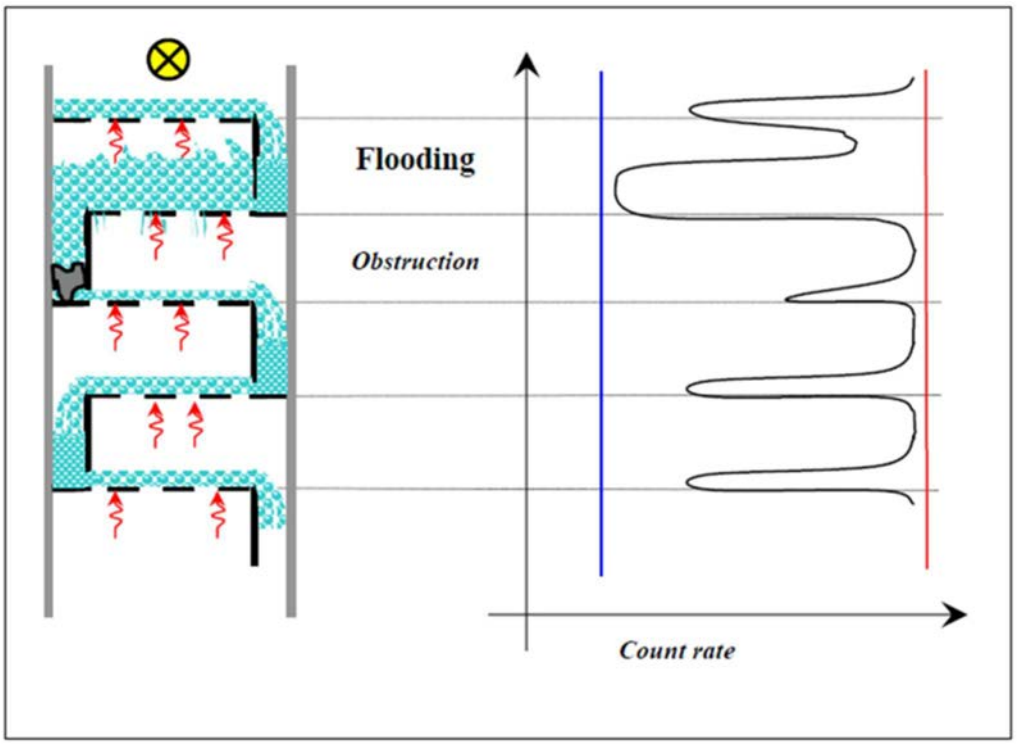

FIG. 20. Gamma profile of part of column with flooding (Courtesy A. Hills).

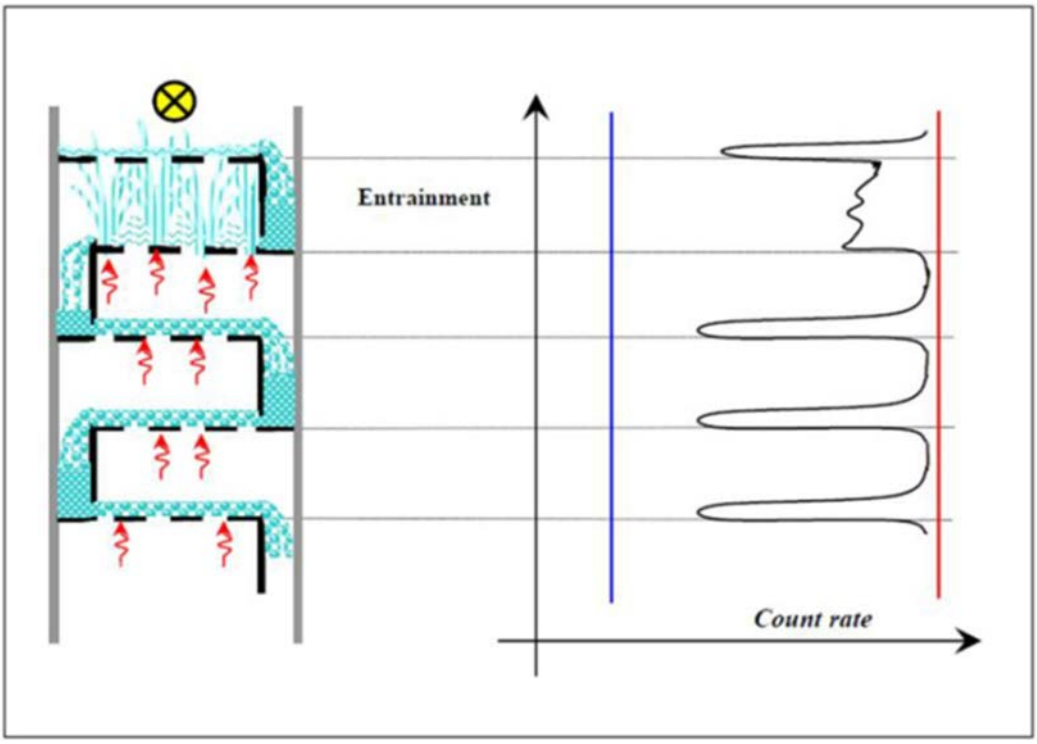

FIG. 21. Gamma profile of column part with entrainment (dragging) (Courtesy A.Hills).

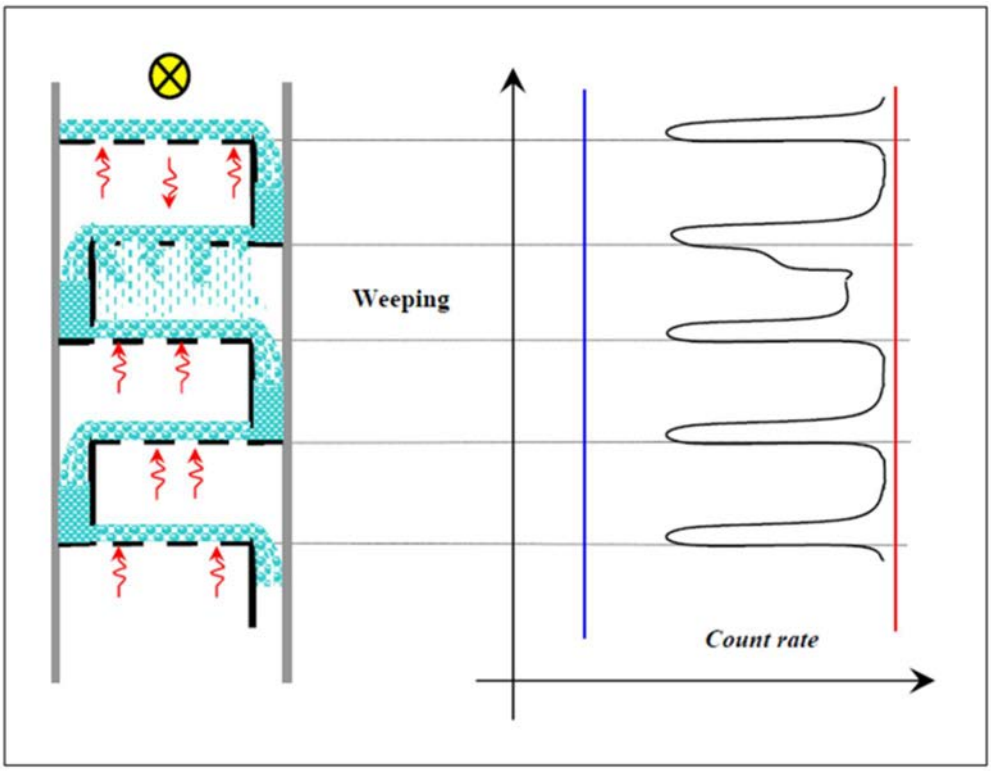

FIG. 22. Gamma profile of a column part with weeping (shower) (Courtesy A. Hills).

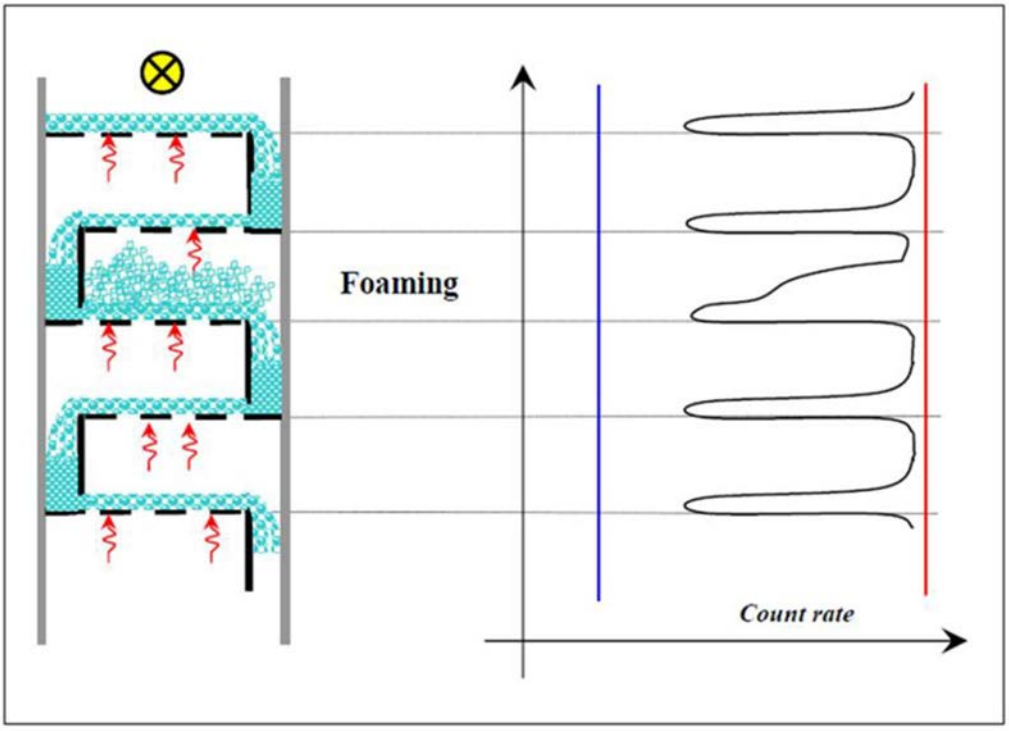

FIG. 23. Gamma scanning of a column sector with foaming (Courtesy A. Hills).

2.5. METHODOLOGY OF GAMMA SCANNING OF PIPES

Gamma scan technique for pipes is a derivation of general gamma scanning technique. It can be used to detect solids build-up, corrosion of walls or wall defects inside the pipes. It can be used as well to monitor the transport of liquids or gases throughout the pipelines, especially identifying gas, vapor and liquid presence and homogenization during transportation of oil/gas mixture from the oil separator or collecting station to end users. Before executing any pipe scanning, the information about the inside diameter and wall thickness of the pipe, as well as the medium in the pipeline (gas, liquid or slurry) must be requested [5, 6].

Figure 24 gives the principle of gamma scan for pipe scanning. The source and detector are fixed diametrically opposite each other at a set distance apart by the use of a rigid yoke system, and measurements of mean density can be taken very quickly; each measurement takes less than 30 seconds.

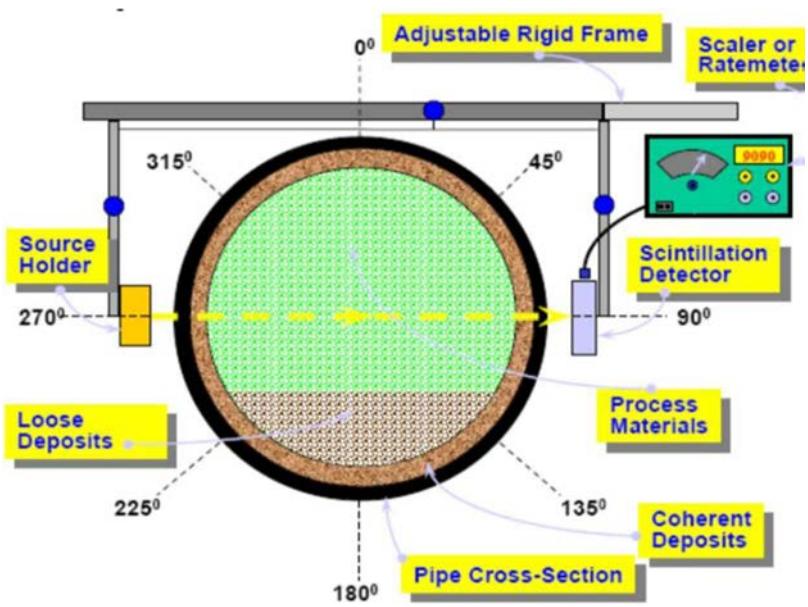

FIG. 24. Gamma scan principle for pipe scanning (Courtesy CANTI).

Figure 25 presents a real test of pipe scanning.

FIG. 25. Gamma scan in process for pipe scanning (Courtesy CANTI).

The gamma-ray transmission technique can be used to locate blockages within pipelines and accurately quantify the amount of deposit within a liquid or gas line, for example coke build-up in overhead transfer lines. For quantification of a deposit inside the pipe, two gamma scans are necessary, one horizontal X and the other vertical Y (Fig. 26). Difference between X and Y scan profiles allow thickness of deposit to be calculated.

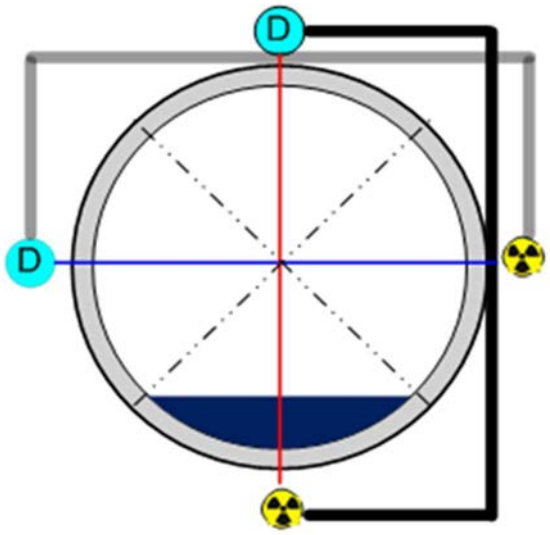

FIG. 26. Difference between X and Y scan profile allows thickness of deposit to be calculated.

By applying the gamma ray scanning technique to piping, can quickly [12, 13]:

- Locate blockages;
- Locate scale or coke buildup;
- Locate corrosion;
- Locate liquid in vapor lines;
- Locate areas of lost refractory or lining in a pipe;
- Measure flowing densities;
- Evaluate the fluidizations of catalyst.

A variation of this technique can be used to measure the integrity of refractory lining. Alternatively, the system can be fixed in place as a ‘densitometer’ and the line monitored continuously to establish build-up rate of deposit, or to identify the extent of effects such as liquid slugging in gas lines.

2.6. METHODOLOGY OF NEUTRON BACKSCATTER SCANNING

2.6.1. Introduction

There are several radiation detection techniques available to detect and measure the levels and material phases inside a process vessel. Two commonly used methods are: gamma ray absorption transmission and neutron backscatter. The choice of selection depends on the available access to the vessel and the nature of the material inside the vessel. A difference between gamma absorption transmission and neutron backscatter method is that the latter can be carried out with access to only one side of the vessel, while the gamma-ray transmission technique needs access to both sides of a vessel.

The major difference between the neutron backscatter and gamma absorption methods for level and interface measurements is that neutron backscatter method is applied mostly for liquid interfaces where the gamma method does not give good contrast and results due to small variations in density among liquids.

Neutron backscatter technique is simple to use and facilitates direct on-side measurements and is ideal for troubleshooting where a "yes" or "no" answer is important. Figure 27 shows the principle of neutron backscattering technique [12, 14].

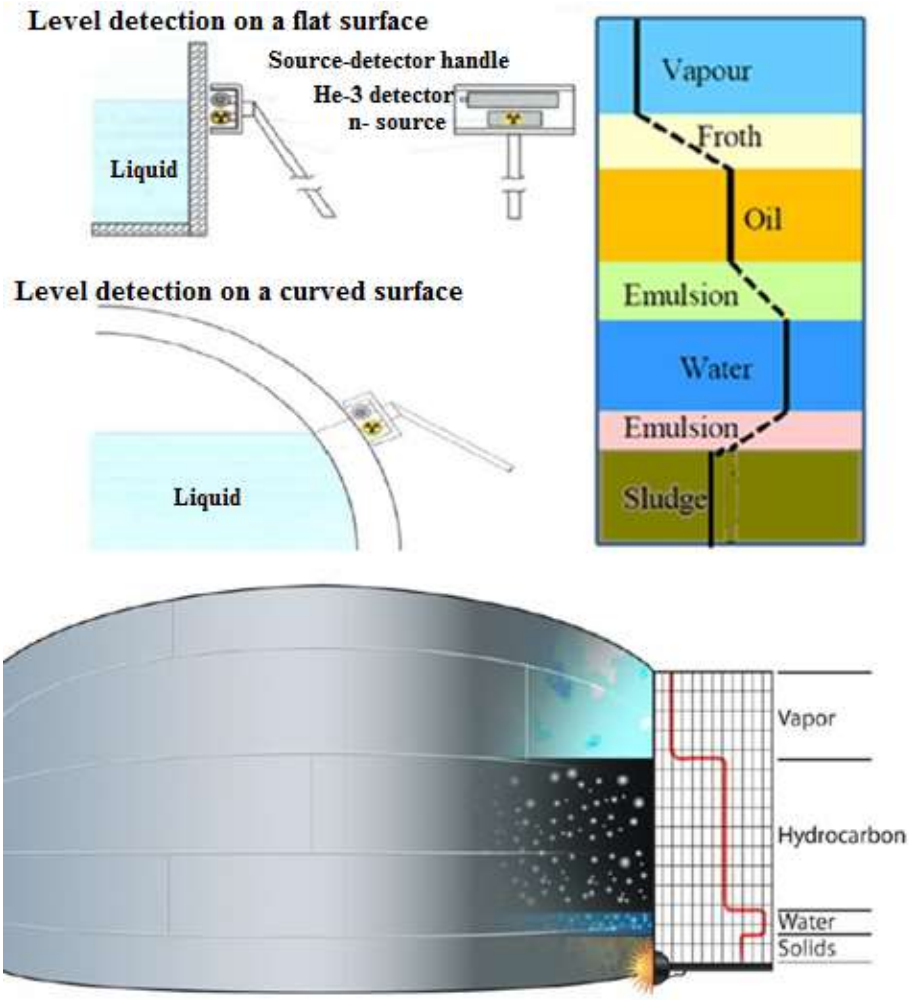

FIG. 27. Principle of neutron backscattering technique (Courtesy A. Hills).

2.6.2. Neutron detectors

The main neutron detectors used in field measurements are ^{3}He and BF_3 pressurized gas tubes.

2.6.2.1. ^{3}He proportional detector

The most used detector for thermal neutrons has been the gas-filled sensitive proportional detector, charged to a pressure of several atmospheres with ^{3}He gas (Fig. 28). ^{3}He filled proportional counters come in a variety of active length and diameters and pressures. They offer many of the performance characteristics required by field applications: high sensitivity, moderate operating voltage and excellent spectral resolution. Multiple detectors can be arrayed with a single high voltage and counting electronics channel. ^{3}He is limited to count rates of $< 10^5$/sec by gas recombination effects.

Helium-3 (^{3}He) neutron proportional counter is sensitive to thermal neutrons and is normally used in conjunction with a moderator material. For applications where the surrounding medium acts as a moderator, the detectors can be used unmoderated.

FIG. 28. Some models of He-3 neutron proportional detector (Courtesy GE).

2.6.2.2. BF_3 Neutron proportional detector

Boron trifluoride (BF_3) neutron proportional detector is sensitive to thermal neutrons, but is less sensitive to gamma radiation than Helium-3 (^{3}He) detector. Some models of BF_3 detector are shown in Figure 29.

FIG. 29. Some models of boron trifluoride (BF_3) neutron proportional detectors (Courtesy GE).

Relative characteristics of ^{3}He and BF_3 neutron proportional counter are:

- Boron has a lower neutron cross section (3840 Barns) compared with He-3 (5330 Barns), therefore boron detector is less sensitive to neutrons than helium detector;
- The energy released per reaction is higher in ^{10}B than in ^{3}He, which enables BF_3 counters to discriminate against gamma pulses;
- BF_3 detector functions at much higher voltages than ^{3}He detector (1 - 4 kV).

2.6.3. Principle of neutron backscattering method

Neutron radiation intensities, emitted by a $^{241}Am/Be$ neutron sealed source are measured by suitable electronic equipment, which depends on the neutron deceleration properties of the medium of incidence. The slowing down process or moderating of neutron energies continuous until thermal equilibrium is reached — this is known as thermalization (thermal neutrons). The most probable neutron energy at room temperature is 0.025eV.

Neutrons lose energy by transferring it during each collision with hydrogen nuclei, upon which the direction motion is changed. The actual amount of energy loss during each collision depends on the mass of the target medium nucleus, as well as, on the angle of incident.

The distance travelled by a fast neutron between its introduction into a slowing down medium and its thermalization depends on the number of collisions made by the neutron and the distance between collisions. Elastic scattering can be considered as the interaction of fast neutrons and low atomic number absorbers.

The process where a neutron loses energy as it approaches a thermal condition is known as moderation. The substance in which this process occurs is called moderator. The energy transferred to the target nucleus is Eo-E where:

$$Eo-E = Eo\,[1-((M-m)/(M+m))^2] \tag{23}$$

Eo = energy of incident neutron. E = energy of scattered neutron. m = mass of incident neutron.
M = mass of scatter nucleus.

It is possible that all the neutron energy be transferred on collision with a hydrogen atom. The average neutron energy transferred to a target nucleus on collision is:

$$f = 1-e^{-k} \tag{24}$$

k = average logarithmic energy decrement.

For hydrogen, with k=1, the mean energy transfer during a collision with fast neutrons is 63% of the energy of the neutron, while for carbon, with k= 0.159, it is 14.7%.

2.6.4. Factors affecting measurement accuracy

Moisture in insulation: A common problem with thermally insulated vessels is that moisture from rain or condensation accumulates in the insulation. This causes false readings and it is advisable to repeat measurements at several positions on the vessel in such situations.

Non-uniform insulation thickness: Vessels lined with variable thickness of insulation material may be difficult to measure, due to the varying distance between the liquid in the container and the detector.

Proximity of human body: The instrument reacts to all hydrogen-containing material, including the human body. The measuring head should consequently be held far from any part of the body during measurements in order to avoid misleading readings. This is also advisable from a safety point of view.

Proximity of plant equipment: Equipment or vessels containing hydrogenous materials or liquid nearby would necessitate measurements being carried out as far away as possible.

Proximity of concrete: Concrete contains crystal water and should be avoided as far as reasonably possible.

Poor signal: Small differences between liquid and vapour signals may be caused by low hydrogen content of the liquid or similar hydrogen-rich material lining in the vessel, a too large total distance (wall, lining and insulation thickness) from the liquid, or a combination of these.

Angle and curved surfaces: A type of parallax error is introduced when the measurement is performed on, for example, the curved surface of a horizontal vessel. The liquid closest to the measuring head has the largest effect on the reading, and in practice this is directly across the wall on a line perpendicular to its surface, consequently, the level will be located slightly above the true level. If the measurement is performed on the bottom half of the vessel, an opposite effect, i.e. too low apparent level, will be registered. This error is more evident for thick-walled (insulated) vessels.

2.6.5. Characteristics of neutron backscatter on various hydrogen liquids

Various measurements can be carried out in order to investigate the behaviour of hydrogen liquids upon neutron backscattering.

Test 1: Consider the effect of hydrogen content on thermal backscatter neutrons

The outlay of the experiment is shown in Figure 30. The detector and neutron sealed source (^{241}Am-Be) encapsulated in a glass tube, were submerged in various hydrogenous liquids to investigate the behavior of backscattered neutrons.

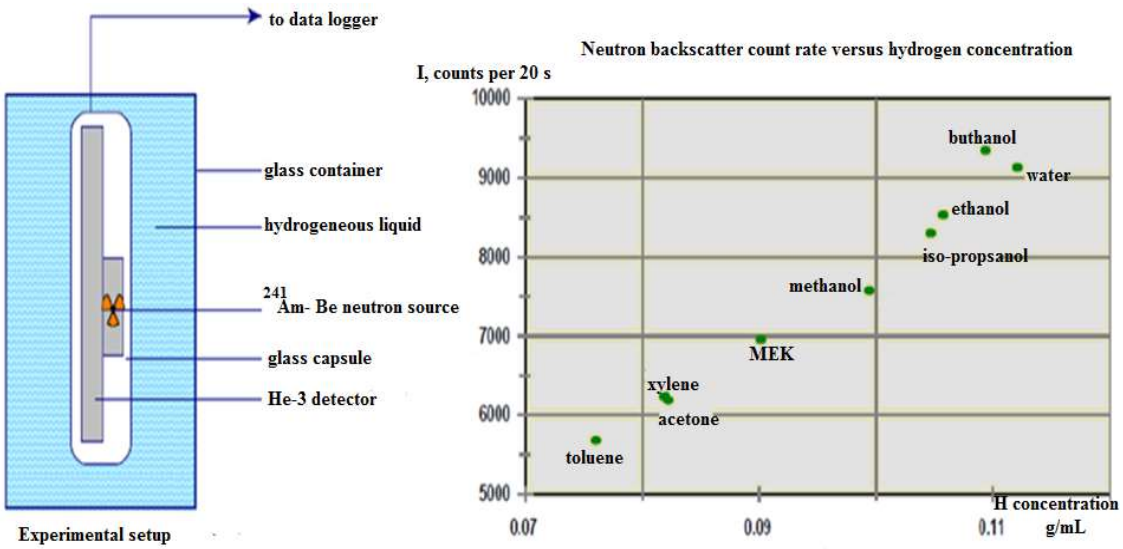

FIG. 30. Experimental setup: Effect of hydrogen content on thermal backscatter neutrons (Courtesy A.Hills).

The results obtained are shown graphically in Figure 31. From the graph, it is clear that there is a definite upward trend for an increase in hydrogen concentration; the count rate increases with an increase in hydrogen concentration.

Test 2: Height of liquid (thickness) versus radiation count rate

Neutron backscatter intensity as a function of liquid layer thickness (or height) for different hydrogenous liquids, using a 1Ci ^{241}Am-Be neutron source was investigated.

The experimental setup to investigate the relation of neutron count rate from the liquid thickness (or height) in a liquid reservoir (or tank) is shown in Figure 31. Figure 32 presents the relation between the measured neutron intensity versus the liquid height (thickness) for different liquids.

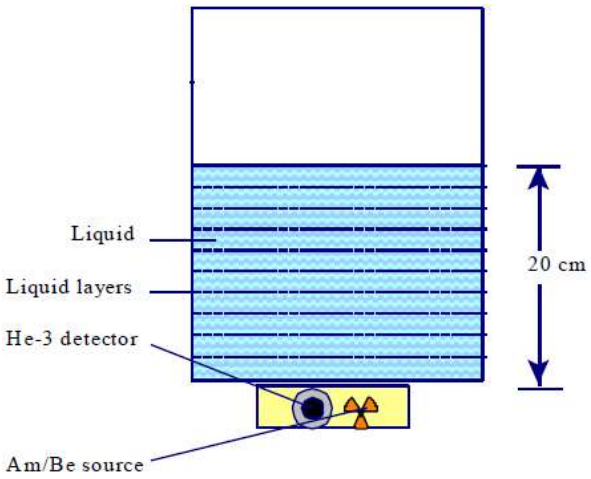

FIG. 31. Experimental setup to investigate the relation of neutron count rate from the liquid thickness (or height) in a liquid reservoir (or tank) (Courtesy A. Hills).

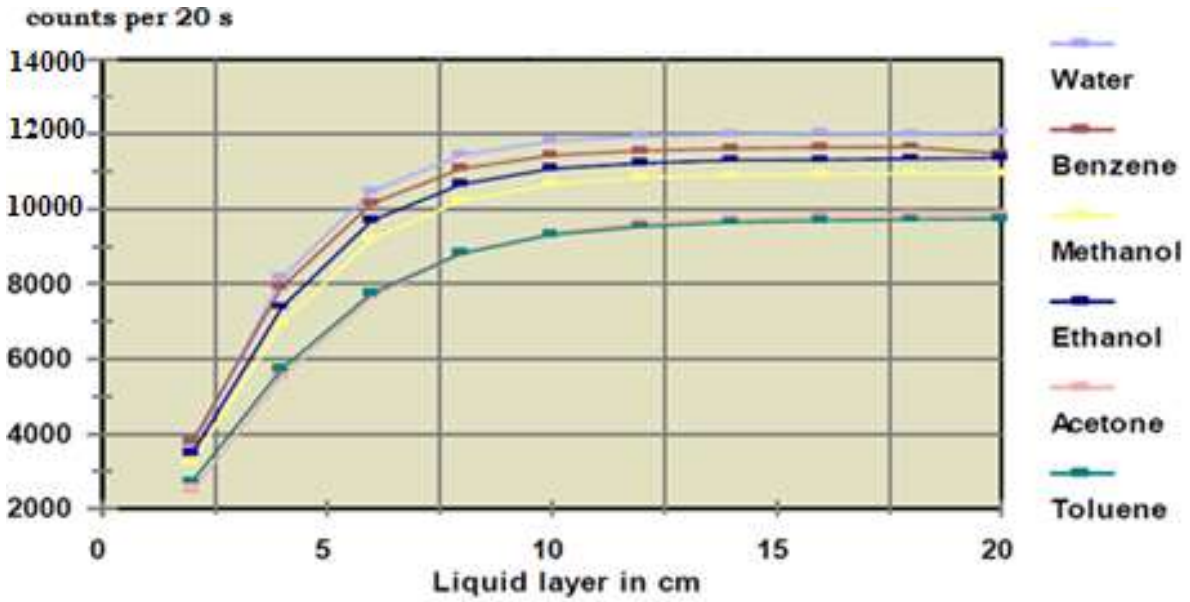

FIG. 32. Measured neutron intensity versus the liquid height (thickness) for different liquids (Courtesy A.Hills).

Thermal neutrons are counted for each liquid layer thickness. The average of several readings is recorded for calculation of the mean count rate. It can be concluded that the optimum thickness is reached at a thickness of 9 to 10 cm liquids.

Test 3: Thermal neutron intensity versus distance from the liquid reservoir wall

The objective of this test is to simulate real cases in industrial environment, that is, when the measuring head of a neutron level gauge is not in close contact with the liquid container shell or wall. That is when the container is furnished with isolation (lagging) material. Can liquid levels still be measured? Figure 33 shows the experimental setup to investigate the relation between the recorded thermal neutron intensity versus distance from the liquid reservoir (tank) wall.

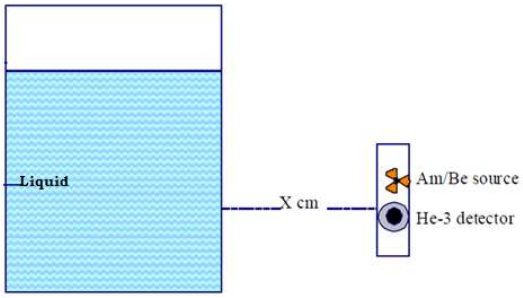

FIG. 33. Experimental setup to investigate relation neutron intensity versus distance from the liquid reservoir (tank) wall.

Figure 34 presents the recorded thermal neutron intensity versus distance from the liquid reservoir (tank) wall.

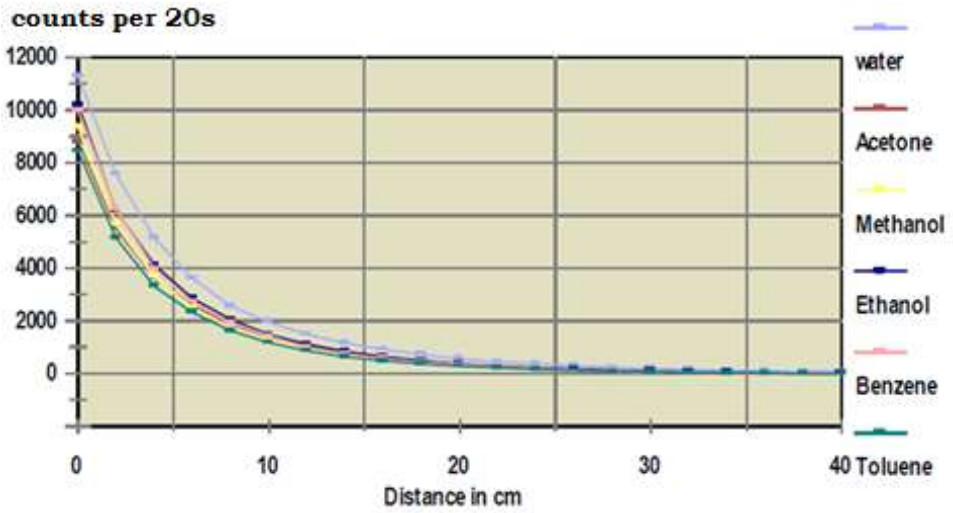

FIG. 34. Relation between the recorded thermal neutron intensity versus distance from the liquid reservoir (tank) wall.

The conclusion is that the level and interface of liquid inside the reservoir (tank) can be measured relatively easy up to 15-20 cm behind the wall; for more wall thickness up to 20-25 cm a longer count interval is necessary; the neutron backscatter technique is not sensitive practically after 25-30 cm wall thickness.

3. SEALED SOURCE APPLICATIONS: CASE STUDIES

3.1. INTRODUCTION

With the advancement of data gathering and handling it is important to note that fundamental physics behind each measurement involving radioisotopes has not changed much. These mature techniques have found many applications in industry and are very competitive. There have been carrying out many tens of thousands of gamma and neutron scanning's from public and private companies worldwide every year.

The range of on line, non-intrusive process troubleshooting and diagnostic services that can be offered using sealed source techniques many, among them the most spread are:

- Level and interface measurement in processing vessels, storage tanks and reservoirs;
- Deposit and blockage detection in processing lines and transporting pipelines;
- Gamma scanning of trayed and pack-bed columns, towers and vessels to determine:
    - ✓ Liquid levels on trays;
    - ✓ Areas of foaming or liquid weeping;
    - ✓ Tray positions;
    - ✓ Tray damage and debris;
    - ✓ Flooded regions;
    - ✓ Position of beds;
    - ✓ Mal-distribution through the beds.

This section describes some typical case studies of the sealed source troubleshooting and diagnostic techniques, selected among many thousands of services provided worldwide. Little preparation is needed on site to carry out these services, for example, there is no need to remove lagging from vessels or pipelines, and results are available immediately.

3.2. GAMMA SCANNING OF VARIOUS COLUMNS: CASE STUDIES

Processing columns can typically be split into two main categories; trayed and packed beds. Packed beds are becoming increasingly popular. Packed bed towers are more susceptible to damage because of pressure surges as compared to trayed vessels. A critical consideration in the effective operation of a packed tower is the mechanism for fluid distribution. Poor vapor or liquid distribution can result in a significant efficiency reduction. With the increased use of packed beds, the application of gamma scan technique to troubleshoot problems has become crucial. Usually in packed bed towers, a gamma ray grid scan is performed using four equal length chords. The chords are selected to run through the bed such that two intersect the other two at an angle of 90 degrees. This arrangement allows the measurement of the efficiency of the distributor system, as well as to detect position of the beds and any blockages within.

Gamma scan is a very effective, well-established troubleshooting technique. The benefits coming from this activity is huge, a simple gamma scanning of an isolated column in a petroleum refinery bring a net benefit of more than US$100 000, while the scanning of a processing column in a chain process can bring a benefit of up to US$ 1million.

3.2.1. Case study 1: Gamma scanning of a distillation column without problems (courtesy A.Hills)

Problem: Gamma ray scan has been performed on a Wash column, which was part of an extractive distillation operation that removes impurities from the alcohol at low concentration.

Results: Figure 35 presents the gamma scan profiles. From the two scan profiles, it is clear that all trays are in position and carry approximately the same amount of liquid.

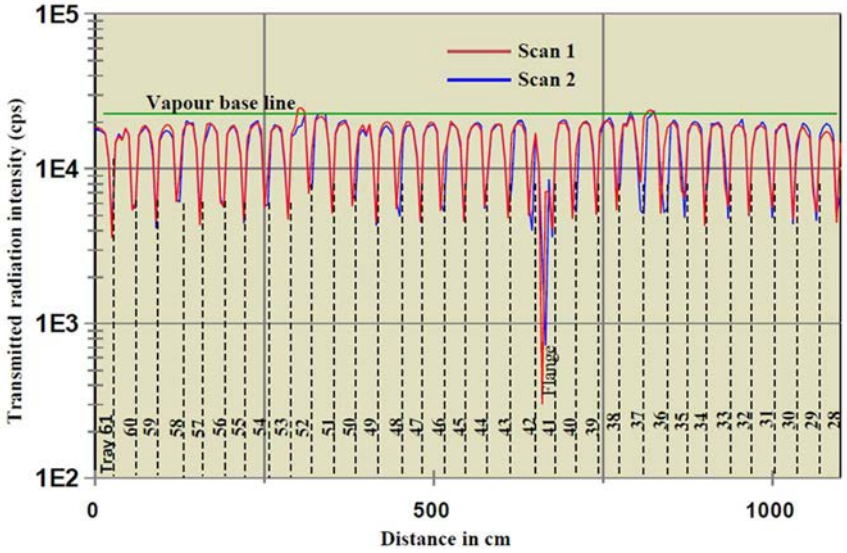

FIG. 35. Column scan profiles showing no problems with tray position and performance.

Conclusion: Both profiles indicate a column under good operating process conditions. This information allows the process engineer to eliminate a potential shutdown by finding that the inefficiencies were not due to internal problems and that process personnel should concentrate on external causes.

3.2.2. Case study 2: Gamma scanning of a vacuum column with packed bed (courtesy A.Hills)

Problem: A major oil refinery was experiencing a high differential pressure in the vacuum column with packed beds limiting production. A tower scan was needed to identify the cause and location of the problem.

Results: Figure 36 presents the gamma profile of the vacuum tower (red line).

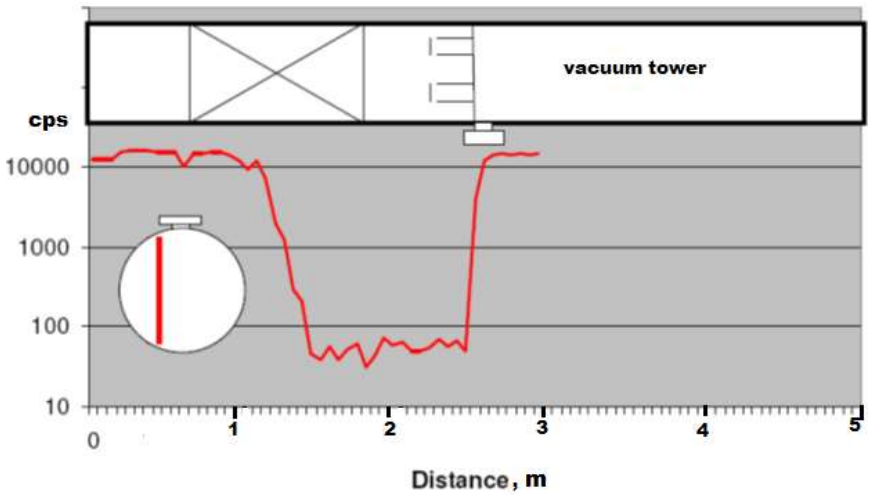

FIG. 36. Gamma profile of the vacuum tower.

Conclusion: A packed bed had collapsed on to the chimney tray below. The fallen packing was limiting the pump-around draw.

3.2.3. Case study 3: Gamma scan inspection of a packed bed tower (courtesy A.Hills)

Problem: Two gamma scan profiles were obtained on packed bed tower to help determine the position of the liquid distributor and associated liquid height.

Results: The graph below (Fig. 37) shows the results of two gamma scans.

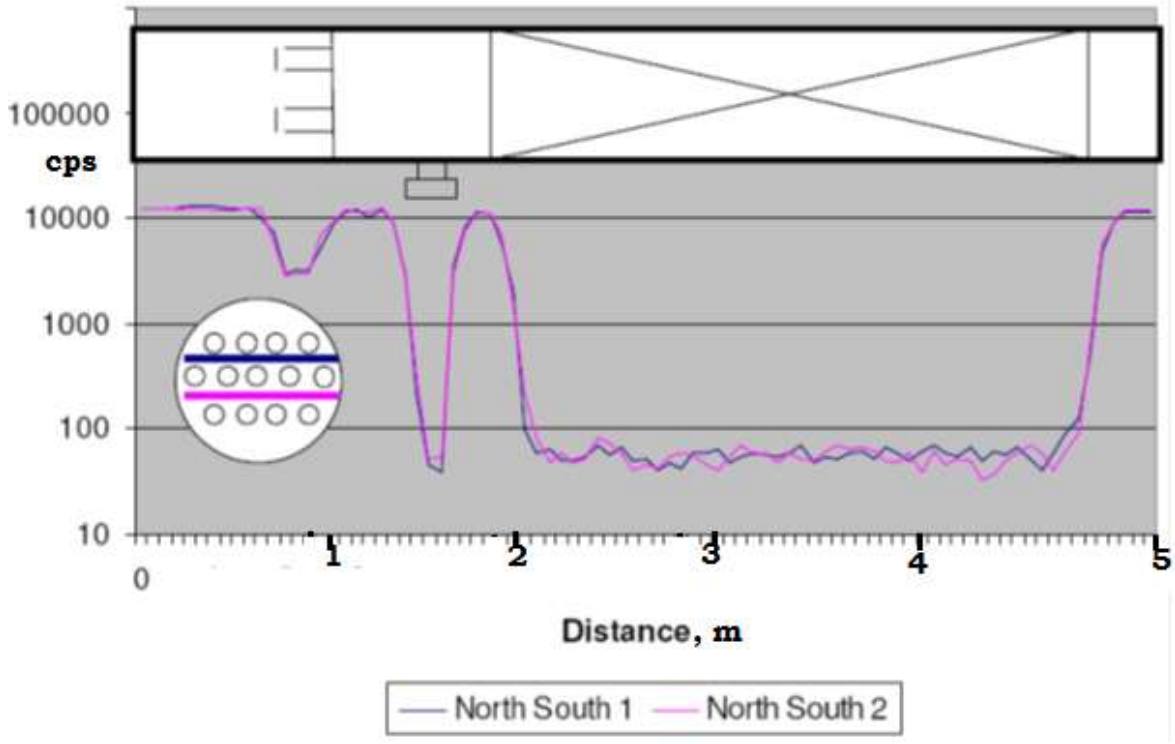

FIG. 37. Two Gamma scans of a packed bed tower.

Conclusions: Both gamma scans showed the draw tray above the liquid distributor to be damaged and causing the maldistribution suspected according to deterioration of the product quality.

Regarding the packed bed part of the tower, because both profiles were the same, it indicated that the packed bed was intact.

3.2.4. Case study 4: Gamma scan inspection of a packed bed tower (courtesy A.Hills)

Problem: Gamma scan grid was carried out in a packed bed column to establish the position of beds and identify any mal-distribution through the beds. Grid gamma scanning of the packed bed was performed (Fig. 38).

Results: There were conducted two set of grid scans, before and after maintenance. Figures 39 and 40 present gamma profiles obtained.

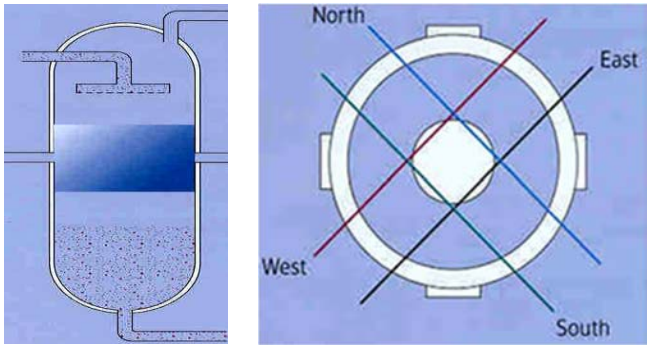

FIG. 38. Grid gamma scanning of the packed bed.

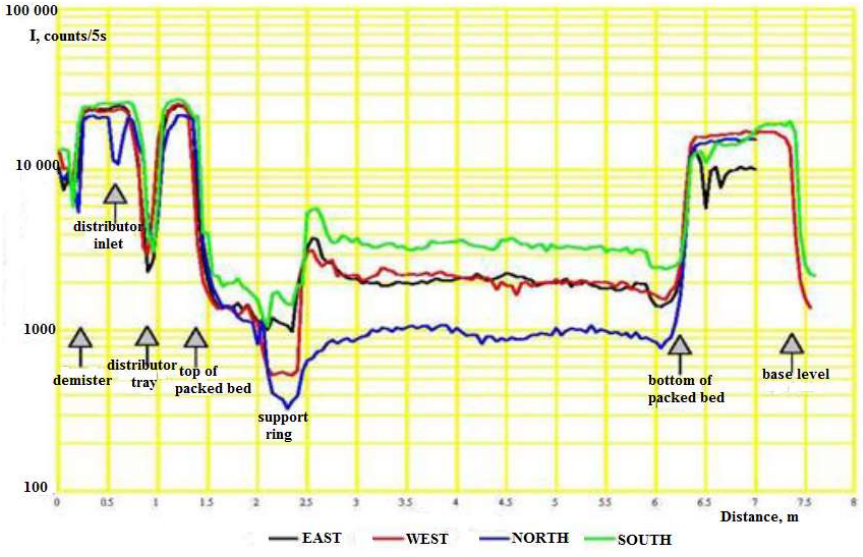

FIG. 39. Four gamma profiles performed in a packed bed column, before maintenance.

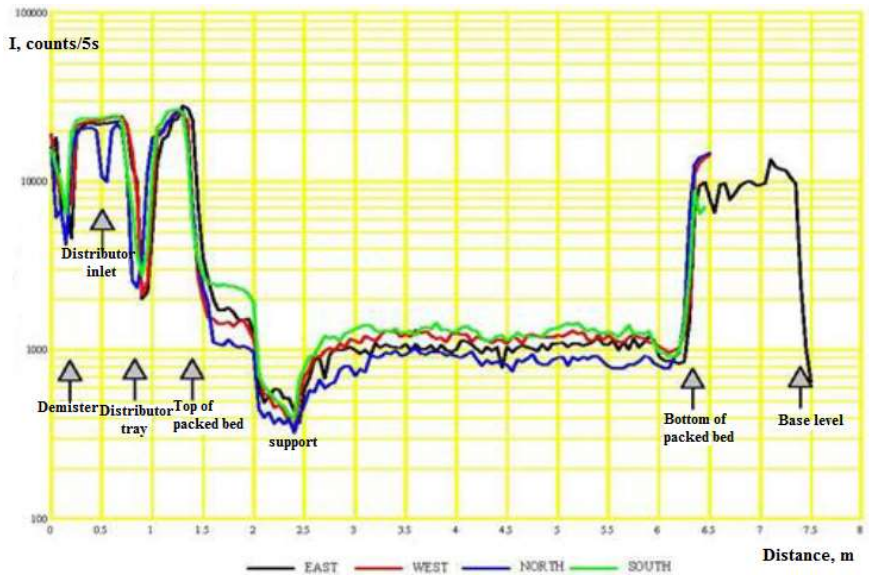

FIG. 40. Four gamma profiles performed in a packed bed column, after maintenance.

Conclusions: It is clear from the gamma profiles (Fig. 39, before the maintenance) that the region intersected by the North scan line displayed a much greater mean density through the length of the bed than the region intersected by the South scan line. As the other East and West scan lines are very similar, the indication was that there was a preferential flow of liquid through one region of the bed. The density difference was constant throughout the length of the bed, indicating a problem with the distribution of liquid onto the bed.

The column was subsequently opened to effect repairs and a large hole was confirmed to be present on the North side of the distributor tray, causing liquid to preferentially flow down this side. The second set of scans (Fig. 41, after maintenance) show the mean density of liquid through the bed to be uniform and confirm that the cause of the mal-distribution was identified and repaired.

3.2.5. Case study 5: Zinc oxide bed remnant life measurement (courtesy A.Hills)

Problem: A variation of the gamma scanning service enables the remaining life of zinc oxide absorbent in sulphur removal systems to be determined. It relies on the fact that there is a density difference between the fresh zinc oxide and the used absorbent that has converted to zinc sulphide. The technique allows consumption of the absorbent to be monitored and the remaining life to be predicted, thus allowing maximum absorbent utilization. The method is suitable for vessels up to 2.5 meter diameter and 50 mm wall thickness.

Results: An initial gamma scan of the vessel was carried out in August 2010 (red trace), and a comparative scan was carried out 6 months after the bed had been changed in April 2011 (blue trace). Figure 41 shows both gamma profiles.

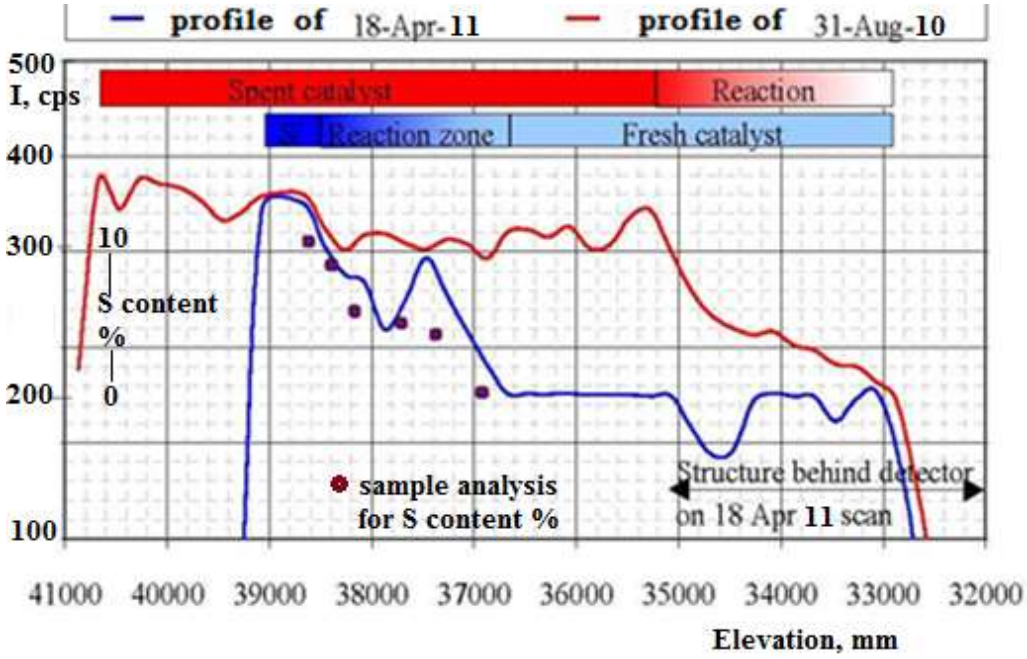

FIG. 41. Gamma scan profiles in a processing vessel for investigating consumption of the zinc oxide absorbent in sulphur removal system.

Conclusions: The initial scan of the vessel, carried out in August 2000 (red trace), demonstrated that the absorbent was almost fully utilized, and in fact sulphur breakthrough was detected in October 2010.

The comparative scan carried out 6 months after the bed had been changed (in April 2011, blue trace), indicated that the sulphur front was now at the top of the bed with approximately 4 meters of fresh absorbent remaining. As this plant was shut down a month after this scan, samples of the absorbent were taken and analyzed for sulphur content for comparison purposes to verify the technique. The samples matched the scan very closely. The customers have used the resulting information to confidently defer the replacement of absorbent until a later date.

3.2.6. Case study 6: Comparative gamma scanning of two stripping vacuum columns to investigate flooding as a result of blockage in downcomer (courtesy A.Hills)

Problem: The column is a stripping column under vacuum that separates carbon dioxide (CO_2) and potassium carbonate (K_2CO_3) solution from potassium bicarbonate ($KHCO_3$) by reboiling $KHCO_3$ using steam. The tower is open to the atmosphere and operates at atmospheric pressure and a temperature of 112ºC. The steam used for reboiling is at 800 kPa and 160ºC respectively.

Pressure and temperature problems were experienced to control the operation of the column. Due to these symptoms, the product was not according to prescribe quality and purity. It was presumed that flooding might be the cause of this malfunctioning.

Results: Sixteen-meter portions of the two columns were scanned under the same operating conditions, using a 2.2 GBq (60 mCi) ^{60}Co radioactive sealed source. Since this column forms an important integral part of the system, a second scan was performed on an identical column operating normal, in order to compare the scan profiles to facilitate interpretation of the scan data obtained. The response curves are shown graphically in Figure 42.

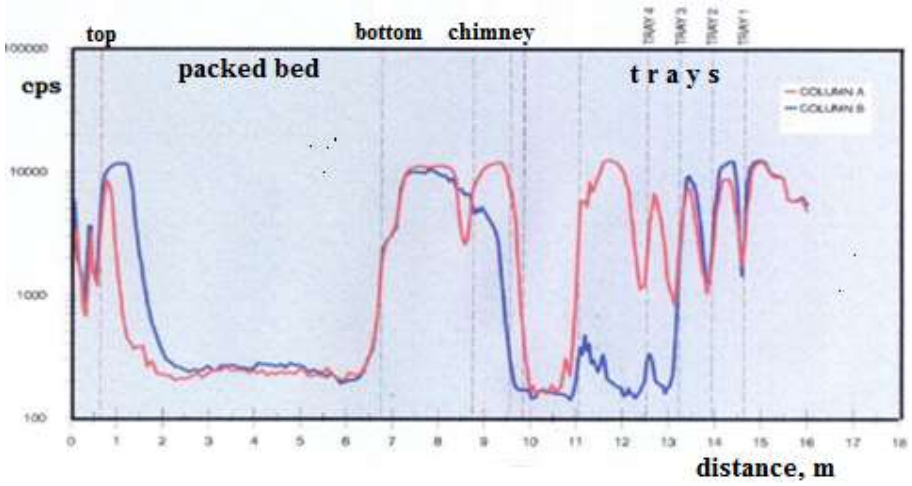

FIG. 42. Gamma profiles in two similar stripping vacuum columns.

Also shown in the figure are the positions of the top bed, sieve trays and chimney trays and other relevant equipment that could have interfered with the transmitted radiation as indicated on the schematic drawing of the units.

Conclusions: From the response curves obtained the following deductions can be made:

Column A (red scan line):

- The top packed bed is in position and located app. 0.3m below the expected position as indicated on a mechanical drawing of the unit;
- The chimney tray is in position;
- From the regular attenuation 'peaks' coinciding with tray positions, it is concluded that the trays are in position and carries nearly the same amounts of liquid on it;
- •The transmitted radiation intensities recorded through the vapour spaces between the trays are approximately the same, indicating good liquid/vapour disengagement in these areas.

Column B (blue scan line):

- The top packed bed is in position and is located nearly 1 m below as indicated on the mechanical drawing of the unit;
- From the high intensity levels recorded at the position of the chimney lid bottom (compared with column A), it is concluded that the chimney lid bottom is severely damage and possibly collapsed.
- A low intensity of transmitted radiation is recorded in the region between the bottom chimney and tray 3. A liquid build-up on tray 3 could have caused this flooding, which in turn, could have been the result of a blockage on tray 3 or in its downcomer;
- Tray 1 and 2 are in position and carries liquid with good liquid/vapour disengagement in the vapour space between them.

Flooding occurs, as in this case, when the pressure across the column rapidly increases. The liquid level drops and separation efficiency is completely lost. The scan data facilitated the planning of a scheduled maintenance shutdown.

3.2.7. Case study 7: Gamma scanning of a pack bed tower to investigate fouling (courtesy A.Hills)

Problem: In a pack bed tower, fouling was suspected.

Results: Two gamma scan profiles (red and blue) were performed on a packed bed tower to investigate the suspected fouling. Both gamma scan profiles are shown in Figure 43.

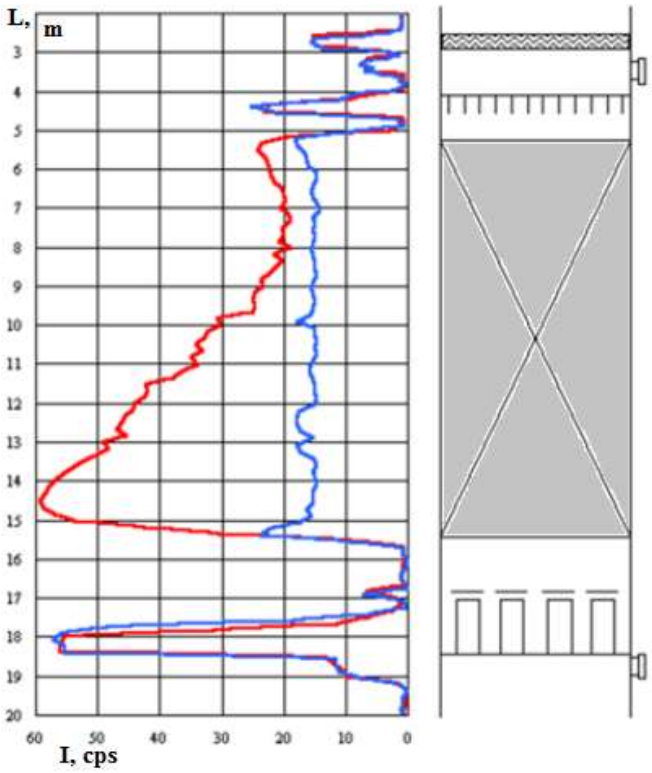

FIG. 43. Two gamma scan profiles (red and blue) were performed on a packed bed tower to investigate the fouling.

Conclusions: The initial scan (red) showed that the demister pad, distributor, packed bed, and chimney tray were at the proper elevations. The bed however had experienced severe fouling, especially in the bottom two thirds of the packing. The column was shut down and the packing replaced.

The scan taken after the turnaround (blue) exhibited a far more uniform bed density. Some higher densities were observed at the top and bottom of the bed due to the hold down plate and bed support, and part way down the bed due to external mechanical interference.

3.2.8. Case study 8: Gamma scanning of a trayed column for flooding (courtesy A.Hills)

Problem: A trayed column was suspected to be damaged because of bad quality product; the flooding was suspected but its location was not possible to find. The end users asked the service provider to carry out gamma scanning for troubleshooting.

Results: Figure 44 shows two-gamma scan profiles performed on the column, one when the column performed badly, and after when it was waterwashed.

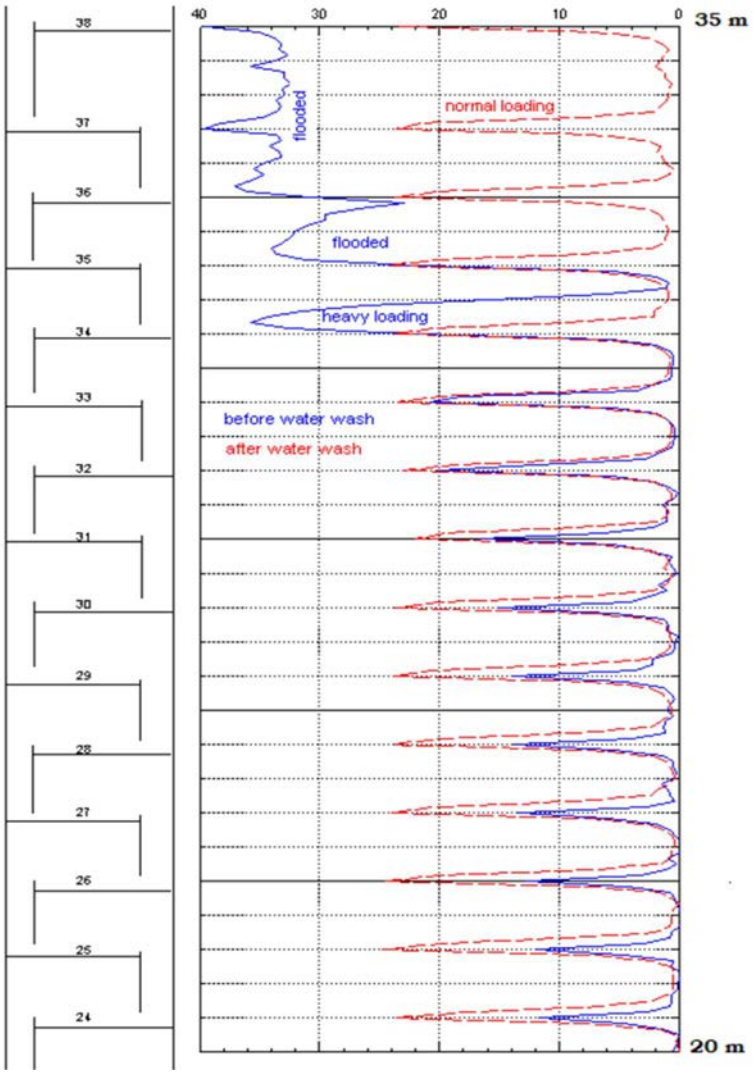

FIG. 44. Two gamma scan profiles performed on a trayed column suspected for flooding.

Conclusions: The first gamma profile showed that the column was flooded from tray 24 up through tray 38 due to fouling (blue trace), in particular the zone from tray 34 till tray 38 was severly flooded.

An overnight waterwash brought the column back into normal operation (red trace). This avoided a complete shutdown for inspection.

3.2.9. Case study 9: Scan investigation on a stripper column to monitor the process behaviour over a period of time (courtesy A.Hills)

Problem: A process solution is stripped of in the CO_2 stripper column, by boiling the CO_2 off. The solution from the absorber is pre-heated in the lean/rich heat exchanger from 50ºC to 90ºC. The solution is fed into the CO_2 stripper on the 18th tray (out of the 20-tray column). The trays are all valve trays, the lower eighteens are two pass trays and the top two, are single pass trays. The solution flows down the column, counter-current to the CO_2/steam passing up the vessel. In the bottom of the column the solution is collected on a chimney tray and fed to the reboilers. The reboilers are kettle type exchangers, with steam on the tube side. The vapour containing CO_2 and steam is passed back into the column below the bottom tray, and flows up the column to the 19th and 20th trays, where it is washed with reflux water (process condensate) before leaving the stripper. There is a mesh type demister in the top of the column.

Results: Three gamma scan profiles in interval of 1 month each were performed to monitor the process behavior over time.

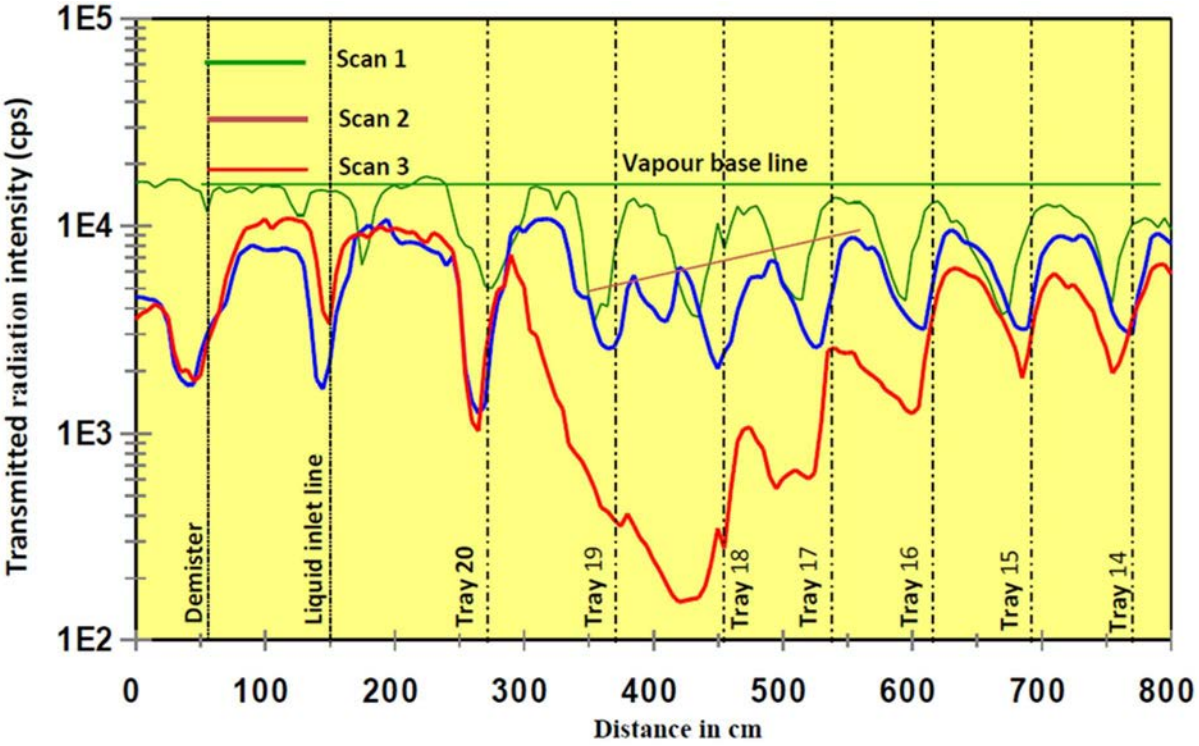

FIG. 45. Gamma scan profiles obtained during three scans on the stripper column (Courtesy A.Hills).

Figure 45 presents the gamma scan profiles obtained during three scans on the stripper column.

Conclusions: Gamma scan profiles on a stripper column shows process behavior decline with time from scan 1 to scan 3:

- Green line: It shows normal process operation without problems. It serves as a reference scan with good liquid/vapor disengagement between trays;
- Blue line: Process problems start to develop between trays 19 and 17;
- Red line: Process problems progress from tray 20 to tray 15. Trays in this time are severely flooded.

After the gamma scan 3 the column was shut down for maintenance and conclusions were confirmed; gamma scan located and predicted problems in advance, before they reached a point of no return.

3.2.10. Case study 10: Gamma scanning of two packed bed columns to investigate the liquid distribution (courtesy A.Hills)

Problem: Gamma scanning of two packed bed columns was carried out to investigate their performance for the liquid distribution, which is the most common cause of unexpected poor separation in packed bed columns.

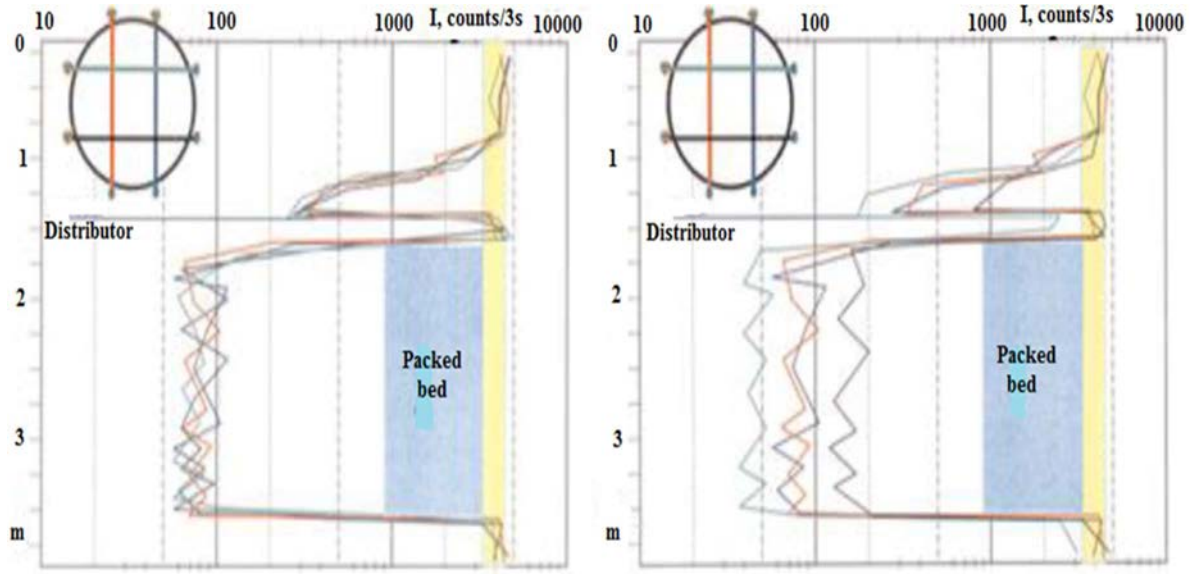

FIG. 46. Grid gamma profiles of 4 scanning performed for each column.

Results: Figure 46 shows the grid gamma profiles of 4 scanning performed for each column.

Conclusions:
a. Perfect distribution is not achievable in both cases, but it is not necessary in practice;
b. The packed bed column left was performing well;
c. The packed bed column right is performing badly.

3.2.11. Case study 11: Gamma scanning of a stripper column (courtesy A.Hills)

Problem: Product purity problems were experienced and could not be solved during the operation of the stripper column. It was presumed that collapsed trays or malfunction areas inside the column could be the cause of the problems.

Results: A gamma-ray scan was consequently carried out on the entire length of the column, using a 0.55 GBq (15 mCi) ^{60}Co sealed source. Obtained scan profile is shown graphically (Fig. 47).

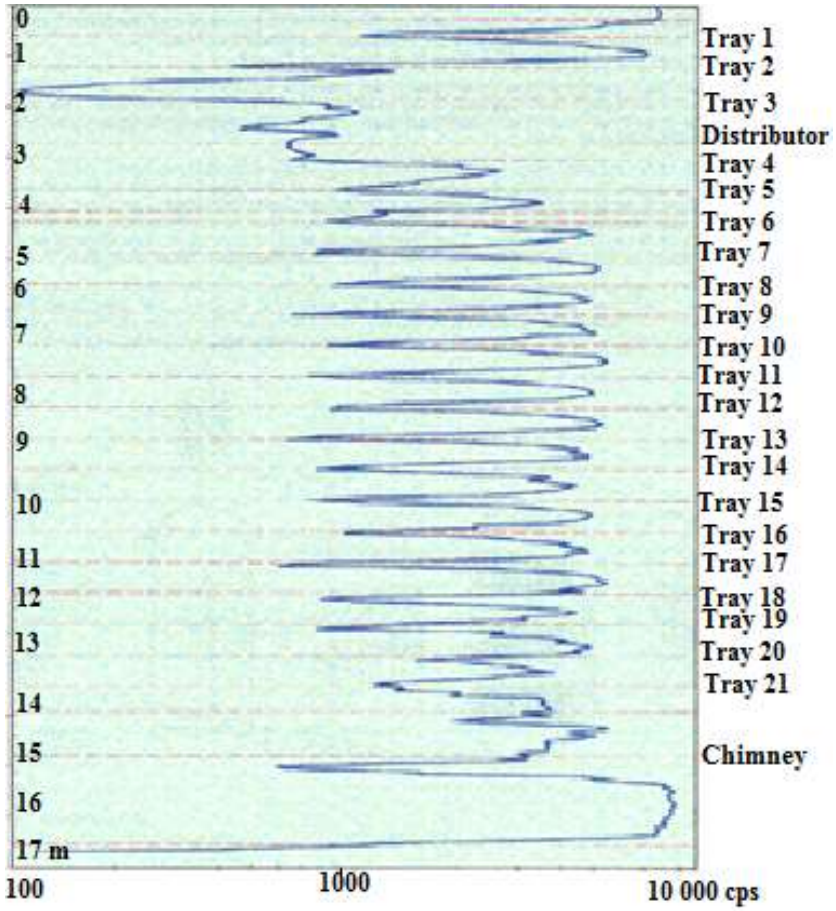

FIG. 47. Gamma scan profile of a stripper column.

Conclusions: The following deductions were made from the scan profile.

Tray 1 was in position and carried liquid. Tray 2 appeared to be in position. Abnormally high absorption density material was located on tray 3 (relatively higher than liquid, indicating the presence of solid material on the tray, and low count rate).

A deviation from the expected profile was measured between tray 2 and tray 4. This indicated a high liquid level on tray 4 and could be attributed to a blockage on the tray or in its downcomer. Poor liquid/vapour disengagement was measured in the vapour space between tray 2 and tray 6.

An unidentified object not indicated on a mechanical drawing of the unit was located between tray 3 and the distributor. Distributor may be functioning abnormally.

A relatively low liquid level was recorded on tray 20, indicative of partial damage to the tray. From the regular attenuation ‘peaks’ coinciding with tray positions it was concluded that all the trays from 6 to 19 were in position and carries approximately the same amount of liquid.

The fact that the signal level recorded through the vapour spaces between trays 20 and 21 did not return to the vapour base line, indicates poor liquid/vapour disengagement between them. This may have been the result of weeping of tray 20. The same effect was evident between tray 21 and the draw-off line. The liquid base level was located at 16.5 m.

3.2.12. Case study 12: Gamma scan for flooding in a pre-fractionation column (courtesy A.Hills)

Problem: The primary function of the pre-fractionator is to split the incoming condensate (crude oil) into two components. The heavy component goes to the bottom portion of the column, which consists mainly of components heavier than kerosene. Light components, which consist mainly of naphtha, are extracted at the top of the column. Product problems were experienced with the operation of a pre-fractionation column.

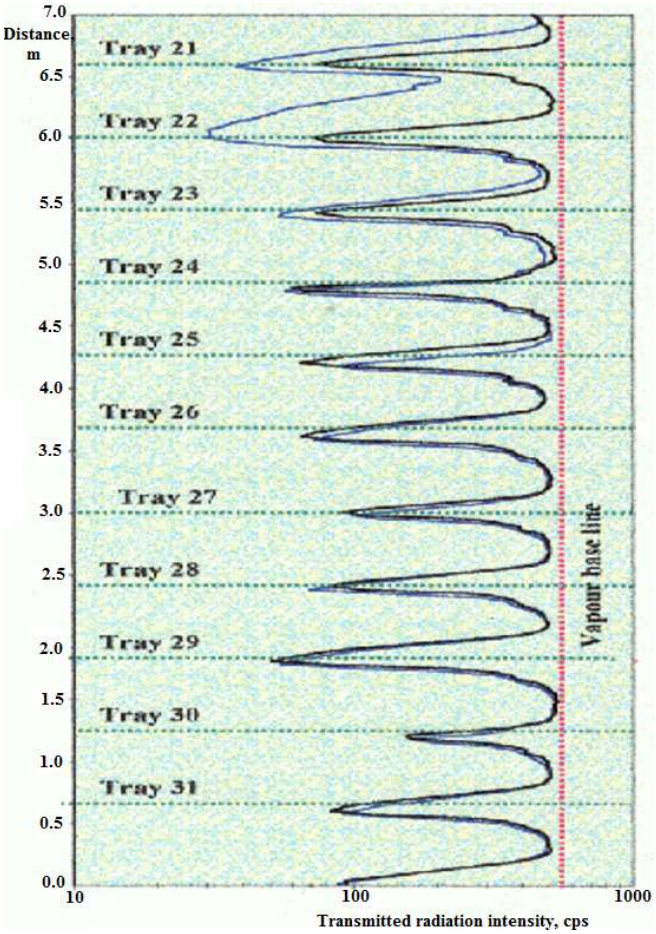

FIG. 48. Gamma scan profile of a pre-fractionation column.

Results: Gamma-ray scans were consequently carried out to investigate and locate possible malfunction areas or anomalies inside the column. A 7-meter portion of the column from tray 21 downwards were scanned under two different crude feed conditions namely 18000 barrels/day (blue line) and 15000 barrels/day (black line). A 1.1 GBq (30 mCi) ^{60}Co sealed source was used, and two scan profiles obtained one after other for comparison, are shown graphically (Fig.48).

Conclusions: The following deductions are made from the scan profiles:

An abnormally high liquid level is measured on tray 22 during the blue scan line. This may be attributed to a partial blockage in the downcomer of the tray or on the tray.

Poor liquid/vapour disengagement is recorded between trays 22 and 21. This may be due to liquid entrainment (carry over) from tray 22 to tray 21.

The relatively high liquid level recorded on tray 21 most probably is coming from liquid entrainment from tray 22 to tray 21.

A relatively high liquid level was recorded on tray 29 during both scans. This could be attributed to incorrect functioning of the tray with possible fouling (dirt) on the tray causing a slight downcomer backup of liquid.

An abnormal low liquid level detected on tray 30 during both scans was measured. This confirmed that tray 30 behaved abnormally (an indication of tray damage).

The scan carried out under a feed rate of 15 000 barrels oil per day (black line) indicates that:

Try 21 and 22 are normal as expected. This behaviour confirms that tray 22 functions abnormally (blue line) under a high feed rate condition. The indication is that under a high operating condition a resistance to the downcomer flow exists, effecting of a build-up of liquid in the downcomer of tray 22.

From the regular attenuation 'peaks' coinciding with tray positions it is evident that all the trays in this portion of the column were in position and carried liquid at the time of the scan.

The signal intensities recorded through the vapour spaces between the trays were at approximately the same level, indicating good liquid/vapour disengagement in these areas.

Observing more in details the tray 22 and 21, it can be seen that liquid level on:

- tray 22 (15 000 barrels/day black line) = 150 mm;
- tray 22 (18 000 barrels/day blue line) = 360 mm.

The decrease in radiation intensity or the increase of vapour density between tray 22 and 21 (blue line) is due to the existence of liquid entrainment and foaming. The difference or reduction is 65% in radiation intensity. Therefore, tray 22 is heavily flooded with a high degree of foaming. This happens at 6.3 m to 6.5 m.

3.2.13. Case study 13: Gamma scan investigation on a Tail Gas Wash column. (courtesy A.Hills)

Problem: Temperature and pressure problems were experienced along the entire length of the tail gas wash tower. This tower is part of a Synthol process system. Tail gas is the lightest hydrocarbon gas released from a refining process.

A column scan was consequently requested and carried out in order to investigate possible internal tray damage, or anomalies, which could have affected the performance of the tower. The purpose of this investigation was also to facilitate the planning of a scheduled maintenance shut down.

Results: The gamma scan was carried out on the top 15 m portion of the column, using a 0.55 GBq (15-mCi) ^{60}Co sealed source. Figure 49 shows the gamma profile. Also shown in the figure are the positions of the trays and other relevant equipment, which could have interfered with the transmitted radiation, as indicated on a mechanical drawing of the unit. All distances in the figure refer to a specific reference point situated above tray 47.

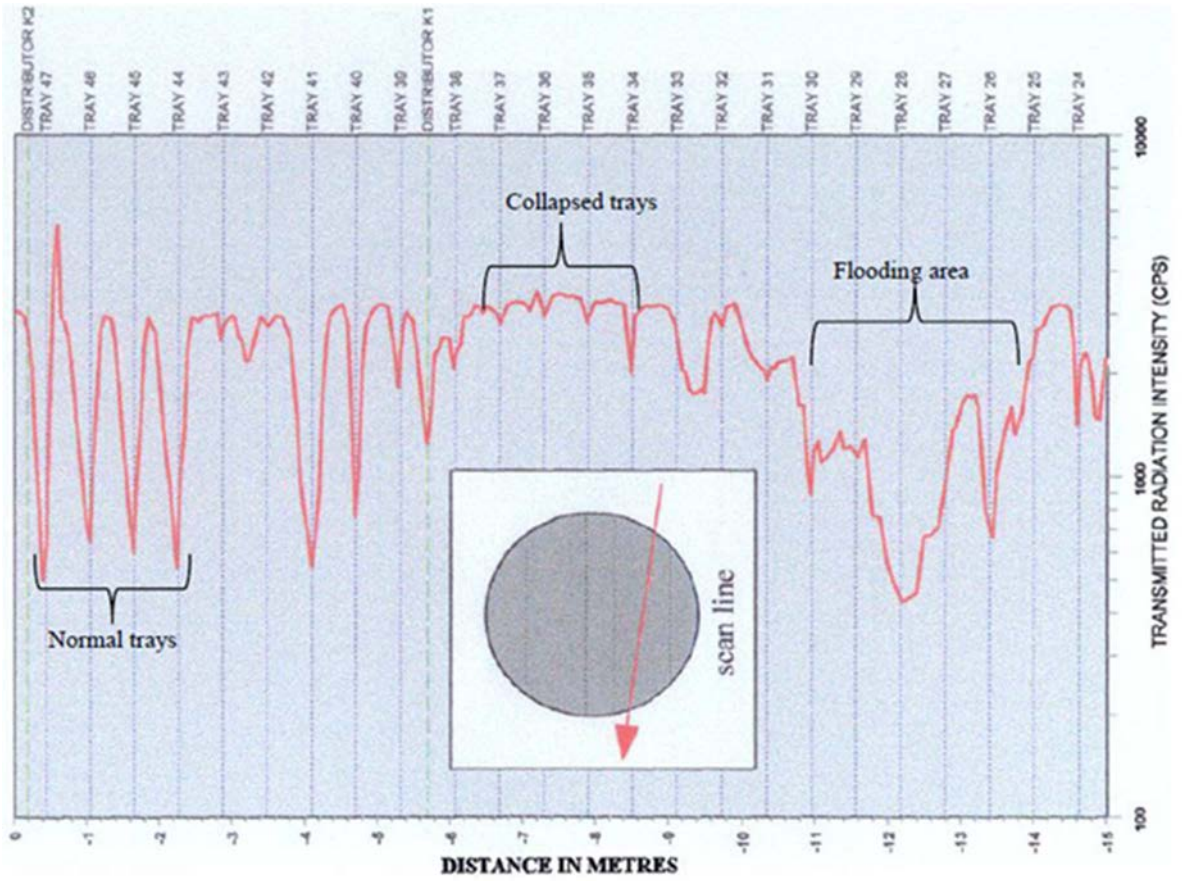

FIG. 49. Gamma scan profile on the top 15m portion of the column (Courtesy S. Charlton).

Conclusions: The following observations were made from the scan data:

- Trays 47 to 44 are in position and carried liquid, as indicated by the fairly regular attenuation 'peaks' obtained at tray positions during the time of the scan;
- The signal intensities recorded through the vapour spaces between the trays (47 to 44) were approximately the same heights, indicating good liquid/vapour disengagement in these areas (the intensity signals return approximately to the same vapour baseline);
- Trays 43 and 42 are severely damaged and had collapsed;
- The relatively high liquid level recorded on tray 41 may be attributed to debris from trays 43 and 42 on to tray (tray 41);
- The deviation from the expected profile between tray positions 39 to 29, indicates a lack of liquid, which could be due to severe damage to these trays or because they had partially or totally collapsed;
- The extremely low signal level recorded on trays 28 and 27 may have been due to debris on the trays above it, causing a partial blockage in the tray downcomers;
- Tray 26 is in position and carried liquid;
- Tray 25 is damaged;
- A relatively low liquid level is recorded on tray 24, which is partially damaged.

Some trays are damaged at a point of no return. Column resulted totally out of control for operators — it was opened for maintenance.

3.3. GAMMA SCANNING OF PIPES: CASE STUDIES

By applying the gamma ray scanning technique to piping, can quickly:

- Locate blockages;
- Locate scale or coke buildup;
- Locate liquid in vapor lines;
- Locate areas of lost refractory or lining in a pipe;
- Measure flowing densities;
- Evaluate the fluidizations of catalyst.

3.3.1. Case study 1: Horizontal gamma scan for pipe blockage detection (courtesy CANTI)

Problem: A pipeline used for transport of sllury, was suspected to be blocked.

Results: A gamma scan profile was performed along the pipe. Figure 50 (left) shows the pipe, the gamma source - detector setup and the horizontal gamma scan profile along 25 m of the pipe where the problem was suspected.

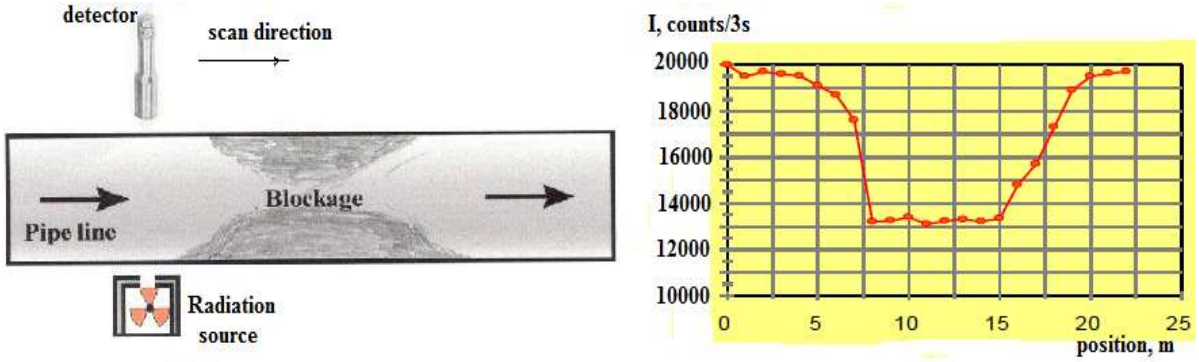

FIG. 50. Gamma scan for pipe inspection for blockage (or scaling).

Conclusion: The gamma scan profile indicated a blockage (or scaling) in the middle of the pipe length (between 8–10 m).

3.3.2. Case study 2: Vertical gamma scan on a pipe suspected for blockage (courtesy CANTI)

Problem: A blockage was identified in a cross section of a pipeline used for transport of slurry. A vertical gamma scan was performed on this pipe section to determine the thickness of blockage layer.

Results: Figure 51 shows the vertical gamma scan profile of a cross-section of a pipeline suspected for blockage.

Conclusion: There was a blockage of nearly 5 cm on the bottom part of the pipe.

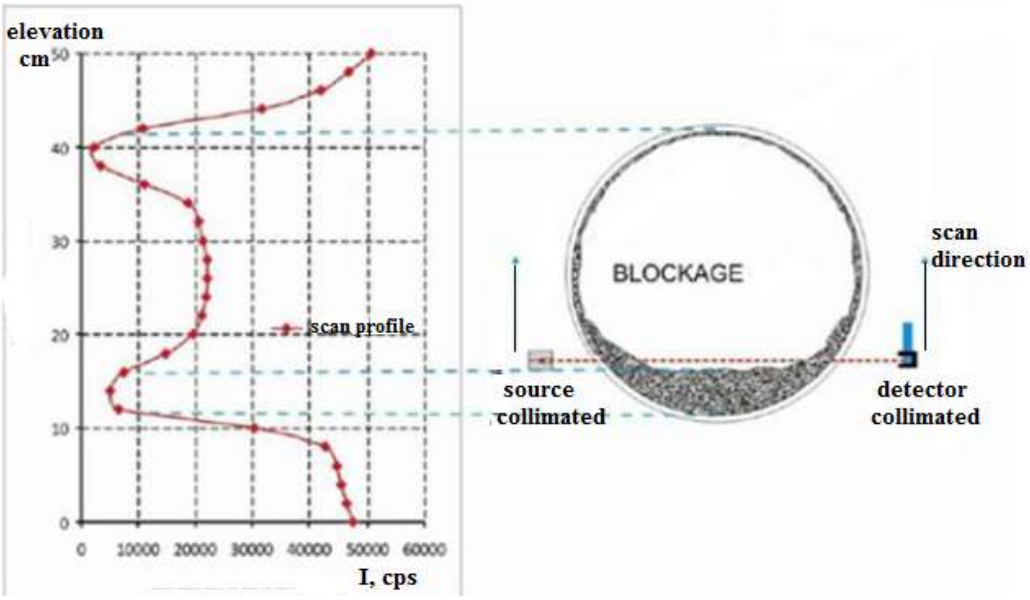

FIG. 51. Vertical gamma scan profile of a pipe section.

3.3.3. Case study 3: Horizontal and vertical gamma scanning on a segment of a pipeline suspected for massive scaling (courtesy CANTI)

Problem: A segment of a pipeline suspected for massive scaling.

Results: Figure 52 shows horizontal and vertical gamma scan profiles on a segment of a pipeline suspected for massive scaling along the pipe.

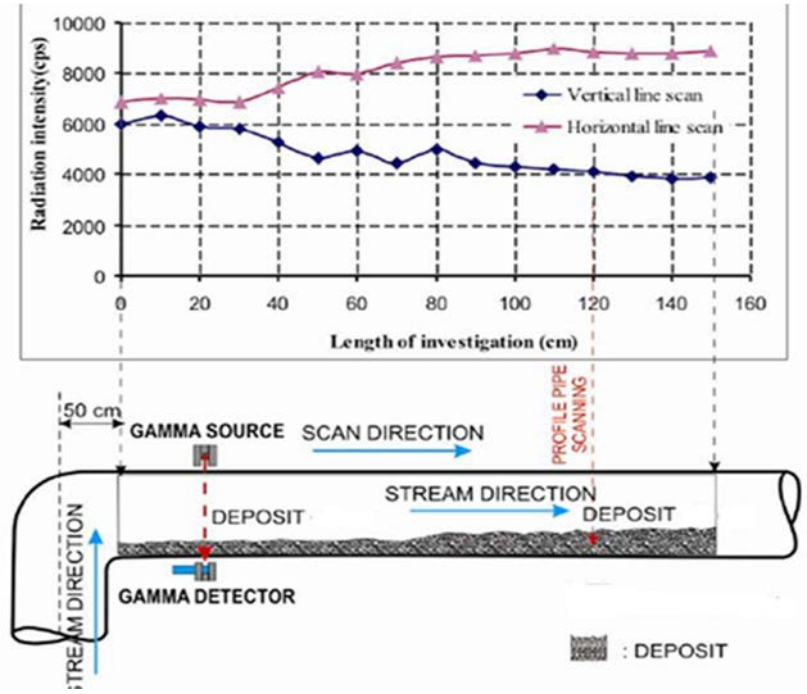

FIG. 52. Horizontal and vertical gamma scanning on a segment of a pipeline suspected for massive scaling.

Conclusion: There was a non-uniform deposit along the bottom line inside the pipe, with deposit thickness increasing from left to right.

3.3.4. Case study 4: Gamma scan along a pipeline suspected for scaling or blockage (courtesy CANTI)

Problem: A pipeline was suspected for scaling or blockage in different parts.

Results: Figure 53 shows the horizontal gamma scan profile along the pipe.

FIG. 53. The horizontal gamma scan profile along the pipe.

Conclusions: The gamma profile shows the deposits (blockages) inside the pipe in almost regular intervals to each other.

3.3.5. Case study 5: Gamma absorption technique for monitoring the behavior of oil/gas flow through a transportation pipeline (courtesy J. Thereska)

Problem: The oil Primary Collecting Station (PCS) distributes various hydrocarbours to end users using the same pipeline. It is important for plant operators to identify transported liquids, their frequencies as well as their lengths in time and space. The pipe internal diameter was 51 cm and it was considered fully filled with oil.

Results: The demonstration has been conducted in an oil distribution plant for monitoring oil distribution pipeline. A 2''x2" NaI detector and a ^{137}Cs sealed source (185 MBq -5 mCi) were installed in vertical position of a pipeline where the normal diesel was flowing (Fig. 54).

FIG. 54. Demonstration of the gamma absorption technique for monitoring the oil flow through a transportation pipeline.

The oil transport pipeline was inspected using gamma absorption technique for nearly two hours. The count rates recorded with sampling time 5 s. The experimental data, gamma intensity (I, count rate, cps) versus time (t, s), in the fixed detector — source position is presented in Fig. 55.

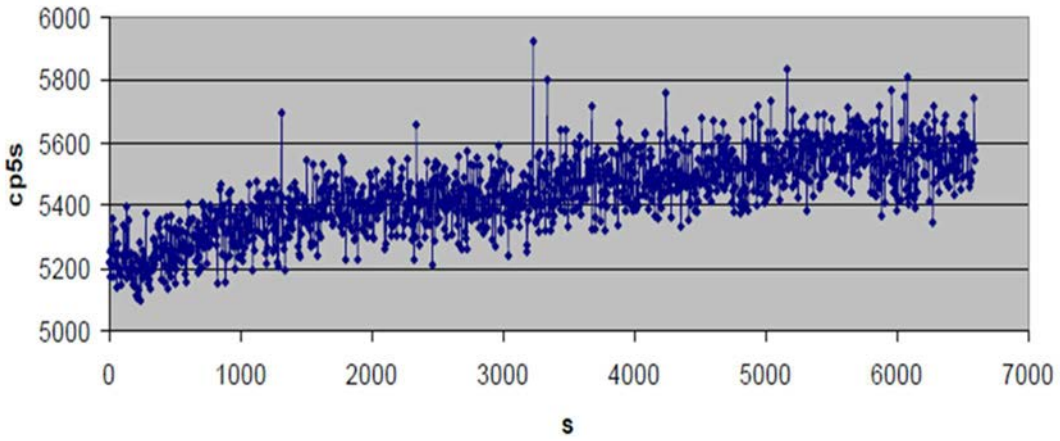

FIG. 55. Gamma density profile during the oil transport.

Conclusions: The results provided a good estimation of a normal flow regime of the diesel transport through transporting pipeline; the mean value was considered.

$$I = (5400 \pm 200) \text{ counts } /5s$$

that means within the homogeneity of 4%, which is accepted as normal.

3.3.6. Case study 6: Gamma scanning of a pipe for inspection of possible corrosion (courtesy J. Thereska)

Problem: A stock of pipes was inspected because of suspecting for internal corrosion due to their long-term storage in open air conditions.

Results: The gamma scan profile along the pipe is presented in Figure 56. Detector and source were placed opposite to each other and moved uniformly along the pipe (across the cord line).

FIG. 56. Demonstration of gamma scanning technique for pipe inspection for possible corrosion.

The gamma scan profile along the pipe is presented in Figure 57.

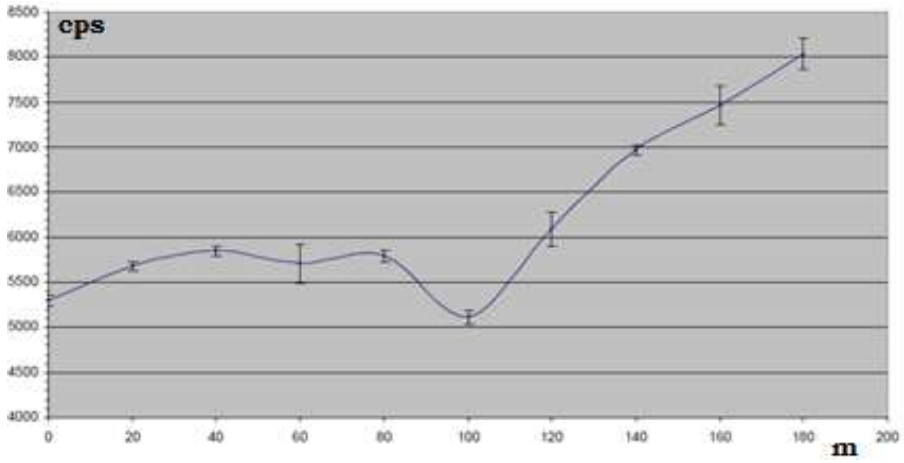

FIG. 57. Gamma profile along the pipe.

Conclusions:

a. Different wall thicknesses were observed in the middle and at the end of the pipe;
b. Right end of pipe from 120 cm on, was thinner than normal wall thickness;
c. Suspect of right side corrosion.

3.3.7. Case study 7: Gamma scan investigation on a FCC Transfer line (courtesy A. Hills)

Problem: The main function of a Fluidized Catalyst Cracking (FCC) reactor is to convert vacuum gas oils into gasoline and gas (Fig. 58). The fine ceramic powder catalyst facilitates cracking reaction process when comes in contact with hydrocarbons. The deposit build-up of carbon catalyst on the inside

walls of the transfer line is a common problem in the FCC reactor. Gamma scanning of transfer line pipe was requested to be performed several times.

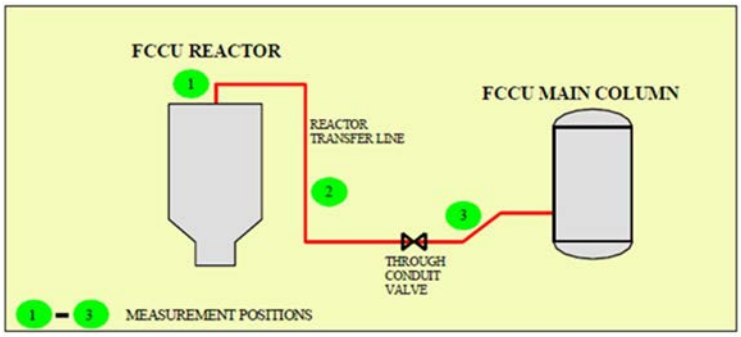

FIG. 58. FCC Transfer line and three pipe sections where gamma scan monitoring for the deposit build-up of carbon catalyst on the inside walls was performed.

Results: A 370 MBq (10 mCi) ^{137}Cs sealed source was used to inspect an 880 mm diameter line. This sealed source is suitable for detecting small changes in density, which can be correlated with deposits in the pipeline.

The density (ρ) and the mass absorption coefficient (μ) of the carbon/catalyst deposit for ^{137}Cs was experimentally determined in laboratory by simulating the deposit material into the pipe. The radiation transmitted through the pipe is a function of the initial radiation intensity without absorber (empty pipe), Io. Either of the variables x or ρ can be measured if one of them is kept constant. If the thickness is known or can be measured, density can be determined by the relation:

$$\rho = \ln(I/Io)/(-\mu x) \quad (25)$$

If the density is constant or is known, the deposit thickness can be determined from a similar equation:

$$x = \ln(I/Io)/(-\mu\rho) \quad (26)$$

Three gamma scan profiles were obtained every month. Typical results are shown graphically (Fig.59).

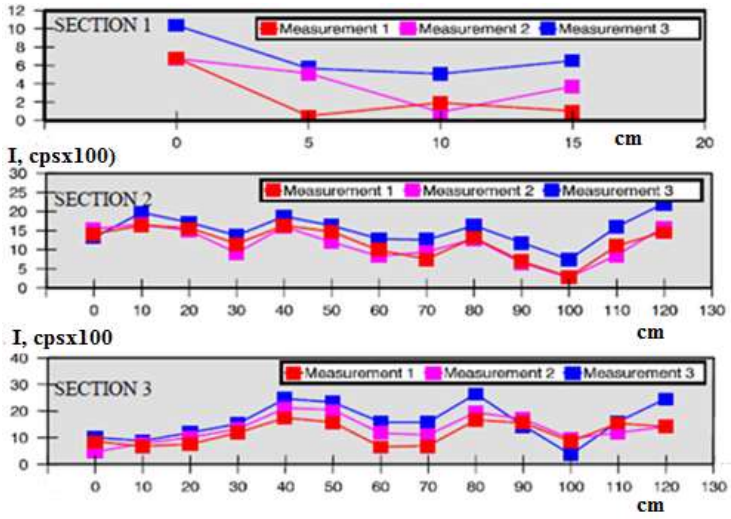

FIG. 59. Deposit measurement results.

Conclusions: Non-uniformity of gamma profiles in three sections with the time indicated that section 1 has more problems than the sections 2 and 3. Anomalies in count rates along the pipes were caused by material collapsed inside the pipeline and creating deposits inside the pipes.

3.4. NEUTRON BACKSCATTER SCANNING: CASE STUDIES

Neutron backscatter technique is used for measuring liquid levels and interfaces by detecting differences in hydrogen concentration. As know, liquids differ in their neutron moderating effect due to their hydrogen content or their absorbing properties. A key factor in a neutron deceleration process, when measuring liquid levels in containers, is the hydrogen concentration of the component. The higher the hydrogen concentration of liquid, the shorter are the distances migrated by the thermal neutrons and the higher will be the intensity of thermal neutrons in the vicinity of the thermal neutron detector.

The main applications of neutron backscatter scanning are level and interface location of mostly hydrogen liquids present in crude oils storage and separation tanks or other processing vessels. A 37 GBq (1 Ci) ^{241}Am-Be neutron sealed source is mostly utilized in field applications [14].

3.4.1. Case study 1: Neutron backscatter scanning in a crude tar tank in an oil refinery to measure liquid interfaces of various types of liquid hydrocarbons, which are stored in the tank (courtesy A. Hills)

Problem: Neutron backscatter scanning in a crude tar tank in an oil refinery was asked to measure liquid interfaces of various types of liquid hydrocarbons, which are stored in the tank.

Results: Figure 60 shows oils storage tanks (left) and neutron backscatter scanning in progress (right). Two neutron backscatter profiles were obtained at two positions along the length of the crude tar tank for comparison. The results obtained are shown graphically in Figure 61.

FIG. 60. Oils storage tanks (left) and neutron backscatter scanning in progress.

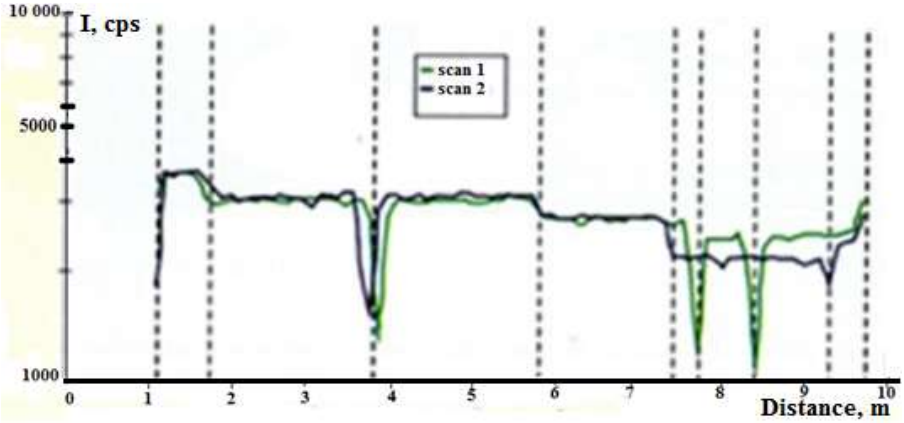

FIG. 61. Two neutron backscatter profiles obtained at two positions along the length of the crude tar tank.

Conclusions:

a. Four oils interfaces were found, indicating four different hydrogen content liquids:

- Interface one, located between 1.1 m and 1.75 m;
- Interface two, located between 1.75 m and 5.5 m;
- Interface three, located between 5.5 m and 7.4 m;
- Interface four, located between 7.4 m and 9.6 m.

b. Three low peaks were found, indicating mechanical structures inside the tank, which in fact were not showing in mechanical designs.

3.4.2. Case study 2: Neutron backscatter scanning in a knock out drum for oil level measurement (courtesy A. Hills)

Problem: Neutron backscatter scanning was asked to be performed in a knock out drum for oil level measurement.

Results: Figure 62 shows the performance of a neutron backscatter scanning on a knock out drum for oil level measurement. A 37 GBq (1 Ci) ^{241}Am-Be neutron source was employed in this case.

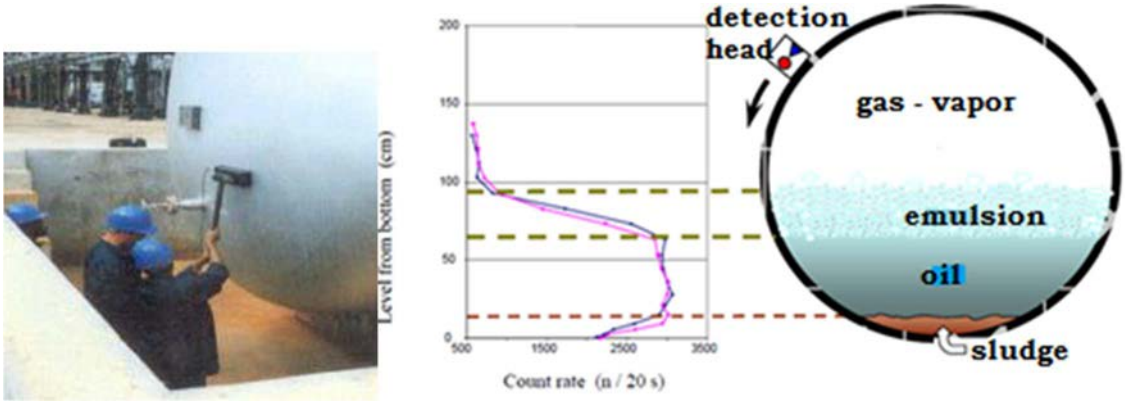

FIG. 62. Neutron backscatter scanning in a knock out drum for oil level measurement.

Conclusion: There were four different phases inside the knock out drum that indicated the presence of sludge, oil, emulsion and vapour. In fact, the oil phase is more consistent and has a height of nearly 50 cm.

3.4.3. Case study 3: The neutron backscatter profile of an insulated pipework suspected for moisture between pipe wall and insulation (courtesy CANTI)

Problem: An insulated pipework was suspected for moisture between pipe wall and insulation. The company asked the service provider to perform the neutron backscatter scan to solve this problem.

Results: Figure 63 shows the neutron backscatter profile of the insulated pipework suspected for moisture between pipe wall and insulation. A 37 GBq (1 Ci) ^{241}Am-Be neutron source used in this case.

Conclusion: The profile shows places under insulation where moisture was accumulated.

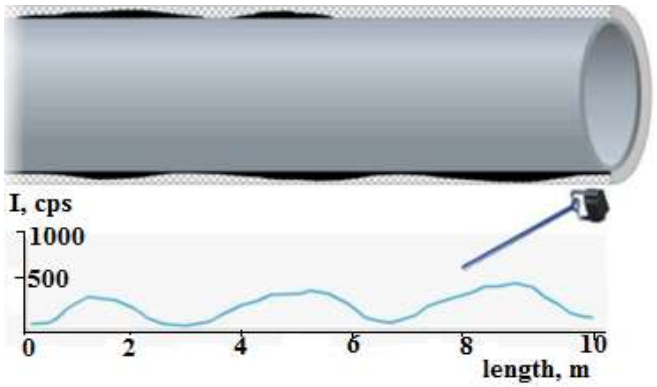

FIG. 63. Neutron backscatter scan along an insulated pipework suspected for moisture between pipe wall and insulation.

3.4.4. Case study 4: Neutron backscatter scan for determination coke formation inside the walls of a column (courtesy V. Yelgaonkar)

Problem: Coke formation inside the walls of a column happens time after time when the process parameters are not optimal. Coke deposits on the column wall cannot be identified applying the gamma scanning technique, due to low density of coke. Engineers suspected coal formation in a segment of a processing column after the gamma scan profile performed on the whole column gave some indications for coke deposits. Neutron backscatter scanning was asked to be performed on this small segment of the column.

Results: Figure 64 shows the neutron backscatter profile obtained using a 37 GBq (1 Ci) ^{241}Am-Be neutron source.

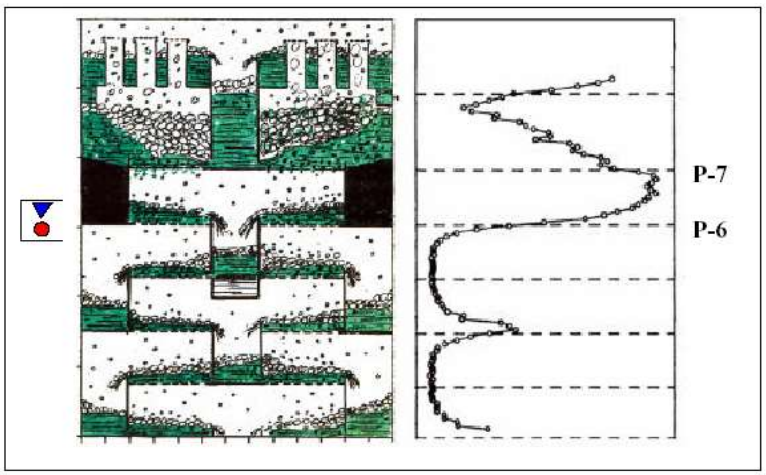

FIG. 64. Neutron backscatter scan for determination coke formation on walls of a column.

Conclusion: On the try 6, there was a blockage by coke formation.

3.4.5. Case study 5: Neutron backscatter scanning of an oil separator (courtesy A.Hills)

Problem: The performance of an oil separator depends on the foam layer dynamic inside the separator. It is important to monitor the foam layer dynamic inside the separator. The neutron backscatter scanning is a technique of choice in this case. Figure 65 shows the oil separator and the neutron backscatter performance.

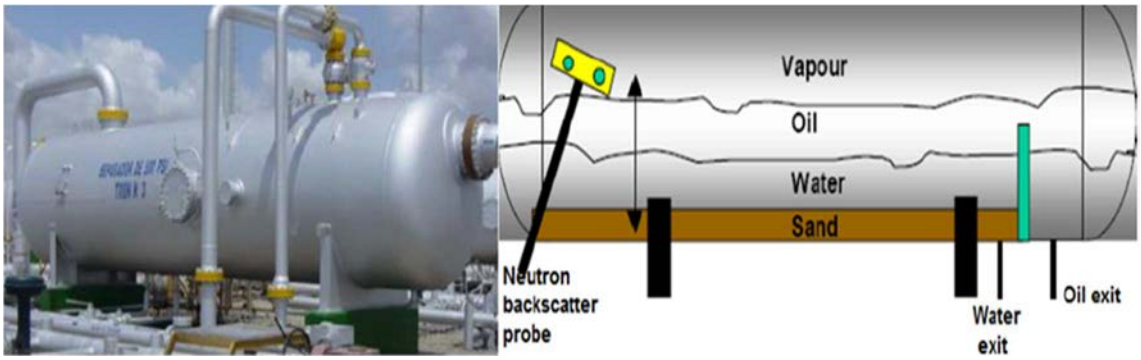

FIG. 65. Neutron backscatter scanning on an oil separator.

Results: Figure 66 presents the obtained neutron backscatter profile of a section of the oil separator for identification of the foaming, level, layer thickness and interfaces. Six neutron backscatter scans were performed in three days (two each day, morning and afternoon) to investigate the dynamic of interfaces with the time of operation.

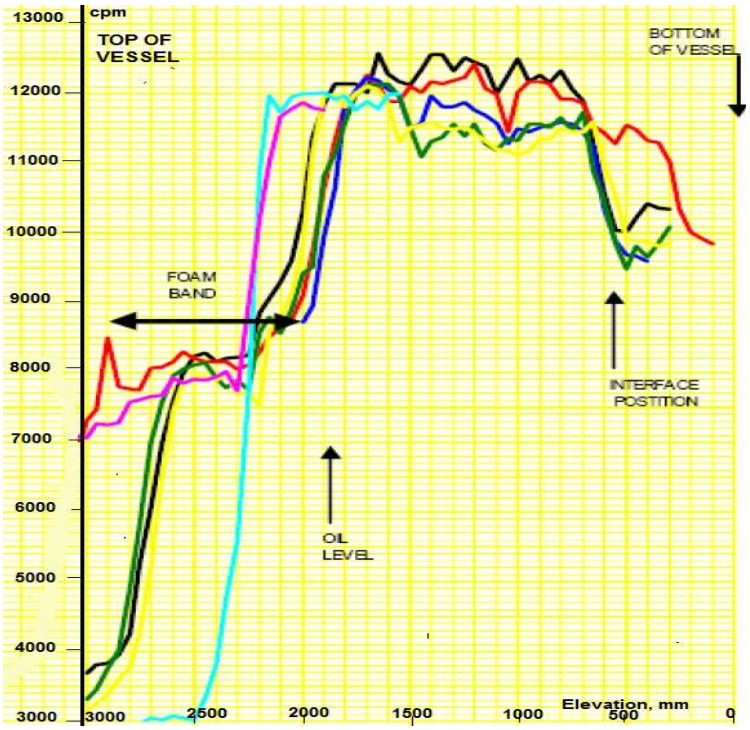

FIG. 66. Neutron backscatter profile of a section of the oil separator for identification of the foaming, level, layer thickness and interfaces.

Conclusions: As seen from Figure 66, the interfaces are not sharply separated. Due to foam and emulsion creating between phases, the interfaces are fluctuating and displaced all the time. The foam band is relatively large of nearly 1 m and is fluctuating in level and layer thickness of many centimeters in few hours or few days of continuous operation. The conclusion was very important for the end users to plan the oil discharge from the oil separator.

4. LABORATORY MODELING OF GAMMA SCANNING

4.1. VARIOUS LABORATORY DESIGNS FOR MODELLING GAMMA SCANNING

There are many laboratory setups for simulation of columns and towers and for getting experience with gamma scanning technique (Fig. 67).

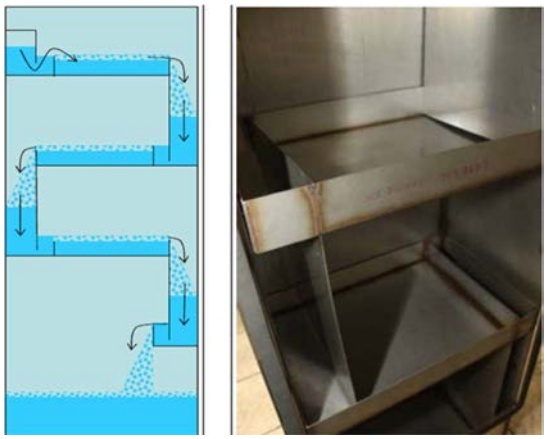

FIG. 67. Typical simple laboratory scale trayed columns (Courtesy, BATAN and IPEN).

Simple columns are designed and a relatively small collimated sealed source of nearly 18.5 MBq (500 μCi) ^{60}Co has been employed. Depending of the size of models, NaI(Tl) collimated detectors 1”x1” or 2”x”2 can be used. Source and detector movements normally are set to 1–2 cm increments and the counting time of 5–10 seconds. The activity of the gamma source is calculated to give count rates of some thousands cps through the air and of few hundreds cps though the water when the background is around 50 cps.

4.2. IAEA TRAINING COURSE ON COLUMN SCANNING

In the framework of the IAEA regional projects, training courses have been conducting on “column scanning simulation” on a laboratory setup (Fig. 68).

FIG. 68. Laboratory design for simulating a column with different internal structures.

Figure 69 shows the equipment employed for gamma scanning.

FIG. 69. Equipment employed for gamma scanning (Courtesy, ALTAÏX Systems)

Homemade software for online constructing the gamma profile was used (Fig. 70) [13].

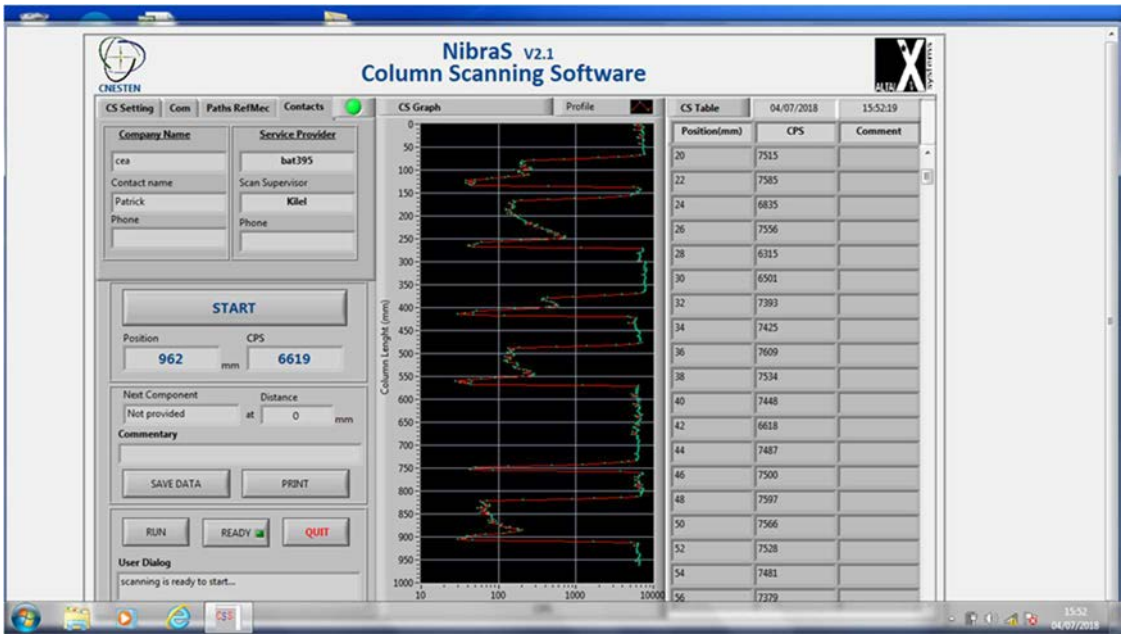

FIG. 70. Homemade software for online constructing the gamma profile (Courtesy, CNESTEN).

Figure 71 shows a gamma scan profile of one model of the gamma scan setup.

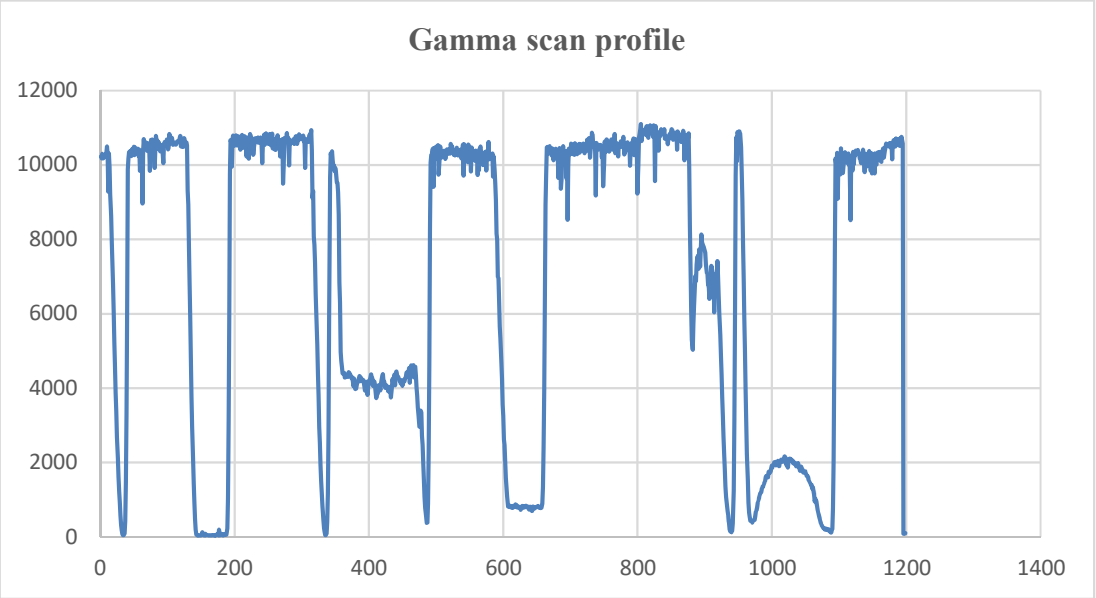

FIG. 71. A gamma scan profile of labscale column (Courtesy J.Thereska)

5. PLANNING AND EXECUTION OF SEALED SOURCE FIELD WORK

5.1. BACKGROUND

The success of sealed source applications depends upon proper designing, planning and implementation of the technique. Various aspects need to be considered while planning a sealed source field work.

On receiving a request from an industry, a member of the 'service provider' visits the experimental site/plant for assessing the feasibility of conducting the experiment and detail discussions with the plant engineers:

- Knowledge of the system and process. Plant visit and discussions with process team is required;
- Properties of the process materials (phases, density, viscosity, etc..);
- Process parameters (process flow sheet, volume, pressure, temperature, etc..);
- Mechanical parameters of the system (wall thickness, etc...);
- Risks generated by the process and its environment (explosive atmosphere, chemical toxicity, etc);
- Elaboration of procedures to be submitted to the national authority.

The radiation risks arising from routine use of the sealed source(s) together with the probability and magnitude of potential exposures arising from incidents should be considered in the safety assessment, which includes:

a) Consideration of the dose rates;
b) Potential exposures of workers and the public, for a range of scenarios representing normal use and reasonably foreseeable accidents and incidents;
c) Limits and technical conditions for operation of sealed sources.

Serive provider team shall consist of three specialists including one team leader/manager, one supervisor and one technician.

In a case of the gamma scanning field work, responsibilities should be clearly defined prior to any field work taking place. They usually take following format:

Client – Responsible for supplying the service provider with sufficient information to enable work to be carried out, safely, and efficiently.

Projects Manager (Level 3): Person ultimately responsible for planning and execution of entire job. This includes defining work scope and allocating sufficient trained and competent personnel and resources to conduct work. Project manager is responsible for ensuring compliance with any statutory legislation to ensure protection of workforce, members of public and environment. Project manager is ultimately responsible for interpretation of data obtained and for supplying a suitable report to customer within an agreed time period.

Senior Field Technician (Level 2): Person on site responsible for carrying out instructions of the Project Manager. He/she shall be responsible for ensuring that site work is carried out safely and in accordance with agreed work scope. He/she will ensure that suitable barriers and warning signs are deployed so as not to compromise the safety of the site workforce and members of the public.

Junior Field Technician (Level 1): Depending upon the particular column and work scope there will be one or more Level 1 personel. He/she is responsible for safely and efficiently carrying out the instructions of the Senior Field Technician.

Part of the preparatory work are:

- Record the temperature at different points on the column (external wall, pipes,..)
- Draw the scaning lines on column wall
- Install the guide steel cable for guiding the source and detector along the scanning line.
- Put the gamma ray sealed source into the collimator-source holder

5.2. PROCEDURES FOR CONDUCTING SEALED SOURCE FIELD WORK

Following sequential procedure/steps are conducted by the Service Provider Team for conducting sealed source field work:

5.2.1. Plant visit and feasibility assessment

On receiving a request from an industry, a member of the Service Provider Team visits the experimental site/plant for assessing the feasibility of conducting the work and detail discussions with the plant engineers. If it is feasible to conduct the radioisotope inspection, the user industry is asked to fill-up the PART-A of the safety planning form (SPF), which contains information such as name and contact details of the industry, purpose of radioisotope diagnosis, availability of conventional techniques for given application, information about column/tower etc. Industry has to certify that "no alternative technique is available for this application" and undertaking for abiding all the safety rules/regulations during the radioisotope work.

5.2.2. Selection of radioisotope and amount of activity

After the feasibility assessment the suitable sealed source is selected, and amount of activity required for obtaining a reliable gamma scan profile is estimated. Subsequently, the PART-B of the SPF is filled by scientists/engineers responsible for conducting the radioisotope work, which contains information about radioisotope, transportation details, number of tests to be conducted, number of people involved, similar kind of experiments done earlier etc. The PART-C is filled by the concerned Health Physicist.

5.2.3. Approval from Regulatory Authority

Since the field radioisotope work is conducted in public domain, it is also required to take approval of National Regulatory Authority for conducting the radioisotope inspection on case to case basis. In addition to this, the necessary approval for transport of radioisotope sealed source to the work site is also obtained. Accordingly, an application is raised furnishing all the details and relevant information to competent authority.

5.2.4. Preparation of work area and execution of gamma scanning

The area/location where the radioisotope gamma scanning is conducted is prepared for the execution of the test. Installation of sealed source and the detector is performed by well-trained and qualified radioisotope practitioners

5.2.5. Analysis of radiation hazards

After completion of the field radioisotope work, PART-D of the SPF is filled by the accompanying Health Physicist or members of the Service provider team. Wherever, the Health Physicist is involved a detailed Radiation Surveillance Report is prepared by him and submitted to competent authority for their review.

As the radioisotope sealed sources used in gamma scanning are encapsulated, normally they do not produce any disposable waste.

5.2.6. Example of radiological safety assessment in gamma scanning field work

A typical example of estimation of the radiation dose received during a gamma scanning of an industrial column in a refinery is given below.

5.2.6.1. Procedure adopted

A distillation column in a refinery experienced a problem, and refinery engineers called the service provider to see what the problem was and if possible, to carry out gamma scanning profiles. The sealed source ^{60}Co with activity of 1.1 GBq (30 mCi) was used to scan the distillation column. Four profiles were performed to find and solve the problem.

5.2.6.2. Initial handling in the laboratory

During transport of ^{60}Co to the refinery, care has been taken that the dose rate at surface of the gamma source container have been not higher than 2 mSv/h (200 mRem/h), while inside the vehicle cabin the radiation dose rate not higher than 15 μSv/h (1.5 mRem/h) [16, 17].

5.2.6.3. Handling at the application site

Five practitioners (radiation workers) and the radiation protection officer (RPO) performed four gamma scanning operations at the application site.

Source loading and reloading to transport container was done by Handel tong (3m) under RPO supervision; the dose received during this step was distributed equally between workers. Sealed source movement up to down during distillation column scanning was performed under the RPO supervision to respond for any emergency cases, like source stuck, source fall down, etc. Safety measurement was taken by RPO during gamma scanning to avoid unnecessary exposure to radiation.

5.2.6.4. Radiological safety

The Harshaw model 6600 TLD Card Reader, fully automated instrument was used for extremity, environmental and whole body thermoluminescence personal dosimetry. The doses received from each radiation worker were recorded and are presented in Table 4.

TABLE 4. DOSE RECORDS (TLDS READINGS) FOR GAMMA SCANNING

Scan tests	Personnel	Effective dose (mSv)
1	A	0.310
	B	0.320
	C	0.205
	D	0.236
	E(RPO)	0.366
2	A	0.215
	B	0.297
	C	0.209
	D	0.253
	E	0.200
	F (RPO)	0.294
3	A	0.121
	B	0.125
	C	0.107
	D	0.136
	E	0.092
	F (RPO)	0.163
4	A	0.051
	B	0.072
	C	0.065
	D	0.060
	E	0.084
	F (RPO)	0.100

Results in Table 4 have shown that for radiation workers the effective dose obtained during a field test was between 0.366 mSv and 0.051 mS with an average of 0.140 mSv.

More in details the results of dose estimation were as follows:

Test 1	from 0.366 mSv to 0.205 mSv	average 0.287 mSv
Test 2	from 0.294 mSv to 0.200 mSv,	average 0.239 mSv
Test 3	from 0.163 mSv to 0.092 mSv	average 0.124 mSv
Test 4	from 0.100 mSv to 0.051 mSv.	average 0.072 mSv

5.2.6.5. Conclusions

- The effective dose (mSv) was proved to be within the permissible range for radiation workers;
- Comparing the averages of the four tests, it is evident the trend of effective dose received from the practitioners was getting lower, this is because of experience in sealed source handling and safety culture was improved;
- Optimization of steps of loading/unloading source also had a great effect. The need for training is there since it will still lower these values.

6. BENEFITS ESTIMATION OF GAMMA SCANNING

6.1. ECONOMIC BENEFITS

Economic benefits of sealed radioactive source applications are considerably high and already proofed and recognized by industrial end-users. The gamma scanning technique has been considered as one of the most beneficial sealed source applications in industry [9, 10, 11, 12, 13].

6.1.1. Safety benefit

Few industrialists would dispute the benefits of spending money on safety improvements. Indeed, the unit engineer may well find that expenditure proposals with safety implications are actually the easiest to justify. Thus, a proposal to use gamma ray scanning to locate the buildup of ice deposits in a flare stack line is unlikely to meet with rejection because of the potential seriousness of the line becoming blocked.

6.1.2. Environmental benefit

Increasingly, as society grows more and more environmentally conscious, industrial corporations are giving as much weight to these issues as to employee safety, though in some cases, this stems from national or international legislation, which contains severe penalties for non-compliance with agreed standards. Whatever the motivation, expenditure proposals for projects leading to significant benefits to the environment are at least assured of a sympathetic hearing.

6.1.3. Economic benefit

Economic benefit may be simply defined as a net increase in profit. That is, the gross increase resulting from the study, less the total cost of performing the measurements.

6.2. COST-BENEFIT ANALYSIS

Frequently, the economic benefit is expressed in terms of a benefit: cost ratio, which is defined as the ratio of the net profit increase to the service cost. Arguably, this is best done by presenting case studies, which exemplify the benefits that can be realized. These show that benefit to cost ratios of between 10:1 and 1000:1 may be achieved. Probably, a benefit to cost ratio of 30:1 is reasonably representative. There are few short-term investments, which will give a return of this magnitude. The cost effectiveness of applications should be widely promulgated to encourage industrialists to take full advantage of the technology.

This analysis does not include management of disused sources.

6.2.1. Cost-benefit analysis for gamma scanning for inspection of a refinery column in comparison with conventional visual inspection

As an example, the welfare effect of using gamma scanning technique instead of conventional inspection for refinery columns is analyzed.

Assume that a processing column in a refinery or petrochemical plant has a problem that is observed by the reduction of yield or deterioration of quality. Gamma scanning technique is very efficient and

competitive for troubleshooting inspection of processing columns. Inspection using sealed source technique costs around US $5000 per column, while conventional visual inspection costs about US$10000.

Experience has shown that using sealed radioactive source inspection the problem can be solved faster, that means the shutting-down period of a suspected column reduces at least two days than needed by conventional inspection. The production loss from shut-down a processing column on average is estimated at US $50 000 per day (for a medium size refinery). Thus, the net benefit for a column is calculated as the net savings in inspection costs plus the net savings in reduced production loss from a shorter shut-down time, i.e.,

$$\text{Annual net benefit} = (10000\text{-}5000) + 2 \times 50\,000 = \text{US } \$105\,000 \text{ per column.}$$

6.2.2. Cost benefit estimation for some sealed radioactive source applications

The different ways in which the benefits are derived are:

1) Troubleshooting. Sealed source technology is used to diagnose specific causes of inefficiency in plant or process operation. In this context, it should be noted that in very many cases the benefit is derived in the form of savings associated with plant shutdown minimization and loss prevention.

2) Process optimization. The measurements provide information that facilitates improvements either in the throughput or the product quality.

Interesting information was provided by a survey, conducted by a petrochemical company in the eighties [2]. Plant managers were asked to provide information about the benefits that their units had derived from radioisotope applications. The company in question, TRACERCO, was not only the user, but also the supplier of the sealed source technology. For this reason, the information obtained was unbiased, since the plant managers had no vested interest either in under-valuing or in over-valuing the benefits that they had realized.

Recognizing that the sealed source application may not be wholly responsible for the economic benefit, each example considers an estimate, made by the manager of the plant in question, of the percentage contribution made by sealed source technology to the solution of the problem

Some of the applications reported in that survey are listed in Table 5.

TABLE 5. SAVINGS ESTIMATES IN A PETROCHEMICAL COMPLEX

Plant	Job Details	Contribution (%)	Savings (US $)
Dimethylamine Plant	Gamma scan is used to investigate production limitations as part of a de-bottlenecking exercise. Gamma ray scans on the overhead line from a stripper column revealed the presence of serious liquid carry-over. Design changes made resulted in a production increase of US $400 000 per annum.	25	100000
Diphenyl OxidePlant	Attempts to operate the plant at higher rates were frustrated by a bottleneck in a fractionation column. Production staff believed that the problem is caused by damage to trays. Gamma scanning revealed that there was no internal damage and that the column functioned well at normal rates. However, scans at different feed rates revealed that the column was operating close to its upper limit of liquid capacity: its design was such that it was not capable of handling higher throughput. As a result of the study, a new column was designed for installation at next scheduled shutdown. Prior to the gamma scans, a special shutdown of seven days duration was planned to conduct a visual inspection of column internals. Gamma scans removed need for this action, thereby saving seven days lost production.	100	150000
Paraxylene Plant	Pre-shutdown gamma ray transmission scans on the suction catch-pot of a compressor unexpectedly revealed that the internal filter was damaged. As a result, additional maintenance effort was programmed in, to effect the repairs. Had the damage been discovered only after bringing the plant off line, the shutdown would have been extended by half a day, equivalent to production losses of US $50 000.	100	50 00
Amines Plant	The formation of deposits in the flare system on the Amines units was a potentially hazardous occurrence, since such deposition could restrict the route for flammable gases to be safely vented to atmosphere in the event of plant malfunction. Recognizing this, the plant operators periodically shut down the units to visually inspect and, if necessary clean out, the pipework. The total shutdown time was typically ten days per year. The radioisotope applications team developed a neutron backscatter technique that was used to identify the location of any deposits and to measure their thickness. The measurements were performed with the plants on line and without any break-ins. By eliminating unnecessary shut downs, production losses estimated at US $ 1 000 000 per annum were saved.	100	1000000
Aniline Plant	Gamma scanning was used to measure the buildup of catalyst on the walls and pipework of the aniline reactors. By conducting the measurements at intervals over the plant's operating cycle significant progress was made towards understanding the mechanisms responsible for catalyst deposition. Corrective actions, taken on the basis of the findings of the studies, extended the life of the catalyst by approximately 30%, resulting in cost savings of US $400 000 per annum.	25	100000

7. ISO STANDARDS FOR GAMMA SCANNING OF PROCESSING COLUMNS

7.1. BACKGROUND

Quality assurance and quality control (QA/QC) of products and services is need of the day. The product manufacturers and service providers have to follow certain prescribed procedures and protocols to provide quality products and services to consumers and clients. To meet this requirement, they need authentic certification that they follow acceptable national/international standards. Standards contribute to making the development, manufacturing and supply of products and services more efficient, safer and competitive. Standards also make trade between countries easier.

The credibility of a service provider, which should be one of the major concerns of any service management, is increasingly dependent on the documented evidence of quality assurance and quality control (QA/QC) implementation according to the international conventions and standards. The more customers request these conditions and the more contracts are relying on its demonstrated evidence, the more service providers will be convinced that, in order to compete, appropriate QA/QC implementation is indispensable for the survival of a service company in the long run. laboratory managers will appreciate this easily. Their strong support for a comprehensive effort in this direction will be mandatory to cope with the requirements of setting up a complete quality system in a particular area of an application laboratory.

Accreditation is a confirmation procedure of the competence of the service provider laboratories to carry out their specific tasks. In order to be accredited, a laboratory should demonstrate its technical and organizational competence in its areas of application. Accreditation can be achieved through implementation of a quality management system.

There are general and overall Quality Management Systems like ISO 9000:2000 and ISO 17025, which has been successful in helping organizations to deliver quality products or services. applications laboratories have been introducing the ISO systems for their product and services to industrial end-users. Accreditation to ISO 9001:2000 regarding the Quality Management System (or management aspects) is in process in many countries. However, it should be noted that ISO 9000 series addressed only the management aspects of an organization. For laboratories providing calibration and testing services, there are loopholes that are not covered by this system. For this reason, standard known as ISO 17025 was introduced. In this standard, not only the management aspects of the organization were addressed, the technical aspects were also given a comprehensive coverage to ensure that an accredited laboratory would be able to deliver quality products or services.

7.2. ISO PROPOSAL: NON-DESTRUCTIVE TESTING - GAMMA RAY SCANNING METHOD ON PROCESS COLUMNS

There is a need for an ISO standard on the gamma ray scanning method. Gamma ray scanning technique is a mature technique in routine service to end users worldwide, so it deserves to be an ISO standard related to this technique. The standard will contribute to making the development and supply of gamma scanning services more efficient, safer and competitive. It will also make cooperation between countries easier. The particular ISO standards are bricks of any quality management system.

Applications laboratories in many developing and developed countries are expanding into a new frontier in ensuring good quality services to process plant owners, from petroleum refineries, petrochemical and chemical plants at different workplaces throughout the country and surrounding regions.

The gamma ray column scanning technique is widely used in the oil, gas and chemical industries. Gamma scanning has become an important non-destructive and non-invasive tool for on-line diagnosis of process malfunctioning in the last decades. The end-users are becoming more and more aware about the usefulness and potential of this technology and thus the demand is increasing steadily. Tens thousands of gamma scan services are provided every year worldwide, mostly by private companies. Standards contribute to making the development and supply of products and services more efficient, safer and competitive. Standards also make cooperation between countries easier. The ISO procedures shall be applicable to the inspection of all columns. These shall include columns with different diameters, wall thicknesses and tray configurations and shall also include columns with packed beds.

An ISO standard proposal is prepared and submitted to the International ISO Committee for approval by the International Society for Tracer and Radiation Applications (ISTRA) at the end of 2017. This International Standard, once approved, will be applicable to the testing of all kind of columns. This includes columns with different wall thicknesses, tray configurations and with packed beds. The major user of gamma ray scanning method is chemical industry, especially petrochemical and refinery industries. This standard will be applicable to the inspection of all material process columns. This standard will be applicable in an analogue way for gamma ray scanning of reactors, vessels as well as pipes.

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