World Journal of Engineering and Technology, 2023, 11, 476-492
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

# Gamma Photon Column Scanning of Prototype and Industrial Distillation Columns

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**How to cite this paper:** Chirume, W., Dongo, J.S., Dzingai, C., Mashingaidze, R.T., Mudono, S., Alami, R. and Baricholo, P. (2023) Gamma Photon Column Scanning of Prototype and Industrial Distillation Columns. *World Journal of Engineering and Technology*, **11**, 476-492.
https://doi.org/10.4236/wjet.2023.113034

**Received:** March 31, 2023
**Accepted:** July 10, 2023
**Published:** July 13, 2023



## Abstract

Monte Carlo simulation of gamma photon transport and interaction with the distillation column and its contents was performed in order to predict the effects of gamma photons when they interact with matter. The results of the interaction and transport of gamma photons are presented as energy deposition on the distillation column and its contents. Energy attenuation was more pronounced on the column walls and trays as compared to the region between the trays, where there is mostly vapour space. Gamma column scanning was then used to verify the Monte Carlo simulation results by scanning and investigating the integrity of two laboratory prototype distillation and industrial distillation columns. One of the prototype distillation columns was 1 m tall with four trays and the other one was 1.8 m tall consisting of six trays and a packed bed. Commonly encountered distillation column malfunctions such as collapsed tray, weeping, flooding and foaming were simulated in the two prototype distillation columns and scanned. The industrial distillation column was a 26 m tall benzole prefractionator column, consisting of 60 single pass trays and a diameter of 0.8 m. A 10 mCi $^{60}Co$ gamma radiation source and NaI(Tl) scintillation detector were used to scan the distillation columns. The results from the two prototypes showed that all the simulated malfunctions were clearly detected except for foaming. The results from industrial distillation column showed that all the trays were in their correct position although tray number 32 could be partially damaged and just below tray 41, the scan revealed that there was a loss of column wall thickness. The obtained density profile for the industrial distillation column showed some small variations from the expected density profile and this was attributed to external features on the distillation column and wind bursts that shifted the source and detector from the chosen scan line orientation.

## Keywords

Gamma Photon Transport, Distillation Column, Malfunctions, Monte Carlo Simulation

## 1. Introduction

Malfunctioning in distillation columns can seriously affect plant operations and result in low yield and product quality, which will lead to heavy financial losses. When a column shows abnormal behaviour, it is necessary to investigate its interior and quickly rectify the problem in order to minimize operational losses [1]. In continuous production plants like refineries and petrochemical industries, process equipment performance is analyzed using process models, where input variables are either fixed (equipment size and internal composition), or can be directly measured (temperature, pressure and flow rate), or calculated (composition of feed, heat consumption and reaction efficiency) [2]. The output data are product composition, and operational parameters, among others. Process models are robust enough to account for normal measuring errors and parameter variations. However, they cannot account for uncontrolled or human factors, such as physical (corrosion, mechanical damage or defective assembly); process (contamination, unexpected physical-chemical phenomena, fouling or saturation); operational (operational disturbance, instrument reading error or coking) and human (problems, badly made repairs or human mistakes). Gamma column scanning is mainly applied as a non-destructive technique that allows verification of the process and online troubleshooting of the equipment [2]. Gamma column scanning is the most efficient method to investigate and troubleshoot distillation columns, heat exchangers and pipes among others. It is an online and non-invasive method [3] that can be used to detect mechanical and process malfunctions in distillation columns. It is widely used for evaluating the operating characteristics as well as hydraulic conditions inside the distillation column. Gamma column scanning provides essential information that can be used to track any deteriorating effects, optimize the performance and identify maintenance requirements of distillation columns well in advance before scheduled maintenance shutdown. It gives engineers and operators an insight into the needed spare parts in the next scheduled maintenance shutdown enabling them to avoid ordering spare parts on an emergency basis, which is costly thus reducing repair downtime and costs [4].

Gamma column scanning is based on the attenuation of gamma photons as they traverse through matter. The attenuation of gamma photons passing through the column will result in changes in intensity of the transmitted beam and can be correlated to the densities of the materials in the column under inspection. The high-energy gamma ray is attenuated differently in different media and this attenuation when interpreted will give useful information about the process. The quantity of the absorbed or transmitted gamma rays is an indication of the actual quantity and nature of the material between the radioactive source and the detector represented graphically as a density profile where distillation column height is plotted against measured intensity.

Conventional methods of detecting distillation column malfunctions take a long time to establish and locate the exact position of the malfunction due to the opaque nature of the distillation column. Thus this work was conducted to explore and troubleshoot through simulations and experiments and identify different types of distillation column malfunctions in chemical and petrochemical industries using the gamma photon column scanning technique.

## 2. Methodology

This work was carried out in three separate stages namely:

1) Simulation of gamma radiation transport through the distillation column using Fluka Monte Carlo software package.

2) Gamma column scanning on two different laboratory distillation column prototypes.

3) Gamma column scanning on an industrial distillation column.

### 2.1. Simulation of Gamma Column Scanning

Monte Carlo simulation of radiation transport and interaction with matter (distillation column and its contents) was performed, as it is the most reliable way of predicting the effects of gamma rays when they interact with matter [5]. Three prototype distillation columns were modelled in Fluka geometry. The first distillation column to be modelled was an empty column with seven trays; the second was the laboratory prototype 1 m tall Perspex distillation column; the third column was a 1.8 m tall, galvanized steel laboratory distillation column. Fluka is a particle physics Monte Carlo software package for simulation of radiation transport [6]. A beam of $^{60}Co$ gamma photons moving from the left side and incident on the model distillation column was simulated. These photons were tracked right from birth and during interaction with the distillation column until their energy fell below minimum threshold or when they escape the region of interest with energy deposition results being stored. To verify the simulation results, the real gamma column scanning experiment was performed on two laboratory prototype distillation columns and one industrial distillation column.

### 2.2. Laboratory Experiments on Gamma Column Scanning

The first experiment was performed on a 1 m tall Perspex column on which a cylindrical metal container was inserted, and had 2 trays and a lead block placed at the bottom of the column. The cylindrical metal container with a perforated base containing stones at the bottom, Styrofoam in the middle and a metal block at the top was inserted inside the Perspex column and sat on the top tray. Styrofoam being less dense was used to simulate foaming. The base of the metal container was perforated to act as a sieve tray and weeping was mimicked by water leaking through the holes. A 0.15 m thick lead block was partially immersed in water with a height of 0.09 m from the bottom of the column.

The 1.8 m high column made from galvanized steel had six trays and a packed bed (consisting of stones, lead block and bricks). A lead block was placed on tray number 4. Styrofoam was inserted between tray 4 and 5 to mimic foaming. Flooding was simulated on tray 6 by completely immersing the tray in water. A water pump was used to circulate the water in both columns. A microcontroller based stepper motor winch was fabricated and used to move up or down the radiation source and detector simultaneously on the opposite sides of the distillation column as shown in **Figure 1** below.

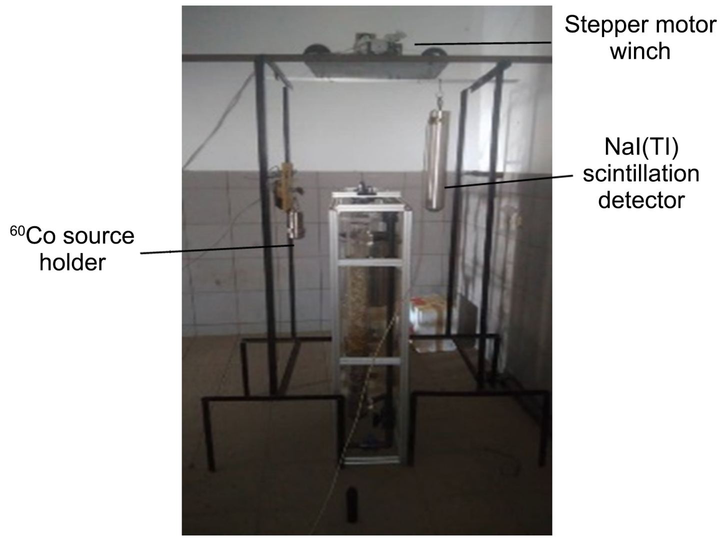



**Figure 1.** Gamma column scanning experimental setup on a 1 m tall distillation column.

The $^{60}$Co radiation source was placed in a radiation source holder and the detector was connected to the data acquisition system linked to a personal computer for display. The source and detector were moved in 2.5 cm incremental steps on both prototype distillation columns. This was achieved through the use of a Hall Effect sensor used to count the number of revolutions the stepper motor shaft made corresponding to a 2.5 cm displacement. When the required number of revolutions was achieved, the stepper motor stopped initiating 12 seconds microcontroller program delay to give ample time for the measurement of radiation intensity. The process was repeated until the full column length is scanned.

### 2.3. Industrial Gamma Column Scanning

A 26 m high industrial distillation column with a wall thickness of 10 mm and a diameter of 0.8 m consisting of 60 single pass trays as shown in **Figure 2(a)** and **Figure 2(d)** was scanned offline. A 10 mCi $^{60}$Co gamma source and NaI(Tl) scintillation detector were positioned in the South West (source) and North East (detector) scan lines starting at the top of the distillation column as shown in Figure 2(b). The center of the top manhole N1 was chosen to be the reference point whilst source and detector were lowered down the column concurrently in 5 cm steps. The intensity was measured and recorded using the Colscan data acquisition system connected to a PC with Nibras softwareas shown in Figure 2(c).

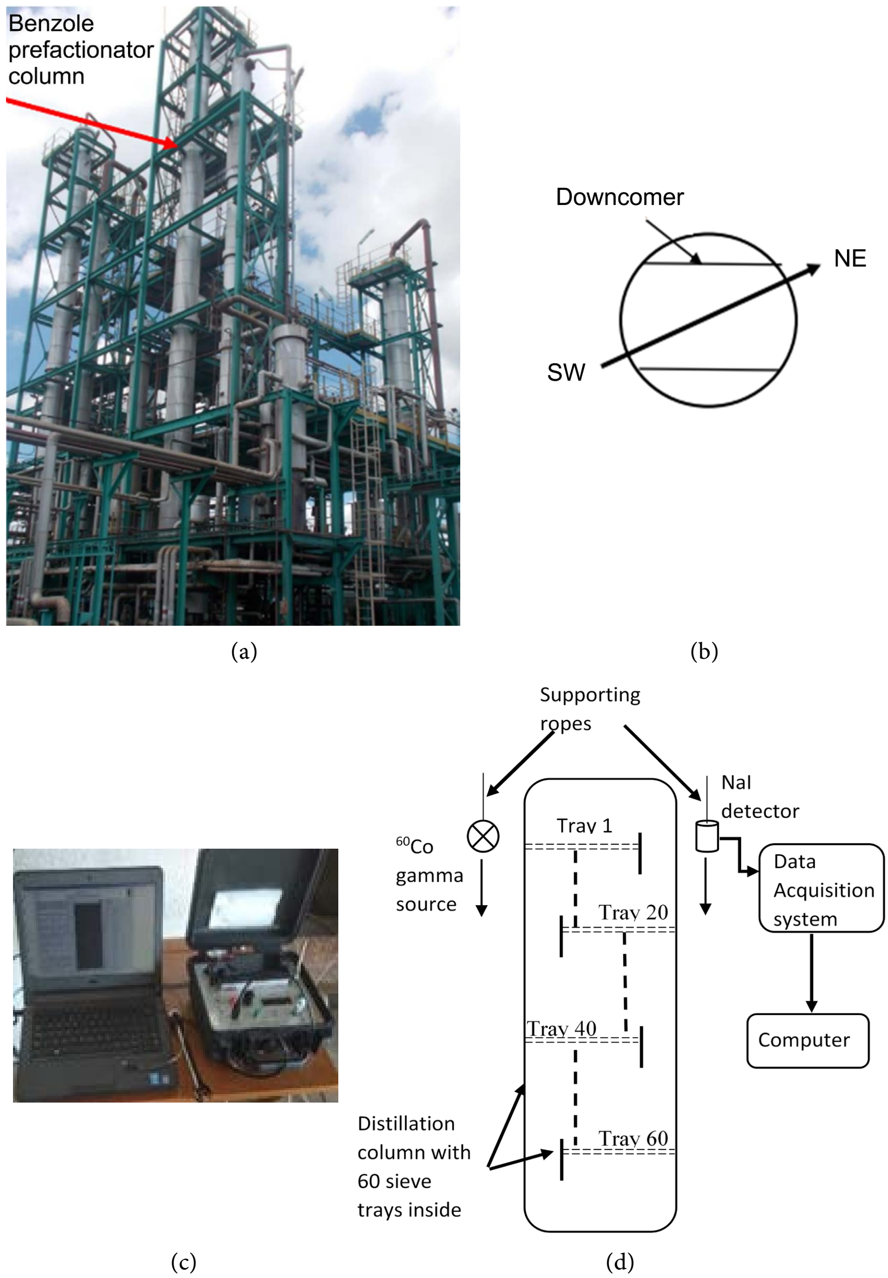



Figure 2. The scanned industrial distillation column indicated by a red arrow on the far left (a) and the scan line orientation (b) using a Colscan data acquisition system (c) and illustration of industrial gamma column scanning and tray arrangement inside the distillation column (d).

## 3. Theory/Calculations

Define Gamma rays are high-energy photons emitted as one of the three types of radiation as a result of radioactivity. It is the most energetic form of electromagnetic radiation of high frequencies above $10^{19}$ Hz. They are a form of indirect ionizing radiation which deposit energy within the target material through a two-step process. The photons' energy is transferred to charged (secondary) particles in the form of kinetic energy [7]. Lack of charge makes gamma photons more penetrating than charged particles possessing the same amount of energy. This is because gamma photons being electrically neutral, they do not lose energy via Coulombic interactions, as is the case with charged particles. Gamma photons travel a considerable distance in the target medium before interaction takes place, leading to either partial or total transfer of photon energy to electrons. The interaction of gamma photons with matter follows well-established physics laws. When gamma radiation passes through matter, it interacts with the target material by a number of competing mechanisms *i.e.* photoelectric effect, scattering, pair production resulting in loss of intensity [7].

The effects of gamma photon passing through a medium are a result of many individual interactions since a photon can interact many times before it is absorbed or escapes from the medium [8]. The above processes release kinetic energy to electrons, which escape the atom and interact with the medium as secondary particles [9]. Gamma rays interacting with a layer of homogeneous medium follow an exponential attenuation and are characterized by an attenuation coefficient that is a measure of the cross section or the probability of interaction of the gamma rays with the target material. The three competing interaction mechanisms combine to produce attenuation of the incident gamma radiation as it passes through the target material. Attenuation is the removal of the gamma photons from the beam due to absorption and scattering events [10]. The attenuation property of gamma radiation will determine how much shielding is required to reduce the intensity to any desired level. The attenuation of gamma rays obeys the Beer-Lambert law [1]. When a gamma ray of intensity $I_o$, is incident on an absorber material of thickness $x$ (also known as radiation path length), density $\rho$ and linear attenuation coefficient μas illustrated in **Figure 3** below, the transmitted gamma ray intensity $I$ is given by:

$$I = I_o e^{-\left(\frac{\mu}{\rho}\right)\rho x} \tag{1}$$

where, $I$, is the measured intensity of radiation transmitted through the material between the radioactive sealed source and scintillation detector. $I_o$ is the intensity of the incident radiation without a medium to absorb radiation between the radioactive sealed source and scintillation detector and it is a constant. $(\mu/\rho)$ is the mass attenuation coefficient of the material measured in $m^2/kg$, $\rho$ is the density of the absorbing material between the source and scintillation detector measured in $kg/m^3$ and $x$ is the radiation path length through which the transmitted radiation travel measured in meters. The exponential decay in Equation (1) states that

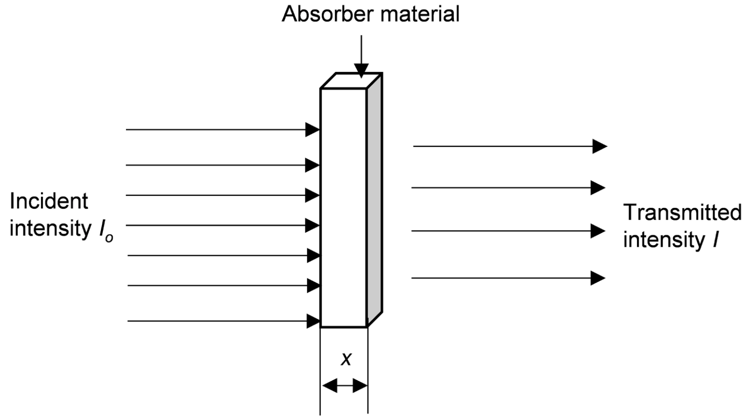



**Figure 3.** Attenuation of gamma rays by an absorber of thickness $x$, mass attenuation coefficient $\mu$ and density $\rho$.

the radiation intensity measured by a detector is inversely proportional to the density of the medium that exists between the source and the detector [11]. It follows that attenuation is a function of photon energy and is directly proportional to the density of the material. In low-density materials, the attenuation of gamma rays is less as compared to high-density materials.

Gamma column scanning is a non-invasive and non-destructive technique used for internal inspection of the column along its height and is not affected in any way by temperature and pressure [4]. This technique is safer than radiographic applications as the intensity of the sealed source is only 0.1% of the intensity used to test welds by radiography methods [1]. During the scan, orientation of source and detector should remain the same even in windy conditions; therefore, guide ropes are used to maintain the orientation. The transmitted radiation intensity from the radioactive source measured by the scintillation detector is recorded on a computer connected to the detector through a data acquisition system. The gamma photons' intensity reaching the detector varies depending on the differences in the material density between the source and detector. The intensity variation recorded on the computer is plotted against the elevation of the distillation column to produce a density profile, which is then analysed for the identification of the distillation column malfunctions. Inside a column each tray and the space above it gives a picture of its operating state, therefore, gamma column scanning can also be used to determine the liquid level above the tray. Depending on severity of the fault, the liquid levels will point out to the existence of weeping, entrainment and flooding. The scan profile can also show the absence or collapse of trays from their original positions. The absorption peak or minima points represent the position of trays inside the distillation column. Since trays carry liquid above the trays the intensity of radiation increases. Between trays there are regions of vapour, where there is very small amount of suspended materials to absorb the radiation and result in a transmission peak or maxima recorded by the radiation detector [12]. Distillation column malfunctions commonly encountered can be grouped into three categories, which are mechanical, flow rate and process related [13] and can be summarised in **Table 1**.

A baseline gamma column scanning is performed at start up or when the column is operating efficiently in order to establish reference conditions. Future gamma scans will be compared with the baseline scan to determine how the column is responding with time or with changes in operating conditions. Some operating conditions such as feed rate, temperature and pressure among others are kept constant during the investigation or they are recorded down if there is any change. This helps in the interpretation of the scan if anomalies are observed. Prior to the gamma column scan, inside diameter and column wall thickness should be known. Type of material for the trays and packing in case of packed beds and down-comer orientation should also be well known. Most importantly previous problems encountered e.g. pressure problems should also be known. Mechanical drawings of the unit showing internal structure, such as elevations, tray arrangement, nozzle and pipework locations as well as other special features are needed. This information is vital when interpreting data from obtained density profiles and for identifying and visualizing possible mechanical problems. It is also very important to perform a scan and obtain a scan density profile before and after maintenance shutdown. The latter scan should be carried out when the column is operating under normal condition. These two sets of scan profiles can be used for comparison in the future and any deviation from the scan obtained under normal operating condition will point out to the existence of a malfunction in the column [14].

**Table 1.** Common distillation column malfunctions and their description [13].

| Type of column malfunction | Description of the malfunction |
|---|---|
| Mechanical | • Missing, collapsed and buckled trays<br>• Damaged demister pads, liquid and vapour distributors and packing.<br>• Partially damaged trays resulting from corrosion.<br>• Level control problems on chimney trays and base liquid level.<br>• Blocked down comers. |
| Process | • Bad liquid and vapour distribution in packing.<br>• Liquid holdup due to fouling and plugging.<br>• Foaming on trays, condensers, reboilers and accumulators.<br>• Superheated or subcooled feed or reflux |
| Flow rate | • Slight, moderate and severe entrainment.<br>• Weeping or dumping on trays<br>• Flooding or dry trays due to loading conditions. |

The gamma column scanning technique solely relies on the gamma ray photon energy and the nature of the medium between the source and the detector. The gamma ray source should have enough energy to penetrate the column thickness and the material inside the column. The widely used gamma ray sources are $^{60}Co$ (1.33 MeV and 1.17 MeV) with a half-life of 5.27 years and $^{137}Cs$ (662 keV) with a half-life of 30 years [4]. The required activity for a gamma source for scanning a distillation column depends on the diameter and the shielding material of the column and the energy of the gamma source itself [3]. The activity $A$, of the gamma source can be calculated as follows:

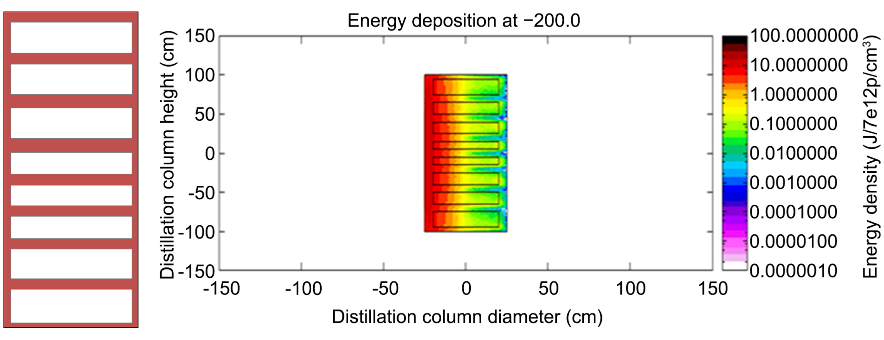
$$A = \frac{Dd^2 2^{2W_t/HVL}}{T} \quad (2)$$

where, $D$, is the dose rate required measured in R/hr, $d$ is the diameter of the column measured in meters. $W_t$ is the total wall thickness of column plus wall thickness of scan and detector container measured in meters. $T$ is the gamma ray constant for a specific source (1.31 R/h on a distance of 1 meter for $^{60}Co$ source) [3] and the material half value layer ($HVL$), the thickness of a material where 50% of the incident radiation energy has been attenuated (0.025 m for steel for $^{60}Co$) measured in meters. To make provisions of the source and detector containers, it is suggested that 0.2 m should be added to the column diameter [4].

## 4. Results

### 4.1. Simulation and Experimental Result

Figure 4 depicts the Fluka simulation of radiation transport results of an empty distillation column with seven trays as shown in Figure 4(a). The result is represented as energy deposition on the column in the form of a colour map as shown in Figure 4(b). Tray positions can be easily located as they are corresponding to the blue colour appearing on the right side of the column. The results show that attenuation of radiation energy is more pronounced at tray (regions where blue color is seen) positions while there is less attenuation in regions between the trays.




(a) (b)

Figure 4. Phantom of the distillation column modeled using Fluka geometry with seven trays (a). Simulated $^{60}Co$ radiation energy deposition on the model distillation column with Fluka software (b).

Figure 5(a) below is a colour map showing gamma column scanning simulation results of a 1 m tall laboratory distillation column prototype. The prototype was modelled using Fluka geometry as represented in the respective mechanical drawing of Figure 5(b). The colour white represents the lowest intensity as can be seen on the color map key on the far right of Figure 5(a). Figure 5(c) shows the density profile obtained after scanning a distillation column with a mechanical drawing depicted in Figure 5(b).

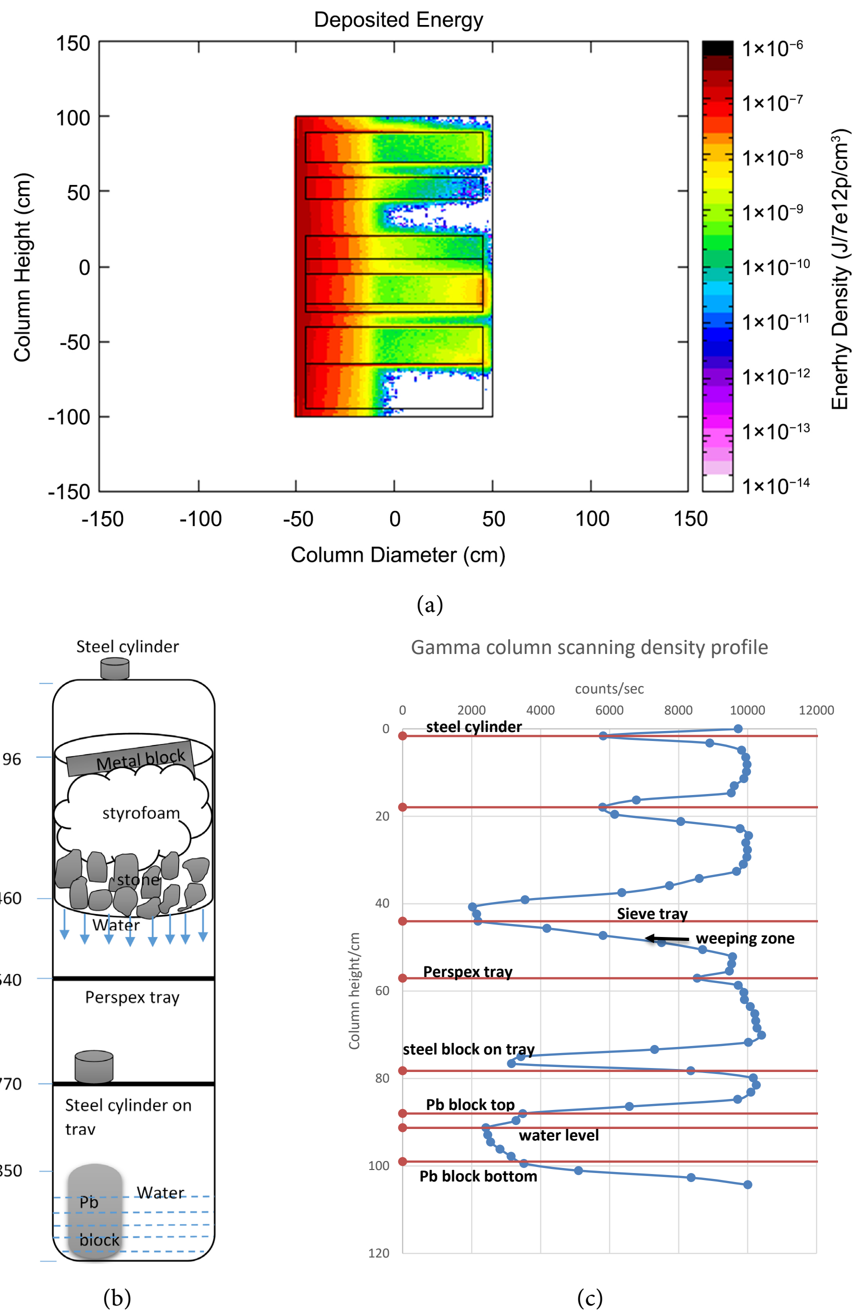
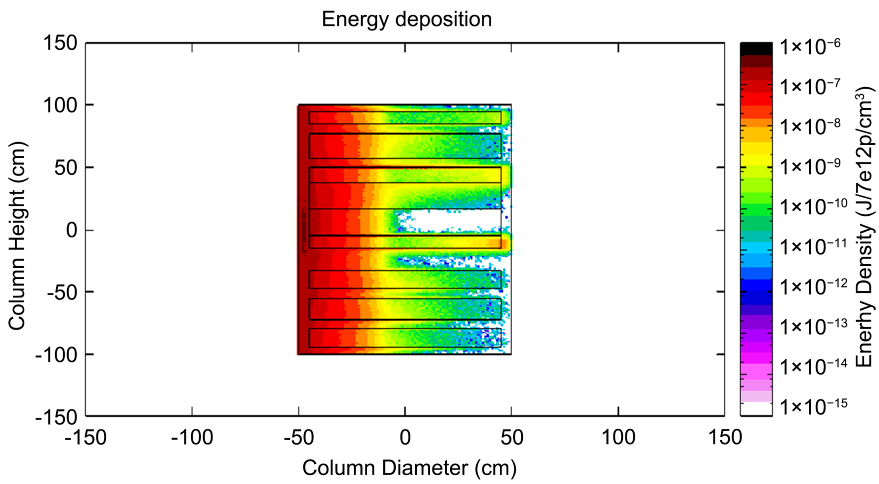
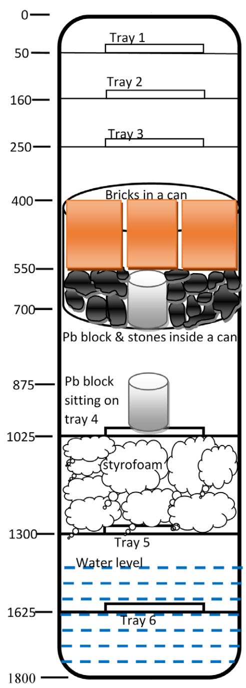



**Figure 5.** Simulated $^{60}Co$ radiation energy deposition on a 1 m tall Fluka model perspex distillation column (a), mechanical drawing of the 1 m distillation column (b) and density profile obtained from scanning the 1 m distillation column (c).

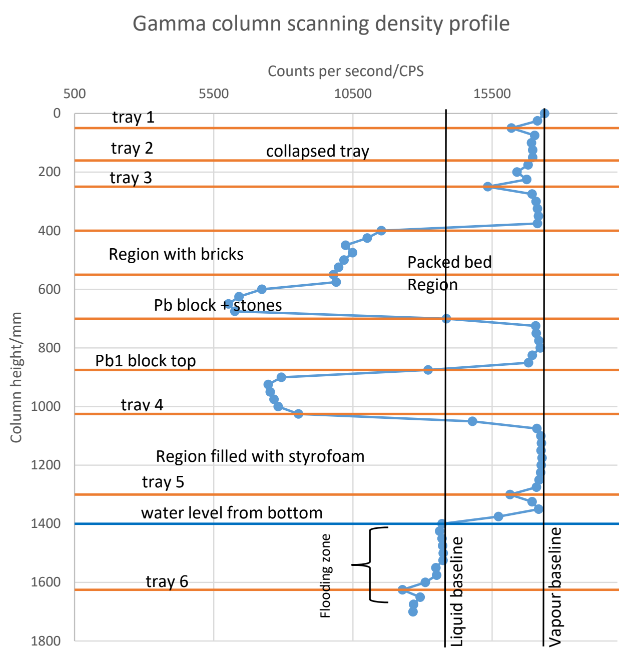
Fluka simulation of gamma energy deposition on a distillation column is represented in Figure 6(a). The density profile in Figure 6(c) was obtained after scanning a distillation column represented by a mechanical drawing shown in Figure 6(b). A packed bed was simulated in the metal container packed with stones, lead block and bricks. The mechanical drawing shows that there are six trays, but the density profile shows that all other trays are in their correct positions except tray number 2 which is collapsed. Styrofoam was used to simulate foaming between tray 4 and 5 in Figure 6(b).




(a)




(b)




(c)

Figure 6. Simulated $^{60}Co$ radiation energy deposition on a 1.8 m tall galvanized iron distillation column prototype using Fluka software (a), mechanical drawing of the distillation column (b) and density profile obtained from scanning the distillation column (c).

### 4.2. Industrial Gamma Column Scanning Results

The results in Figure 7 show that all trays are in their correct position. Absorption peak at tray 17 is due to the construction joint.

The density profile of Figure 8 shows that all trays are in their correct position. The absorption peak corresponding to tray 32 is not aligning with the rest of the trays. Tray 32 could be partially damaged.

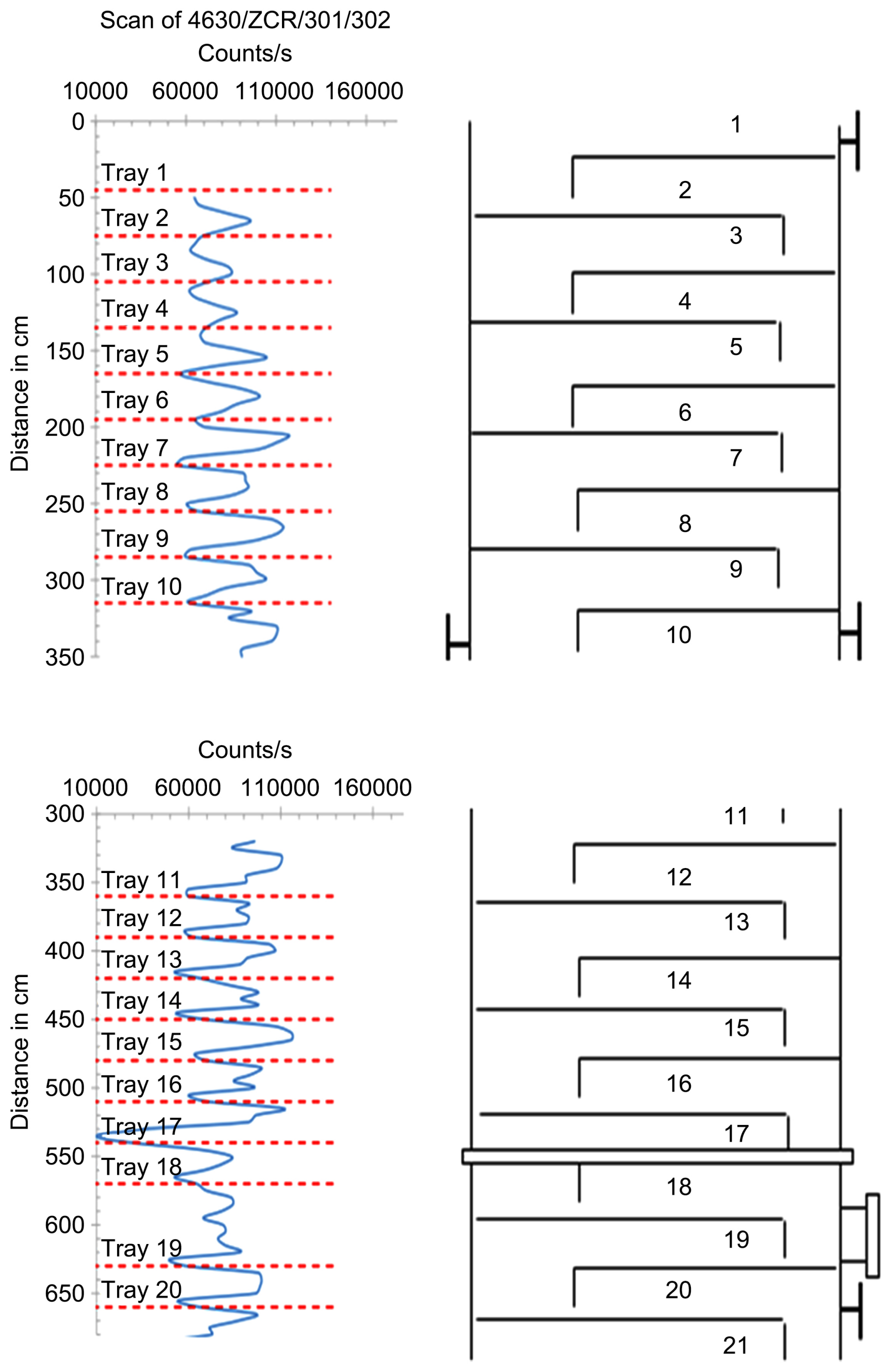



Figure 7. The density profile (left) obtained after scanning the distillation column from tray 1 up to tray 20 with a mechanical drawing on the right.

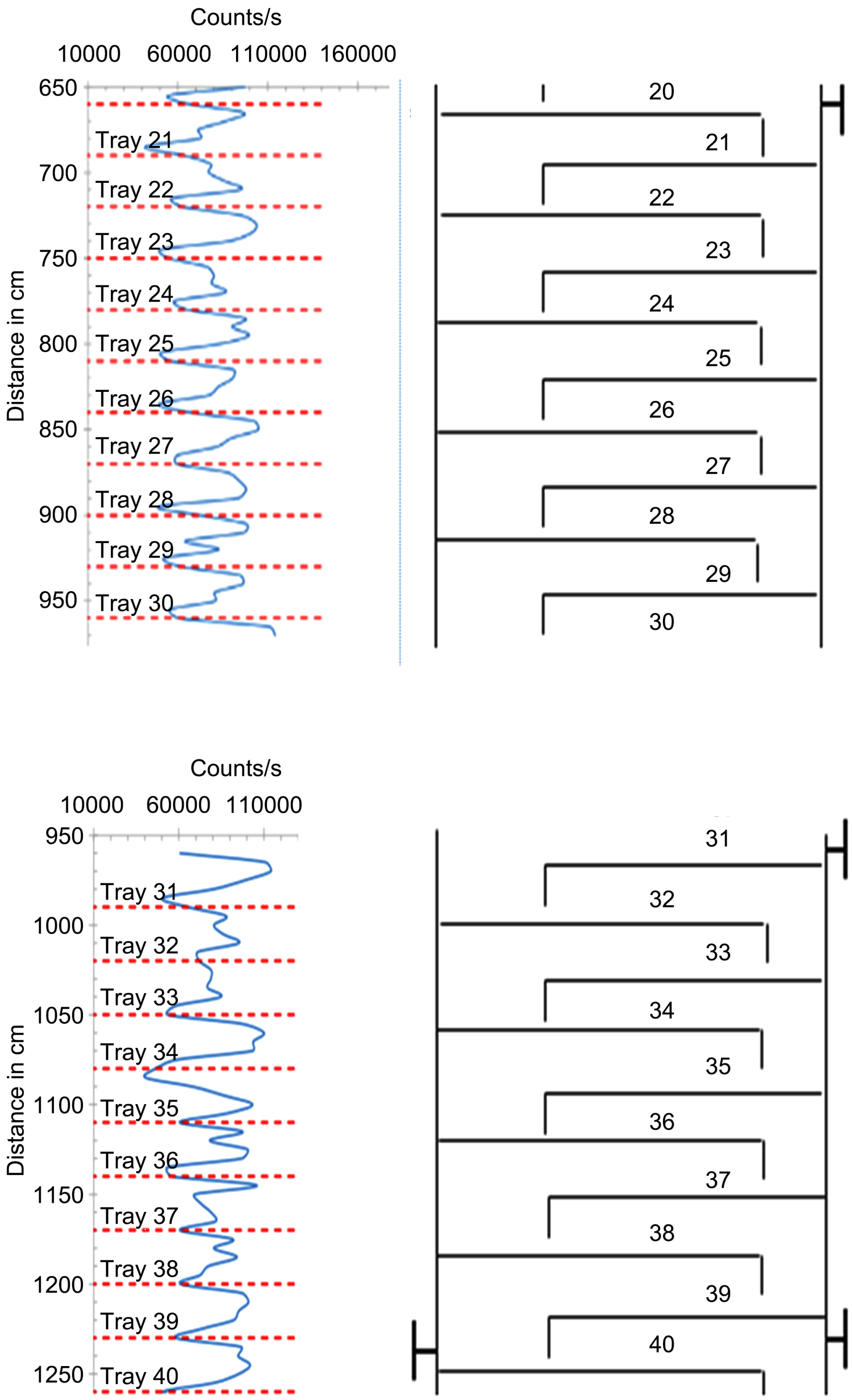



**Figure 8.** The density profile (left) obtained after scanning the distillation column from tray 21 up to tray 40 with a mechanical drawing on the right.

The density profile of **Figure 9** shows that all trays are in their correct position. Absorption peak at tray 42 is due to a construction joint. Slightly below this joint there is a transmission peak which could be a signature for loss of thickness on the column wall.

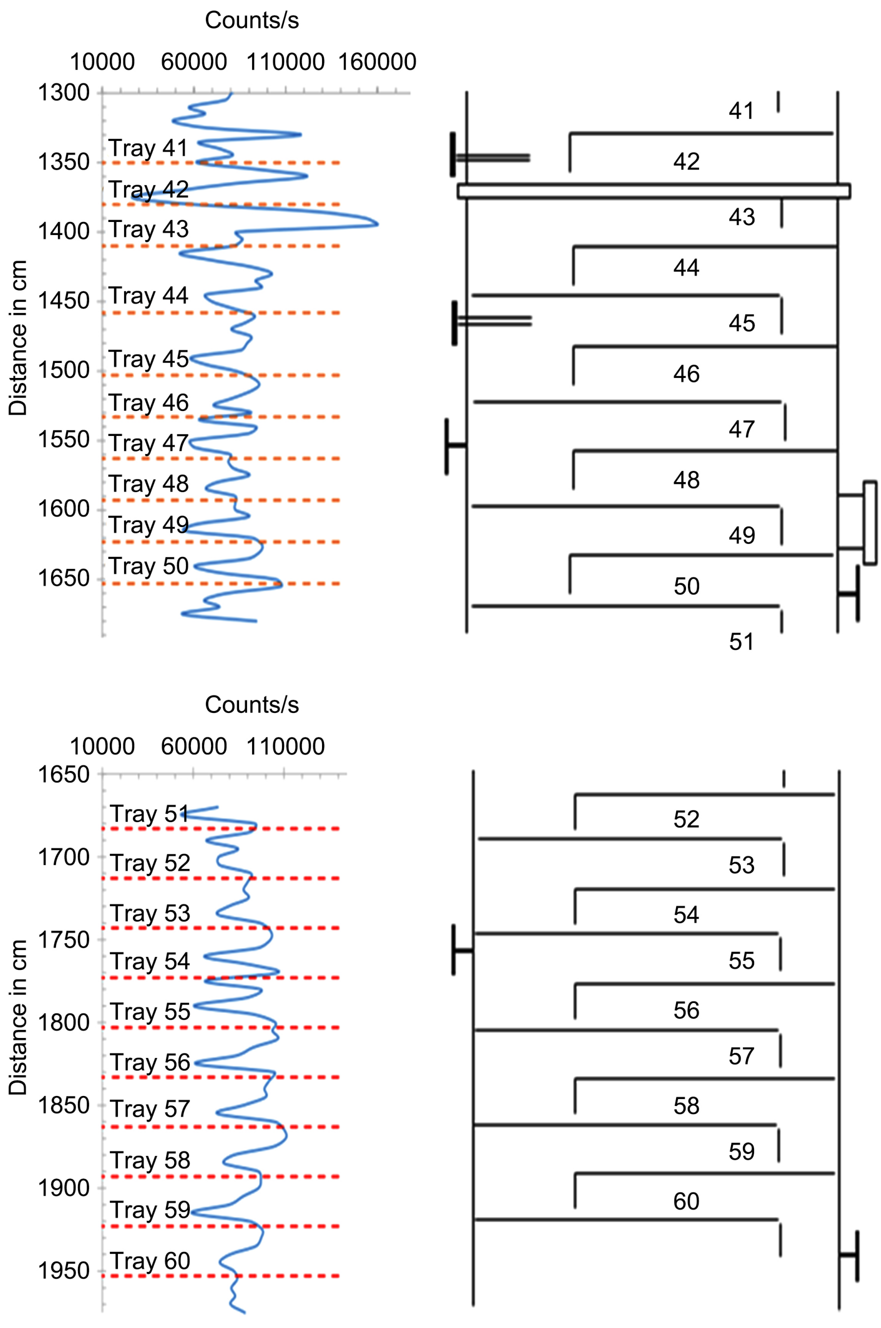



**Figure 9.** The density profile (left) obtained after scanning the distillation column from tray 41 up to tray 60 with a mechanical drawing on the right.

## 5. Discussions

### 5.1. Simulation of Gamma Column Scanning

Simulation results were represented as energy deposition on the column in the form of a colour map. **Figure 4** shows that attenuation of gamma photon energy is more pronounced at tray (regions where blue colour is seen) positions while there is less attenuation in regions between the trays where there is no solid material to attenuate the gamma photons. **Figure 5(a)** and **Figure 6(a)** show that lead attenuated almost the entire radiation energy incident on it and this can be attributed to its high atomic number. The higher the atomic number the denser the material and the more it can attenuate the radiation incident on it. High atomic number implies that the element in question offers a large interaction cross section to the incident gamma radiation. Regions in between the trays which are filled by air and Styrofoam could not attenuate more radiation owing to their low density.

Gamma photons were attenuated more at regions with more dense materials such as stones, trays, water and metal blocks and this resulted in a corresponding absorption peak (minima points on the density profiles). Vapour space in between successive dense material are less dense and therefore attenuate less and result in a transmission peak (maxima points on the density profile). These transmission peaks give an indication of where the vapour base line is located. In **Figure 5**, the vapour base line was around 10000 counts per second. The liquid base line can be deduced from the density profiles to be slightly above 2200 counts per second. The density profile in **Figure 5(c)** and **Figure 6(c)** show that water level was detected at 9 cm and 40 cm from the bottom of the distillation columns respectively. Weeping was detected just below the metal container with a perforated base in **Figure 5(b)** as indicated on the corresponding density profile. It also shows that Styrofoam could not attenuate a significant amount of gamma radiation. The lead block in **Figure 5(b)**, is partly immersed in water and the exposed part of the block attenuated less gamma photons as compared to the combined effect of water and lead block at the bottom part of the distillation column. The results in **Figure 6** also show that tray 2 is missing from its position, since there is no attenuation signature that corresponds to the presence of a tray at that position as suggested by the mechanical drawing. The density profile of **Figure 6(c)** also shows that water level at the bottom of the column was detected and tray number six was flooded as the intensity above and below it could not reach the vapour base line. It also shows that the packed bed comprised of less dense material at the top and denser material at the bottom.

## 5.2. Industrial Gamma Column Scanning

The results of industrial gamma column scanning experiment (**Figure 7**, **Figure 8**, **Figure 9**), show that all trays are in their correct positions, except trays 32 and 52 which could be partially damaged. The absorption peaks observed at tray 17 and 42 are due to a construction joint. Slightly below tray 42 (feed tray) there is a transmission peak, which could be a signature for loss of column wall thickness. This can be attributed to the presence of corrosive hydro sulfuric acid or hydrogen sulphide ($H_2S$) in high concentration at the feed point. The industrial density profile showed some small variations from the expected density profile and this could be attributed to external features on the distillation column and wind bursts that introduced some source and detector misalignment from the chosen scan line orientation.

## 6. Conclusions

The simulation and experimental results are in good agreement with the theory. Several distillation column malfunctions, such as weeping, flooding, missing tray and foaming were simulated in the distillation column prototype and scanned. Weeping, flooding, missing tray and liquid level were successfully located inside the prototype distillation column, except for foaming. The less-dense Styrofoam, which was mimicking foam, could not absorb an appreciable amount of gamma rays. This was attributed to the high energy of cobalt 60, which was hardly attenuated by Styrofoam. In order to detect foaming a low energy gamma source such as Caesium 137 or Americium should be used.

The obtained experimental results provide convincing evidence that gamma column scanning can be used to investigate and troubleshoot distillation column malfunctions in real time without the need to stop operations or open the distillation column. Thus, this method can help in reducing downtime by locating the exact location of malfunctions in an opaque distillation column.

The obtained scan profile from industrial gamma column scanning can be used as a reference scan, which can help identify any further variations under operational conditions (online). It is recommended that the scan be repeated when the plant is in normal operation.

## Acknowledgements

We would like to acknowledge Zimchem Refiners for granting us the permission to carry out this work at their BTX plant, the IAEA and NUST Research Board for funding.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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