CORROSION IMAGING AND THICKNESS DETERMINATION USING MICRO-CURIE RADIATION SOURCES BASED ON GAMMA-RAY BACKSCATTERING: EXPERIMENTS AND MCNP SIMULATION

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Gamma radiography is used to monitor the corrosion of pipelines in remote locations; usually high radioactivity ($10^{11} - 10^{12}$ Bq) is used. The technique is also not useful for imaging pipes with thick walls or large vessel walls. In this work, Compton backscattered radiation was used for the wall-thickness determination and corrosion imaging of pipe and flat materials using extremely-low-activity sources with radioactivities on the order of $10^4 - 10^5$ Bq. A two-dimensional scanning system was designed to scan object surfaces, and the signals from a NaI(Tl) scintillation detector were fed into a computer for image construction using the LabView program. Thicknesses greater than 1 cm and 1.5 cm could be measured for Fe and Al and for polyvinyl chloride (PVC) and poly methyl methacrylate (PMMA), respectively. It was also possible to detect changes of less than 1 mm in depression depth for depressions measuring 3 mm in diameter. One- and two-dimensional images artificial defects on a pipe surface were successfully constructed.

Keywords: corrosion imaging, MCNP, thickness determination

1. INTRODUCTION

Gamma-ray nondestructive industrial radiography is a technique used world-wide for the inspection of pipelines that extend for miles in remote locations where electricity is not available. Pipelines corrosion and erosion represent the most prevalent failure mechanism, with pipelines wall thickness being one of the most important parameters to measure. When gamma direct radiography is used for imaging large-diameter pipes, especially those used for transporting petroleum or liquid gas, sources with high radioactivities of $1.85 \times 10^{11} - 3.7 \times 10^{12}$ Bq (5–100 Ci) are used.

Radiation exposure from industrial radiography is reviewed by many investigators in several countries [1–5]. Several industrial radiography radiation accidents have been reported [6–9]. Many international and national reports have been published on radiation safety and accidents with respect to industrial radiography [10–12]. Accidents are caused by the loss or theft of gamma-ray sources or by negligence that leads to high overexposure or even death.

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Despite the high radioactivity used in industrial radiography, the technique fails to produce images of large-diameter pipes. Most of the radiation emitted from the source is absorbed by the liquid contained in pipes or the pipe wall, and a small or negligible fraction reaches the other side of the pipe, where the radiographic film or image plate is located. In direct radiography, the images of both sides of a pipe overlap, making image interpretation difficult. Moreover, the technique does not function if no access to the other side of the pipe is available or if the object is a vessel or tank.

In the last decade, tangential radiography technique was developed [13–15]. In this technique, only part of the pipe wall through which gamma- or X-ray radiation passes tangentially is imaged; radiation that passes through the liquid within the pipe is ignored. In large-diameter pipes or pipes with thick walls, the radiation path through the walls is large, and attenuation is high. Small defects in pipe walls can be missed. Several rounds of exposure are needed to image same section of a pipe. The risk associated with this technique is similar to that experienced with direct radiography because high-radiation-level sources are also used.

In this work, we used Compton backscattered radiation for the wall-thickness determination and corrosion imaging of a large pipe using extremely-low-activity sources with radioactivities on the order of $10^4$–$10^5$ Bq (few micro-Curies). This level of radioactivity is close to the exemption level for sources, and it is $10^7$–$10^8$ times lower than the activity used in conventional gamma-ray industrial radiography. Accordingly, the radiation risk associated with this imaging technique is negligible. The detector and radiation source are located on the same side of the pipe, not on opposite sides, as in conventional radiography. Thus, the method functions without requiring access to the other side of the object of interest. In addition, the method is effective for imaging corrosion in large vessel walls as well as in areas where direct radiography or tangential radiography fail. Little or no attenuation of radiation occurs in the liquid contained in pipes. Recently, Abdul-Majid and Balamesh [16,17] used a collimated beam to image the corrosion under the insulation of an industrial pipe by the gamma-ray backscattering method using a $1.85 \times 10^8$-Bq (5-mCi) radioactive source. The same authors imaged steel metal plates containing depressions of various diameters and at various depths using micro-Curie $^{137}$Cs source [17]. In this work, further experimental studies are presented on spatial resolution, inspecting materials other than steel and use $^{60}$Co a higher energy radioactive source in addition to $^{137}$Cs. Theoretical studies were also presented by using General Monte Carlo N-Particle Transport Code Version 5 (MCNP-5) calculations.

A sketch of the system used for pipe-wall imaging and thickness determination in this work is shown in Fig. 1. A $4.8 \times 10^5$-Bq (13-μCi) $^{137}$Cs source or a $1.1 \times 10^4$-Bq (0.3-μCi) $^{60}$Co source is attached to the base of a 2” × 2” NaI(Tl) scintillation detector. During imaging or thickness measurement, the source and detector are placed very close to the object to be inspected. Part of the incident radiation scatters back to the detector; the radiation generated
by the Compton interaction is lower in energy than the primary radiation. The detector measures both the direct and scattered radiation. The Compton scattered gamma-ray energy $E'$ following the incidence of a gamma ray of energy $E$ is given by the following equation:

$$E' = \frac{EE_e}{E(1 - \cos \theta) + E_e},$$

where $E_e$ is the rest mass of an electron (0.511 MeV) and $\theta$ is the scattering angle. For a scattering angle of 180°, $E'$ is 0.184 MeV for $^{137}$Cs and a primary gamma ray with an energy of 0.662 MeV and 0.212 MeV for $^{60}$Co and primary gamma rays with energies of 1.172 MeV and 1.332 MeV. The measured spectrum when $^{137}$Cs is used is shown in Fig. 2. Both the primary

![FIGURE 1. Sketch of gamma-ray backscattering using a point source.](image1.png)

![FIGURE 2. Gamma-ray spectrum.](image2.png)
and scattered radiation peaks are clear. As shown, a window can be selected to measure the backscattered radiation only and most of undesired radiation is rejected improving signal-to-noise ratio. The amount of backscattered radiation is proportional to the pipe-wall thickness. For a given primary radiation source, the amount of scattered radiation increases with thickness before count saturation is achieved. For Fe, count saturation is observed at a thickness of approximately 1–1.5 cm when $^{137}\text{Cs}$ is used \[18,19\]. Different saturation thicknesses have been reported for different sources \[20,21\]. For materials of higher atomic number, high-energy radiation must be applied and vice versa. Details regarding backscattering interactions and analytical treatments can be found in the literature \[22–25\].

In most applications of gamma backscattering for thickness determination found in the literature \[19–21\], both the primary and scattered radiation are collimated. This configuration makes the detection device heavy and requires the use of higher-activity sources. The smallest activity reported is 30 mCi for $^{203}\text{Hg}$ (279 keV) in a system that weighs 7.27 kg (16 lb) \[21\]. The system has a relatively light weight because of the lower energy used, which requires less shielding, but a smaller thickness range is covered. In this work, no shield or collimators were used; the only weight was that of the detector and a laptop computer. In other applications \[26,27\], X-ray machines are used. X-ray machines are generally heavy, and their emitted radiation energies are below those emitted from radioactive sources, which limits their applications to thin-wall pipes. Moreover, X-ray machines provide a continuous radiation spectrum and no well-defined backscatter peak. Harding and Harding \[23\] described a commercially available backscatter imaging device, ComScan, which utilizes an X-ray machine that operates at a maximum voltage of 160 kV with a mean X-ray energy of approximately 60 keV. The machine can be useful for imaging low-atomic-number materials such as aluminum but is not useful for imaging materials such as iron.

Other applications of Compton backscattered radiation include imaging weapons hidden under clothing \[28\], landmines \[29\], historical objects \[23\], explosives \[24\], and biomedical and industrial objects \[25\]. In these various applications, different methodologies are used. In point-by-point imaging, a narrow, collimated beam is focused on a point on the surface of the object of interest, and scattered radiation at a fixed angle is measured by a single detector. In line-by-line imaging, a slit beam is incident on the surface of the object, and scattered radiation is measured by a linear detector array. In these methods, heavy collimators and a large-activity source or a large number of detectors are used. In plane-by-plane imaging, a broad beam is incident on the object surface, and the scattered radiation passes through a pinhole in an absorber and then falls onto two-dimensional film. For corrosion measurements, which usually require high-energy radiation, a thick absorber is needed to stop the primary radiation \[23,24\]. Monte Carlo simulation of nondestructive testing has been discussed by Shengli et al. \[30\], and the implementation of this simulation technique for medical imaging
has been discussed by Driol et al. [31]. The technique used in this work is different from the above-mentioned techniques in that both the primary and scattered radiation are measured by the same detector, which results in a very light weight and very-low-activity system.

2. MATERIALS AND METHODS

2.1. Detection System

The detector used was a 2” × 2” NaI(Tl) model NAIS-2x2 scintillation detector. The detector was connected to a fully integrated multichannel analyzer (MCA) tube base containing a high-voltage power supply and preamplifier and is commercially known as “Osprey.” The signal was fed into a computer-based Gene Software Multichannel Analyzer. The detector and nuclear electronics components were all supplied by Canberra Industries, USA. The energy window was selected to only measure the counts of single-scattered radiation, as shown in Fig. 1. All other counts were rejected. The well-defined backscattered radiation peak on the multichannel analyzer and the selection of a well-defined window offer a clear advantage over the widely distributed backscattered radiation produced when X-ray machines are used.

2.2. Imaging System

For imaging purposes, counts under the backscattered radiation peak window were recorded. A scanning system, consisting of a platform capable of independent movement in both the horizontal and vertical directions, was developed. The platform carries the detector and source only, and it is driven by two smart motors controlled by LabView drivers through a serial port. The MCA (Osprey) is interfaced to a personal computer through an Ethernet connection using LabView. A C-language interface was developed to allow for communication between the Osprey C Lynx library and LabView. A LabView program (containing several VIs) was developed to acquire the counts from the MCA and form an image from the backscatter counts.

2.3. Samples

Step wedges were used for thickness measurements and imaging. The used iron and aluminum step wedges were each 100 mm long and 50 mm wide and composed of five steps. In addition, five-step polyvinyl chloride (PVC) and poly methyl methacrylate (PMMA) step wedges, each 200 mm long and 70 mm wide, were used. These materials are widely used in industry to fabricate pipes or sheet metals.
TABLE 1 Wall thickness $W$, depression depth $d$, and depression diameter $D$ for different pipe sections; all dimensions are in mm

<table>
<thead>
<tr>
<th>Section</th>
<th>Wall thickness (W)</th>
<th>Depression depth (d)</th>
<th>Depression diameters (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>5.5</td>
<td>10, 5, 3</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>4.5</td>
<td>10, 5, 3</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>3.5</td>
<td>10, 5, 3</td>
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<tr>
<td>4</td>
<td>5</td>
<td>2.5</td>
<td>10, 5, 3</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>1.5</td>
<td>10, 5, 3</td>
</tr>
</tbody>
</table>

A 400-mm-long iron pipe with a 197-mm internal diameter was used. Each 80 mm of the pipe wall was machined to the same thickness such that there were a total of five thicknesses that differed from each other by 2 mm. In each thickness $W$, three depressions of equal depth $d$ and different diameter $D$ were made. The thickness and depression dimensions are given in Table 1.

Imaging was also conducted on a carbon steel pipe (measuring 280 mm in outside diameter, 9 mm in wall thickness, and 1,250 mm in length) with artificial defects created on its outer surface. These pipe dimensions are representative of those normally used in many industrial plants. The defect was nearly circular and approximately 70 mm in diameter with a nonconstant depth that was deepest at the center at approximately 3 mm (Fig. 3). A Perspex cylindrical pipe with a diameter of 260 mm that was filled with water was inserted inside the steel pipe for water-filled-pipe measurements.

2.4. MCNP calculations

Backscattered radiation and spectrum calculations were performed using the multipurpose MCNP-5 code [32].

FIGURE 3. Artificial defect on pipe surface.
3. RESULTS

3.1. Step-Wedge-Thickness Measurements and Imaging

Using the setup shown in Fig. 1, it can be observed that radiation backscatters from a region in the pipe around the point source. The intensity of the backscattered radiation coming from locations far from the source should be small because of the attenuation of both incident as well as scattered radiation within the object. The region of interaction was studied experimentally and by MCNP calculations by using square Fe objects of different areas and thicknesses. Figure 4 shows the counts of backscattered radiation obtained over a 30-s period using a $^{137}$Cs source for four materials. As the square object increases in thickness, more scattered radiation reaches the detector, resulting in more counts. The increasing trends of the counts are similar, but as the object becomes thicker, a greater degree of interaction with the object materials takes place, and accordingly, more scattering of radiation occurs. The counts are expected to approach saturation for larger object areas. The MCNP calculated spectrum up to 0.7 MeV is shown in Fig. 5. The similarity between the calculated and measured spectra (Fig. 2) is clear.

The results of thickness evaluation by gamma backscattered radiation for the different materials using $^{137}$Cs are presented in Fig. 6 based on

![Graph showing backscatter counts from plates of different sizes for four materials.](image)

**FIGURE 4.** Measured and MCNP calculated backscatter counts from plates of different sizes for four materials.
measurements and by MCNP calculations using the step wedges. The figure indicates that there is good agreement between the results yielded the two methods. The iron counts were higher because of the higher density and atomic number of the element. The counts increase almost linearly up to approximately 1 cm and then approach saturation near approximately 1.5 cm. As the thickness increases, the incident as well as scattered radiation undergo more attenuation in the object, and the backscattered radiation undergoes a greater extent of self-absorption before reaching the detector. The other materials displayed less backscattered radiation. The counts continued to increase almost linearly with thickness for the PVC and PMMA materials. Al displayed behavior intermediate to that exhibited by the iron and PVC.

Using the scanner and LabView program, images of step wedges were obtained using two methods. First, the system response at the midpoint of
each thickness of the step wedge was recorded, and an image was constructed. Second, each step wedge was scanned, starting from the thinner part continuously in 1-mm increments. Images of the Fe and PVC step wedges obtained using $^{137}$Cs and of the Fe step wedges obtained using $^{60}$Co are shown in Fig. 7 for a counting time of 30 s per step. The darker region in the grey scale indicates lower counts and a thinner wall. In the left, the image darkness decreases with the increase in each step thickness, except for the last thickness, where it increases. These patterns occurred because the effective interaction region was larger than the width of the step (Fig. 4). As observed in the right images, when the scanner was set to move continuously, the system could not differentiate each thickness separately, again because the gamma interaction region was wide. Darker lines appeared at the bottom of the image because the detector was nearing the edge of
the step wedge. In the last step, there was not enough material to provide backscattering. The PVC image is less clear than the Fe image because of less interaction with the object material atoms. Visibility could be improved by extending the collection time or source strength. In the Fe step wedge image using $^{60}$Co, visibility was not as good as that of $^{137}$Cs because of the smaller activity used. Again, improvement could be achieved with a longer collection time or stronger source. The main advantage of $^{60}$Co over $^{137}$Cs is the higher penetration of gamma rays makes it more useful for thick wall measurements. Similar images were obtained for Al and PMMA materials.
3.2. System Sensitivity to Defect Size

The system sensitivity to defect size was examined by placing the detector in contact with the pipe surface at the depression depths indicated in Table 1, and counts over a period of 300 s (5 min) were obtained. Figures 8 and 9 display the backscattered radiation recorded at different wall thicknesses, depression depths, and diameters. In Fig. 8, depressions of the same diameter are grouped, whereas in Fig. 9, those of the same depth are grouped. Clearly, the counts decrease with an increase in defect diameter or depth. For the smallest counts of $10^6$ in Fig. 8, the theoretical statistical standard deviation is $10^3$. This value is much smaller than the difference in counts of 200,000 between one depression depth and another having the same diameter but differing by only 1 mm in depth. As shown in Fig. 9, for depths of 3.5 mm and above, it was possible to distinguish depressions of the same depth that differed by approximately 2 mm in diameter. Higher accuracy can be reached by increasing the collection time.

It can be concluded that the detection limit is less than 1 mm in depth for depressions measuring at least 3 mm in diameter. Below a diameter of approximately 3 mm and for depressions measuring approximately 2.5 mm in depth, it becomes difficult to detect changes in depression size unless the counting time is significantly increased.

![Graph showing counts for 300 s of backscattered radiation using $^{137}$Cs for depressions of different diameters and depths; each group of columns has the same diameter.](image)

**FIGURE 8.** Counts for 300 s of backscattered radiation using $^{137}$Cs for depressions of different diameters and depths; each group of columns has the same diameter.
3.3. Imaging Pipe Defects

The defect on the pipe surface shown in Fig. 3 was imaged by scanning 170 mm in one dimension across the middle in 1-mm steps when the pipe was empty and when it was filled with water. Images obtained using $^{137}$Cs with collection time steps of 1 s, 10 s, 30 s, and 60 s and images obtained using $^{60}$Co with a 30-s step are shown in Fig. 10. The images generally improved significantly between collection times of 1 s and 10 s per step for $^{137}$Cs. The total scanning time at 1 s per step was less than 3 minutes. Using $^{60}$Co, a lower-activity source, the image darkness was reduced, even when compared with an image taken over a collection time of 10 s or 30 s when using $^{137}$Cs. The effect of water inside the pipe on defect imaging was insignificant, which represents a major advantage of this technique compared with direct radiography, in which most of the radiation is absorbed by the liquid contained in pipes before reaching the image receptor, especially in large pipes.

Two-dimensional scanning was performed over the same defect to produce two-dimensional images. The scanning area was 120 x 80 mm, and the detector moved in 2-mm steps with collection times of 10 s per step. The image generated using $^{137}$Cs is shown in Fig. 11.

4. DISCUSSION AND CONCLUSIONS

This study clearly demonstrates the feasibility of integrating very-low-activity gamma sources with a backscattering method for pipe-wall-thickness
determination and imaging. The system described depends on single-photon counting. Accordingly, the system is much more sensitive than radiographic films or image plates, and it is also much safer to use. The system was tested with four materials widely used in industry.

As shown in Fig. 6, the theoretical statistical standard deviation for most counts was 200–400 for a 30-s counting time. Two or three standard deviation is still much less than the difference in counts obtained from two thicknesses that differ by 1 mm. Accordingly, changes of less than 1 mm in thickness can be detected. The recorded sensitivity was 320 counts/mm/s. There were always background counts at zero thickness, which is attributed to Compton scattered radiation within the detector material and casing.

The standard deviation of net counts can be computed from the following equation [33,34]:

$$\sigma = \sqrt{\sigma_g^2 + \sigma_b^2},$$

where $\sigma_g$ and $\sigma_b$ are the standard deviation of gross counts and background counts, respectively. The Background counts are those the system gives without a pipe (thickness equal to zero). From Fig. 6, taking a middle thickness value of 5 mm, the coefficient of variation is about 0.5%.
For Fe, it can be concluded that the measurable thickness range of the detection system is at least 1 cm. The system exhibited a slightly wider thickness range for aluminum, whereas the PVC and PMMA counts increased almost linearly for thickness greater than 1.5 cm. The thicknesses that can be measured depend mainly on the gamma-ray energy and the material atomic number and density. In low-atomic-number and low-density materials, the linear attenuation coefficient \([35,36]\) is smaller, and incident radiation can penetrate more deeply; the level of self-absorption of backscattered radiations is also lower. In addition, the attenuation of incident and scattered radiation is reduced when higher energy is used.

The radiation doses from the sources used in this study are negligible. The specific gamma-ray dose constants for \(^{137}\)Cs and \(^{60}\)Co are \(1.032 \times 10^{-4}\) and \(3.703 \times 10^{-4}\) (mSv/h)/MBq at 1 m, respectively \([37]\). A 1-\(\mu\)Ci (3.7 x 10^4 Bq) \(^{137}\)Cs source and a 0.3-\(\mu\)Ci (1.1 x 10^4 Bq) \(^{60}\)Co source yield approximately
4 μSv/h at 1 m. At 4 hours of exposure per week near the source without any shield, a radiation worker will receive 1 mSv/y, which is within the public radiation exposure limit. This radiation exposure level indicates that no license for using the sources is required. Thus, a significant amount of money and time can be saved.

Although ultrasonic methods can be used for thickness measurement from one side of an object of interest, the object surface has to be well prepared and polished. This process is time-consuming and can be expensive. The method presented here can function very well for unprepared surfaces. A single thickness measurement can take few seconds. The method, therefore, takes about the same or shorter period than the ultrasonic method if surface preparation is required. In addition, ultrasonic methods cannot be used for high-temperature objects because the grease used between the sensor and object surface melts down. With the backscattering technique, a distance on the order of a few millimeters between the detector and the object surface can be used to avoid direct contact without affecting the collected data and allowing for hot-surface measurements. Although the measurements performed in this study were on a pipe, the technique is expected to operate successfully for imaging the walls of large vessels.

The line imaging technique (Fig. 10) used in this study has clear advantages over the widely used tangential radiography method. Both techniques measure only part of a pipe surface, essentially producing a line image, but in this technique, much lower radioactivity is used, and a wider pipe-wall thickness is covered. Scanning of 170 mm in 1-mm, 1-s steps took less than 3 min and in 1-mm, and 5-s took less than 15 min. This is close to the imaging period in tangential radiography, keeping in mind no image processing or development is required. Two-dimensional imaging is also possible (Fig. 11), but a relatively extended measurement period is required to produce an image. But in many applications two dimensional images are not necessary, and it is enough to take a line image or inspect the pipe at few points to have an idea of its condition.

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