Hindawi
International Journal of Corrosion
Volume 2023, Article ID 4924399, 9 pages
https://doi.org/10.1155/2023/4924399

Research Article

Investigation of Wall Thickness, Corrosion, and Deposits in Industrial Pipelines Using Radiographic Technique

Prince Amoah [1,2] **Sandyson Owusu-Poku** [1] **and Gordon Asartenga Ajubala** [2]

[1]*Graduate School of Nuclear and Allied Sciences, University of Ghana, P.O. Box AE1, Atomic Energy, Accra, Ghana*
[2]*Nuclear Regulatory Authority, P.O. Box AE 50, Kwabenya, Accra, Ghana*

Correspondence should be addressed to Prince Amoah; amprince77@gmail.com

Received 24 February 2023; Revised 6 July 2023; Accepted 15 July 2023; Published 24 July 2023

Academic Editor: Michael J. Schütze

In this study, radiographic techniques were used to inspect large-diameter pipes that are used for transporting fluids in some industries in Ghana. Radiographic approaches such as the double wall technique (DWT) and tangential radiographic technique (TRT) were used to evaluate the remaining wall thickness, deposits, and corrosion in the pipes. Two steel pipes with known varying wall thicknesses ranging from 4.00 mm to 13.00 mm with a diameter of 150.00 mm were examined to authenticate the accuracy and reliability of the tangential method that was used to measure the remaining wall thickness. The tangential configuration resulted in a higher material thickness, which therefore required more time of exposure compared to the DWT method. The exposure angle of the source to the tangential part of the specimen was approximately 87°. The film generated was compared with a normal pipe piece that was not machined to serve as a control. From the radiograph obtained, an average of 6 and 7 rounded indications depicting pitting corrosion were revealed on the radiograph of the internally and externally fabricated pipe, respectively. Radiographs after the TRT revealed that the recorded wall thickness obtained from the film is about twice the value of the calculated true wall thickness.

1. Introduction

Radiography in general is applied in numerous fields such as engineering, and medicine. Industrial radiography remains one of the most important techniques in nondestructive testing (NDT), and it remains the most widely used method because it offers enormous advantages over other NDT modalities [1]. NDT is a group of inspection techniques used to detect, locate, and assess flaws in materials without affecting, in any way, their continued usefulness or serviceability. NDT has the ability to inspect castings and weldments and to measure wall thicknesses in an accurate and comprehensive manner. NDT science is a broad field that covers a variety of testing methods and applications. In terms of methods and techniques, the NDT modalities rely on different physical phenomena such as the electromagnetism, the acoustic emission, the thermal emission, and the penetration of high-energy radiation through materials and structures. As an industrial test method, NDT provides a cost-effective means of testing while protecting the object's usability for its designed purpose [2, 3]. Industrial radiography testing (RT) is the examination of the structure of materials by nondestructive methods which involves utilizing ionizing radiation to make a radiographic image.

The reliability and safety of industrial equipment in the power plant and petroleum industries are substantially influenced by degradation processes such as corrosion, erosion, deposits, and blocking of pipes, which might reduce production, cause leaks, fires, or unpredictable and costly shutdowns due to lack of repairs and replacements. Ghana is a member of the West African Gas Pipeline Project (WAGP), an international company transporting natural gas in Nigeria, Benin, Togo, and Ghana in a safe, responsible, and reliable manner to create value. Local industries have contributed to the pipelines used for this gas transport project. These pipelines buried underground and in water bodies could be susceptible to corrosion. Corrosion can trigger serious mechanical failures, which lead to large economic loss, sometimes combined with environmental pollution, or risk of personnel injuries [4, 5]. This study focuses on

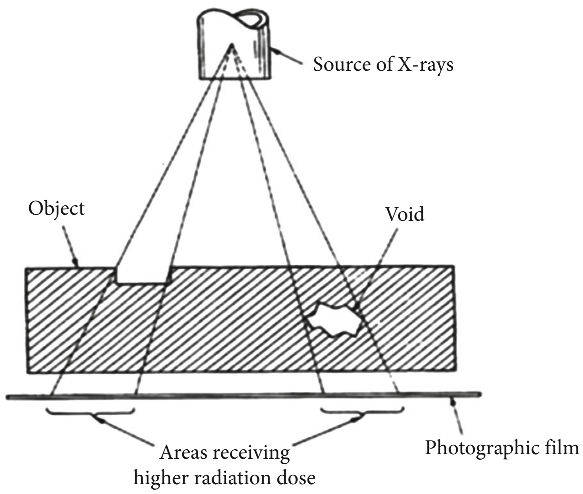

Figure 1: A classical radiography set-up [3].

extreme corrosion activities in the pipelines of industries in Ghana using radiographic techniques. The mild steel used in this study is locally manufactured, and these companies produce it for many industries in Ghana.

From the concept of effective attenuation coefficient (μ_{eff}), the transmitted ray is directly considered by the attenuation coefficient in Beer's Law [6]. Figure 1 shows a set-up for a classical radiography.

$$I = I_o e^{-\mu_{\text{eff}} t}. \quad (1)$$

In practice, the effective attenuation coefficient (μ_{eff}) will depend on the radiation energy, the wall thickness (because of radiation hardening in the object), and the geometrical set-up used for inspection (this determines the scatter contribution). The will always be smaller than the theoretical μ as obtained for the monoenergetic narrow beam energy or from theoretical models like data available from the National Institute of Standards and Technology (NIST) [7].

The quality of the radiographic film is the film density (D). It is expressed as follows:

$$D = \log 10 \frac{I_o}{I_t}, \quad (2)$$

where D is the density of radiographic film. I_o is the intensity of incident radiation. I_t is the intensity of transmitted radiation.

X-ray tubes and radioactive sources always produce a certain fuzzy image of the specimens because of their finite dimensions. The nonclear frame (or partial shadow surrounding) of the specimen is technically known as the penumbra or unsharpness. It has an isometric form. The value of geometric unsharpness (U_g) depends on the size of the source (s), the thickness of the specimen (d), and the source-to-film distance (SFD). The general formula relating these parameters is as follows:

$$U_g = \frac{\text{sd}}{(\text{SFD} - d)}. \quad (3)$$

It is desirable to keep U_g to minimum in order to detect fine defects.

2. Tangential Radiographic Technique (TRT) and Double Wall Technique (DWT)

In setting up the TRT, as shown in Figure 2, the source is placed far from the tube in order to project the two walls of the tube on the film. Because of the finite dimension of the radioactive source, the penumbra or unsharpness appears on the film [2]. The value of geometric unsharpness U_g is given by the following equation:

$$U_g = \frac{s(0.5\text{OD} + d)}{\text{SFD} - (0.5\text{OD} + d)}, \quad (4)$$

where U_g is the geometric unsharpness. SFD is the source-film distance. OD is the external diameter of tube.d is the insulation thickness. s is the source size.

The equation shows that unsharpness is inversely proportional to the source-film distance. To decrease the fuzzy effect, a relatively long source-film distance is required.

By changing the SFD, the operator can arrange the tube position to project suspected defects on to the film with optimum resolution and contrast parameters.

Figure 3 shows the attenuation coefficients for different layers in a typical pipe with deposit.

The relationship that determines the radiation exposure angle α, as shown in Figure 3, is given by

$$\alpha = \frac{\cos^{-1}(0.5\text{OD})}{\text{SFD} - 0.5\text{OD}}. \quad (5)$$

This angle is a function of the SFD and OD of the pipe.

Due to geometrical unsharpness, the measured thickness of the pipe wall on the radiogram (T_a) shown in Figures 2(a) and 2(b) is not exactly the real pipe wall thickness (T_W). The accurate evaluation of the real pipe wall thickness is very important to determine the remaining pipe thickness and, consequently, to assess the corrosion or deposit rate [2, 3]. The relation between T_W and T_a is given by the formula:

$$T_W = T_a \frac{\text{SFD} - 0.5\text{OD} - d}{\text{SFD}}. \quad (6)$$

The difference between T_W and T_a (magnification correction) is significant when the SFD is relatively short. This correction has to be taken account for obtaining high accuracy.

If a radiation beam is passed through an insulated pipe with a deposit, the formula for penetrated radiation intensity (I) is as follows:

$$I = I_O e^{-2(\mu_c X_c + \mu_s X_s + \mu_d X_d + \mu_m X_m)}, \quad (7)$$

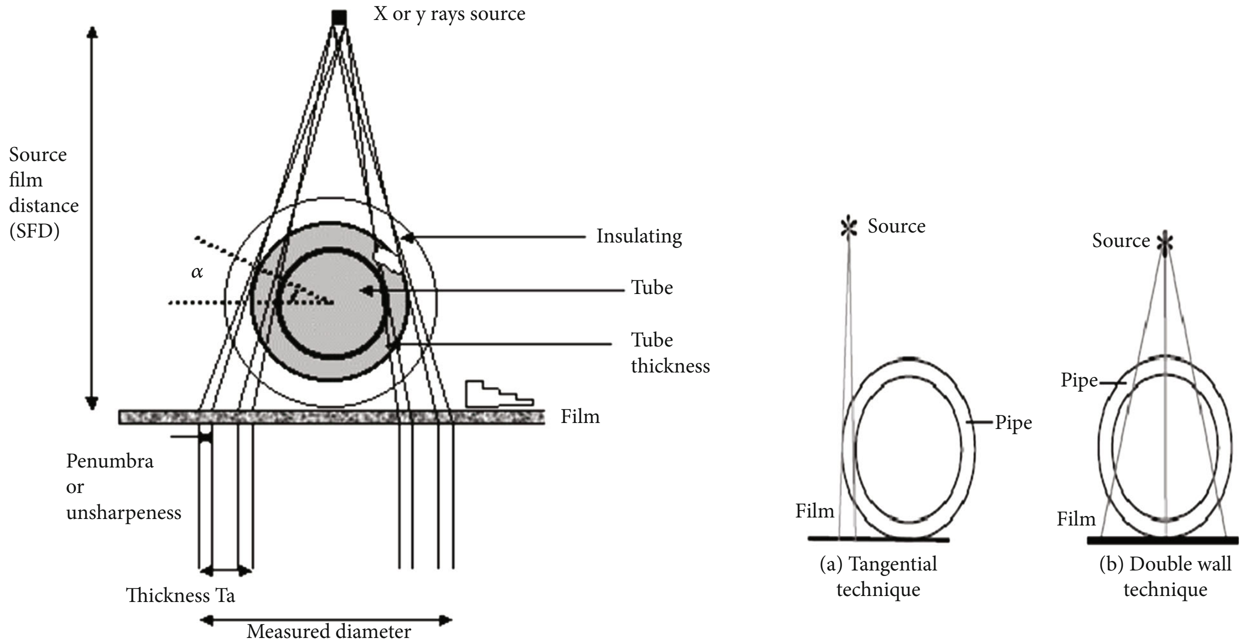

Figure 2: Tangential and double wall radiography schematic set-up [3].

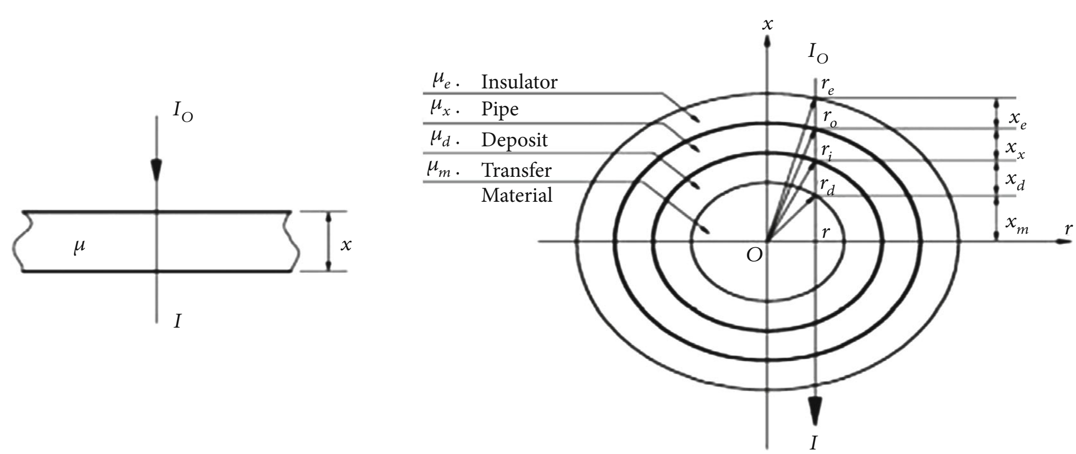

Figure 3: Attenuation coefficients for different layers of a pipe [8].

where X_c, X_s, X_d, and X_m are the thickness traversed in the insulation, steel, deposit, and material being transported, respectively, and μ_c, μ_s, μ_d, and μ_m are the attenuation coefficients of the insulator, steel, deposit, and transported matter, respectively [2].

Using geometry principles in Figure 2, the thickness traversed in every layer can be calculated with respect to a certain coordinate (r).

Penetrated insulation thickness is $2X_c$, where

$$X_C = \sqrt{r_C^2 - r^2} - X_S - X_d - X_m. \quad (8)$$

Penetrated steel thickness is $2X_s$, where

$$X_S = \sqrt{r_O^2 - r^2} - X_d - X_m, \quad (9)$$

Penetrated deposit thickness is $2X_d$, where

$$X_C = \sqrt{r_i^2 - r^2} - X_{m.} \quad (10)$$

Penetrated material thickness is $2X_m$, where

$$X_m = \sqrt{r_d^2 - r^2}. \quad (11)$$

r_c = insulation radius. r_i = inner diameter radius. r_d = deposit radius.

Using the general equation of transmitted radiation intensity, the specific formula for different types of piping can be derived as follows:

Table 1: Composition of Mild Steel.

Element	Iron (Fe)	Carbon (C)	Manganese (Mn)	Silicon (Si)	Sulphur (S)	Phosphorus (P)
Chemical composition in wt. %	0.119	0.150	0.33	0.28	0.045	0.076

Figure 4: Machining of pipe using the lathe machine.

For uninsulated empty pipe ($X_C = 0$, $X_d = 0$, and $X_m = 0$),

$$I = I_O e^{-2\mu_s X_s} \quad (12)$$

For insulated empty pipe ($X_d = 0$, $X_m = 0$),

$$I = I_O e^{-2(\mu_c X_c + \mu_s X_s)} \quad (13)$$

For insulated empty pipe with deposit ($X_m = 0$),

$$I = I_O e^{-2(\mu_c X_c + \mu_s X_s + \mu_d X_d)}. \quad (14)$$

The limits of the tangential inspection technique are based on the maximum penetrable wall thicknesses of pipes ($L_{\max}$), depending on the radiation energy. $L_{\max}$ determines the maximum wall thickness which can be inspected at a given pipe diameter.

The DWT is suitable for larger size pipes or lower X-ray radiation energies, where the tangential projection technique is not applicable. The source is kept perpendicular with respect to the pipe axis. Usually two exposures are taken by rotation around the pipe at 90 degrees

3. Methodology

Experimentation for this study was carried out at the Ghana Atomic Energy Commission (GAEC) Non-Destructive Testing laboratory at Kwabenya in Accra. The test pipes used were produced from mild steel pipes of diameter greater than 150.00 mm and were obtained from some selected factories or industries in Ghana. The chemical composition of the mild steel is indicated in Table 1. Figure 4 shows images of selected industrial pipes manufactured in Ghana with outer and inner diameter dimensions of 161 mm and 148 mm, respectively, and a length of 150 mm. The parameters of the interiorly fabricated pipes are given in Table 2. Pictorial and orthographic views of the interiorly and exteriorly machined pipes are shown in Figures 5–9.

3.1. Insulation and Deposit Material. The deposit material used in this project is moist sand, and this was prepared from sand mixed with water in the internal diameter of the pipe. Figure 10 shows moist sand in an exteriorly machined pipe. This is to simulate the deposit left in pipes when the pipe is operational. The deposit thickness cast in the pipe was not uniform and ranges between 10.00 mm and 45.00 mm.

The insulation material used in this work is a fibre wool insulator obtained from a petrochemical industry with approximately 30.00 mm thickness. It is used to conserve the temperature and other thermodynamic property of the transported media. It also protected the pipe surface from environmental attack.

For the tangential radiographic technique, the source-film-distance (SFD) of1485.00 mm was maintained both for insulated and noninsulated pipe but with exposure times of 45, 50, 55, 80, and 90 seconds. The exposure angle between the source, the tangential position, and the central axis of the pipe was 87°. The source had to be collimated to prevent backscatter and also to focus the beam on the

Table 2: Parameters of interiorly fabricated (machined) pipe.

Step	Step block thickness (mm)	Pits (drill) diameter (mm)	Pits depth (mm)	Outer diameter (mm)	Inner diameter (mm)	Step block length (mm)
INTERIOR MACHINED PIPE LENGTH OF PIPE = 302.00 mm						
Step 1	4.50 ± 0.20	3.00 ± 0.20	0.50 ± 0.02	163.00 ± 2.00	154.00 ± 1.00	49.00 ± 0.50
Step 2	6.40 ± 0.20	3.20 ± 0.20	0.80 ± 0.02	163.00 ± 2.00	150.20 ± 1.00	49.00 ± 0.50
Step 3	7.50 ± 0.20	4.00 ± 0.20	1.20 ± 0.20	163.00 ± 2.00	148.00 ± 1.00	49.00 ± 0.50
Step 4	8.50 ± 0.20	4.50 ± 0.20	1.60 ± 0.20	163.00 ± 2.00	146.00 ± 1.00	49.00 ± 0.50
Step 5	9.40 ± 0.20	5.00 ± 0.20	2.00 ± 0.20	163.00 ± 2.00	144.20 ± 1.00	49.00 ± 0.50
Step 6	10.50 ± 0.20	6.00 ± 0.20	2.50 ± 0.20	163.00 ± 2.00	142.00 ± 1.00	57.00 ± 0.50

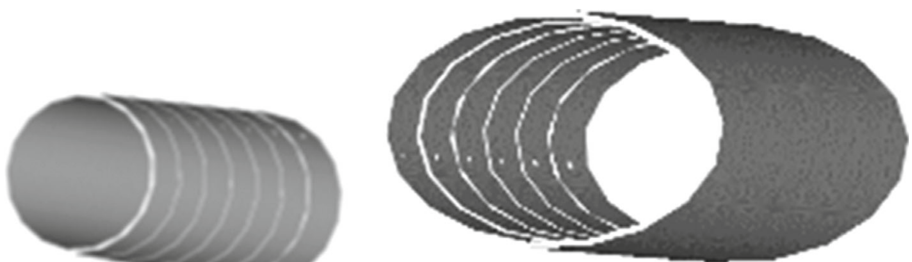

Figure 5: Pictorial view of both exteriorly and interiorly machined pipe.

Figure 6: Interiorly machined pipe (test pipes).

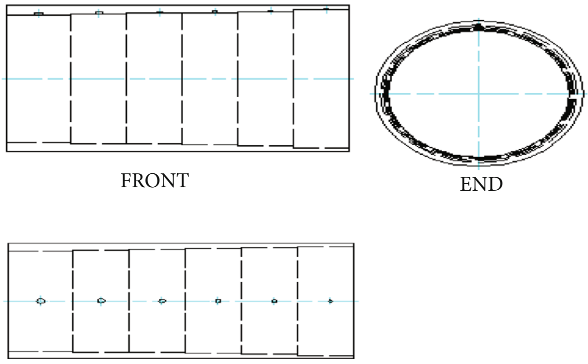

Figure 7: Orthographic views of the interiorly machined pipe.

Figure 8: Exteriorly machined pipe (test pipes).

target area of interest; its activity at the time of conducting the test was 45 curies (Ci). The method was able to measure wall thickness on two sides of the pipe in the same exposure. The radiation source was placed above the pipe being radiographed tangentially rather than at centre of the pipe. Shading of the tangential radiograph between the two sides allows observation of local corrosion, erosion, deposits, and pitting. The tangential paths of radiation within the pipe walls projected the edge location and the pipe thickness to be evaluated.

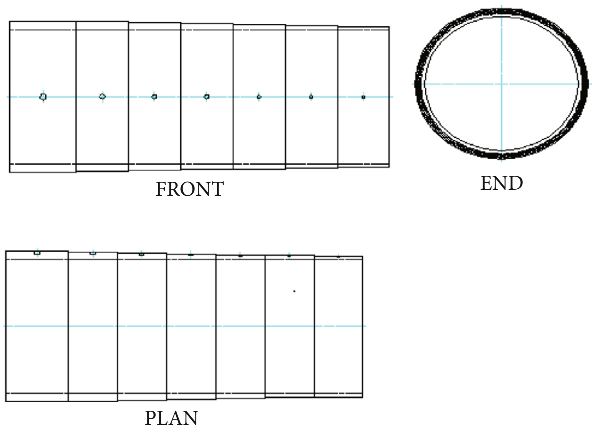

Figure 9: Orthographic views of the exteriorly machined pipe.

Figure 10: Moist sand in the exteriorly machined pipe.

In setting up the double wall technique, the source was positioned perpendicular with respect to the pipe axis, projecting the double wall of the pipe on the radiographic film as shown in Figure 11. Here, the steps on the pipe (erosion corrosion) and the size of the pipe's diameter are captured on the film. A source-film distance of 1450.00 mm was used for both insulated and noninsulated pipes with exposure times of 32, 38, 43, 68, and 78 seconds.

The density transmission applied in the double wall technique configuration was the classical density measurement radiography where the gamma rays penetrate through two walls of the pipe tube placed between source and film. On the side of the pipe, the steps were kept for comparison of density with the defect density.

4. Results and Discussion

4.1. Comparative Analysis of Results. Figures 12 and 13 provide comparison between the measured wall thickness from the film, the calculated true wall thickness, and the ultrasonic thickness gauge measurement that served to validate the results of the calculated true wall thickness.

A comparison between the measured wall thickness from film and calculated true wall thickness for externally fabricated pipe by the tangential radiographic method is presented in Figure 12. The recorded wall thickness obtained from the film is about twice the value of the calculated true wall thickness. The maximum standard deviation of the recorded thickness from the film was 0.1414 with a standard error of 0.07.

The overestimation of the measured wall thickness from the film (radiograph) was a results of the magnification factor. This overestimation of the measured wall thickness from film can be used to accurately predict the true wall thickness if due calculations are taken into consideration.

4.2. Comparison between Calculated True Wall Thickness and Ultrasonic Thickness Gauge Measurements for Externally Fabricated Pipe. From the experimental data, the true wall thickness calculated was compared with the thicknesses obtained using an ultrasonic thickness gauge. The ultrasonic thickness readings were to serve as validations for the experimental procedure.

From the results obtained in both thicknesses, there was no significant difference between the ultrasonic thicknesses and that of the calculated true wall thicknesses. Figure 13 shows how closely related the results of the calculated true wall thickness and the ultrasonic thickness measurements are. With the maximum difference between the two different methods being 0.26 mm and the minimum difference being 0.02 mm. The insignificant difference indicates the importance of the tangential radiography method in measuring the external wall thickness of pipelines in process industries. Figure 14 presents a comparative graph between the calculated true wall thickness, ultrasonic thickness gauge measurements, and actual wall thickness for externally fabricated pipe. Some of the advantages of the tangential radiography methods over the ultrasonic thickness are its ability to inspect pipelines with insulators without the costly removal of the insulations and also provision of permanent records.

4.3. Comparison between Measured Wall Thickness from Film and Calculated True Wall Thickness for Internally Fabricated Pipe. The combined action of chemical attacks and mechanical abrasions or wear as a consequence of fluid motion leads to erosion corrosion. Most metals/alloys are susceptible to erosion corrosion. Some of these metals rely on the protective surface film for corrosion protection. These types of metals are particularly vulnerable to corrosion. Examples of these metals include aluminium, lead, and stainless steel. The corrosion attack occurs as a result of the failure of the protective film to form because of the erosion caused by suspended particles.

Most pipelines in process industries are manufactured with stainless steel. Internal corrosion (erosion corrosion) leads to reduction in the wall thickness of the pipelines. This is because pipelines in such industries are mostly subjected to high-velocity fluids. Gradual reductions in the pipe thickness lead to break in the pipelines, resulting in spillage.

Table 3 compares the measured wall thickness from the radiograph (film) to that of the calculated true wall thickness. From the graph, the measured wall thickness from the radiograph is found to be approximately 1.22 times the value of the calculated true wall thickness. With a standard deviation ranging from 0.047 to 0.085.

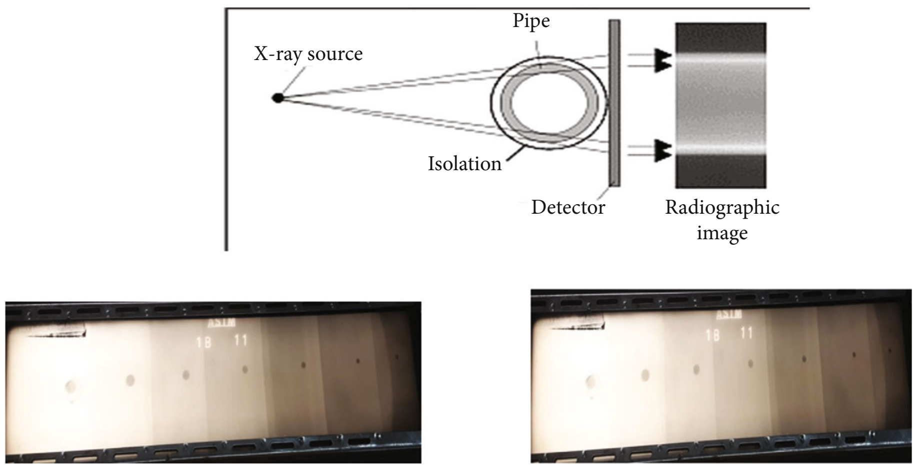

Figure 11: A typical radiograph and samples of the processed radiographs of the pipe.

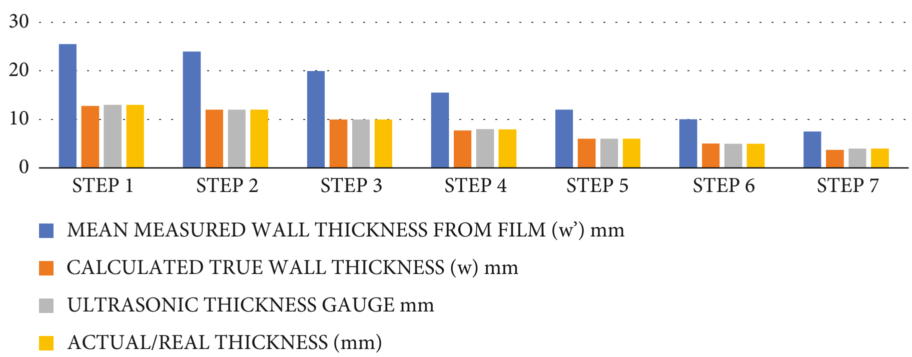

Figure 12: A bar chart of measured wall thickness, calculated true wall thickness, and ultrasonic thickness measurement of externally fabricated pipe.

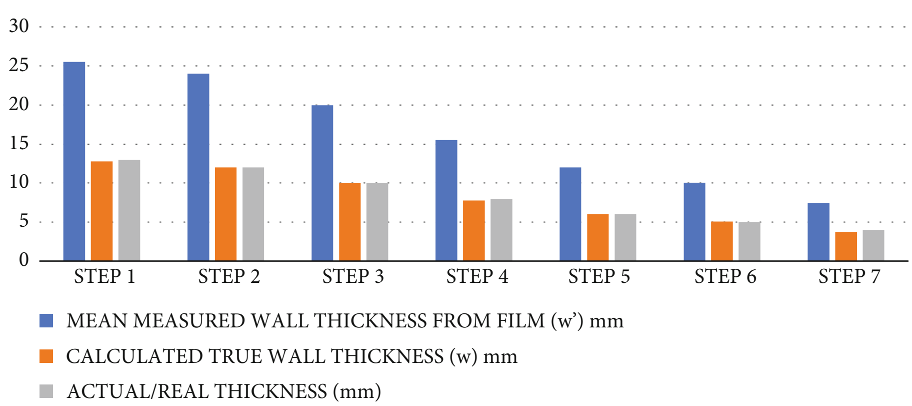

Figure 13: A graph comparing the mean measured wall thickness from film calculated wall thickness and actual wall thickness against corresponding steps.

From this analysis, the remaining wall thickness of pipelines in the process industries can be estimated.

A comparison between the true wall thickness calculated and the ultrasonic thickness gauge measurements was made for the internally fabricated pipe after the experiment. With the ultrasonic thickness readings serving as validations for the experimental procedure used.

The similarities between the remaining wall thicknesses obtained from both the true wall thickness and ultrasonic gauge measurements were noticeable. With no significant difference between the ultrasonic thicknesses and that of the calculated true wall thicknesses. The maximum difference between the two different methods is 0.27 mm, and the minimum difference is 0.03 mm. This insignificant

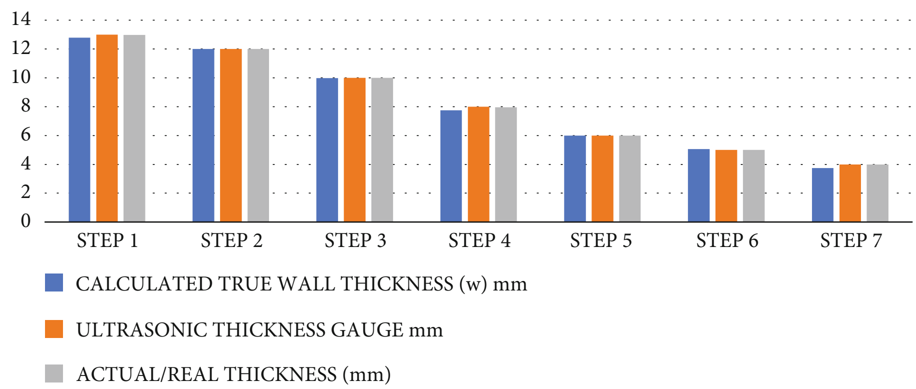

FIGURE 14: A graph comparison between calculated true wall thickness, ultrasonic thickness gauge measurements, and actual wall thickness for externally fabricated pipe.

TABLE 3: Comparison of wall thickness of pipe.

Steps	Mean measured wall thickness from film (mm)	Calculated true wall thickness (W) (mm)	Ultrasonic thickness gauge (mm)	Actual/real thickness (mm)
Step 1	25.53 ± 0.30	12.78 ± 0.60	13.00 ± 0.50	12.98 ± 0.20
Step 2	24.00 ± 0.30	12.0 ± 0.60	12.00 ± 0.50	12.00 ± 0.20
Step 3	19.95 ± 0.30	9.98 ± 0.60	10.00 ± 0.50	10.00 ± 0.20
Step 4	15.5 ± 0.30	7.75 ± 0.60	8.00 ± 0.50	7.96 ± 0.20
Step 5	12.00 ± 0.30	6.00 ± 0.60	6.00 ± 0.50	6.00 ± 0.20
Step 6	10.05 ± 0.30	5.05 ± 0.60	5.00 ± 0.50	5.00 ± 0.20
Step 7	7.48 ± 0.30	3.74 ± 0.60	4.00 ± 0.50	4.00 ± 0.20

difference indicates the significance of the tangential radiography method in measuring the internal wall thickness of pipelines in process industries. Some of the advantages of the tangential radiography methods over the ultrasonic thickness are its ability to inspect pipelines with insulators without the costly removal of the insulations and also provision of permanent records. Results on the determination of corrosion deposits in the pipes are presented in another publication [9].

5. Conclusion

The DWT and TRT techniques were extensively explored in this research work to effectively evaluate remaining wall thickness, corrosion, and deposits in pipes. On the whole, the DWT was used predominantly to examine for corrosion and deposits in the experimental pipes, whereas the TRT technique was also used to evaluate the penetrated wall thickness of the corrosion attack in the tangential position. The TRT setup led to increased material thickness which required more exposure time compared to the DWT method.

The exposure angle of the source to the tangential part of the specimen was approximately eighty-seven degree (87°) and which is calculated using the values of SFD and the OD of the experimental pipe. DWT was able to identify both pitting corrosion and uniform corrosion in the internally fabricated pipe. This was true for the externally fabricated pipe as well. This affirms the double wall technique's success rate in the detection of corrosion in pipelines. Similar to the insulated external machined pipe, the insulating material's absorption or attenuation coefficient had no or negligible impact on the density measurements. This implies that when the need arises, pipelines can always be insulated and will never interfere with any assessment method to access their internal profile (condition).

The findings of this study indicate that regular inspection of the internal corrosion of large diameter pipes will allow process industries to estimate the lifespan of pipes and save excessive maintenance costs through shorter inspection times.

Data Availability

No data is available.

Disclosure

An earlier version of some portions of this manuscript was presented as part of a thesis [9] by the second author at the University of Ghana.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

The authors are grateful to the Ghana Atomic Energy Commission for making available the Non-Destructive Testing Laboratory for carrying out the experimental part of this project.

References

[1] G. Mozurkewich, "Non-Destructive Testing Activities, Needs and Trends in the Automotive Industry," in *16th World Conference on Nondestructive Testing*, Montreal, Canada, 2004.

[2] IAEA TECDOC-1445, *Development of Protocols for Corrosion and Deposits Evaluation in Pipes by Radiography*, International Atomic Energy Agency, Vienna, 2005.

[3] K. Edalati, N. Rastkhah, A. Kermani, M. Seiedi, and A. Movafeghi, "The use of radiography for thickness measurement and corrosion monitoring in pipes," *International Journal of Pressure Vessels and Piping*, vol. 83, pp. 736–741, 2006.

[4] R. Drai, A. Benchaala, M. Zergoug, A. Badidi Bouda, Y. Kabir, and J. Hadj Djilani, *Corrosion and Deposit Determination in Pipes by Radiography*, International Atomic Energy Agency (IAEA), INIS repository, 2005.

[5] M. Balaskó, E. Sváb, A. Kuba, Z. Kiss, L. Rodek, and A. Nagy, "Pipe corrosion and deposit study using neutron- and gamma-radiation sources," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 542, pp. 302–308, 2005.

[6] E. Yılmaz, H. Baltas, E. Kırıs, İ. Ustabas, U. Cevik, and A. M. El-Khayatt, "Gamma ray and neutron shielding properties of some concrete materials," *Annals of Nuclear Energy*, vol. 38, pp. 2204–2212, 2011.

[7] E. Calzada, F. Grünauer, B. Schillinger, and H. Türck, "Reusable shielding material for neutron- and gamma-radiation," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 651, pp. 77–80, 2011.

[8] A. Boateng, K. A. Danso, and C. P. K. Dagadu, "Non-destructive evaluation of corrosion on insulated pipe using double wall radiographic technique," *Chemistry and Materials Research*, vol. 3, pp. 73–83, 2013.

[9] S. Owusu-Poku, "Radiographic Evaluation of Wall Thickness," in *Corrosion and Deposits in Pipelines*, University of Ghana Graduate Thesis Collection, 2019.