Abstract: The principle of corrosion measurement/monitoring by means of tangential film-based radiography is already known. Most of this experience, however, is limited to qualitative determination of internal defects. The ability to reliably measure remaining wall thickness in pipes has not yet been established. Based on this fact, the International Atomic Energy Agency organized a Co-ordinated Research Project bringing together eleven Member States to study “validation of protocols for corrosion and deposits determination in small diameter pipes by radiography.”. The general scope of the project covered radiographic measurement of corrosion and deposits in straight and bent small diameter pipes made of carbon or stainless steels corroded/eroded on the outer or inner surfaces with or without insulation. During the execution of the project, experimental work was carried out by laboratories in the participating countries between 1997 and 2000. The project produced a draft IAEA Tecdoc and a draft ISO standard covering this subject. Based on the results of this project, a new project was established to extend the work to larger diameter pipe, and twelve countries were invited to participate. From the Americas, the participants are Canada and Uruguay. It is expected to define the limits of detection for each radiation source using the tangential method and to explore the double wall technique beyond this limits. This paper summarizes the results of the first project, and discusses the scope and expected results from the current activity.

Keywords: radiography, corrosion, pipelines

1. Introduction

The International Atomic Energy Agency (IAEA) promotes the industrial applications of radiation technology which include Non-Destructive Testing (NDT) under its various programmes. One of the ways for promoting this technology is through coordinated research programmes (CRPs) and research contracts. These are undertaken keeping in view the current status of the technology and the need for undertaking some research. Such research contracts and agreements are worked out between the Agency and universities, colleges, research centres, laboratories and other institutions in Member States.

Pipe is a common feature in industries. It provides the most economical, safe and efficient way of transporting chemicals in the form of liquids and gases from one point to another. However, pipe experiences degradation with time which if not detected might create problems such as leaks and bursts which finally can lead to catastrophe. Corrosion, erosion, deposits and pipe blockage are some of the possible causes for this.

For years, many testing methods either destructive or non-destructive in nature were developed and applied on pipe to ensure integrity and reliability. Of many parameters, pipe wall thickness is considered as one of the most important to be monitored and measured with a high degree of accuracy.

Up to now, appreciable R & D efforts have been made to investigate this aspect. Measurement of wall thickness on long pipelines is accomplished with a number of established systems such as ultrasonic and eddy current ‘intelligent pigs’. However, for plant piping, the existence of many bends and a variety of pipe diameters, some having insulation cover, do not allow the use of these systems.

A new method, preferably non-destructive in nature, is required to precisely perform this measurement whose data will be used as a basis for determining whether or not the pipes need to be replaced. Theoretically, it is believed that radiographic method would be able to perform this function. It has the potential to be used to perform inspection without the need of costly removal of insulation material during operation of the plant. Furthermore, it offers an additional advantage of being capable to perform measurement in high temperature environments.

The principles of corrosion measurement/monitoring by means of tangential film-based radiography are already known. Most of this experience, however, is limited to qualitative determination of internal defects. The ability to reliably measure remaining wall thickness in pipes has not yet been established and no standard is available.

It was based on these facts that an effort was undertaken by the Agency together with some Member States to organize a CRP on “validation of protocols for corrosion and deposits determination in small diameter pipes by radiography (CORDEP)”. Member States involved in this three years project were Algeria, China, Costa Rica, France,
India, Korea, Malaysia, Sri Lanka, Syria, Tunisia and Turkey. The general scope of the CRP covered radiographic measurement of corrosion and deposits in straight and bent small diameter pipes made of carbon or stainless steels corroded/eroded on the outer or inner surfaces with or without insulation.

The results of various participating laboratories were reviewed and compiled. These are quite encouraging and demonstrate the capability of the radiographic technique for corrosion detection and measurement. A Technical Document (TECDOC) and an ISO draft were prepared and are under revision.

Encouraged by the results of previous CRP on small diameter pipes, a new CRP for the large diameter pipes has been initiated to extend the results to larger diameters. The participating laboratories this time are from Algeria, Canada, Germany, Hungary, India, Iran, Malaysia, Pakistan, Romania, Syria, Turkey and Uruguay.

2. Scope of CRP on Radiographic Evaluation of Corrosion and Deposits in Large Diameter Pipes

The scope of this CRP includes the evaluation of radiographic techniques (Ir192, Se75, Co60 sources and x-rays) to evaluate artificial defects and simulated or natural corrosion attack on carbon steel and stainless steel piping from 6 inches in diameter (168 mm) up to 20 inches (508 mm) with and without insulation.

The major objective is to define the limits of detection for each radiation source using the tangential method. Internal and external defects will be included in the experimental programme. Film and nonfilm detection will be considered. The double wall technique will be further explored for application to the pipe sizes in this range. Results will be verified by other methods.

A further TECDOC is proposed based on the results of this CRP and the ISO Draft Proposal will be extended to include the larger diameters.

3. Lessons from previous CRP in Small Diameter Pipes

The Co-ordinated Research Programme (CRP) of the IAEA on “Validation of Protocols for Corrosion and Deposit Evaluation in Pipes by Radiography” aimed at developing protocols and instructions for identification and measurement of the corrosion attack and deposits in pipes in industrial installations during operation (on-line and maintenance). The CRP addressed the needs of end-users in terms of developing reliable and appropriate NDT measurement protocols which should refer to general requirements of international standards, (e.g. ISO 5579 RT basic rules, ISO 1160/3 RT circumferential weld in pipes, etc.) with full implementation of recognised quality assurance methodologies.

The activities of the CRP were implemented in the three groups. Each group carried out the Round-Robin Tests in order to compare the measurement results to determine the optimum test parameters.

The general scope of the CRP covered radiographic measurements of corrosion and deposits in up to 6” straight pipes and bends made of carbon or stainless steel corroded/eroded on the outer or/and inner surface without insulation or having thermal or/and bituminous insulation covering the outer diameter of pipe, some of them with deposit or sediments inside the pipe working in power sector, in petroleum and gas industry, in water installations. Film based tangential radiography and double wall double image technique was used as the basic method and film density measurement technique used as an alternative or complementary method. The results of radiographic testing were verified by ultrasonic measurements and destructive testing when appropriate.

Results obtained by all the countries for all pipes in their respective groups were discussed in a joint meeting. Evaluation was done considering the success rate in detection of defects and finding their nature as well as the minimum remaining wall thickness. Thickness loss caused by erosion/corrosion phenomena was measured with a maximum deviation of 1.5 mm (for two pieces) and 1 mm maximum for the others (25 pieces) The best accuracy achieved for thickness loss measurement was 0.5 mm.

The following conclusions were drawn from the CRP’s work:

- Tangential radiography and density measurement techniques are complementary methods. However for insulated pipes only tangential radiography is recommended, since the density measurement method requires complicated simulations. It is expected that the wall thinning due to uniform corrosion is irregular in the pipe’s cross section, so the density measurement method is not recommended, because this method give only the average wall thickness.

- For determination of the depth of pits, the density measurement method is recommended as limited to the small diameter pipes (≤6 inches). Tangential radiography is a more time consuming method for pit depth measurement, because it is difficult to get the tangential position of pit, thus requiring a large number of shots. In the density measurement method, use of low energy is advisable to get a high contrast. It is important to locate the pit (local corrosion area) correctly. It should lie on film side during exposure to prevent an underestimation of its depth.

- In the tangential radiography the maximum penetration thickness of pipe wall has to be considered for the energy selection of x-rays. To prevent the burn-off in outside extremity of the pipe, a filtration is necessary in order to cut the low energy components of x-ray beam. If available Ir-192 isotope is recommended instead of x-ray to get a better definition in tangential technique.

- Low speed films are recommended especially for density measurement technique. For tangential technique, the speed of film is not very important. A lead-intensifying screen shall be used in close contact with films. A lead plate shall also be used behind the film to protect against backscattering.
4. Theoretical aspects related to radiographic pipe inspection

4.1. Introduction to radiography

4.1.1. Radiation sources

Common radiation sources used for NDT are X-ray between 30kV and 450 kV and gamma ray sources (radioactive isotopes such as Iridium-192, Cobalt-60, Thulium-170 or Selenium-75. All are examples of electromagnetic radiation. These two types of radiation differ only in their wavelength and the way they are produced. Gamma rays are emitted during the disintegration of radio-active atomic nuclei. Unlike x-rays, the energy of gamma radiation sources cannot be altered. It depends upon the nature of radioactive source and is fixed for a particular source. The intensity is also not controllable, since it is impossible to alter the rate of disintegration of a radioactive gamma sources.

4.1.2. Radiation absorption in materials

When x-rays or Gamma rays pass through the specimen the intensity reduces due to attenuation of the rays. The intensity of the rays coming out of the specimen is given by:

\[ I = I_0 e^{-\mu t} \]  

Where:  
\( I \) = Intensity of the transmitted radiation  
\( I_0 \) = Intensity of incident radiation  
\( \mu \) = Linear absorption coefficient of the material through which radiation passes. It depends on energy of radiation and atomic number of material.  
\( t \) = Thickness of specimen in radiation direction

The above equation is true for narrow beam geometry (very good beam collimation) usually not encountered in practical applications. But practically besides the primary radiation also scattered radiation exposes the film. This additionally exposure (additionally film blackening) can be considered for example by an additionally “build-up factor”. This is defined as:

\[ I = B I_0 e^{-\mu t} \]  

Where B is called the ‘Build-up Factor’, considering the contribution of the scattered radiation. But this concept implies a constant scattering background like it is valid for flat plates and weld inspection. This concept is not applicable to the pipe inspection with it very large range of penetrated wall thicknesses.

The absorption coefficient \( \mu \) is connected with half value layer (HVL) by a relationship:

\[ \mu = \frac{0.693}{\text{HVL}} \]

For practical purposes, the half value layer and tenth value layer would be great advantage for calculations. Both values \( \mu \) and HVL depend on the material and the energy range used at the RT inspection.

4.1.3. Geometrical unsharpness

X-ray tubes and radioactive sources always produce a certain ‘isometric’ unsharpness because of the finite dimensions of the focus or source. The value of geometric sharpness (Ug) is given by following equation:

\[ U_g = \frac{d \cdot t}{\text{SFD}} \]

Where “d” is the size of the source; “t” is the wall thickness of the object; “SFD” is the source to film distance. It is desirable to keep \( U_g \) to minimum in order to detect fine defects.
4.1.4, Films and Detectors

Radiographic films are coated with sensitive emulsion of silver bromide on both sides of the cellulose triacetate or polyester base. The size of silver bromide particles determines the speed of the film. Fast films save exposure time but give lesser resolution than the slow films. For the x-ray energies higher than about 120 kV, film is used in conjunction with the foils of lead called ‘intensifying screens’. These screens improves the x-ray absorption and result in a higher signal-to-noise-ratio at the same exposure time. They also prevent scattered radiation with low energy reaching the film, improving contrast. In modern day radiographic film is quickly getting replaced by non-film type of radiation detectors. There is a wide range of such detectors from simplest fluorescent screen to linear diode array. All these permit on-line inspection and hence such method is called Real Time Radiography (RTR). Most of them are amenable to computerization by digitising the image. There is yet another computer supported detector called Imaging plate. It is a modified fluorescence screen, where the fluorescence is hampered and must be stimulated by laser stimulation with a red HeNe-LASER beam. At this time the imaging plate (BaFBr:Eu) emits blue light, which intensity is proportional to the exposed radiation dose of the imaging plate. Because of the Laser stimulation this technique does not provide real-time imaging.

4.1.5. Optical Film Density

Film density is a means of expressing the degree of darkening produced on a film. It is expressed as follows:

\[ D = \log_{10}(I_o/I_t) \]  

Where \( D \) is density of radiographic film, \( I_o \) is the intensity of incident light from the film viewer, \( I_t \) is the intensity of transmitted light which reaches the eye of the inspector.

4.1.6. Quality of Radiographs

Any radiographic image is characterised by three basic properties:

i) optical density of the film
ii) contrast resolution
iii) special resolution  

Optical density is determined by the film speed, and exposure time for a given specimen. Contrast on a film is governed by the specimen type, radiation used as well as by the film type. Resolution of the image is mainly influenced by the inner film unsharpness (determined by the radiation energy) and geometrical unsharpness of the geometrical set-up arrangement. Overall, the combined effect of all the 3 factors decides whether the image is capable of revealing intended flaws. For verifying its capability, a device called image quality identifier (IQI) or penetrameter is used.

4.1.7. Image quality Indicators (IQI)

As a check on the quality of the radiograph and the techniques adopted, a penetrameter, otherwise known as image quality indicator, is used during the exposure. The penetrameter is placed suitably on the test material and the exposure is taken. A variety of penetrameters are suggested by different standard organisations and are used in industrial radiography; none of which give information about the reliability of wall thickness measurementes by radiography.

4.2. Double wall Technique (DWT) for Pipe Inspection

4.2.1. Double wall single image (DWSI):

![Figure 1. Double wall technique (DW).](image-url)
If there is no access to the inside of the pipe either to keep film or source, this method can be adopted. This is mostly suitable for pipes of diameter above 85mm. Sources can be kept on the pipe or away from the pipe depending on the diameter of the pipe, SFD required and accessibility. See Fig. (1a).

### 4.2.2 Double Wall double image (DWDI)

This technique is adopted for smaller size pipes of diameter up to 85mm. The source is kept at an angle with respect to the weld so as to avoid the overlap of the top and bottom welds. Usually two exposures are taken by rotating the pipe through 90 degrees. See Fig. (1b).

### 4.3. Tangential Radiography technique (TRT)

Although the methods described in 4.2 are commonly used for RT of pipes, there is a certain geometrical set-up for pipe inspection and direct wall thickness measurement (Fig. 2). This method is called tangential exposure method. Here the parts of radiograph which lie below the tangential location on the pipe only are interpreted. The middle part of the pipe image is ignored. To get the proper image at tangential location, the energy of radiation used must be higher than that used for double wall inspection of the same pipe. This is the effect of the maximal penetrated wall thickness \( L_{\text{max}} \) at the point of the inner pipe surface.

![Figure 2. Tangential Radiography Technique (TRT)](image)

The most important application of this method is in absolute measurement of the wall thickness of the pipe. This is because the wall thickness is seen in profile in tangential radiography, almost like a longitudinal section of the pipe. Care must however be taken to correlate only that part of the pipe wall which lies at the tangent. Minor rotation will bring a different segment in image.

#### 4.3.1. Tangential RT and Wall thickness assessment

If a monochromatic radiation beam is passed through an insulated pipe with deposit, as shown in Fig. (3), the formula of transmitted radiation intensity \( I \) is, as follows:

\[
I = I_0 B e^{-2 \left( \mu_c x_c + \mu_s x_s + \mu_d x_d + \mu_m x_m \right)}
\]

Where \( \mu_c, \mu_s, \mu_d, \mu_m \) are the linear absorption coefficients of the insulator, steel, deposit, and transported matter, \( x_c, x_s, x_d, x_m \) are the transmitted thickness of the insulation, steel, deposit and transported matter.

Using geometry principle showed in Fig. (3) the transmitted thickness of every layer can be calculated according to a certain co-ordination \( r \):

\[
I = I_0 B e^{-2 \left( \mu_c x_c + \mu_s x_s + \mu_d x_d + \mu_m x_m \right)}
\]
Figure 3. Absorption of radiation

Transmitted transported matter thickness:
\[ x_m = \sqrt{r_d^2 - r^2} \]  
(7)

Transmitted deposit thickness:
\[ x_d = \sqrt{r_i^2 - r^2} - x_m \]  
(8)

Transmitted pipe wall thickness:
\[ x_s = \sqrt{r_o^2 - r^2} - (x_d + x_m) \]  
(9)

Transmitted insulator thickness:
\[ x_c = \sqrt{r_c^2 - r^2} - (x_s + x_d + x_m) \]  
(10)

Where: \( r_c \) = outside radius of insulator, \( r_o \) = outside radius of pipe, \( r_i \) = inner radius of pipe, \( r_d \) = inner radius of deposit.

When using tangential radiographic method the minimum transmitted pipe thickness is zero, which is the pipe outside tangential point. The maximum transmitted thickness (\( L_{\text{max}} \)) is the chord which is through the tangential point on pipe inside the diameter (see Fig. (2)). Because the thinnest portion will cause a too dark image (burn-off) and the thickest portion will cause a too bright image, the selection of optima irradiation sources energy and RT parameters are very important.

Using the general formula (6), we can get the particular formula for different types of piping, such as bare empty pipe (\( x_c = 0, x_d = 0, x_m = 0 \)), bare empty pipe with deposit (\( x_c = 0, x_m = 0 \)), insulated empty pipe (\( x_d = 0, x_m = 0 \)), insulated empty pipe with deposit (\( x_m = 0 \)).

Using the equation (6), the theoretical intensity co-ordinator (I-r) curves can be made, as shown in Fig. (4). The inflection points of the curves will correspond with the boundaries between different layers. The distances between the inflection points will correspond with the thickness of layers.
It may be noted that the real traversed maximum thickness is much more than pipe-wall thickness while using the tangential radiography technique. Selection of irradiation source must therefore be according to the maximum of the transmitted thickness, \( L_{\text{max}} \):

\[
L_{\text{max}} = 2w \sqrt{\frac{\text{OD}}{w - 1}}
\]

Where \( w \) = pipe-wall thickness, \( \text{OD} \) = outside diameter.

Selection of higher energy radiation ray helps in reducing the contrast. Higher contrast would extend the low density zone corresponding to the wall much inside the diameter of the pipe. That makes the determination of wall thickness difficult. Lower contrast picture obtained at higher radiation energy has better delineation of the ID profile.

The technique of Tangential Radiography can be used for assessing the residual wall thickness in those segments of process pipelines where corrosion or erosion are likely to have occurred. It can similarly be used for assessing the scaling of ID or finding deposit inside the tubes. This CRP addresses the problem of determining effectiveness of application of technique determination in corrosion depth determination in the pipelines.

4.3.2. Density measurement method and pit depth evaluation

When a pit is just located on a side tangential wall, its size and depth can be easily evaluated by the TRT radiography (Fig. (5a) pit 1). In other cases the DW radiography and density-thickness reference curves (Fig. (5c)) should be used. The pit distribution, its size, will be obviously shown on the DWDI film. Its depth, however, will be evaluated by the following procedure.

When a pit (Fig. (5b) pit 2) is located on the axis area, the pit depth and remaining wall thickness can be determined by using measured densities of the pit and sound wall, and the reference density-thickness curve of a step wedge is exposed (Fig. (5b, c)). For establishing the density-thickness reference curve, the stepped wedge should be made from the same material as the tested pipe and its thickness should cover twice the pipe wall range.

When a pit is located on some angle from the axis (Fig. (5b) pit \( \alpha \)) the real depth (\( H \)) should be calculated using a correction formula:

\[
H = \Delta \cos \alpha
\]

Where \( \Delta \) = transmitted pit wall length, \( \alpha \) = pit location angle.

![Figure 5. Measurement of corroded depth.](image)

4.3.3. Magnification correction

According to the geometrical set-up of the tangential exposure technique (see Fig. (2)) there is a magnification factor inherent to this set-up. To consider this, a correction on the estimated wall thickness must be done. The following correction can be applied. The true wall thickness is:

\[
w = \frac{w' \cdot (f - R)}{f}
\]

Where: \( w' \) is the apparent wall thickness, \( R \) is the pipe radius (including insulation), \( f \) is the Source Film Distance (SFD).
4.4. Limits of tangential inspection technique

One of the main aims of the CRP is to establish the application limits of tangential inspection technique. As a starting point BAM provides a diagram (see Fig. (6)). It is based on maximum penetrable wall thicknesses of pipes ($L_{\text{max}}$) in depending on the radiation energy. $L_{\text{max}}$ determined the maximum wall thickness which can be inspected at a given pipe outside diameter $D_a$.

If a given combination of outer pipe diameter and wall thickness is exceeding the limiting dashed line for the chosen energy, this energy cannot be applied for successful tangential inspection, because the position of the inner wall cannot be determined from the radiograph. As alternative a higher radiation energy can be used (e.g. replace Ir 192 by Co 60), or the double wall inspection technique must be used. Here the double wall technique (DWT) can be applied.

![Figure 6. Suggested application limits for tangential inspection techniques](image)

5. General Procedure for the current CRP

Each country shall manufacture at least 2 reference blocks as described in this document, covering the diameters and wall thickness to be tested.

Transmission densitometers shall be calibrated using X-ray step tablets certified by the BAM. Density measurements shall be corrected to reach a ± 0.1 precision.

Developing systems shall be checked using certified pre-exposed strips, which are to be developed at the same time as the films.

Reference blocks shall be tested according to the procedure and for each radiographic arrangement described in this document. Results will be interchanged between participants working with the same diameters, establishing the limits of each radiation source and exposure technique.

Other probes will be tested, with artificially introduced natural defects, according to the established limits.

5.1. Standard reference objects

Type and size of defects to be considered are as follows:

i. Step block with holes inside and outside (one pipe specimen with machined steps inside and outside)

ii. Each step will be chosen to range from 0 to 0.7 t in steps of 10% wall thickness rounded up to nearest half mm; 20 – 50 mm in length; precision in wall thickness shall be ± 0.1 mm.

iii. Hole diameter will be equal to remaining wall thickness, minimum of 2 mm.

iv. Hole depth shall be 10, 20 and 50% of the step thickness spaced at different circumferential positions (separated by 120°), holes shall be flat bottom.
v. Where steps are located at the inside surface of the pipe, material will be removed by grinding or machining to a depth of 15\% of maximum wall thickness of the pipe, forming a flat surface. Length covering all the steps. 30° separation from closest holes. Precision shall be ± 1\%.

vi. Where steps are located at the outside surface of the pipe, material will be removed by drilling with a 20 – 25 mm diameter tool, parallel to the pipes axis to a depth of 15\% of maximum wall thickness of the pipe. 30° separation from closest holes. Length covering all the steps. Precision shall be ± 1\%.

5.2. Pipe Dimensions and kind of tests

Twenty four specimens will be required distributed amongst twelve participants covering commonly used outside pipe diameters and suitable wallthickness ranges to reach the application limits of tangential radiography technique.

On every pipe size radiographic tests will be performed in 6 different positions for the tangential method and in 5 different positions for the double wall technique, exposing every artificial discontinuity to the tangential or center position respectively. Each test will be performed with and without removable glass wool insulation of approximately 50 mm thickness.

Additional defects can be introduced in separate blocks or in the reference block, provided they do not interfere with the ones described before. These could be artificially induced to simulate shapes and sizes of natural defects.

Samples for erosion, corrosion and pitting shall be selected in the same diameter and thickness ranges as above.

5.3. Procedure

Tangential projection technique (shadow shots) shall be used using Ir 192 and Co60 radiation sources. The same specimens and reference blocks may be used for double wall technique. Beyond the limits of this technique for Co 60, double wall single view technique will be used.

Figure 7 shows the experimental setup. Position 1 is applicable up to outer diameter max 220 mm (8 inch nominal). Larger pipes should be exposed according to position 2.

![Figure 7. Radiographic set-up for tangential projection technique](image)

Double wall technique should be used in the case, where tangential technique fails because of too high L_{max} (wall thickness cannot be measured because inner pipe diameter cannot be detected). Experimental set-up showed in Fig. (1a) is preferred for large pipe diameter depending on the geometrical unsharpness.

Radiation sources can be X-ray (including 2 mm Cu prefiltering), Se 75 or in most cases Ir 192. Limit energy for x-ray inspection should be 20 % higher than recommended in ISO 5579.

Many details about the radiographic procedure have been established to allow better comparison of rexperimental results, regarding radiographic arrangement, radiation sources, SFD, Ug, desired density range, exposure time
calculation, screen/film systems, magnification correction, shielding against scattered radiation, IQI, film processing and film evaluation procedure.

6. Conclusions

The current CRP is well underway with experiments being carried out in all of the participating countries. With this level of cooperation, the major objective of defining the limits of validity of the technique will be achieved, the results will be published in a TECDOC, and an ISO document produced which will make it available to all.

7. References