TRANSCATTER X- RAY TECHNIQUE FOR THE INSPECTION OF INSULATED, OIL-CARRYING PIPELINES

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INTRODUCTION

Pipelines are subjected to corrosion and require periodic inspection. These pipes are generally covered with an insulating material, that is contained within a metal jacket. The removal of the insulating material is costly, and can hazardous if asbestos is the material being removed. Because a large number of pipes need to be inspected, a cost effective technique for the characterization of corrosion under insulation is desirable.

Damage to a pipeline can manifest itself in various forms, as illustrated in fig. 1. In cases where the pipeline is tightly covered by a layer of insulation, the rust may be retained resulting in no loss of the total iron content. Sometimes part of the rust can be lost by leaching or by the movement of rust particles due to vibration. In addition to corrosion, metal losses due to erosion can also occur on the inside of the pipe, and these losses are even more difficult to measure. The type of metal losses illustrated in fig. 1 can be identified by means of x-rays or gamma rays. Transmission radiography [1,2] using a radium source is the most widely used technique for these types of measurements because it shows the presence of corrosion and also permits the wall thickness of the steel to be

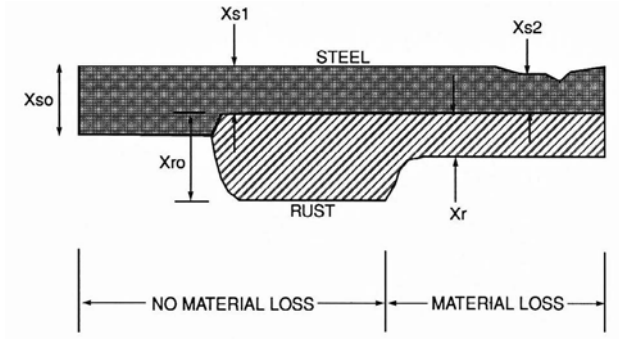

Figure 1. Steel losses due to corrosion and erosion; x_{SO} represents the thickness of the original steel wall, x_{rO} the thickness of the rust layer without loss of material, x_{S1} the wall thickness of the unaltered portion of the pipe, x_r the rust thickness when partial loss occurs, and x_{S2} the wall thickness of the pipe due to both erosion and corrosion.

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evaluated. The most serious limitation of the transmission method is that the sample must be located between the x-ray source and the detector, requiring two opposite sides of the sample to be accessible. When backscatter x-rays are used, both the source and the detector are located at the same side of the sample. This one-sided technique, which will be described here, permits metal losses due to corrosion and erosion to be quantitatively characterized.

THE BACKSCATTER TECHNIQUE

Figure 2 illustrates the principle of the backscatter x-ray technique [3-11]. It shows a typical pipe that consists of a metal jacket on the outside, an insulator, a layer of rust, an uncorroded pipe, and a hydrocarbon. A collimated x-ray beam penetrates the pipe, and a fraction of the backscattered radiation is measured by a collimated detector. The measured intensity at any point of the sample is proportional to the mass density of the sample and the local x-ray intensity. As the beam penetrates deeper into the sample its intensity decreases according to an exponential function. Figure 2 shows that as the detector moves to the right (the y coordinate) its response is a density profile in the depth (the x coordinate) dimension of the sample. Modulated on this density profile is the exponentially decaying intensity function caused by scattering and photo electric losses within the sample. A profile, as depicted in fig. 2, can be used to identify any transition points where a density change occurs, thus permits the thickness of a specific region to be determined. In practice, however, the boundaries becomes blurred for two reasons. First, the intensity of the incident beam is reduced in the depth dimension according to an exponentially decaying attenuation function. Secondly due to the finite size of the x-ray beam and the detector collimator the density profile become blurred. In effect, if the detector attempts to measure the intensity scattered by a specific voxel, it receives radiation from neighboring voxels also. When the magnitude of the beam attenuation function becomes comparable to that of the blurring function, the sharp transitions shown in fig. 2 disappear and are replaced by gradual changes in intensity. The resulting smooth transitions are shown in fig. 3, which depicts the density profiles of steel of various thicknesses and the profile of paraffin as well.

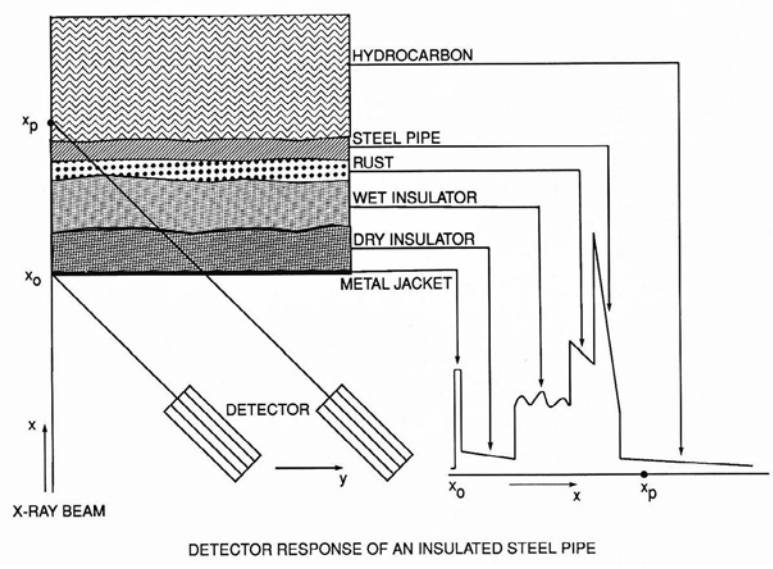

Figure 2. The geometrical arrangement of the x-ray source and the detector for the backscatter technique as described in the text. The ideal density profile of a typical insulated pipe is also shown.

Figure 3 shows that the boundary markings between the steel pipe and the hydrocarbon has vanished, and therefore it is not possible to evaluate the thickness of the steel based on these markings. Figure 3 also shows that the scatter intensity from the paraffin decreases as the steel thickness increases but remains fairly constant in the depth dimension. The transcatter technique takes advantage of this phenomena by computing the steel thickness from the scatter intensity of the paraffin. In effect, the thickness is calculated in the same manner as in the transmission technique by measuring the attenuation of the incident x-ray beam as it passes through the steel sample. In contrast to the transmission technique, however, the *transcatter* technique measures the radiation of the *tran*smitted beam after it is *scatter*ed by the paraffin. In this way the detector can be located at the source side eliminating the need to access both sides of the sample.

Two advantages of the transcatter technique becomes apparent, each of which results in an increased intensity. First, in this technique we do not need to know the intensity distribution in the depth dimension, so the blurring function becomes irrellevent. Because of this, the incident beam can have a large diameter without affecting the depth resolution of the measurement. Secondly, as compared to steel, the attenuation in the hydrocarbon is small, and thus, the scatter intensity of a large voxel of hydrocarbons can be collected without affecting the accuracy of the measurement. Figure 4 shows the experimentally determined calibration curve obtained for steel without rust. It reveals that the sensitivity for thickness measurements is excellent up to about 8 mm (1/3 in). The thickness values so obtained do not descriminate between rust and metal. To find the metal part, it is necessary to evaluate which portion of the evaluated thickness is in the form of rust. Since the new technique uses a *transmitted* beam that is measured after being *scattered* by the hydrocarbon, we named this method the "transcatter" technique. The dominant feature is that no profile in the depth dimension is required, and therefore, lacking a point spread function, a wide detector collimator as well as a large probe size can be used. In the backscatter technique the probe size determines both the depth resolution and the surface area resolution, and the former determines the precision with which the thickness can be evaluated. To be useful, the probe size must be much smaller than the thickness of the steel pipe. For example, if a loss of 10% in wall thickness is to be detected, the probe diameter must be at least 10% of that dimension. The transcatter technique on the other hand deals only with surface area resolution, so the probe size can be equal or even larger than the wall thickness without affecting the precision of the depth measurement. The probe diameter must be comparable to the size of the surface area where the thickness variation is to be measured.

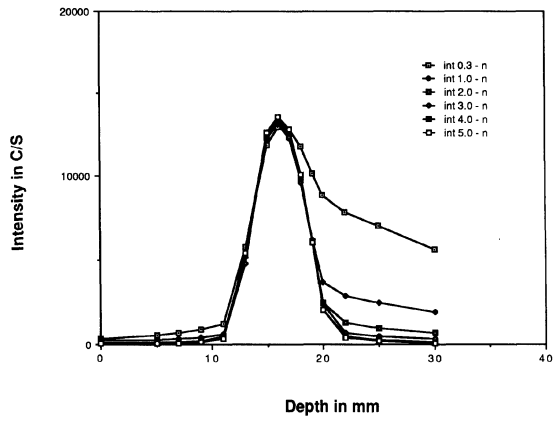

Figure 3. Experimental density profile for steel of various thickness, followed by paraffin, obtained at a tube voltage of 160 KV.

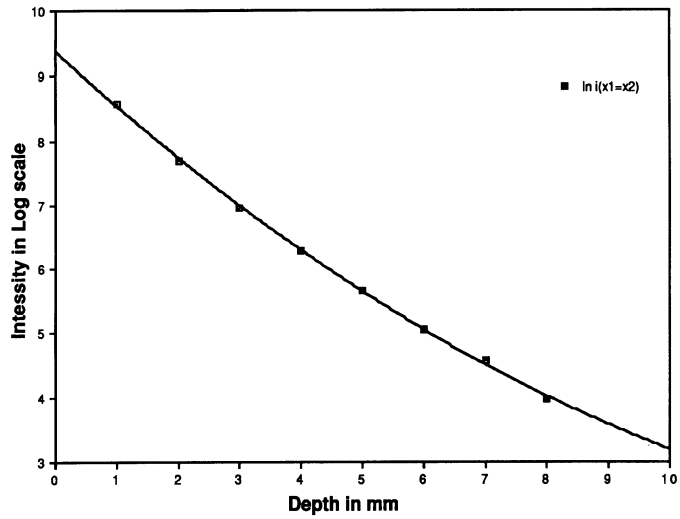

Figure 4. The natural logarithm of the transscatter intensity vs the steel thickness, obtained at a tube voltage of 160 KV for the case where $x_1 = x_2$.

A rather stringent requirement for the transcatter technique is that the measured radiation should come from the hydrocarbon only; and it cannot have components that are directly scattered by the steel. Since steel scatters roughly eight times more radiation than hydrocarbons of equal volume, the detector must be collimated to screen out any backscattered radiation from steel. This requirement necessitates that the transcatter beam, on its way to the detector, must go through a different part of the pipe than that struck by the incident beam. Since the premise is that the pipe thickness is not uniform, this requires that the pipe thickness should be measured at two locations. In the following sections we will discuss a method by which the two thicknesses can be obtained.

THICKNESS EVALUATION USING A DETECTOR PAIR

To obtain the thickness at two points X_1 and X_2, two independent measurements need to be performed from which the thickness x_1 and x_2 respectively can be evaluated. Figure 5 defines the parameters as related to the sample and beam geometry that will be used in the following discussion. This particular technique will be referred to as the "sequential" technique". The set up has two detectors symetrically located on each side of the incident beam. In the first measurement, the primary beam enters at point X_1 and the transcatter beam exits at X_2. The intensity measured at X_2 is I_1. In the second measurement the primary beam is shifted to enter at X_2 and the detector receives radiation which emerges from X_1. The two equations relating the two intensities to the two thicknesses x_1 and x_2 are:

$$\ln I_2 = \ln (\alpha I_o) - \mu_i x_1 - \mu_s x_2 \sec \Theta \qquad (1)$$

and after the beam is shifted to location X_2, as shown in fig.(5),

$$\ln I_1 = \ln (\alpha I_o) - \mu_i x_2 - \mu_s x_1 \sec \Theta, \qquad (2)$$

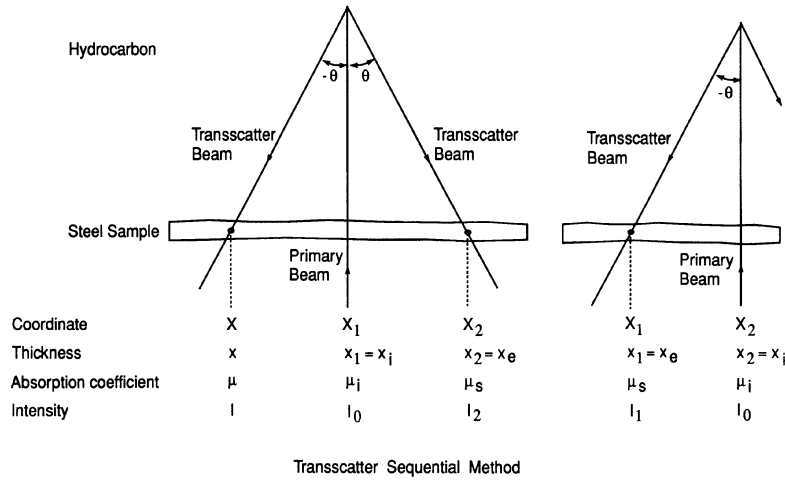

Figure 5. Definitions of the various parameters as used in the text. The right hand figure shows the situation after the incident beam has been shifted from X_1 to X_2.

where I_0 is the intensity of the incident beam, α is the ratio of the intensities of the beam entering, and scattered by the paraffin, μ_i and μ_s are the linear asbsorption coefficients of steel for the incident and scattered beam respectively, and Θ is the exit angle as defined in fig. 5. The thicknesses x_1 and x_2 can be calculated when the values of μ_i and μ_s are known. Due to beam hardening, however, μ_i and μ_s are dependent on both x_1 and x_2. We have developed a nomographic technique by which the thicknesses can be obtained with calibration curves. The mathematical justification of this technique will be the subject of a forthcoming publication. This method is based on the fact that in the sequential technique the location of X_1 and X_2 are reversed with respect to the incident and scattered beam. As a result eqns. 1 and 2 can be represented by one equation with either x_1 or x_2 as one variable and the sum $x_s = x_1 + x_2$ as the second variable. This function can be presented as a family of curves with different values for the sum thickness. This is shown in fig. 6. If the sum value is known, then x_1 and x_2 can graphically be obtained from the sum curve using the intensities I_1 and I_2. The sum is generally not known, the sum value can be found from the two intensity measurements:

$$\frac{\ln I_2 + \ln I_1}{2} = \ln I_a - \varepsilon \qquad (3)$$

where I_a is the intensity for the average value of x_1 and x_2 (which is equal to half of the sum), and ε is an error function of which the magnitude depends on the difference between I_1 and I_2. The error is zero when I_1 is equal to I_2. In the first order of approximation, the error ε is equal to zero and the first order values of x_1 and x_2 are graphically determined using the graphs shown in fig. 6. To obtain the second order approximation, the error can be computed from the first order values of x_1 and x_2 :

$$\varepsilon = \frac{\Delta x_2 - \Delta x_1}{2}, \qquad (4)$$

where $\Delta x_2 = x_2 - x_a$, $\Delta x_1 = x_a - x_1$, and x_a is the average value of x_1 and x_2.
In practice, this means that the second order values of x_1 and x_2 can be obtained from the first order values by adding the value of ε as shown above.

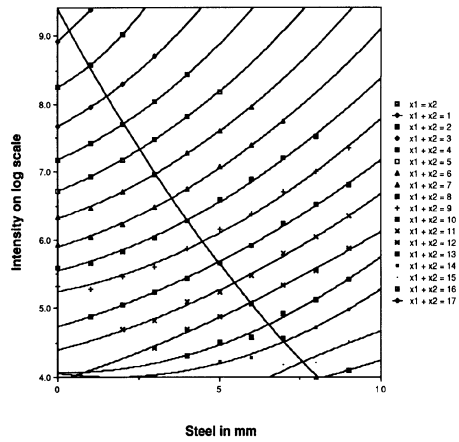

Figure 6. Family of curves of the intensity vs steel thickness for a constant sum x_S, $= x_1 + x_2$ as indicatedin the legend. Also shown is the graph for $x_i = x_S$. from figure 5.

The experimental results show that, the accuracy of the evaluation is less than 5 percent except where the values of Δx are large. Large values of Δx correspond to large material losses.

EVALUATION OF αI_0

As shown in eqns. 1 and 2, the determination of the thickness of steel requires that the value of αI_0. be known. The value of α depends on the density of the hydrocarbons running through the pipe and the angles of incident and exit and can therefore be experimentally determined. The value of I_0 , which is the intensity of the beam at the steel surface, cannot readily be determined because it depends on the intensity of the x-ray pencil beam at the surface of the metal jacket and the absorption of the material between this jacket and the surface of the steel pipe. The thickness of rust that affects the value of I_0 is not known and must therefore be determined. Experiments have shown that the scatter from a steel surface can be measured if rust is present up to about 10 mm thick and this measurement permits I_0 to be evaluated. A profile of rust on steel is shown in fig 7. The second peak on the right portion of the graph corresponds to the scatter from the steel surface.

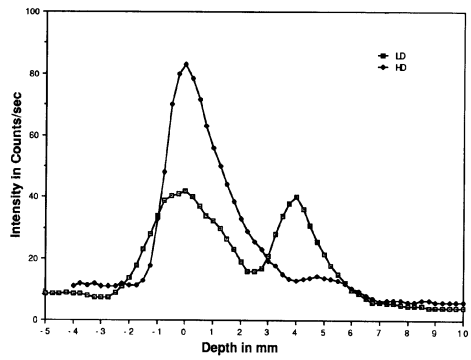

Figure 7.The density profile of high density (HD) and low density (LD) rust obtained at a tube voltage of 160 KV, 45° incident angle, 45° exit angle.

CONCLUSION

Experiments have shown that the transcatter technique permits the wall thickness of steel pipes, 8 mm or less, to be evaluated using an x-ray tube operated at 160 KV. The accuracy of this technique is 5 percent for practical values. When the pipe surface is corroded, a density profile of the rust and the steel metal surface must be obtained to evaluate the intensity of the x-ray beam at this surface. This profile can also mesasure rust 10 mm thick.

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