Application of a NaI(TI) scintillation detector in a portable gamma-ray tomography instrumentation for pipeline profiling to detect CUI

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Abstract:- This paper details a stability test performed on a NaI(TI) scintillation detector to determine its most suitable operating voltage range prior to using it in a portable gamma-ray tomography instrumentation for pipeline profiling. The hardware design for the portable gamma-ray tomography instrumentation, implementation of measurement electronics as well as the software to receive the intensity counts, convert and display a line image that corresponds correctly to the pipe condition of the pipe being scanned is also described. Some test results are included.

A. *Keywords:* Gamma-ray tomography, Gamma-ray transmission, Scintillation detector, Stability test

I. Introduction

Quality control and quality assurance procedures on nuclear instruments are a very necessary requirement to ensure that the instruments in question are safe for use, in good working order to ensure proper behavior, and avoiding the possibility of getting false pulses due to noise, high voltage failures, interference pick-up and leaking. It is also a very important aspect to consider because in most cases, these instruments are related to critical processes that include radiological protection, industrial processes, human health and even national safety. Accurate representation and measurement of radiation parameters must be ensured, for example the accurate measurement of the number of radioactive events, counting times and in some cases accurate measurements of the radiation energy and occurring time of the nuclear events [1]. Quality control tests are done at every various levels starting at the manufacturers of the instruments right up to the end users. There are several IEEE/ANSI standards that are in use as listed in the references [2-7].

A stability test is one of the quality control procedures for detectors that is conducted by end users. A stability test must be conducted before a scintillation detector can be used in order to obtain its most suitable operating voltage, at which point its readings are stable and dependable.

A basic tomography system can be built by mounting a number of sensors around the circumference of a vertical pipe or horizontal pipe. The output signal from the sensors will be sent to a computer wirelessly or via an interface card to be logged. After the signal from the sensors has been received and logged, the computer can then proceed to the next phase of the process, the data processing, after which, a cross-sectional image of the pipe is constructed.

In tomography, multiple projections are used to obtain sets of data from various views across the process vessel. These data are used to provide tomographic images representing the contents of the pipeline or vessel. The tomographic imaging of objects provides an opportunity to unravel the complexities of structure without invading the object [8]

Industrial insulation is something common to all industries dealing with flowing liquids, gases or solids. There are many integrity and safety challenges that have to be dealt with where industrial insulation is concerned. Corrosion under Insulation (CUI), one of the more serious issues, is one that requires urgent attention. Over time, pipes may corrode while set inside the insulation. Since these pipes are shielded from view, any sort of corrosion that occurs often goes unnoticed. These pipes often carry high-pressure, high-temperature gases, oils, hydrocarbons and many other highly dangerous and corrosive chemicals that are used in the processes specific to the industry. An example of this would be a petrochemical plant [9]. The implication of corrosion on these critical pipes is insurmountable. Corrosion causes pipe deterioration, leading to damage resulting in leakages. These leakages often cause fires, massive explosions and fatalities [10].

A non-destructive method is required to precisely perform this measurement. It would be highly cost effective to use the appropriate Non-Destructive-Testing (NDT) technique to detect CUI without removing the insulation. The data collected can be used to determine whether or not the pipes need to be replaced. A radiographic method would be able to fulfil these requirements perfectly. Firstly, it has the potential to perform inspection without the need of costly removal of insulation material during operation of the plant. Secondly, it offers an additional advantage of being able to perform measurement in high temperature, high pressure and harsh environments without short-changing on personnel or equipment safety.

In this paper, a gamma-ray tomography is implemented for the inspection pipelines as it is a non-destructive and contact-less procedure. It can therefore be used for pipes at essentially any temperature. It is able to produce the image of the cross-sectional slices of the investigated pipe. A portable and mobile hardware construction was designed to enable users to easily cart, assemble and disassemble the device wherever necessary. It is also able to operate without the need for plug-in power supply to enable it to be used in remote locations where power supply may be unavailable [11].

II. Gamma-rays

Gamma-rays are attenuated when they travel through matter. The extent of this attenuation is dependent upon the density and composition of the matter, and the distance the rays travel in it. The attenuation of a narrow beam of mono-energetic photons penetrating a homogeneous material follows Lambert-Beer's exponential decay law:

$$I = I_o e^{-\mu x} \ldots\ldots\ldots\ldots\ldots (1)$$

Where I_0 is the incident or initial intensity, x the thickness of the absorber; I the remaining beam intensity and μ is the linear attenuation coefficient. By selecting gamma-ray sources with correct emission energy it is possible to measure the thickness of material of constant attenuation coefficient, or the attenuation coefficient of material of constant thickness. Pulse mode read-out electronics or detectors are used to measure the intensity by detecting and counting individual gamma-ray photons transmitted through the process [10, 11]. In this experiment, since there is no obstacle between the source and detector, the factor that is kept constant throughout the experiment is the distance of travel between the detector and source to ensure the same rate of attenuation.

Conventional gamma ray computed tomography methods measure the attenuation of an incident beam that travels in a straight path through an object. The incident beam is partially absorbed and scattered in the object of interest, with the remaining transmitted radiation traveling in a straight line to the detector. The amount of attenuation is related to the atomic number of the phases distributed in the object, as well as their density distribution. As with radiography, access to both sides of the structure is required. [12]

III. Hardware design

The principle of gamma ray tomography measurement is based on the absorption of gamma radiation in the tested material. The scanning is performed using a small radioactive source and a sensitive electronic detector. The source and detector are kept external to the pipe and positioned on opposite sides at a fixed distance apart. Gamma rays travel from the source through the pipe to the detector where they are counted. A detector records the transmitted radiation and the measurement is then stored as an intensity profile. A stability test is done to determine the most suitable operating voltage range for a scintillation detector which is to be used in data collection. The collected data in the form of intensity is converted to a suitable signal and input in offline mode to produce a tomogram.

In order to construct a tomogram that is reliable enough to detect minute corrosion or erosion, enough data or projection sets must be taken. The Gamma-ray tomography system is divided into three main parts, as shown in Figure 1.

i. Mechanical structure
ii. Communication for data transfer
iii. Computer for data logging and image reconstruction

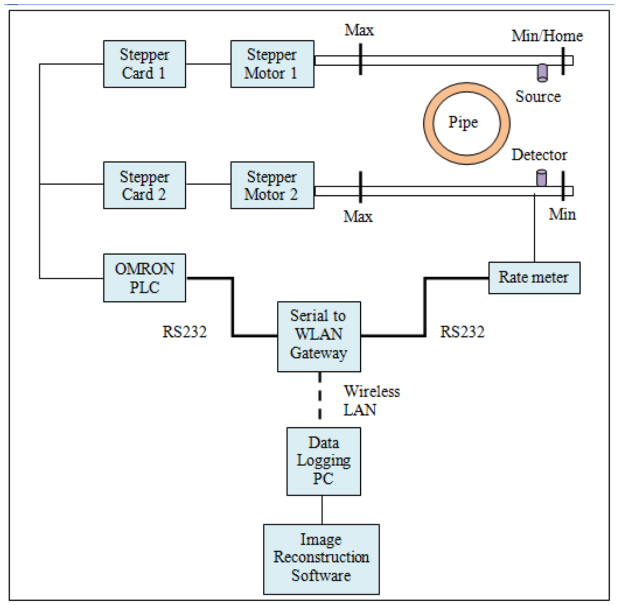

Figure 1: Portable tomographic system

The data for this system is collected and real-time profile imaging is done. The pipeline profile construction is done in offline mode. The data collected is then reconstructed to form a tomogram. Figure 2 describes the mechanical gantry constructed to house the detector and source, and for pipe placement. The source and detector are positioned at opposite ends of the pipe under test and then are moved simultaneously in parallel using stepper motors at precise distances as preset by the PLC. The maximum range of movement for the detector and source is 0-500mm. As such, the maximum outer diameter of the pipe that can be tested by this system is 500mm. The 'tracks' on which the source and detector move on are parallel to each other and can be set up to either move along the x-axis or y-axis. Using this setup, two projection sets are taken, one along the x-axis and another along the y-axis.

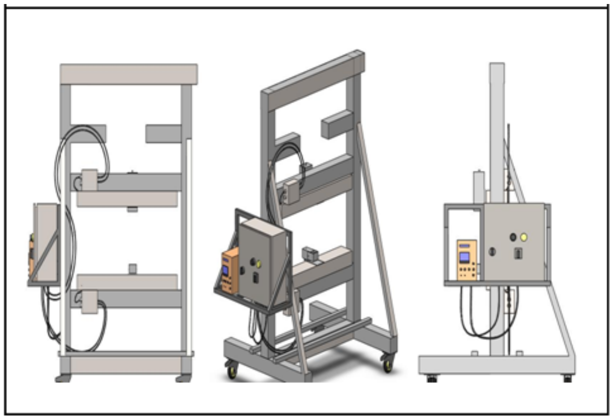

Figure 2: Portable design of the mechanical structure

The gantry with the parallel beams can be replaced with a movable circular gantry that could be easily rotated around the pipe under test as shown in Figure 3 to allow projections at multiple angles to be taken. The rotating mechanism is shifted by specific angular degrees depending on the size of the pipeline. The system moves source and the detector for a parallel beam scanning, and then rotates the gantry at a new projection angle for the next data set. This mechanism enables data to be taken along different angles and then used to reconstruct a tomogram of the pipeline under test.

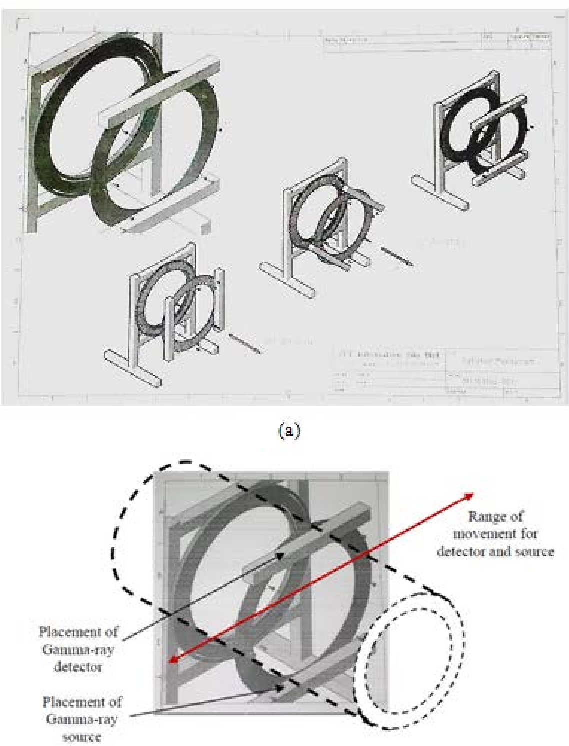

Figure 3: Design of the rotating mechanism

IV. NaI(Tl) Scintillation Detector

Scintillation is the ability of certain materials to display luminescence (light emission) when excited by ionizing radiation. This property enables us to use scintillation to detect ionizing radiation by measuring the light emitted. However, the resultant light from scintillation is very low and requires a fair bit of amplification to convert the few photons into a usable electronic signal. For this purpose we can use photomultipliers or semiconductors. Figure 4 shows the principal design of a scintillation detector with photoelectric conversion by a photodiode [13].

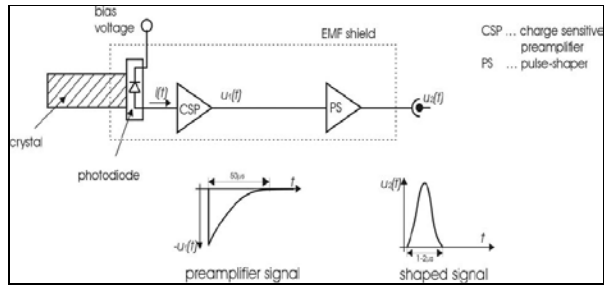

Figure 4: Principal setup for a scintillation detector with photodiode.

Thallium doped Sodium Iodide NaI(Tl) is by far the most widely used scintillation material and has the highest light output. It is available in single crystal form or the more rugged polycrystalline form. NaI(Tl) is very hygroscopic and needs to be housed in an air-tight enclosure. When a charged particle strikes the scintillator, a flash of light is produced, which may or may not be in the visible region of the spectrum. Each charged particle produces a flash. If a flash is produced in a visible region, it can be observed through a microscope and counted - an impractical method. The association of a scintillator and photomultiplier with the counter circuits forms the basis of the scintillation counter apparatus. When a charged particle passes through the phosphor, some of the phosphor's atoms get excited and emit photons. The intensity of the light flash depends on the energy of the charged particles. NaI(Tl) crystal is used as a scintillator for the detection of gamma waves [14].

The scintillation counter has a layer of phosphor cemented in one of the ends of the photomultiplier. Its inner surface is coated with a photo-emitter with less work potential. This photoelectric emitter is called as photocathode and is connected to the negative terminal of a high tension battery. A number of anodes called dynodes are arranged in the tube at increasing positive potential. When a charged particle strikes the phosphor, a photon is emitted. This photon strikes the photocathode in the photomultiplier, releasing an electron. This electron accelerates towards the first dynode and hits it. Multiple secondary electrons are emitted, which accelerate towards the second dynode. More electrons are emitted and the chain continues, multiplying the effect of the first charged particle. By the time the electrons reach the last dynode, enough have been released to send a voltage pulse across the external resistors. This voltage pulse is amplified and recorded by the electronic counter [14].

V. Experimental Setup

5.1 Stability test

HV value settings are obtained experimentally for each respective detector and is its most suitable operating voltage, at which point readings obtained are stable and dependable.

The instruments required for the test to be conducted are the ratemeter, blocks of lead for shielding, checksource (CS-137), and one detector (Named Detector A).

The ratemeter, checksource, detector and shielding are set up as shown in Figure 5. The ratemeter 'Threshold' dial is set to '1'. The ratemeter multiplier is set to 'x.1' and the numerical value set to '1' so that a reading is taken every 6 seconds i.e 0.1 x 1 min = 6 seconds. Setting the ratemeter 'HV Dial Setting' to 1.5 and pressing the 'count' button, the intensity count is noted. The ratemeter 'HV Dial Setting' is gradually increased by 0.01 and the intensity count noted down until it is approximately 5000 counts. The data is tabulated and an intensity vs HV dial setting graph is plotted. The most suitable HV dial setting is determined from the intensity vs HV dial setting graph.

Figure 5: Stability test setup

5.2 Real-time pipe profile construction

The first stage of tomogram reconstruction after setting up the scintillation detector involves the cross-sectional scanning of a pipeline along two axes, namely the x-axis and y-axis. The principle of gamma ray tomography measurement is based on the absorption of gamma radiation in the tested material. The scanning is performed using a small radioactive source and a sensitive electronic detector. The source and detector are kept external to the pipe and positioned on opposite sides at a fixed distance apart. Gamma rays travel from the source through the pipe to the detector where they are counted. The collected data in the form of intensity is converted to a suitable signal to be used in the construction of the pipe profile.

The tools for this are the Portable gamma-ray instrumentation and profiling software, two samples of insulated clean carbon steel pipes (Sample A, B), aluminium, scintillation detector (Detector A), radioactive source (Barium-133, 3.17mCi), polypropylene log, wax log, hollow polypropylene log, hollow metal pipe, concrete log, ratemeter, caliper, measuring tape. Different obstacles are inserted into Sample A and B and measured using the instrumentation. Data is tabulated and used to graph the pipe profile. The specification of the samples, obstacles and the instrumentation setup are detail in Table 1.

Table 1: Sample specification

Sample A: Pipe thickness = 7mm Pipe inner diameter = 156mm Pipe outer diameter = 170mm Insulator = carbon steel / calcium silicate Insulator thickness = 40mm Diameter of pipe + insulation = 250mm
Sample B: Pipe thickness = 6.46mm Pipe inner diameter = 101.65mm Pipe outer diameter = 115mm Insulator = carbon steel / calcium silicate Insulator thickness = 25mm Diameter of pipe + insulation = 165mm
Obstacles: Polypropylene log diameter = 136mm Concrete log diameter = 100mm Hollow polypropylene log inner diameter = 25mm outer diameter = 105mm thickness = 40mm Hollow wax log inner diameter = 40mm outer diameter = 100mm thickness = 40mm
Initial setup: Ratemeter HV dial setting = 2.5 Ratemeter threshold = 1 Source = Ba-133, 3.17mCi Number of points = 60 for sample A, 40 for sample B Stepper motor interval = 5mm Count period = 12 seconds

Figure 6: Polypropylene log, concrete log, hollow polypropylene log, wax log

5.3 Tomogram Reconstruction

Several tomographic reconstruction methods are described in the literature [15-18] and the method of choice depends on the quality of projection data. Although filtered back projection (FBP) gained popularity as a very fast reconstruction technique there are limitations in the image quality produced. To a large extent this is due to the back projection process and the necessary filtering [3]. This project uses a method that can extract and process area of interest similar to that proposed by Rania et al in [19] and image thresholding proposed by Zuliyana et al. in [20] A Gamma tomography analysis software written using C# is used to obtain these tomograms. The method applied in this project is largely mathematical due to the large data sets. In the software written in C#, the user is able to analyze by comparing two tomograms, the tomogram with simulated CUI and the ideal tomogram. Two tomograms are drawn, and the software is able to highlight the difference in both the tomograms reconstructed according to the error percentage that user inputs in the software.

VI. Results

6.1 Stability test results

Intensity count measurement obtained using Detector A is used to construct the graph shown in Figure 7

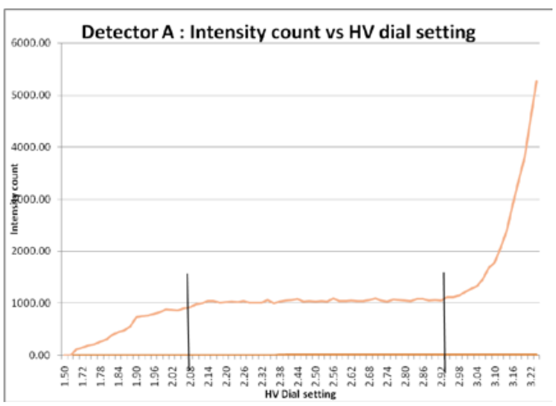

Figure 7

The optimum HV dial setting is approximately midway between the two vertical lines drawn on the graph. From the graphs, the most suitable HV settings for Detector A is 2.5V. This same detector is then applied in the pipe profiler.

6.2 Pipe profile image results

Results shown below in Figure 8 and Figure 9 are for pipe samples A and B having the polypropylene log and hollow polypropylene log as obstacles. The intensities are measured along the x and y-axis.

From the graphs obtained in Figure 8 and Figure 9, the thickness of the pipe, insulation and obstacles can be predicted based on the increase and decrease of the intensity counts. As the gamma irradiates the object under test, a portion of its rays are absorbed by the object and the rest are allowed to pass through. Data obtained is in the form of intensity after traversing the medium.

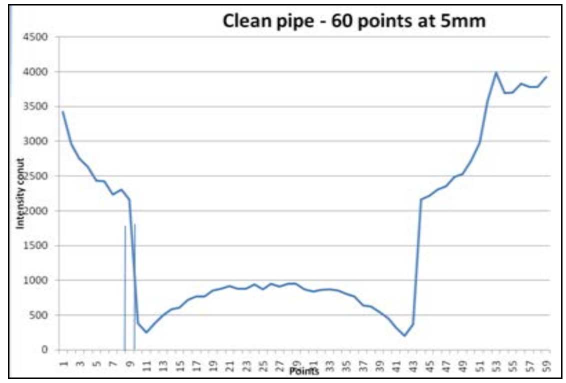

Figure 8 (a)

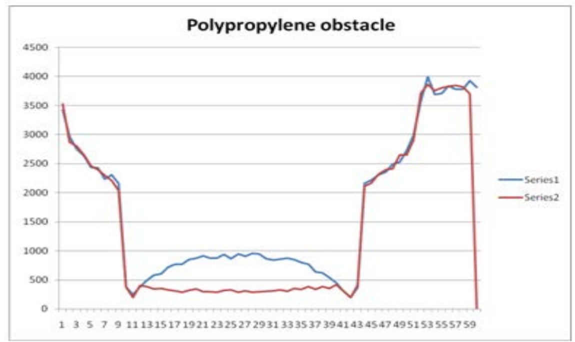

Figure 8 (b)

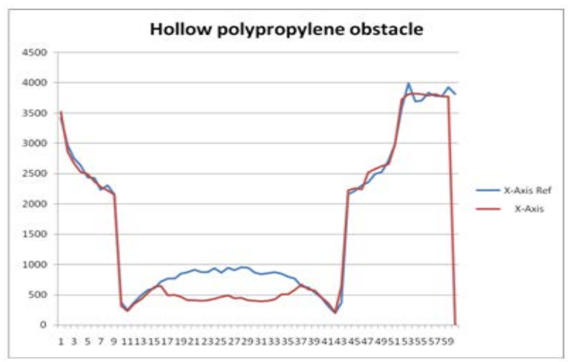

Figure 8 (c)

Figure 8(a-c): Profile for Sample A along the x-axis with selected obstacles

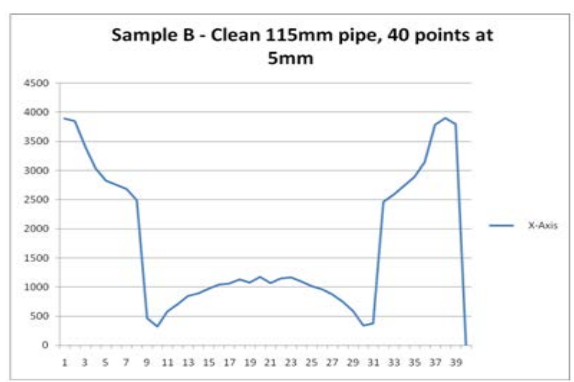

Figure 9 (a)

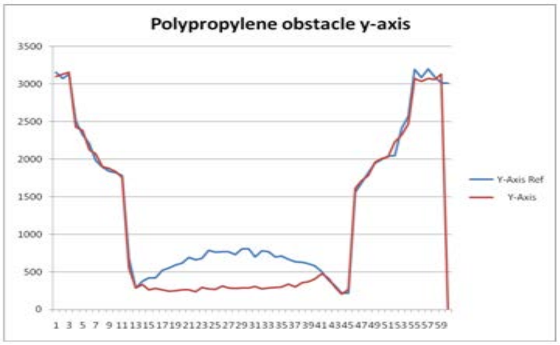

Figure 9 (b)

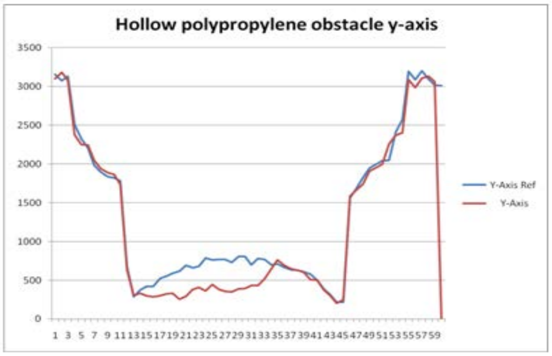

Figure 9(c)

Figure 9(a-c): Profile for Sample B along the y-axis with selected obstacles

The x-axis and the y-axis measurements do correspond correctly to the pipe's physical measurement. The slight differences between the actual pipe at the graphed data is due to the distance between each measurement. Figure 10 shows how the line image produced along the x-axis and the y-axis profiles exactly the pipeline under test.

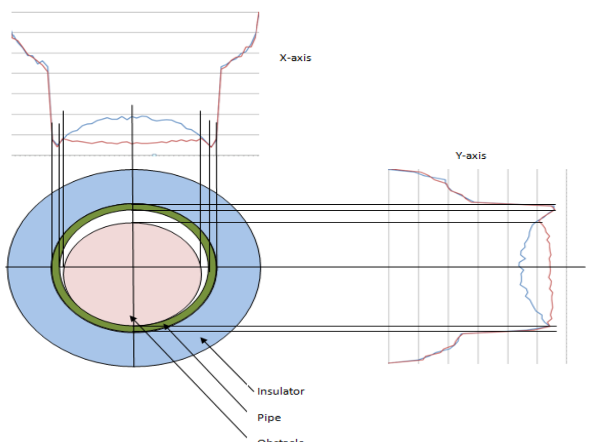

Figure 10

The results shown in the previous section are pipe profiles along one axis for samples having an obstruction placed into its cavity. For CUI, we are not focusing on the particles in the pipeline but on the defects on the pipe body. In order to reconstruct a tomogram for the purpose of CUI detection, pipe profiles along entire circumference of the pipeline need to be measured at selected angles. More projections at different angles are taken to obtain sufficient information to produce a tomogram of the pipeline under test.

Results shown in Figure 11 and 12 are for two pipeline sizes with different simulated CUI conditions. The threshold set is by trial and error. By reducing the interval between measurements, i.e increasing the number of measurement points, a more accurate representation of the pipe can be achieved. This is however limited to the diameter of the pipeline under test. A pipeline having a larger diamter allows for more measurement points and thus the final tomogram will have a higher number of pixels and a smoother looking image. The error tomogram shows the error between the ideal condition and the pipeline with simulated corrosion. By setting the threshold of error to a selected percentage, the red pixels the demarcate the position of the error,or in this case, simulated CUI.

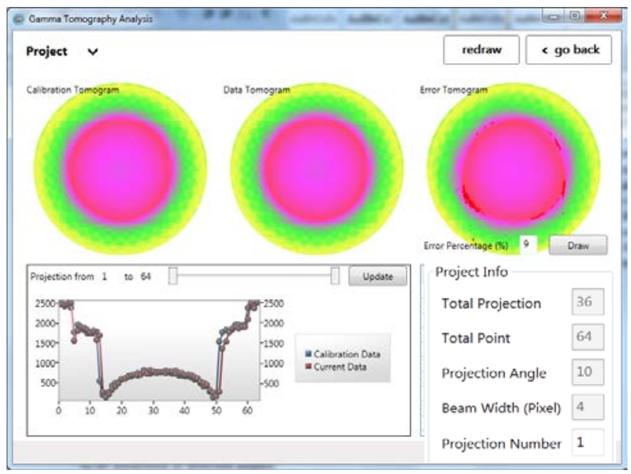

Figure 11: Tomogram for pipeline for 64 points, rotation of 10° each set

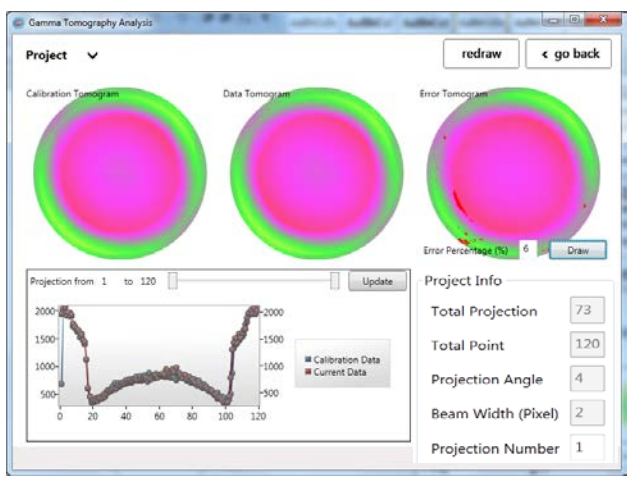

Figure 12: Tomogram for pipeline for 120 points, rotation of 4° each set

VII. CONCLUSION

A stability test must be conducted before a scintillation detector can be used in order to obtain its most suitable operating voltage, at which point its readings are stable and dependable. If the HV dial setting is set to a value that is too high above or too low below its stable range, the intensity counts obtained may not be accurate or even usable. A HV setting that gives an intensity count of more than 6000 may result in the detector being damaged hence the test is stopped once the intensity count logged is approximately 5000 counts.

The line image obtained using the intensity plot method will not and cannot correctly identify the specific location and severity of any defects since its range is only at one projection angle. However it serves to inform the engineer about the possibility of a defect in the pipeline under test.

In order to obtain the tomograhic image of the pipeline under test, the additional rotating mechanism is used. This mechanism enables the axis to be rotated around the pipeline under test thus enabling data to be taken along various angles and then used to obtain the cross-sectional slices of the pipeline under test to check for possible corrosion under insulation.

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