Radiographic Non-Destructive Testing Simulations Using GATE Software Toolkit

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Abstract

A workspace is created within the Geant4 Application for Tomographic Emission (GATE) software toolkit for radiographic Non-Destructive Testing simulations. The workspace contains models for x-ray and gamma ray emissions, test sample geometries, radiation interaction with the test sample, and image receptors to afford a radiographic non-destructive testing setup. The setup is then evaluated by simulating radiographic testing of stainless-steel step-wedges and a carbon steel flawed welded plate. The results are validated by comparing a simulated step-wedge image to an experimental radiograph.

The workspace can be advantageous to the industrial radiography specialists who are unfamiliar with medical imaging software. Running the simulation does not require working knowledge of GATE; the open-source software toolkit.

Keywords: Non-Destructive Testing, radiographic testing, simulation, Geant4, GATE

1. Introduction

Non-Destructive Testing (NDT) is a group of methods used to examine the engineering materials, components, and systems without causing damage to the items under test. Industrial radiography or Radiographic Testing (RT) [1,2] is an NDT method that utilizes gamma rays or X-rays to image the defects or the internal structure of a material. RT is one of the important methods for the safety and reliability assurance in industrial sectors like power generation, oilfields, petrochemical industry, aviation, and steel constructions.

The computer simulations of RT can be used to optimize or improve different processes like developing testing procedures, demonstrating the testing sensitivity, optimizing the radiation dose, and training of NDT personnel.

Despite the widespread of RT applications in all industrial sectors, the simulation products are uncommon. The research of T. Jensen and J.N. Gray on modelling X-ray radiography [3,4] has led them to the development of X-ray simulator (XRSIM) program [5] and then the real-time radiography simulation tool (RTSIM) [6]. Another simulation tool, Sindbad; has been developed focusing on the modelling of radiation scattered from the test sample [7]. A simulation tool that was meant to be practical with a user-friendly interface has been developed to produce radiographs of objects defined using Computer-Aided Design (CAD) [8], which has been developed to combine the analytical modelling of the radiographic testing process with CAD-orientated object description, and to address a wider range of applications [9,10]. The most renowned simulation software for NDT applications is CIVA, which is developed by the French Atomic Energy Commission (CEA). CIVA includes modules for Ultrasonic Testing (UT), Eddy Current Testing (ET), and RT.

Geant4 is a software for the simulation of particle behavior in high energy, nuclear physics, medical and space applications [11,12]. Fast neutron RT using 14 MeV Deuterium-Tritium neutron generator has been investigated by using Geant4 to model the radiographic setup of various samples and testing parameters. Geant4 has successfully modelled the system to help in understanding its response, and the experimental study showed the effectiveness of the technique [13,14]. There have been no reported studies on the X-ray and gamma industrial RT using Geant4 nor one of its dependent software.

The objective of this work is to develop resources and a workspace for the RT simulations for research and educational purposes based on Geant4 Application for Tomographic Emission (GATE) [15]. GATE is a Monte Carlo-based simulation toolkit that was developed to provide a realistic simulation for tomographic emission in medical applications. The toolkit was later extended to include radiotherapy and dosimetry applications [16–18]. Although GATE is based on Geant4, which is written in C++, it doesn't require any knowledge of the programming language. GATE can be used through a simple script language.

The use of GATE in this paper for industrial X-ray and gamma ray radiography simulations is a novel application that is hoped to acquaint the NDT community with GATE capabilities. The available tools in GATE as well as the fact that it is an open source software make it suitable to be used as a platform for developing an RT simulation environment for research education, and training purposes.

2. GATE simulations

2.1 Installation

GATE can be installed on Linux or Mac OS X. The installation process requires the compilation of GEANT4 and GATE packages. Alternatively, a pre-installed version of GATE known as “vGate” is also available. vGATE, which is short for virtual GATE, is a Linux-based system with GATE pre-installed on it. This virtual system can be run through a virtual machine software (such as VirtualBox). GATE can be launched through the terminal by simply typing “Gate”. The user then can start interacting with GATE through feeding the terminal commands. Alternatively, the user could use GATE to execute a macro file that contains a patch of commands.

2.2 GATE tools used for Radiographic Testing simulations

The simulation of radiographic testing setup involves modelling of four processes: radiation emission, the definition of test object geometry, the interaction of radiation with the test object, and radiation detection (see Fig.1)

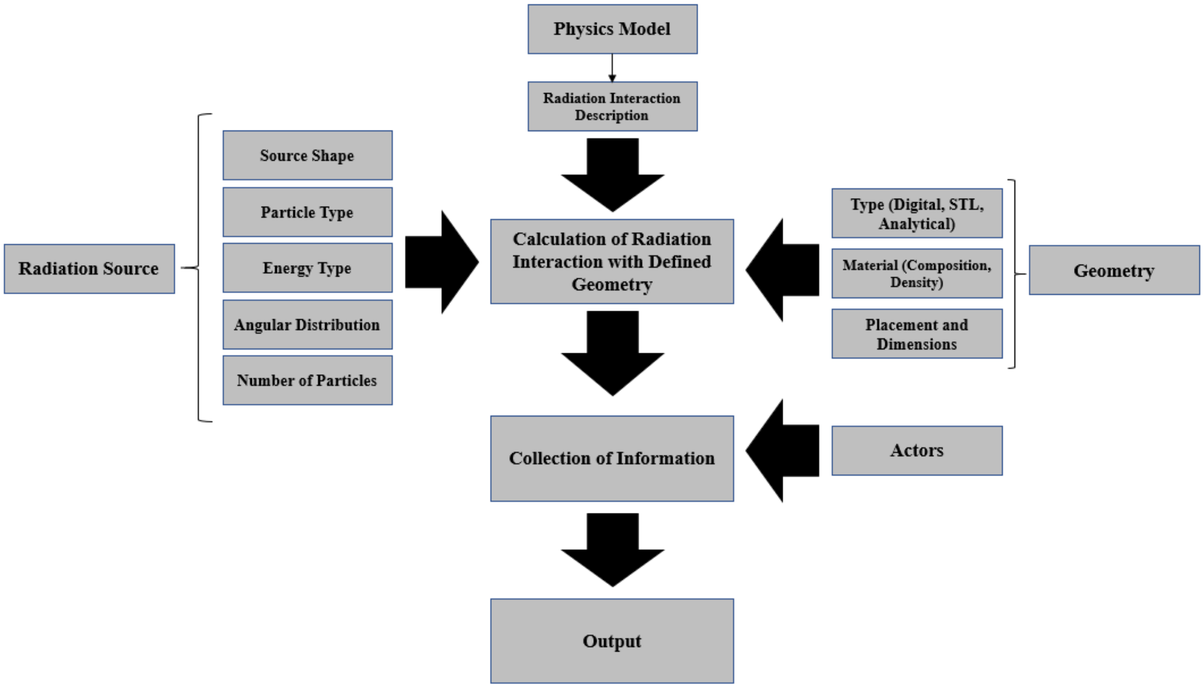


Fig.1 Flowchart of the modelling process

2.2.1 Radiation emission: The description of the radiation source should include the shape of the source (point, volume, surface…etc.), particle type (gamma, electron, positron…. etc.), energy type (mono-energetic, continuous spectrum, gaussian spectrum… etc.), number of particles, emission angular distribution, and position. Additional properties such as half-life and source movement can also be defined.

The gamma ray source ^{192}Ir was defined in GATE as a point source with a discrete spectrum having energies of 316.5 keV (83%) and 468 keV (47%).

The X-ray source was defined as a continuous spectrum with an effective focal spot width of 0.4 mm and a height of 1.15 mm. An aluminum 4-mm filter was used to remove the low x-ray energies. Five energies are available in the workspace: 120, 140, 160, 180, and 200 kVp.

2.2.2 Test object geometry: The geometrical setup of the simulation can be modeled through various methods in GATE. The most simple and direct method is based on creating analytical volumes from simple shapes, such as spheres, cylinders, and cubes. Although analytical volumes are the easiest way to create volumes in GATE, it is difficult to use it to accurately model complicated geometries. Alternatively, the modelling of a complicated geometry can be carried out through importing stereolithography CAD models (STL) or digital volumes. A digital volume is used to construct an object or a phantom by importing tomographic images of the object of interest, and a translation file is then provided by the user to convert pixel values into a material definition. The material definition process is based on assigning a material type to a pixel value range (e.g. assigning steel to pixels with values ranging from 10-20). Digital volumes are most helpful when the object of interest has a complicated geometry and composition. On the other hand, STL models, which represent a single material type, can be created through CAD software. For the test objects, materials database is already available in GATE. Materials like steel, aluminum, and copper can easily be defined, furthermore; the materials properties can be modified, and new materials can be added by assigning a unique name, describing the chemical or fractional composition, and defining the density.

Two step-wedges were created using GATE analytical volumes and a welded plate specimen was created using SolidWorks^{TM}.

2.2.3 Radiation interaction with the test object: Physics models are required by the simulation to describe the radiation interaction with matter, which is calculated using Monte Carlo methods. The selection of the model is application dependent. In some cases, the selection of the model is very significant, as some models can provide more reliable data than others.

Radiation interactions information can be collected in GATE through tools known as “actors”. Actors are customizable tools that can be attached to the volumes to record several types of information about the particle interactions within a volume, such as the number of interactions, dose, flux, and energy deposition.

The standard electromagnetic physics package was used to model the interactions in this study. This package provides accurate description of the physical interaction mechanisms and probabilities for photons and electrons in the energy range 1 keV-10 PeV [19,20].

2.2.4 Radiation detection Models

A radiographic film was defined as a 5 mm thick photo emulsion layer; consisted of 400×800 pixels with a pixel size of 0.1 mm. The film is placed between two lead sheets to model the radiographic screens, the first is the front screen with a 0.1 mm thickness, and the other is a 0.15 mm thick back screen.

Also, a *BaBrF* Computed Radiography (CR) imaging plate, consisting of 600×1000 pixels with a pixel size of 0.1 mm was defined.

Blurring and noise were not modeled for both image receptors, and it was assumed that each interaction would produce a signal in the final image.

3. Testing the developed models

The step-wedged were used to assess the gray values corresponding to different thickness, contrast, and the definition while the welded plate was used to simulate the important RT application of weld testing.

3.1 Stainless steel step-wedges

Two step-wedges were created using GATE analytical volumes, the first one is having steps thicknesses of 2, 4, 6, 8, 10 and 12 mm. Each step is 10mm×10mm.

The setup for the simulated inspection of the X-ray radiography of the stainless-steel step-wedges is shown in Fig.2, and the simulation result of the first step-wedge using 160 kVp is shown in Fig. 3.

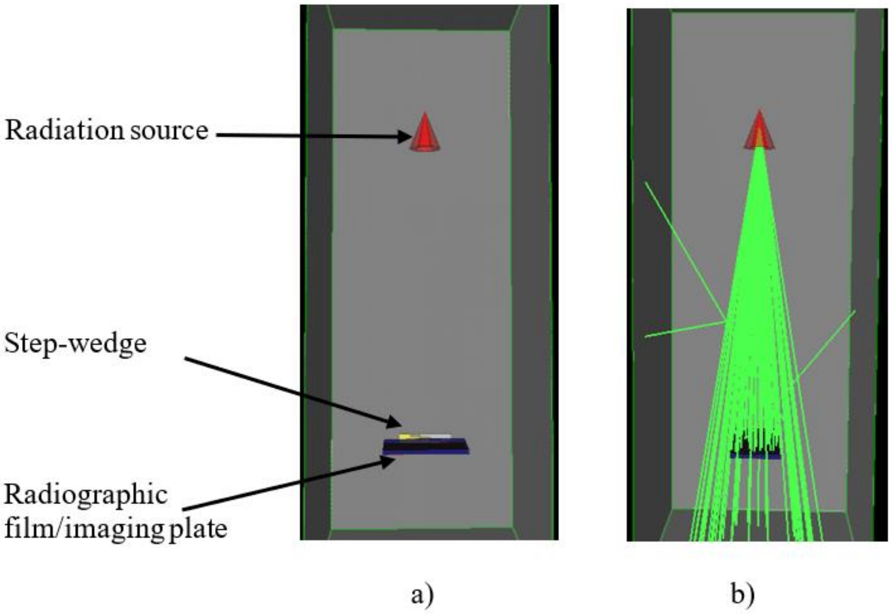
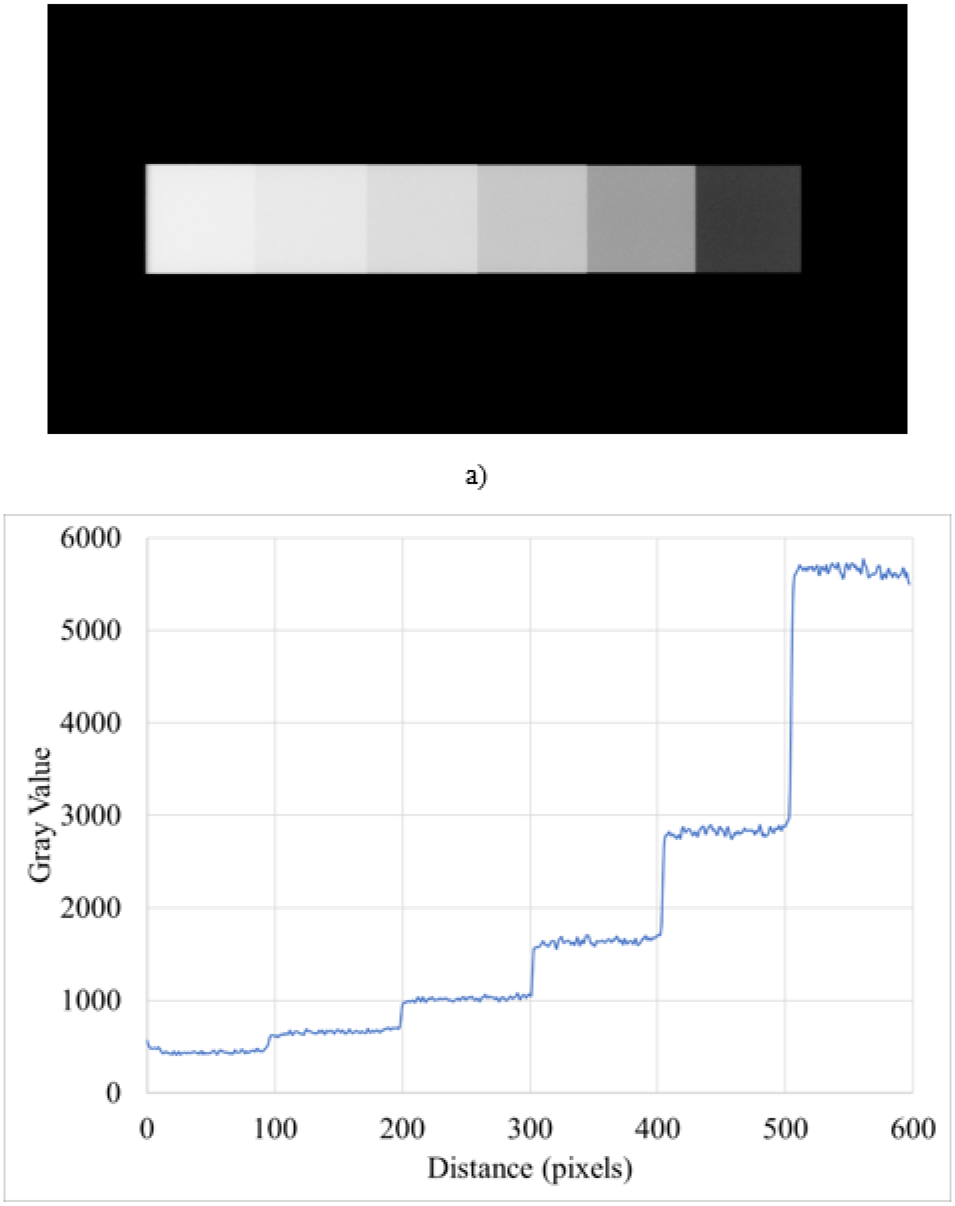


Fig.2 a) Inspection setup. b) X-ray exposure



b)

Fig.3 First Step-wedge X-ray radiography using 160 kVp, a) obtained image. b) grayscale profile

The second step-wedge was created to compare the results to an available experimental radiograph produced by a digital industrial radiography system that uses phosphor imaging plates. The thicknesses of step-wedges were 2.5, 5, 7.5, 10, and 12.5 mm and were tested using 160 kVp. The results are shown in Fig.4.

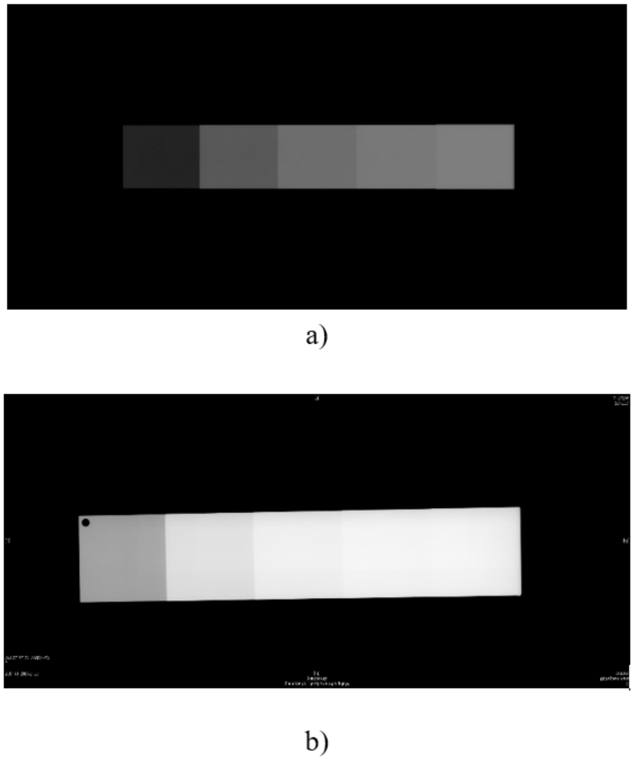
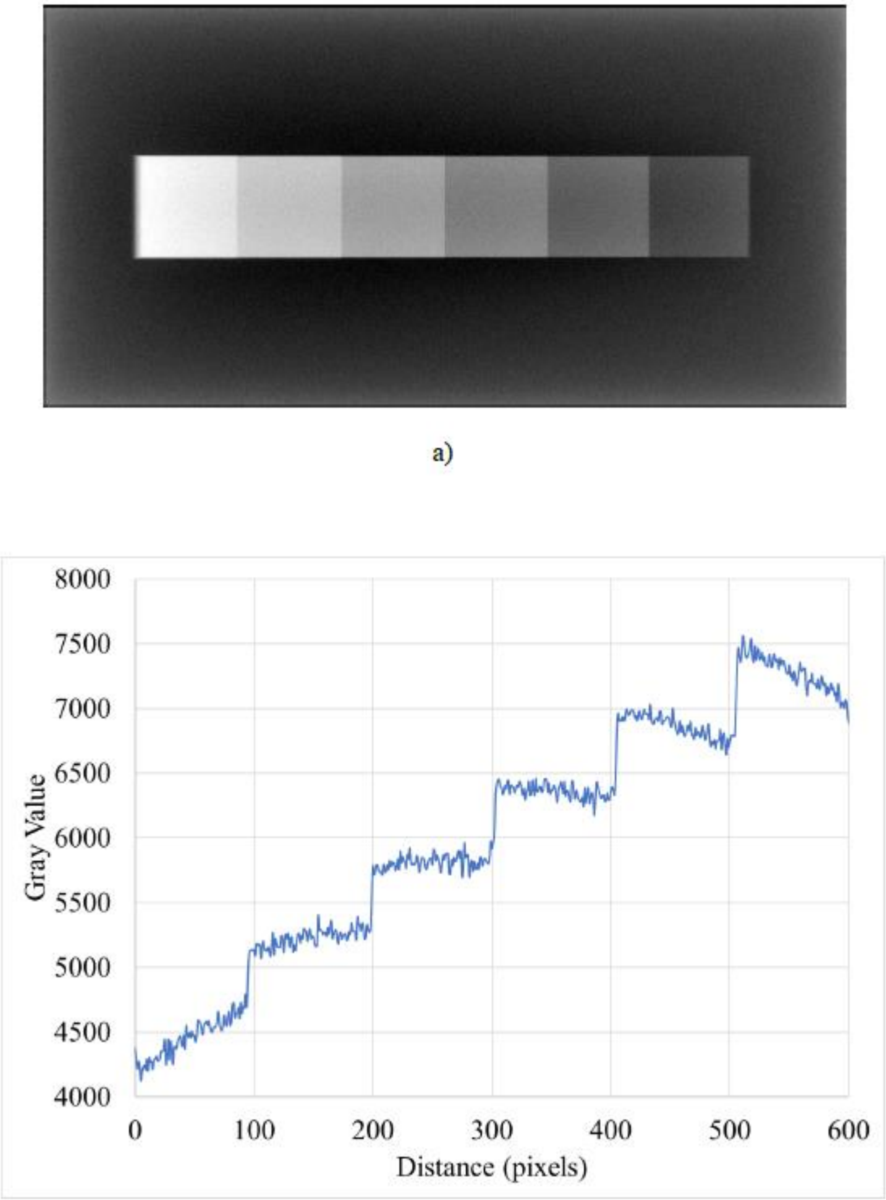


Fig.4. a) Simulated radiograph of the second step-wedge using 160 kVp. b) Experimental radiograph

The film densities (degree of blackening / gray values) were adequate. The grayscale profile was used to evaluate the definition and contrast of the radiograph of the first step-wedge. The sharp transition of the gray values from a step to another in the profile expresses a good definition, however; the contrast decreases as the step's thicknesses increase.

The experimental radiograph of the step-wedge shown in Fig.4 confirmed the pattern of the contrast at the thick steps and showed that the simulation is dependable.

For the ^{192}Ir radiograph, the result (Fig.5) agrees with known gamma radiography feature of lower definition than X-ray radiography; the grayscale profile is noisy due to the high-energy gamma ray interaction with the test sample and the surroundings.



a)

b)

Fig.5 Step-wedge radiography using ^{192}Ir. a) obtained image. b) grayscale profile

For comparison, Fig.6 shows that the contrast between the steps and background is superior when using the ^{192}Ir due to penetrability of the gamma ray.

Fig.7 illustrates that the X-ray has a lower probability of Compton scattering to total interaction mass attenuation coefficient as their average energy is below 100 keV which describes the sharpness in the images from X-ray simulations.

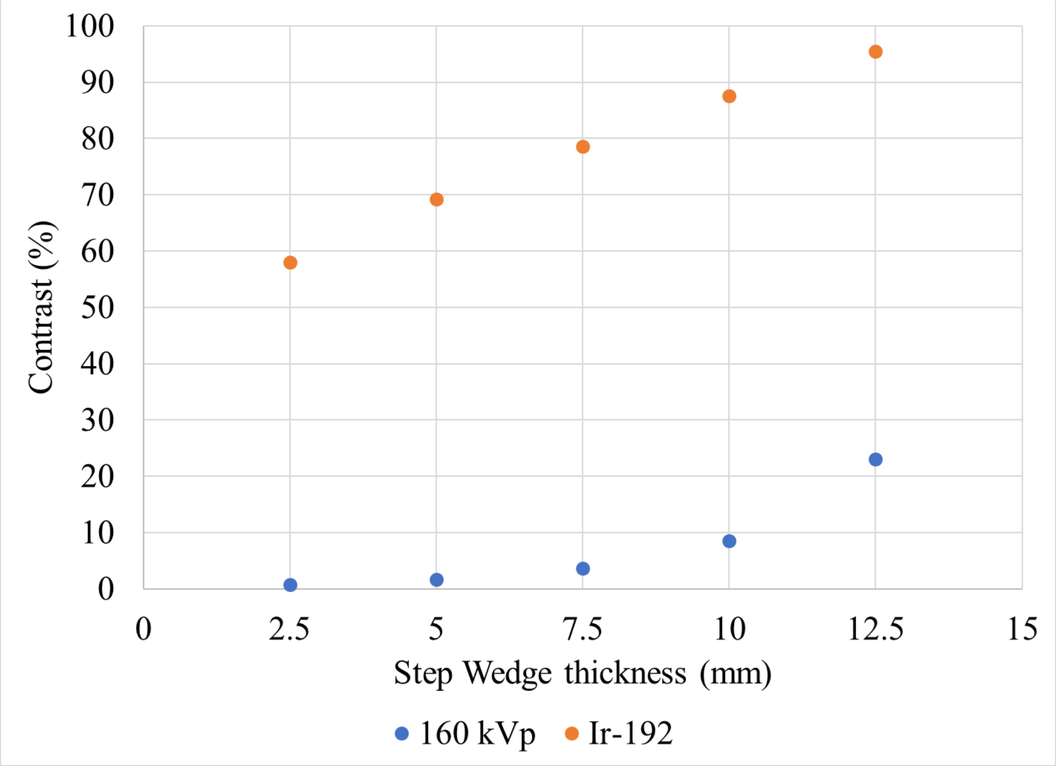


Fig.6 Contrast percentile of the step-wedge using X-ray and Gamma source

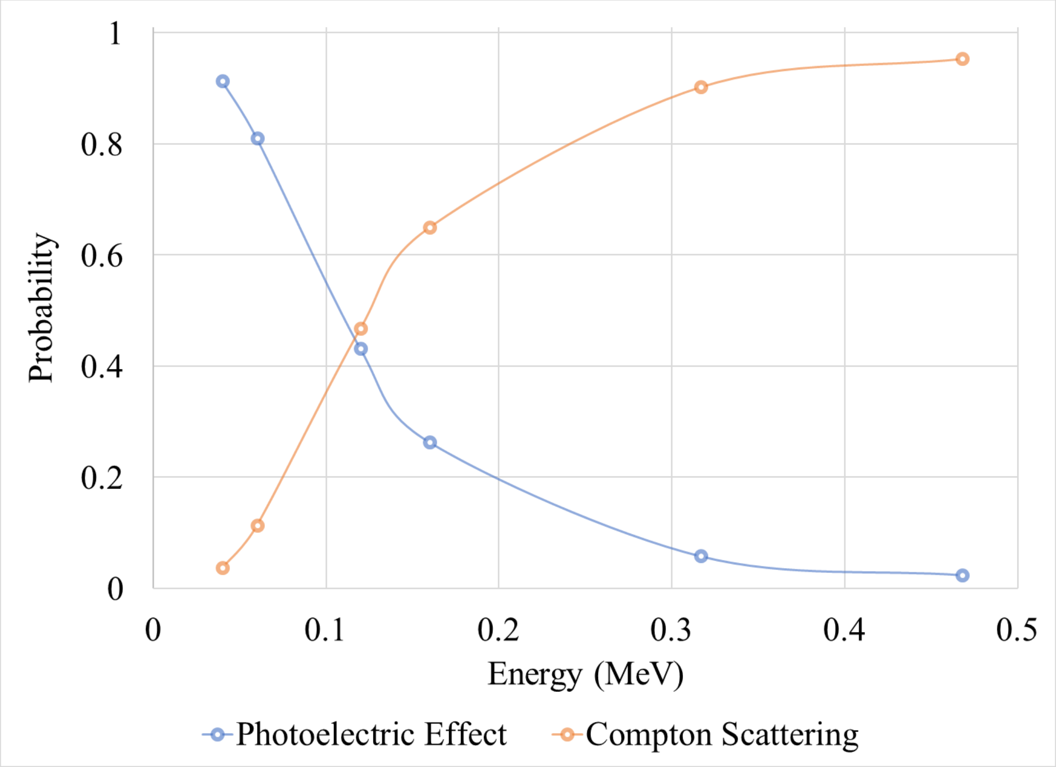


Fig.7 Probability of interaction for Photoelectric and Compton scattering to total mass attenuation coefficient for stainless steel [21]

3.2 *A flawed carbon steel welded plate created using SolidWorks^{TM}* (Fig.8)

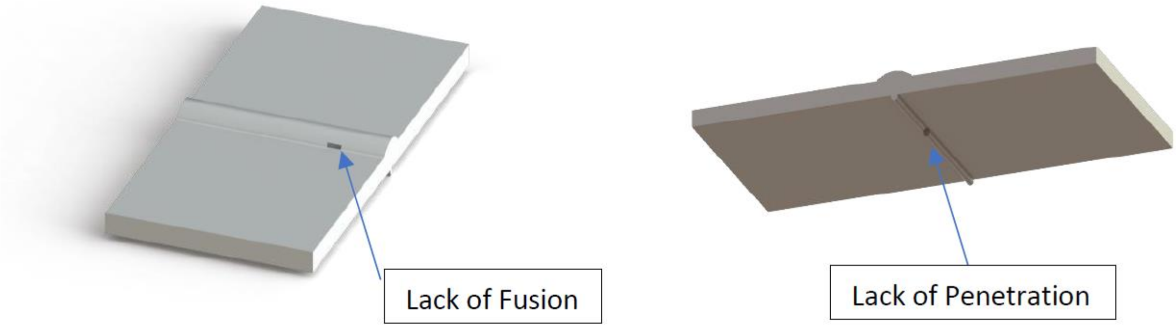


Fig.8 Carbon steel flawed welded plate

Weld inspection is an important and frequently needed RT application. The welded plate model contained two types of welding defects, lack of penetration and lack of fusion. The RT using 160 kVp X-ray (Fig.9) and gamma ray using ^{192}Ir (Fig.10) gave typical images like those obtained in the practical applications. An edge detection algorithm was applied to both radiographs to evaluate the images definition, and the corresponding result is depicted alongside Figures 9 and 10. The X-ray radiograph featured good contrast and definition as indicated by the clear demarcation of the weld and defect edges.

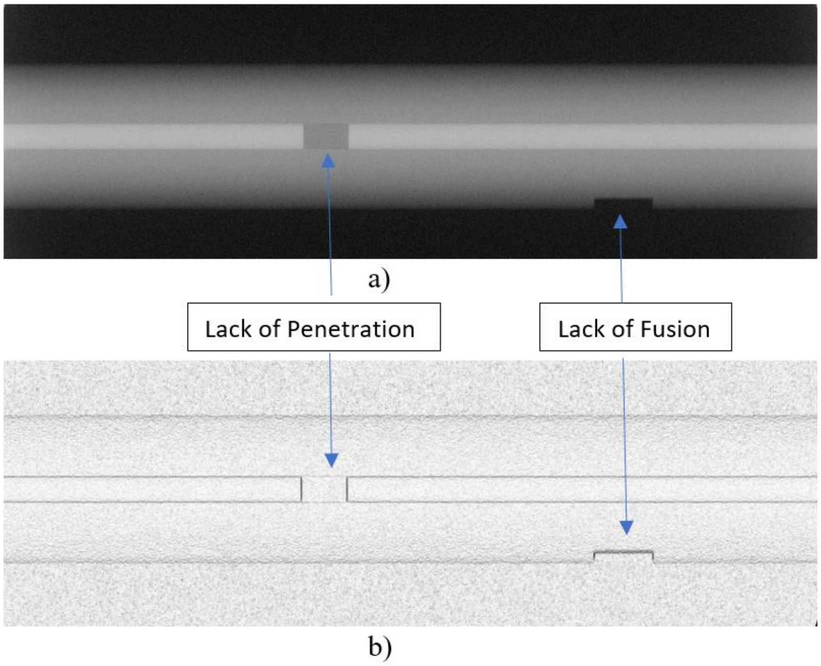
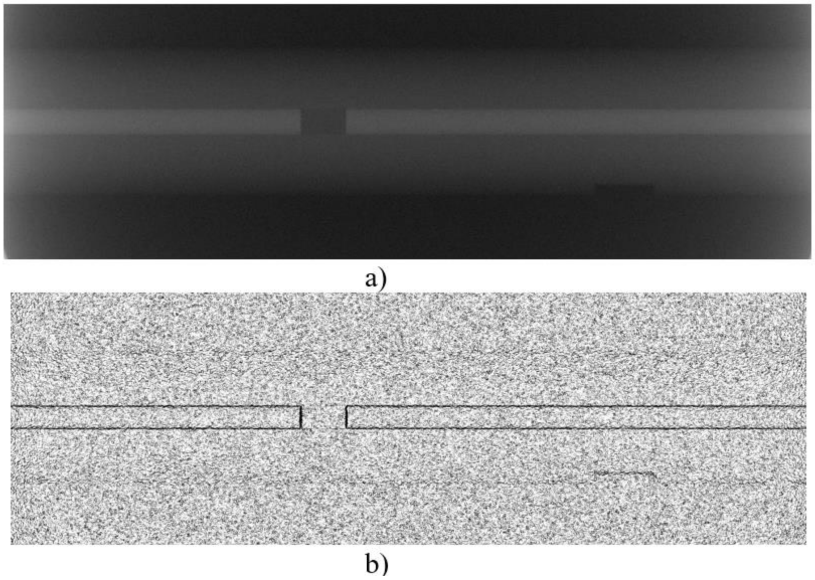


Fig.9 a) Welded plate radiograph using X-ray. b) edge detection profile

Further analysis was carried out on the defects' images, which are the areas of most interest in RT. A line profiles for the lack of penetration (Fig.10) shows the better definition offered by X-ray compared to the ^{192}Ir, which is attributed to the higher probability of photoelectric for the X-ray (see Fig.6). The line profile for the lack of fusion (Fig.11) shows a sharp edge for the X-ray as the Signal-to-Noise Ratio is high compared to ^{192}Ir.


a)

b)

Fig.10 a) Welded plate radiograph using gamma ray. b) edge detection profile

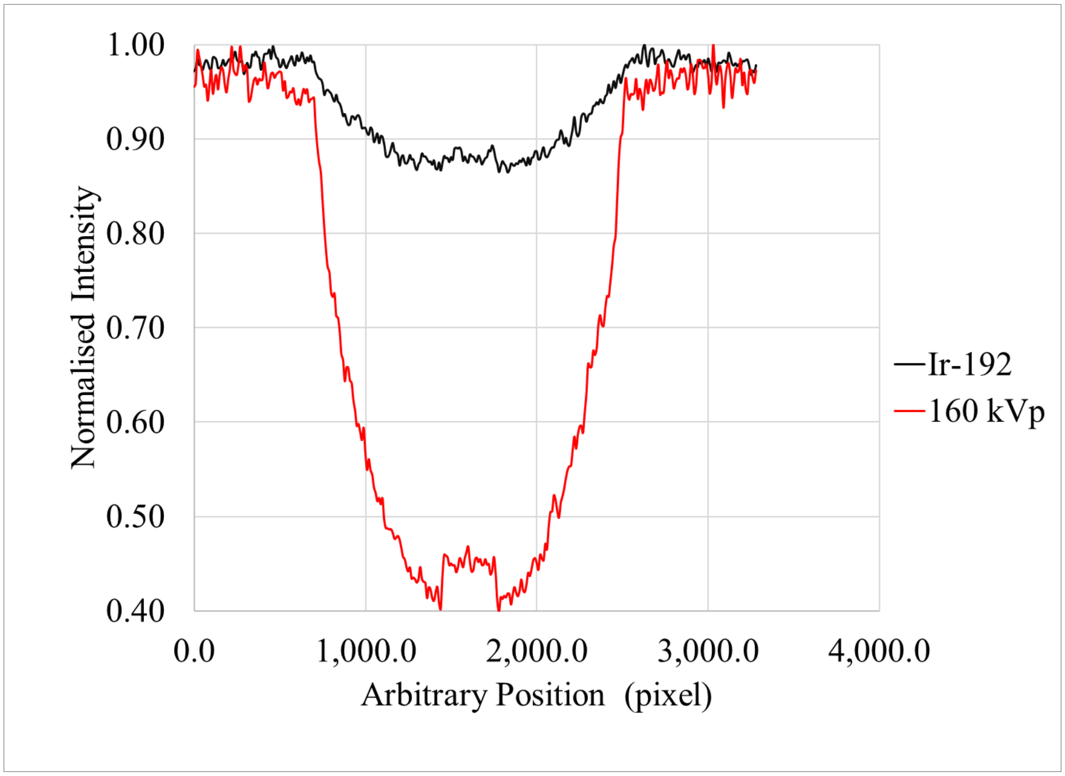


Fig.11 Lack of penetration line profiles evaluation for both X-ray and ^{192}Ir

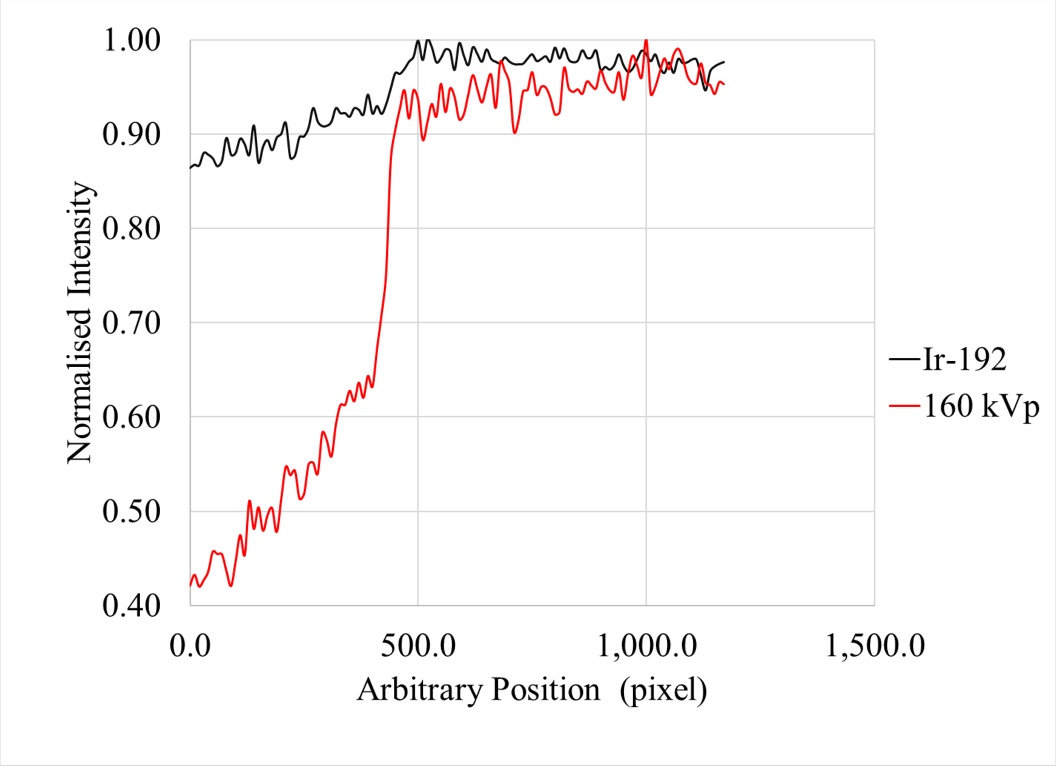


Fig.12 Lack of fusion line profiles evaluation for both X-ray and ^{192}Ir

Both Fig.11 and Fig. 12 were normalized for estimating the edges of the lack of penetration and lack of fusion in the plate.

Although the visual quality of the gamma ray radiograph was acceptable, the analysis revealed a poor definition. Again, the relative poor definition of gamma ray radiographs is recognized in the theory and practice of RT.

The results obtained from the simulations of the step-wedges and the welded plate testing using both X-ray and gamma ray are realistic and denote potential of creating various reliable RT simulation scenarios.

4. Conclusions

The resources, which are developed in this work enable the creation of a workspace for radiographic non-destructive testing applications in GATE simulation software. After installing

GATE, the user can incorporate the developed resources, define the required geometry, and run the simulation, moreover; the test parameters can easily be modified to serve the required application. The developed workspace is an affordable and practical option for RT researchers and specialists.

The workspace is more suitable for research, training and educational purposes. The Monte Carlo methods limitation of lengthy computation time hinders the use of the developed work for industrial applications.

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NOMENCLATURE

CAD	Computer-Aided Design
CEA	French Atomic Energy Commission
CR	Computed Radiography
ET	Eddy Current Testing
GATE	Geant4 Application for Tomographic Emission
kVp	Kilovoltage Peak
NDT	Non-Destructive Testing
RT	Radiographic Testing
RTSIM	Real-Time Radiography Simulation Tool
STL	Stereolithography
UT	Ultrasonic Testing
vGate	Virtual Gate
XRSIM	X-ray simulator

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