SIMULATION STUDIES OF RADIOGRAPHIC INSPECTIONS WITH CIVA

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ABSTRACT

A new gamma and X-Ray simulation module has been integrated to the CIVA software and completes the already available UT and ECT modules. This module is based on a combination of NDT radiographic modules developed at the CEA LETI and at EDF R&D. Direct radiation is calculated from an analytical approach (ray tracer and Beer-Lambert law for the attenuation) while the scattered radiation is simulated by Monte-Carlo modelling. Different types of sources, gamma or X-rays, and different detectors can be simulated. The X ray module uses the same dedicated Graphical User Interface mutual to UT and ECT techniques. It helps to simulate control of specimens where the geometry can be imported from a CAD tool and also to put in evidence the presence of defects (with canonical geometries or also defined from a CAD tool).

In this article, after a description of the different models used, the X-Ray simulation possibilities are illustrated on different practical applications.

Keywords: X-rays, gamma rays, modelling, simulation

1 - INTRODUCTION

Radiographic inspection is used as a non destructive inspection technique in a large application field including the metallurgical industries domain, primary and secondary circuits of pressurized water reactors, transport industry… In order to enable radiographic performance demonstration in cases with poor feed-back and difficult mock-up design and to optimize the test procedures in delicate zones to be inspected, the use of simulation software proves to be very useful [1]. In this context a new X-Ray module has been integrated in the CIVA platform supplementing the already existing UT and ECT modules. This module allows the simulation of Gamma (radioactive sources) or X-ray (X tubes) controls. The code takes the most influential parameters into account and allows simulation of a realistic and complex inspection configuration (source, specimen, defects, and detector) with a large usability as evaluation of the defects detection, facilities to elaborate mocks-up dedicated to Non

Destructive Testing (NDT), but also detectors evaluation. This new module relies on a combination of two models developed by the CEA/LETI (SINDBAD software) and by EDF/R&D (MODERATO software).

The first part of this paper will present the general functionalities of the software describing the models used. Then the possibilities of the X-Ray simulation will be illustrated on practical application cases.

2 – MODELS APPLIED

The radiographic modelling software integrated in CIVA relies on the implementation of two already existing codes: SINDBAD software [2] developed by the CEA LETI and MODERATO software [3] developed by EDF R&D. From those two models it is directly possible, with CIVA X-Ray, to simulate control either from X-Ray sources emitting continuum spectra or from gamma sources created from spontaneous disintegration of radioactive elements as Iridium or Cobalt which emit discrete rays. This differentiation explains the implementation of two different codes in CIVA X-Ray. The Graphical User Interface (GUI) is common to both models; an option in the panel corresponding to the modelling of the source can switch from an X source to a gamma source. The transition from continuum spectra management to gamma rays spectra automatically switches the computation model from SINDBAD to MODERATO. The management of X-Ray spectra allows manipulating data issue from Birch and Marshall Tables or other sources, to create interpolation of those spectra and to graphically visualize it. A module allows the simulation of X-ray tubes with the high voltage included between 30 and 500kV [4] [5]. Gamma source model comes in CIVA software with three pre defined sources: C060, Ir192 and Se 75. Moreover it is possible to model other types of sources from a source editor in which the parameters to be entered are the energy of each emitting ray and the number of photons per disintegration.

For the considered energy ranges, the predominant types of interactions are photoelectric absorption, Compton scattering, Rayleigh scattering and to a smaller extent pair creation. The probability of each interaction depends on the incident energy of the photons which travels through the matter, the density and thickness of the inspected matter. This probability is directly related to the cross section of each type of interaction.

At the lowest energies the predominant interaction is the photoelectric absorption corresponding to the annihilation of a photon into the matter. This photon is absorbed and transfers its energy to an electron of the atomic configuration which can be ejected.

Rayleigh scattering happens at low energy and is the result of an elastic interaction of the incident photon with an electron generating a small deviation of the propagation of the photon, without energy modification.

Compton scattering corresponds to an inelastic interaction generating a loss of energy and a modification of the photon propagation direction.

At least, the last interaction, which is not taken into account in CIVA for Gamma sources, is the electron-positron pair creation. Generally, it could be neglected for typical NDT application. This interaction occurs after interaction of the incident photon with an atom. This interaction can only occur at energies above 1.022 MeV (twice the electron mass) and the probability (cross section) of this interaction will increase with the energy and the Z of the material.
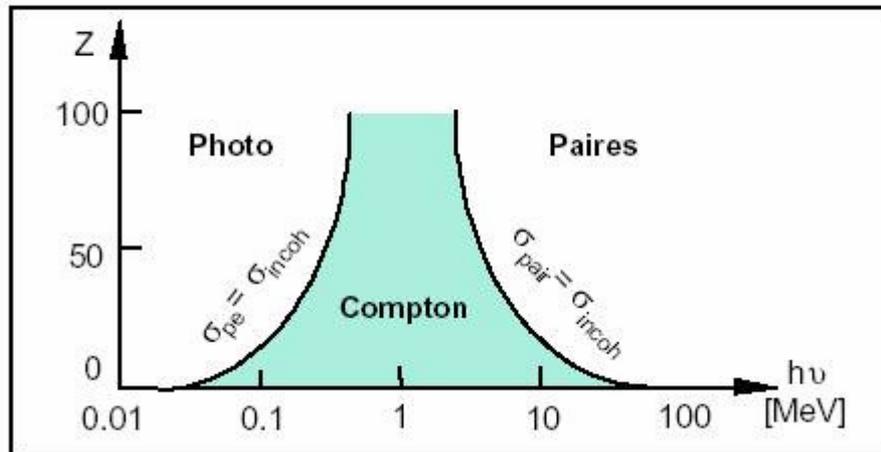
Figure 1: Relative importance of photo-electric effect, Compton Effect and pair production effect in function of the atomic number of the component and the photon energy.

For the simulation and the computation of the photons path we can distinguish two types of trajectories of the photon: On one hand the photons which have not suffered interactions with the matter. In this case the photon passes directly through the matter without being deviated and without losing its energy.

On the other hand, the photons which have interacted within the matter (scattered photons). In this case, the Monte Carlo method consisting in modelling all particle trajectories from all the emitted photons from the source is not feasible on a personal computer. In that way, as we cannot simulate as many photons as a physical source would actually generate, the resulting images including the direct and the scattered radiation will in general be noisy with a poor resolution, and not allow users to detect small details such as defects inside the inspected specimen or cracks. In order to obtain a result with an acceptable computation time, taking into account the scattered radiation and modelling a realistic image, the software combines two physical models: an analytical model of the direct radiation described by a simple exponential law, often referred as "straight line attenuation" (or sometimes called after the physicians who formulated it, the "Beer-Lambert" law) and a Monte-Carlo model that calculates the scattered radiation for a limited number of photons. The combination of these two models aims at providing a final realistic image on a personal computer, in spite of a lack of several magnitudes in terms of the number of photons simulated.

The analytical model is used to calculate the images created from the direct radiation by calculating the ratio of the emitted source intensity on the direct radiation intensity arriving at the detector. The so called "Beer-Lambert" law is an exponential attenuation law taking into account the total cross section of interaction and the thickness of the matter (equation 1). The resulting image of the object is very detailed and therefore able to bring out the finest details. This result, which needs very little computation time, does not take into account the scattered radiation effect. However, it may be sufficient for thin objects and items composed of low density materials, or more generally for any case where the scattered component is supposed to be negligible.

$$I(E)/I_0(E) = \exp(-\mu(E)x)$$

Equation 1: Attenuation law of photons in the matter. I_0, x and µ refer respectively to the intensity, the thickness and the total linear attenuation coefficient. E is the incident energy

To simulate the scattered radiation, a second model has been developed. This method uses a conceptually simple but computation intensive method called Monte-Carlo. The Monte-Carlo method interprets the cross section tables as probabilities, and calculates the path of an individual photon as a random walk, by determining the kind of interaction submitted by the particle and the distance between two interactions with random numbers obeying to associated probability laws. This method models all kind of interactions and provides images of the object including both scattered and direct radiation.

The combination of these models (analytical and probabilistic) consists of successively carrying out the analytical simulation (for the direct radiation), the Monte-Carlo simulation, the scaling of the scattered image to the real doses and the combination of both images. This image processing is described in [6] and [7]. In the radioactive source model the pair production is not handled, sources of higher energy than Co60 should therefore not be used.

Once the photons path computed, the interactions have to be modelled in the detector. Models of detectors are currently different according to the radiographic simulation software integrated in CIVA. From the X-ray tube simulation model, several models of detectors are available: standard detector, CCD, and "tape-film". Noise models, of MTF (Modulation Transfer Function to simulate the blurring due to the detector) and focal blurring from the source are also available in order to estimate, from a really realistic way, the detectability of a defect in radiography.

In the case of radiographical inspection simulation from gamma sources, the detectors are films which have a direct application in industrial radiography Modelling these films requires the conversion of the deposited radiation on the film, the attenuation and the scattering radiation resulting from the inspected part geometry in optical density according the own characteristics of each industrial film. The EN584 norm is used to model these films [8].

3- ILLUSTRATION OF THE RX SIMULATIONS POSSIBILITIES

The CIVA X-Ray radiographic simulation module works on a classical Windows PC (XP or Vista) and uses the same interfaces as CIVA UT (Ultrasounds model) and CIVA ECT (Eddy currents model) modules. The GUI allows the visualisation of the geometrical scene (source, object, and detector) and as with the other modules implemented in CIVA, all the different parameters are positioned in reference to the inspected part. The main advantage of common software for the three main methods for NDT is to allow a comparison of the simulation between those inspection modes. The common GUI of the three methods facilitates to create configurations and to take benefit from CIVA global images.

One of the CIVA particularities is the possibility to create complex geometries:
- Directly from the graphical interface by choosing the part geometry that is going to be inspected among a parametric objects list as planar, cylindrical, conical, elbow, nozzle … (Figure 2b).
- From a 2D CAD tool integrated into CIVA software. Complex part geometry is so defined by a profile, the 3D extension is then realised by a revolution or translation of the profile. (Figure 2a).
- Or from a CAD tool describing 2 or 3D CAD specimen then imported in CIVA (DXF or IGES format). (Figure 2c)

Figures below show some 3D visualization examples of X-Ray defined in CIVA (blue cone represents the opening angle of the source, the detector (green rectangle) is positioned under the inspected scene).
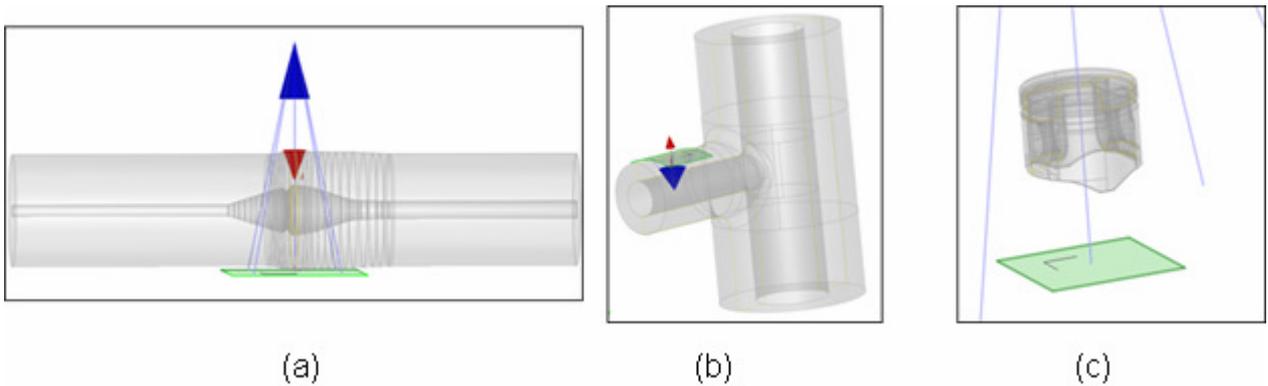
Figure 2: (a) Example of a weld created form CAD 2D CIVA editor, (b) example of a parametric nozzle directly available in CIVA, (c) example of a 3D CAD specimen imported by an external CAD tool.

Large choices of materials are available under CIVA to define both the specimen and defects materials. The management of materials is based on data from Storm and Israel [9]. The user also has the possibility to create alloys by defining the proportion of each element composing it (or the number of atoms of each element). Once the alloy homogenised, it is possible to visualize the total attenuation curve of this component (in cm²/g) in function of the photons incident energy.
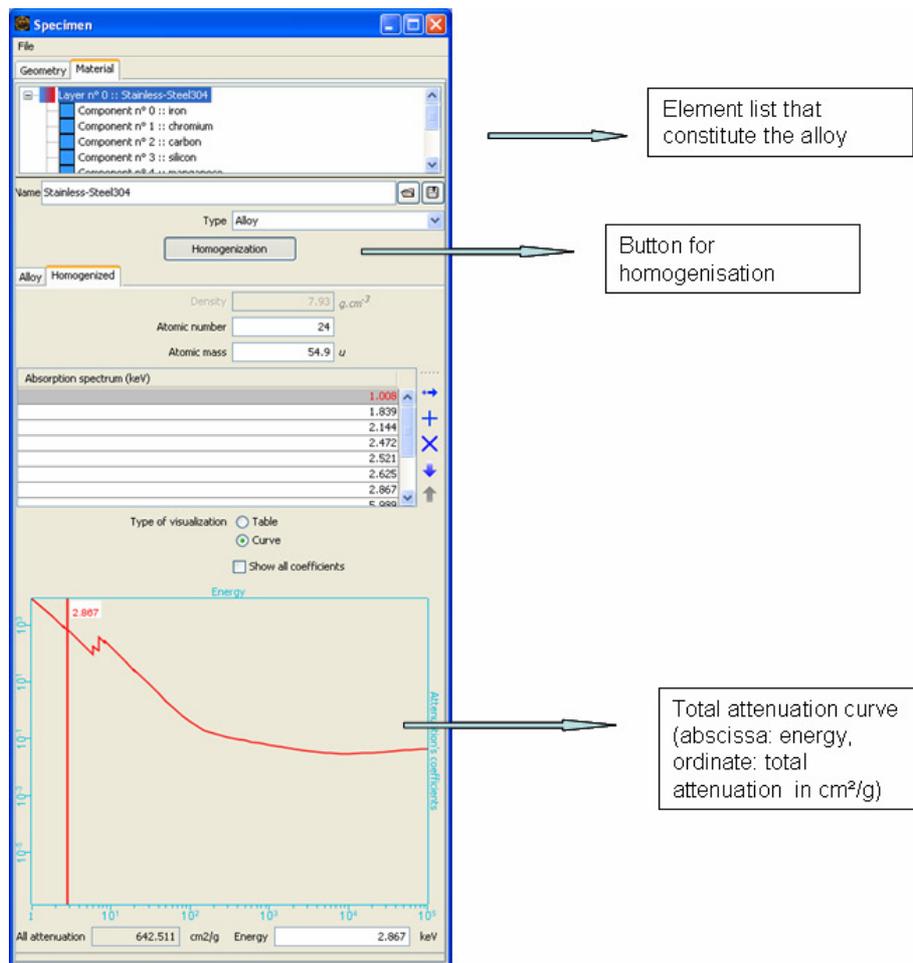

Figure 3: Attenuation curve obtained from alloy creation in CIVA.

Once the radiographic chain is configured, the operator can see from the photon trajectories visualisation (photons path functionality) the effects of the different parameters (as thickness of the component, material density, and incident energy) before launching a computation. Operators can easily investigate the more subtle effects. One can explain the physics behind the observed phenomena. As an example, we present below cases of iron and lead planar specimen where we can visualize the photons path and its propagation from two different gamma sources.
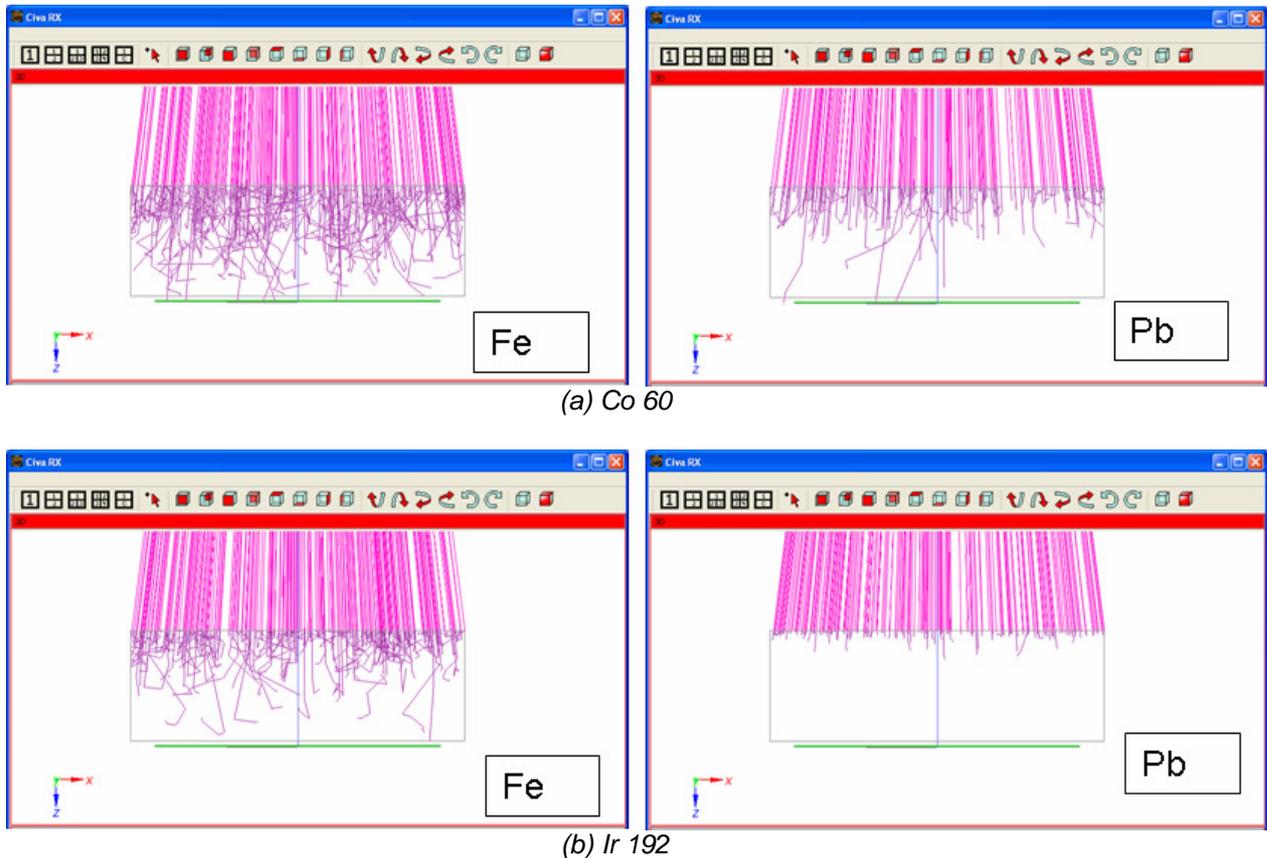

(a) Co 60

(b) Ir 192

Figure 4: Visualization of photons behaviour according to their incident energy and the component they went through. The sources are radioactive sources (a) Co and (b) Ir. The specimen corresponds' in each case, to an iron or lead flat piece. (Respectively from left to right)

In CIVA X-Ray, the operator is free to launch a computation using the analytical model only, the Monte-Carlo model only and also computations combining both models. According to the kind of computation chosen by the user, different images are provided. An export tool enables the exportation of the resulting image to the geometrical scene or in TIFF format.

- In analytical mode, three images can be visualized. These images correspond to the optical density if the detector is a film, the deposited energy at each pixel, and the attenuation value corresponding to the logarithm of the ratio between received intensity over emitted intensity.
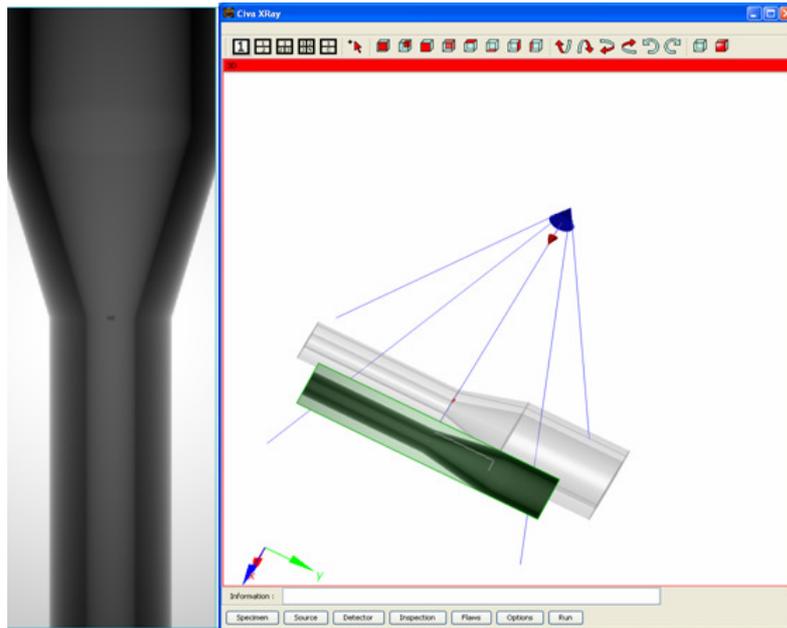
Figure 5: Results of analytical computation (contribution of direct radiation) for a piping that contains an inclusion.

– From a Monte-Carlo computation exclusively, the extracted images correspond to the direct radiation, scattered radiation and combination of scattered and direct Monte-Carlo radiation, computed for a limited number of emitted photons. Figure 4 illustrates the three Monte-Carlo images on the previous piping. This simulation has been realised with one billion photons. This Monte-Carlo computation helps to estimate the effect of the scattered radiation on the detector.
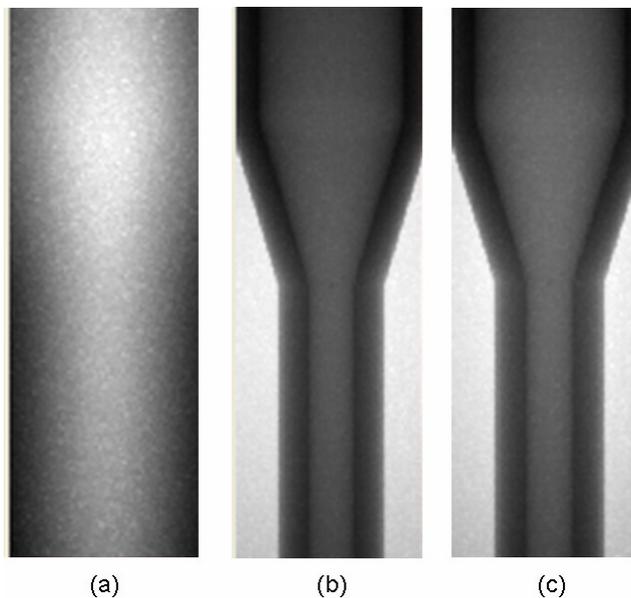

(a)   (b)   (c)

Figure 6: Results of Monte-Carlo computation for the same piping as represented above in figure 5. (a): contribution of scattered radiation exclusively, (b) : contribution of direct radiation exclusively, (c) : sum of the contributions of direct plus scattered.

– Finally, the combination mode, dealing at the same time with the direct radiation from the analytical model and with the scattered radiation from the Monte-Carlo method, provides the final realistic image. Moreover, a Build-Up (BU) cartography (BU=1+

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scattered/direct) is also computed. The scattered radiation contributes to the image in a destructive manner, adding noise and reducing the image contrast. In that way the closer the BU factor is to 1, the better the indication of a defect is. The BU factor is an indicator of radiography "quality". A too high BU factor will hide a possible crack indication. From this cartography it is possible to evaluate and optimise a control procedure and to quantify the proportion and the effect of the scattered radiation.
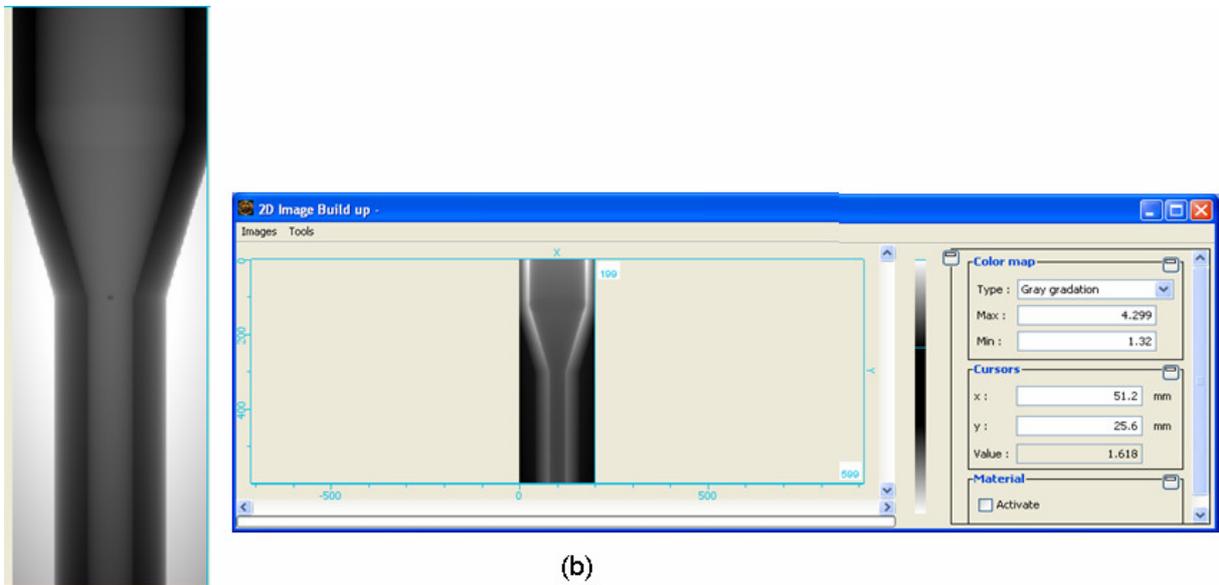

(a)

(b)

Figure 7: (a) Final image corresponding to the combination mode, (b): Build-Up cartography.

All the images have a window on their right which gives information on the minimum and maximum values of the images as well as the value at a point on the image defined by a cursor. This window also presents an interactive tool which allows the user to display the list of path lengths (called segments) along the ray from the source to the cursor pixel of the detector. This feature is particularly useful if the user is in doubt about the result of an assembly created using the object. A ray directly appears on the main CIVA geometrical scene and moved in function of the cursor position on the resulting image.
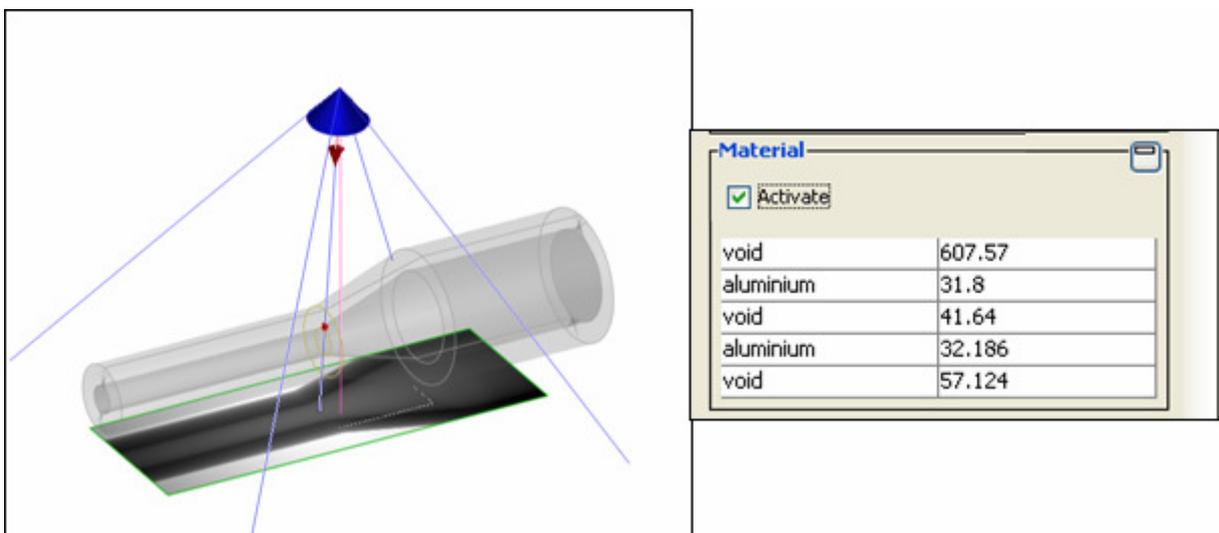
Figure 8: List of materials and thickness (mm) in which the pink ray is passing through. Example applied on an aluminium pipe with an inclusion inside. The information is obtained along the pink ray propagating from the source to the detector.

4-CONCLUSION

In this paper, we have made a presentation of the new X-ray and gamma radiographic control simulation module integrated in CIVA software and based on a combination models: SINDBAD (CEA LETI) and MODERATO (EDF R&D). These models took part in numerous validation campaigns conducted for several years as part of demonstration performances during the NDT qualifications of applications. In this validation framework of radiographic control procedures, the studies and tests were based on both theoretical arguments and practical arguments via comparison with other software and with experimental results.

CIVA X-Ray proves to be very useful in performance demonstration of radiographic controls cases, and have a complete understanding of the RT (radiographic testing) procedure. It seems also very helpful for the conception and optimisation of X-ray's tube and highlight simple physical phenomenon in radiography and photons-matter interaction.

In the context of the next release of the CIVA 10 version, and above all, the ANR (National Agency for Research) project RADIOLA, this module continues to grow and expand its application field.

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