RADIOGRAPHIC TESTING SIMULATION WITH CIVA-RX - ASSESSMENT ON REPRESENTATIVE NUCLEAR COMPONENTS

FRANÇOISE MATHY [1], CLARISSE POIDEVIN [2], GERARD CATTIAUX [3], Thierry SOLLIER [3]

1-CEA-LETI, MINATEC 17, Rue des Martyrs 38054 Grenoble Cedex France
2-CEA-LIST CEA Saclay 91191 Gif sur Yvette Cedex France
3-Institut de Radioprotection et de Sûreté Nucléaire, Direction de la Sûreté des Réacteurs, IRSN/DSR, B.P.17 92262 Fontenay-Aux-Roses France

ABSTRACT

NDE methods are commonly used for the inspection of nuclear installations during maintenance. A new Gamma and X-Ray simulation module has been recently integrated in the CIVA software platform [1] which also allows evaluating the performances of various NDE methods. It is based on MODERATO and SINDBAD softwares. For thick objects, the simulation uses the combination of direct radiation image (computed analytically) and of scattered radiation image (computed with a Monte-Carlo simulation). Several features of the source and the screen film detector important for detectability are taken into account.
Objects such as pipes, nozzles, heterogeneous welds are considered. Not only plane defects have been considered, but also complex 3D CAD defects such as cracks and shrinkages are simulated. Realistic images of simulated inspections on a nozzle and a heterogeneous weld are presented. In the forthcoming CIVA version, the best features of the two codes will be soon available. Validation experiments are planned.

Keywords : simulation, gamma rays, X-rays, radiography, nuclear components, NDE inspection, weld, nozzle, heterogeneous weld, crack, shrinkage, screen film system, build-up, Monte Carlo, CIVA, SINDBAD, MODERATO

INTRODUCTION

NDE methods are commonly used for the inspection of nuclear installations for maintenance operations. The simulation can be very useful to evaluate the performances of NDE methods, in addition to experimental evaluation on mock-ups. A new Gamma and X-Ray simulation module has been recently integrated in the CIVA software platform in addition to already available UT and ECT modules. The RX module [1-3] is based on a combination of NDT radiographic modules developed at the CEA LETI [4-5], SINDBAD, and at EDF R&D [6-7], MODERATO.
The French Institute for Safety and Radioprotection (IRSN) is using the NDE simulation to complete expertises and to give recommendations on NDE applications. Some years ago, a research program funded by IRSN was initiated to study the benefits of X-Ray simulation tools for the assessment of NDE methods on nuclear applications. Some specific cases were studied in order to point out the capabilities of simulation software to provide useful information on the ability of X-ray methods to detect defects in realistic configurations such as complex geometries or materials.
RX inspection for nuclear components has several specificities:
- The sources are Gamma-Rays (Iridium 192 or Cobalt 60).
- The objects under evaluation can have simple shapes (e.g. pipe) or complex shapes (e.g. nozzles, component with weld crown, …). The materials range from ferritic stainless steel to

more complex materials like dissimilar welds with special alloys (e.g. Alloy 182). The thicknesses range from a few mm to 130 mm, which leads to dominant scattering contribution.
- The defects are small and very anisotropic (mainly cracks 20 to 200 µm, with a few millimetres height and a few centimetres length). The aperture is a very important feature.
- The detectors are made of an assembly of sandwiches of radiographic films and metal screens protected by filters.

MATERIAL AND METHODS

In CIVA 9.2, simulation with gamma sources is implemented with the MODERATO software, whereas SINDBAD software is dedicated to X-Ray sources. Nevertheless it is possible to simulate the same cases with SINDBAD if one describes the gamma source as a spectrum. This allows checking some features specific to SINDBAD. The most appealing features of both codes will be available in the next version (CIVA 10).
Due to the dimension of objects and defects, it is necessary to combine the direct radiation image computed from an analytical approach (ray tracing and Beer-Lambert law) and the scattered image (Monte Carlo simulation) –simulated with a moderate number of photons and then filtered either through polynomial fit [7] or a low – spatial frequency filter [3-5]. Indeed the scatter flux carries little information on small details, but lowers the contrast by modifying the base line and adding noise. Estimating the scatter flux with a low spatial frequency method enables to get the scatter contribution with a reduced number of Monte Carlo photons.
The film response, which is strongly non-linear, is described either from the EN584-1 standard ([8,9]), or through external files [5] coming from a mixture of manufacturer data sheet and experimental data. The latter model assumes the optical density is a function of the dose in the sensitive layer in the film, as proposed in the Gray model [10] and has been extended to metallic screen film systems. The graininess noise or a global noise can be simulated but suitable parameters are required. A convenient overall screen film system noise model based on the EN 584-1 [11] is being implemented in CIVA 10.
The quantum noise is simulated in the X-Ray simulation [3]. The noise coming from the scattered flux is scaled compared to the direct flux [4-5]. In the gamma ray simulation, the detectors are film systems, then the quantum noise is not simulated because it has been considered negligible compared to the graininess noise, which is not the case for solid-state detectors.
The detector unsharpness can be described and simulated through its frequency transfer modulation (FTM) [3], but metal screen film system FTMs must be experimentally validated for Iridium 192 and Cobalt 60. Usually it can be neglected compared to the source blurring apart when considering very small defects.
The source blurring can be taken into account either from a decomposition of a volume source into small point sources [6] or through a convolution of the image and a kernel representing the source [3]. The last method is quicker and well suited for defects roughly at the same magnification whereas the first is more precise for several defects at different depths in the object.

TYPICAL APPLICATIONS

In the framework of the study, simulations have been performed on typical applications encountered during inservice inspection of primary or secondary circuits of pressurized water reactors: pipes, nozzles, dissimilar metal welds and irregular profile piping. The former are described as parametric objects, the latter as using CAD geometries with symmetrical shapes. For dissimilar metal welds, heterogeneous materials are taken into account. For defects,

different descriptions are used: planar, curved trapezoid, CAO3D defects or cracks. Image Quality Indicators (IQI) can also be described as defects.
The metal screen film detectors are made of a sandwich of two films inside metallic screens, lead for Iridium sources and stainless steel for Cobalt sources, with filters in front and behind. The detectors are EN 444 Standard [12] compliant.

NOZZLE

Nozzles are described as a parametric object. Inspections are made in a double wall mode either with an Iridium 192 source for the small pipe, or with a Cobalt 60 source for the large pipe. One example of planar defects detection in a primary circuit nozzle is shown on figure 1 and 2. Several identical aperture planar defects perpendicular to the inner wall are placed near the connection with various orientations. We have chosen a moderate aperture for the presentation so that they are clearly visible. The Cobalt source is shifted relatively to the detector to reach the zone very close to the connection. The class of the film is C2.
In the figure 2 (X-Ray source simulation), we can see the build-up (i.e. total / direct) (figure 2c) and its profile along the axis (figure 2d). Simulation is done with a restricted source aperture chosen to get the main part of the scatter contribution in a moderate simulation time. The build-up is fairly high, hence a reduction in contrast. The gradient due to the connection is clearly visible. It can bother the detection of details. The quantum noise is simulated. In figure 2a and 2b, the defects are differently visible according to their orientation, but still above the noise, even in the gradient zone.

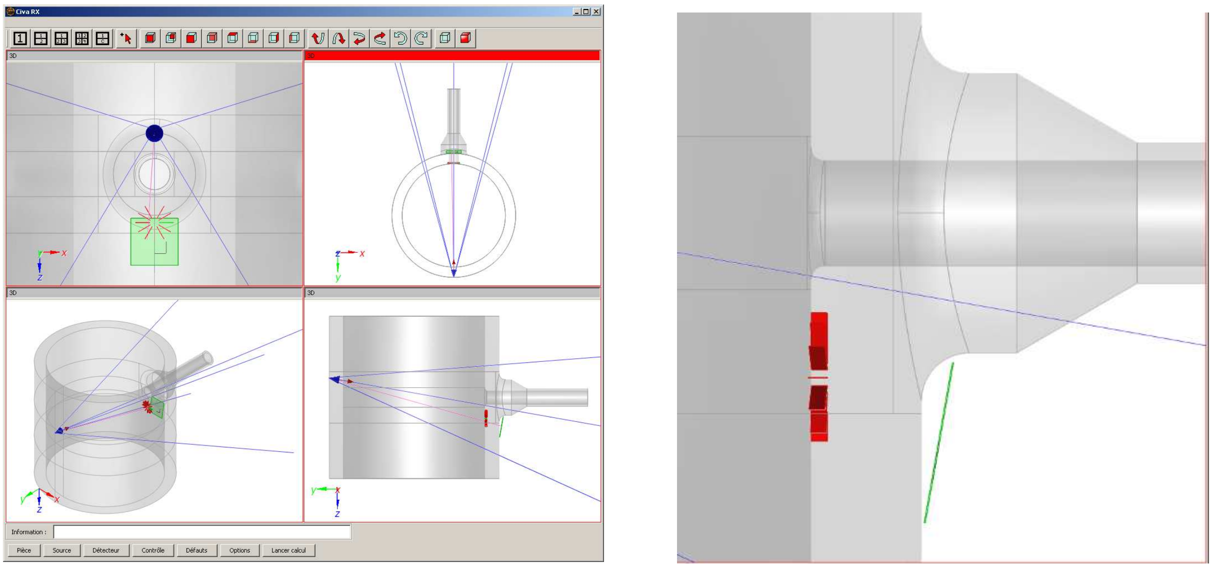

Figure 1 Inspection scene of a typical nozzle. Planar defects perpendicular to the inner wall with several orientations, near the connection. Cobalt source. Double tape-C2 film detector. Double wall examination.

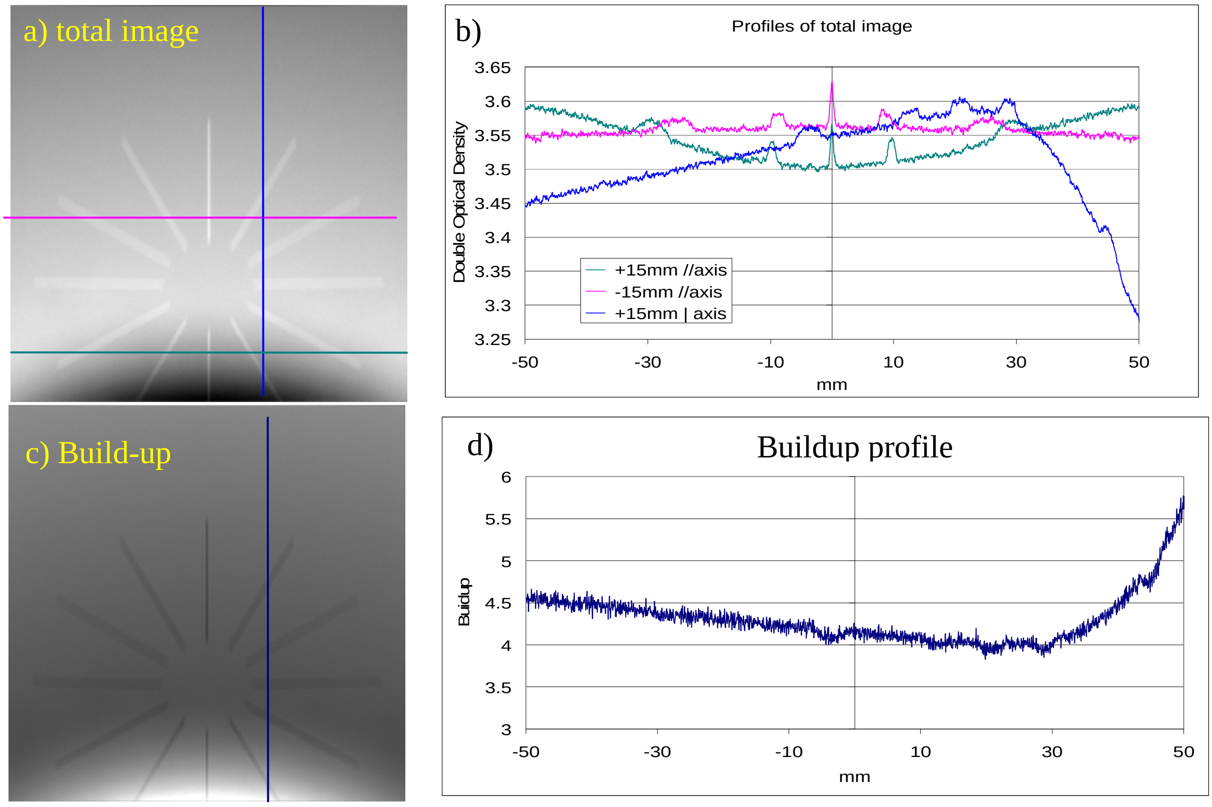

Figure 2 Configuration of figure 1. Planar defects with various orientations. a) Total image. b) Profiles on total image: green and pink. perpendicular to the axis, blue. parallel to the axis. c) Build-up. d) Build-up profile parallel to the axis. Quantum noise simulated (Cobalt 60 described as a X-Ray source).

HETEROGENEOUS WELD

Now we simulate a heterogeneous weld (figure 3). In this case, the irradiation is panoramic. The pipes are made of steel and the weld is made of Inconel. The weld has a small crown on the outside. The object is generated from a 2D CAD profile. There is a mixture of plane defects and complex defects such as cracks and a shrinkage, described with a 3DCAD tool from realistic cases. IQI wires have been added on each side of the wall.
Figure 4 shows the direct Beer-Lambert image using the detailed source blur (gamma source simulation). The optical density is lower in the weld, due to the nature of the material and to the weld crown.

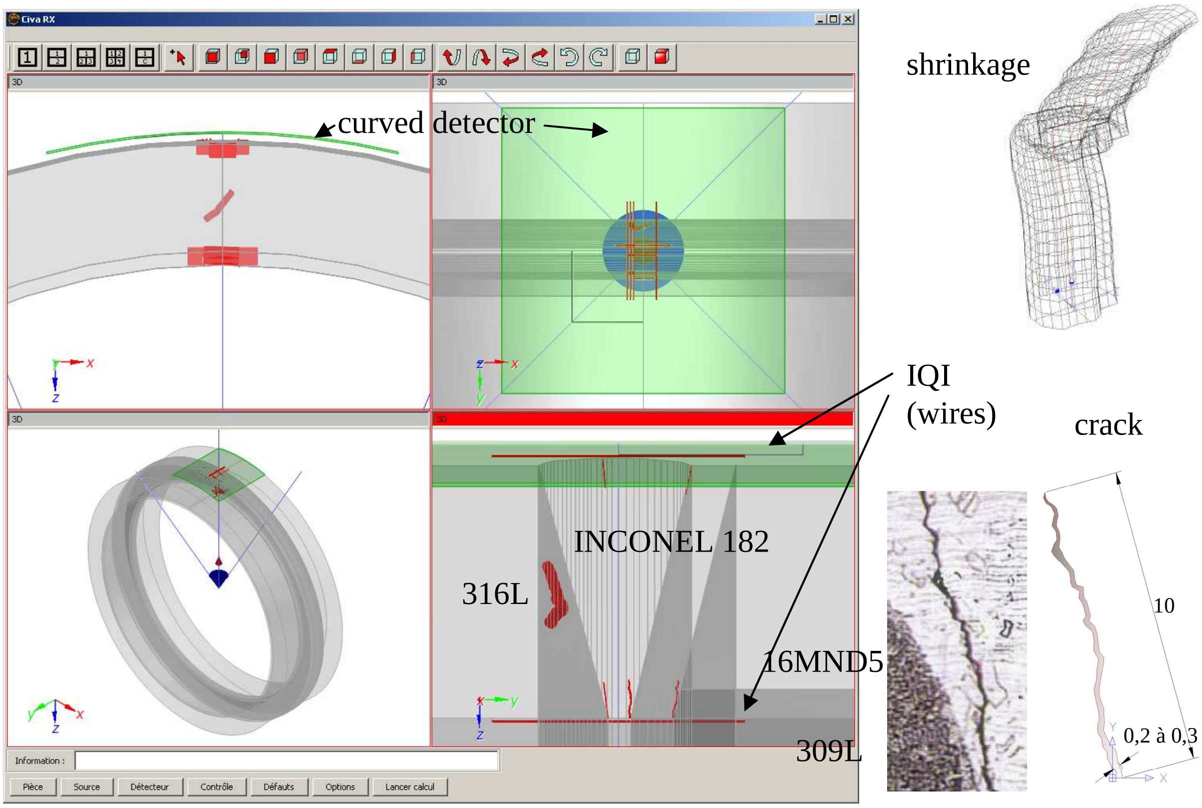

Figure 3 Heterogeneous weld with complex defects. Panoramic irradiation Iridium 192. C2 films.

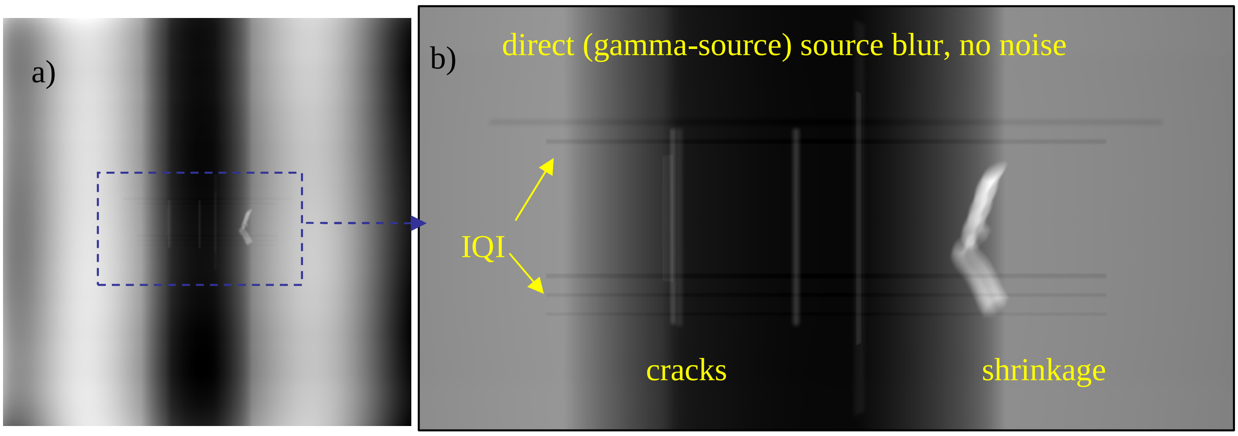

Figure 4 Heterogeneous weld. a, b) Beer-Lambert image with detailed source blur simulation (b: zoom). (Gamma- ray source).

On the total image (figure 5) the defects and the IQI wires are much less visible. The images simulated with the Gamma Source as well as the X-Ray source are shown. Scattering severely reduces the contrast. The images produced with both types of sources are very similar. See also on figure 6 the profiles of the direct and total image (X-Ray source, energy absorbed in screen pixels) and how the contrast is reduced in the total profile. The build-up is roughly 5.

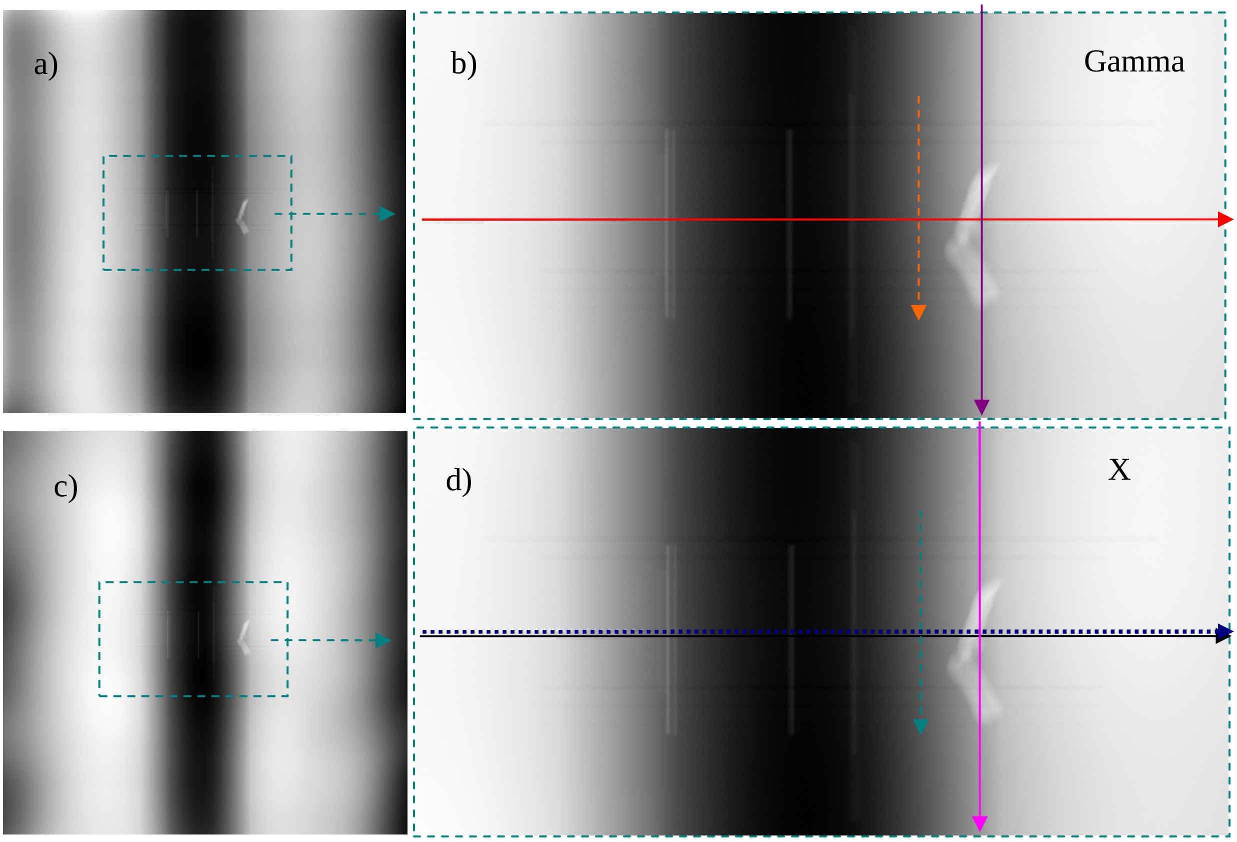

Figure 5 Heterogeneous weld. a, b) Total image without quantum noise (b: zoom) (Gamma-Ray simulation). c, d) Total image with quantum noise (d: zoom) (X-Ray simulation). The dotted blue line indicates the location of the profiles in figure 6. The black , pink, red, purple arrows indicate the location of the profiles shown in figure 7. The small dashed arrows indicate the profiles of figure 8.

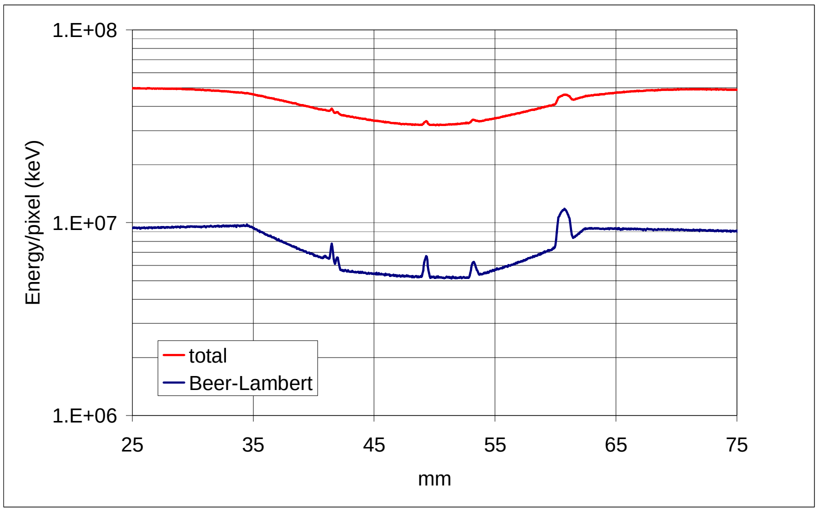

Figure 6 Heterogeneous weld. Perpendicular profiles on the energy images: blue: Beer-Lambert profile. Red: total profile. (Iridium 192 as a X-Ray source).

Figure 7 shows the perpendicular and parallel profiles on the total image for the two types of sources. The profile parallel to the weld crosses the shrinkage. The small discrepancy between the images for the two types of sources, which is not obvious on the images, comes essentially from the different method for filtering the scattering image. In this case, it varies abruptly because of the material and the thickness changes in the weld. Here, the polynomial fit order is rather high (here it is 7), and the filter frequency cut in the X-ray source simulation is not too low. The more the object has soft variations, the more it is easy to get a reliable approximation of the scattered image. Typically, for regular pipes, a polynomial order of 2 is enough with a reduced number of photons for the Monte Carlo simulation.

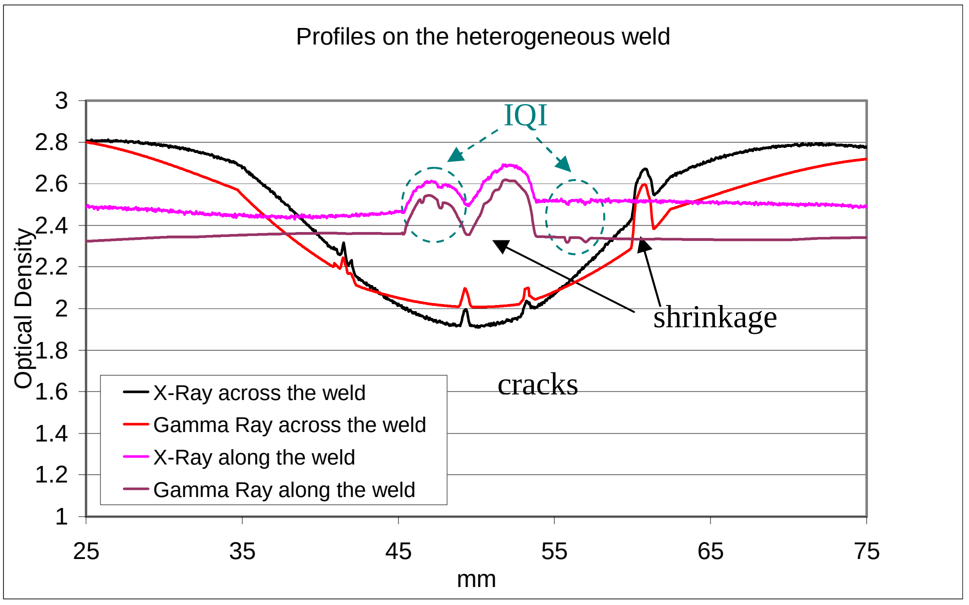

Figure 7 Heterogeneous weld. Perpendicular and parallel profiles on the total image. The profile parallel to the weld crosses the shrinkage. Optical Density on one film. Comparison of results with Iridium 192 described as a Gamma Ray and X-Ray spectrum.

The IQI wires can be seen on the total image, thanks to their length, but less obviously on the profiles. Look at a zoom on them in figure 8. The base line discrepancy comes from the different ways of scatter image filtering. The effect of wire size, wire position and quantum noise can be clearly seen. The geometric blur is bigger if the wire is on the side of the source. The quantum noise is not negligible towards the wire signal. It will be important to have a reliable simulation of graininess noise which is larger than the quantum noise

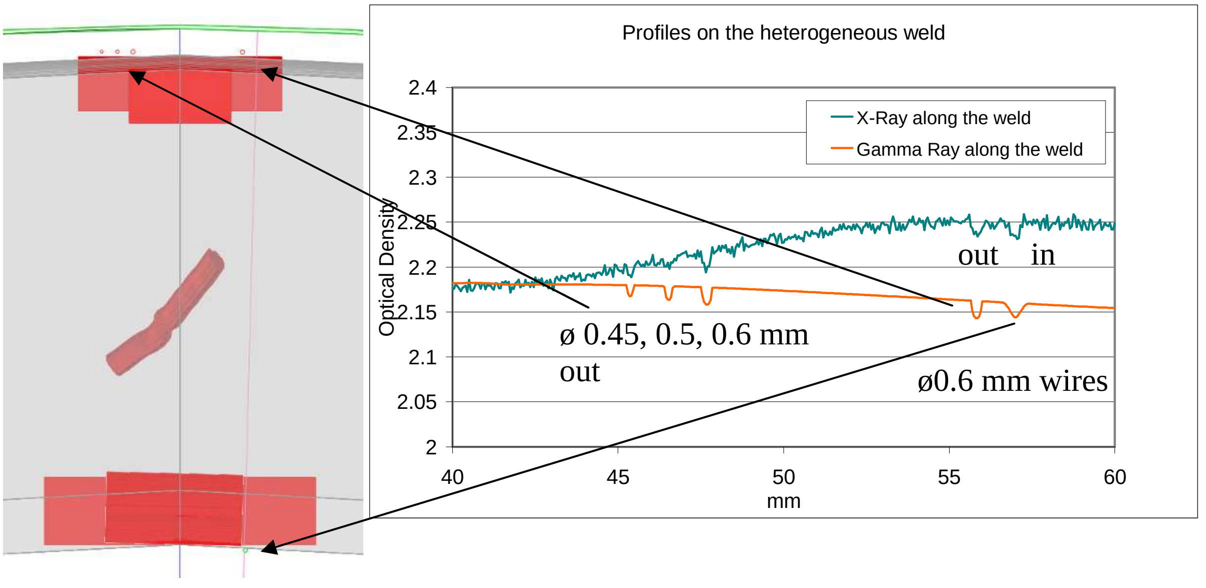

Figure 8 Heterogeneous weld. Profiles zoomed on IQI wires (see the location on figure 5, dotted arrows). Effect of diameter and position. Effect of quantum noise.

SUMMARY

Two simulations have been presented in this paper. They are typical of inservice inspection on nuclear equipments. They show how CIVA-RX can simulate complex configurations and produce realistic images, even for thick objects with small and complex defects.
The film system noise model, as well as the screen film detector unsharpness model, still have to be fully validated. This is important for evaluating the signal to noise ratio therefore also the detectability. In the next release of CIVA, CIVA10 will include the main features of the two codes. Several validation experiments are needed and are planned.

Our thanks to the CIVA team and especially to R. Fernandez, to P. Hugonnard and J. Tabary from the SINDBAD team and to the main MODERATO author, A. Schumm.

1) http://www-civa.cea.fr
2) R. Fernandez, A. Schumm, J. Tabary, P. Hugonnard, "*Simulation studies of radiographic inspections with CIVA*", 17th WCNDT, Shanghai, 2008.
3) J. Tabary, P. Hugonnard, A. Schumm, R. Fernandez *"Simulation studies of radiographic inspections with Civa",* COFREND 2008
4) R. Guillemaud, J. Tabary, P. Hugonnard, F. Mathy, A. Koenig, A. Glière, "*SINDBAD: a multipurpose and scalable X-Ray simulation tool for NDE and medical imaging*", PSIP 2003, Grenoble, France, 2003.
5) J. Tabary, F. Mathy, P. Hugonnard "*New Functionalities in "SINDBAD" Software for Realistic X-Ray Simulation Devoted to Complex Parts Inspection*" , ECNDT 2006
6) A. Schumm, O. Bremnes, B. Chassignole, "*Numerical simulation of radiographic inspection: fast and realistic results even for thick components*". Proceedings of the 16th world conference of Non-Destructive Testing, Montreal, august 2004
7) O. Bremnes, B. Chassignole, O. Dupond, A. Schumm, "*Experimental And Simulation Studies Of Radiographic Inspections Of Pressure Vessel Reactors*" ECNDT London 2006
8) EN 584-1:2006, "*Non-destructive testing – Industrial radiographic film – Part 1: Classification of film systems for industrial radiography*"
9) A. Schumm, U. Zscherpel, „*The EN584 standard for the classification of industrial radiography films and its use in radiographic modelling*", in Proceedings of the Sixth International Conference on NDE in relation to structural integrity for nuclear and pressurized components, 2007.
10) T.Jensen, T.Aljundi, J.N.Gray, and R.Wallingford, "*A model of X-ray film response* ", Review of progress in Quantitative Nondestructive Evaluation, Vol 15, pp441-448, 1996.
11) A. Schumm, U. Zscherpel, "*Radiographic film modelling according to EN584*", COFREND Toulouse 2008
12) EN 444:1994, "*Non-destructive testing — General principles for Radiographic examination of metallic materials by X- and gamma-rays*"