X-RAY IMAGING MODALITIES FOR NUCLEAR WASTE DRUMS INSPECTION

V.Moulin[1], V. Rebuffel[1], M. Antonakios[1], R. Sauze[1], J.P. Gorius[1]
[1]CEA-DRT/DTBS, Grenoble, France

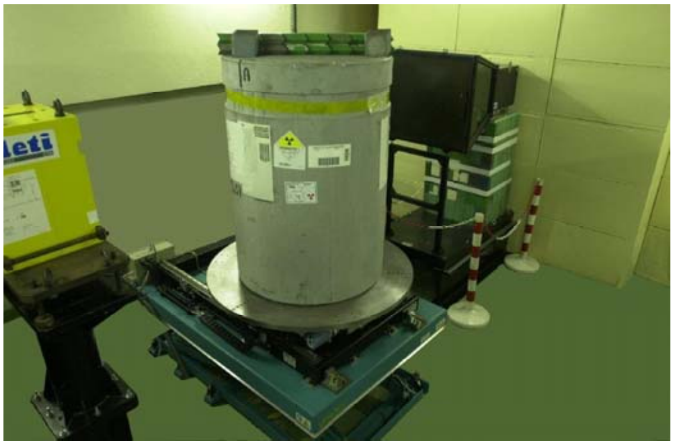
Abstract: X-ray imaging is a suitable technique for nuclear waste drums inspection, especially large and highly attenuating ones. It requires an energy source greater than 6MeV and dose rate over 0.1Gy/s. Controlling waste drums calls for a multi-level strategy: from systematic and fast controls to specific or detailed examinations. Using a high energy (8MeV) experimental set-up, we have studied and validated different modalities for X-ray inspection of these drums: radiography, radioscopy, tomosynthesis, and tomography. Various types of detectors can be used, all of them dedicated to high energy: large screen imager, CdTe-unit detector, linear array. They differ on induced geometry acquisition, global acquisition time, resolution, and possible modalities. Data collection therefore also differs from one device to another.

Introduction: X-ray imaging is an attractive technology for both low level and intermediate nuclear waste inspection, and may even deal with high level ones in some cases. Due to the density and size of nuclear waste drums, a high energy source is required. A 2MeV system is transportable on a trailer, but does not allow to inspect drums that are too attenuating. The leader in this technology is BIR, that produces the WIT system, a truck mounted system capable of carrying out CT and gamma/neutron assay. BIR have developed the x-ray system to work with a linear array and 2 MeV linear accelerator. They have also put a passive isotope detection system into the same truck [WIT01]. The CT technology used was originally developed by the LLNL [BERN95].

Our objective is to focus on the large set of highly dense and attenuating nuclear waste drums, typically involving concrete. The packaging process of nuclear waste usually consists of binding the waste into a matrix (concrete or asphalt), and storing it into steel drums or concrete containers. The volume of the resulting package is between 0.2 and 10 m^3 (diameter from 0.6 to more than 1.4 m) and their apparent density from 1 to 4. Furthermore, this waste is generally radioactive and at high emission level, it may disturb X-ray measurement. An example of such drums can be viewed in Figure 1. The X-ray examination of these drums obviously requires an energy source greater than 6MeV and dose rate over 0.1Gy/s, therefore a linear accelerator (LINAC). Notice that such an accelerator may be portable, but the shielding has to be built on the inspection site prior to setting up the device. The system is then partially portable.

Different examinations have to be performed on these nuclear waste drums. Some of them lead to qualitative tasks: leak test (crack inside the concrete container, cap junction), inspection of the interface between concrete matrix and concrete envelop, detection of air bubbles, of particular structures), while others aim at quantitative measurements: material identification inside the package or matrix attenuation estimation. This last measurement, allowing the matrix effect correction, may be required for other nuclear inspection systems.

The waste drums control requires a multi-level strategy: some examinations concern all the drums, thus should be processed fast, whereas others would be performed on selected drums only, either because of prior information on their contents, or focusing on local suspicious areas detected on the first level control. This multi-level strategy should be based on various modalities, radiography, radioscopy, tomosynthesis, computed tomography – that are discussed in the following – and implemented using convenient detectors and systems.



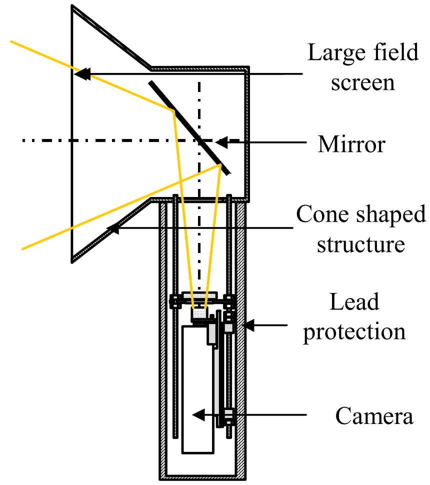


Figure 1: *left:* example of waste drum in concrete package (weight 1210 kg, diameter 840 mm), *right:* diagram of the large field detection system.

Result : The previous remarks point out the needs of a linear accelerator, allowing to dispose of a very energetic x-ray flux (several MeV) and powerful source (10^6 to 10^{12} X/cm^2/s at 1m). The experiments presented hereinafter use a 8 MeV accelerator, mean energy of the flux being about 3 MeV. Dose rate at 1m from the source is 0.3 Gy/s.
The use of such an energetic x-ray flux induces strong constraints of radioprotection, and implies a convenient detection system should be involved. The detector should not be damaged by the X-rays and also be able to stop a sufficient ratio of photons – this last property is quantified by the stopping power. It is directly linked to the signal-to-noise ratio and to the sensitivity. We have developed a high energy experimental set-up, associated with various detectors, in order to study and validate the different drums X-ray inspection modalities.

The first suggested modality is high energy digital *radiography*. A large size scintillator screen allows to perform digital radiography of the drum in a short time with a correct definition. The radiograph can cover a large part of the drum, even the whole drum. Time exposure being approximately a few seconds, inspection time is short – this is the main benefit of this examination modality. Consequently, such control can be performed on-line, systematically on all drums. However, the information that it can provide is necessarily restricted. The radiograph is often difficult to interpret, due to the superimposition of the internal structures produced by X-ray transparency. Furthermore, 3D localization of details of interest is not possible.
In the recent years, a new type of detectors has emerged on the market: flat panels detectors [PURS02]. Some of them are proposed in modified versions allowing high energy, the electronics been displaced on the side – for instance [THAL01]. The main limitation of these detectors is their size, currently restricted to 400 mm. Furthermore, we do not have sufficient background experience on extensive use of this type of detector at high energy flux.
CCD-based detectors offer an alternative. We have developed a system composed of a large field (800x600 mm^2) X-Ray/photons converter screen (Gd_2O_2S : Tb laid on a polyester liner and reinforced by a Tantalum plate), a 45° titling mirror, a specific optical lens, and a high sensitivity CCD camera (HAMAMATSU C4742). The system has a field of view of 0.48m^2 and a pixel pitch of 0.64mm. The geometric definition obtained at 8MeV is close to 0.5 lp/mm and the sensitivity is close to 2% through 30cm of concrete. The maximum acquisition rate is 9 images/sec [ANTO02]. The acquisition system is visible on Figure 1, the detection system being detailed on the right. Examples of collected radiographs are shown on Figure 2. The left radiograph corresponds to the container presented in Figure 1, the border of the image being approximately the external periphery of the container. This container 1,200 mm high and ϕ840 mm container, contains a metallic 223l drum, itself containing four compacted 120l waste drums bound in concrete. Due to container size, nine radiographs have been juxtaposed to get this large

image. Figure 2-middle displays a metallic 400l drum, 1,130 mm high and ϕ740 mm, containing six compacted waste drums packaged in concrete binder. Two enlargements of middle-view are shown on the right hand side.
One way to get a larger field in order to image larger drums in one view, consists of enlarging the converter screen imager. X-Tek has developed a detector with a field of view of 1m x 1.5m [XTEK]. Another way consists of increasing the number of cameras. In that case, an additional digital processing is required to produce a seamless image by combination without distortion of the radiographs.
Notice that this type of detector allows *radioscopy* modality: the object is moving (typically rotating) while an operator is on-line viewing the radiograph. Compared to static radiography, this functionality often helps the interpretation of the structures in the image.

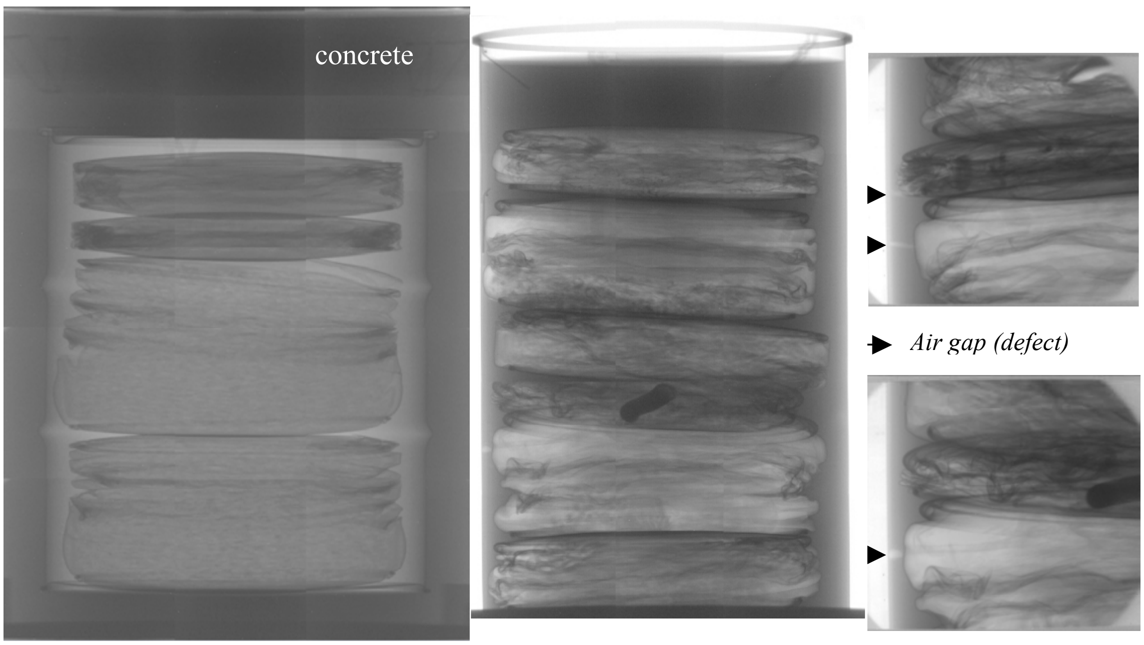


Figure 2: Examples of radiographs made with a large screen imager.

Another type of detector can be used for digital radiography: 1D linear array, the object being translated in the flux ("radiography by translation"). The main advantages of this technique are cost and efficiency. The array length can be significant, allowing to make large object radiography using one translation – the limit in such case is set by the accelerator flux angle. Furthermore, the use of a collimator is possible and enables to reduce scattering radiation. By using two such arrays, details of interest can be localized in 3D. Inspection time is greater than with a 2D detector as those presented above, but the acquisition can be done on-line while the drums are streaming on a conveyor belt (Figure 3). To get a good stopping power, our laboratory has developed a small CdZnTe linear array, which depth can reach 40 mm, ensuring an efficiency greater than any high energy 2D detector [GLAS01] [GLAS03]. The development of a longer array is under study.

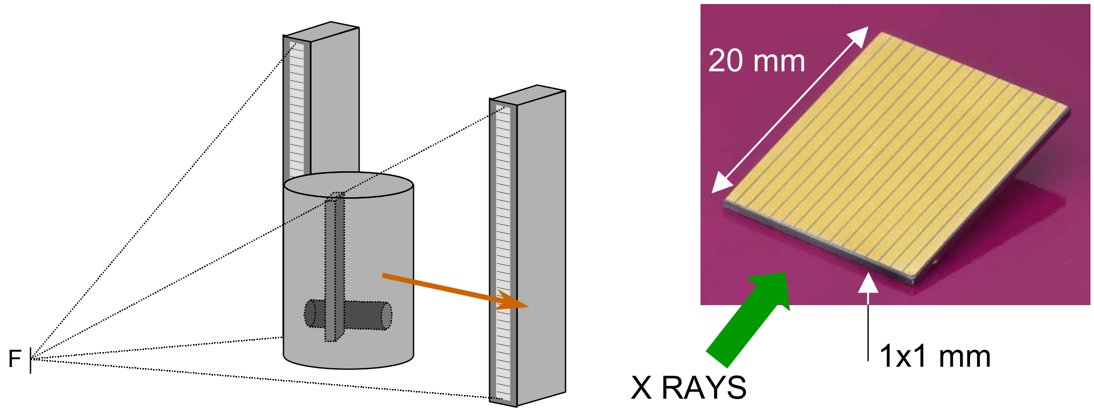


Figure 3: Radiography by translation, geometry using 2 arrays (left) and CdZnTe array (right).

Tangential *tomosynthesis* is another modality that may be considered with a 2D imager. It provides additional information on the peripheral part of the object, with an inspection time still compatible with thorough drum control. This technique is convenient for highly attenuating drums, even those that are opaque to high energy X-rays along their main diameter. Taking benefit of its cylindrical shape, the object is rotating in the x-ray flux, and a 2D detection system acquires radiographs of the periphery (geometry illustrated in figure 4). The obtained radiographs are processed by a dedicated algorithm that combines them to increase signal-to-noise ratio, and acquire an image of equivalent quality to a long time exposure radiograph of a static object. Real-time implementation of this process is possible [ANTO00]. The technique is particularly suitable for delamination defects detection between external envelope and internal binding concrete, but any defect on the periphery will be imaged with a better contrast than a single on-line radiograph (Figure 4). These defects can be detected by an operator, or by an automatic digital process, as it has been done for other attenuating cylindrical objects [REBU03]. Tomosynthesis technique allows thorough control of the periphery of the larger drums in a few tens of minutes. For instance, experiments have shown an examination time of 30 min for the entire periphery of a ϕ 840 mm and 1,200 mm high drum.

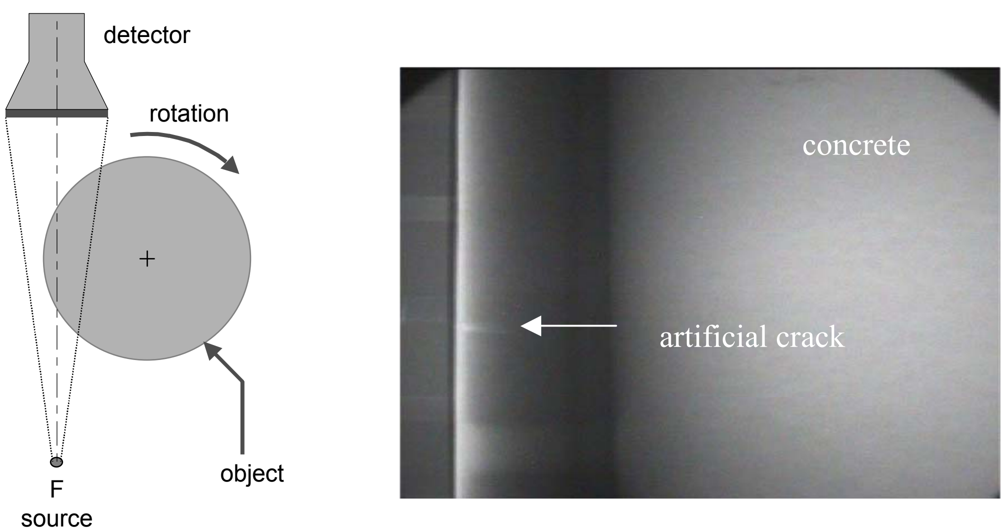


Figure 4: Tangential tomosynthesis, geometry (left) and example of tomosynthesis result (right).

Tomography is a quite different technique, providing information about the internal structures of an object. Different views are acquired around the object, then the volume is reconstructed using a well-known algorithm. Various geometries are possible, leading to 2D, 3D, or spiral tomography. Specific geometries sometimes need to be designed, due, for instance, to constrained required space: tomography with limited angle of views, with limited number of views… Dedicated algorithms exist for these configurations, of course less efficient than in perfect tomographic configuration. In any case, tomography requires more examination time than radiography, but it provides additional information that may be crucial.

Different detector types may be used. With the large screen imager described at the beginning, we can perform a cone-beam tomography for objects up to 600 mm diameter. We can even process objects up to 1,200 mm by positioning the detector in a way that it intersects half part of the conic flux. This method allows to get a reconstructed volume of a large slice of the drum, typically 10 cm high, in a few minutes. Figure 5 presents an example of a concrete block, including cracks and two-densities areas (in this example, to reduce acquisition time, reconstruction has been computed using only 180 equally distributed views, for a 500-voxel side volume, which is not mathematically correct). The operator can easily interpret the volume thanks to 3D volume imaging facilities, and perform geometrical measurements. Figure 5 presents three slices of the reconstructed volume, in horizontal plane (left), and in two vertical planes. The spatial definition obtained is about 1 mm. To get a complete reconstructed volume of the drum, we can perform a stack of such slice reconstruction, or combine the acquisition rotation with a continuous vertical translation, and consider the frame of spiral tomography.

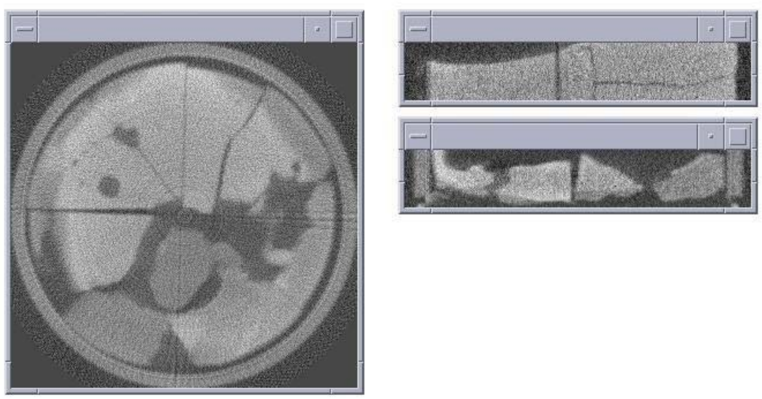


Figure 5: Slices of the cone-beam reconstructed volume, concrete test block.

Tomography technique is also possible using unitary detectors, as the CdTe technology detector developed at LETI. These mono crystals of high density can be deep and efficient even at high energy (stopping power can reach 50% at 3 MeV) [GLAS92]. They offer a large detection sensitivity and an significant range dynamic (up to 6 decades). The system developed at LETI is composed of 25 unitary and not jointing detectors. Each one is collimated, in order to reduce disturbances due to scattering radiation. Notice that in case of self emitting waste, this collimation allows to reduce the influence of the rays emitted by the object.
To perform a 2D tomography in order to reconstruct a slice along a horizontal plane, it is necessary to apply a sequence of translation-rotation motions to the object (Figure 6). There is no object size limit, except the mechanical limits of the rig. Our prototype can handle objects up to 500 mm diameter. For future reference we have planned a system able to process drums up to 1.40 m diameter [PETT04]. This technique is very powerful in terms of quality of the reconstructed image, and the spatial definition we get is about 1 mm. The image quality is

enabled by the high sensitivity of the CdZnTe detectors but also by the individual collimation of each unit and the limited diaphony between neighbouring channels. This allows to get accurate quantitative measurements. Furthermore, this measure is directly interpretable in terms of density, because in high energy fields tomographic image values are representative of the materials density. Nevertheless, a calibration procedure is required to correct beam hardening effect. This density accuracy allows to perform material characterization, identification (distinction Al / Ti, or Pb / tungsten for instance) or matrix correction for spectroscopy.
The example presented in Figure 6 regards a 30 cm x 30 cm test concrete block, containing different items. On this view in false colours, density is proportional to red colour. Structures made of steel, PVC or wood can be easily identified. Spatial resolution is good enough to make even concrete small gravels visible.

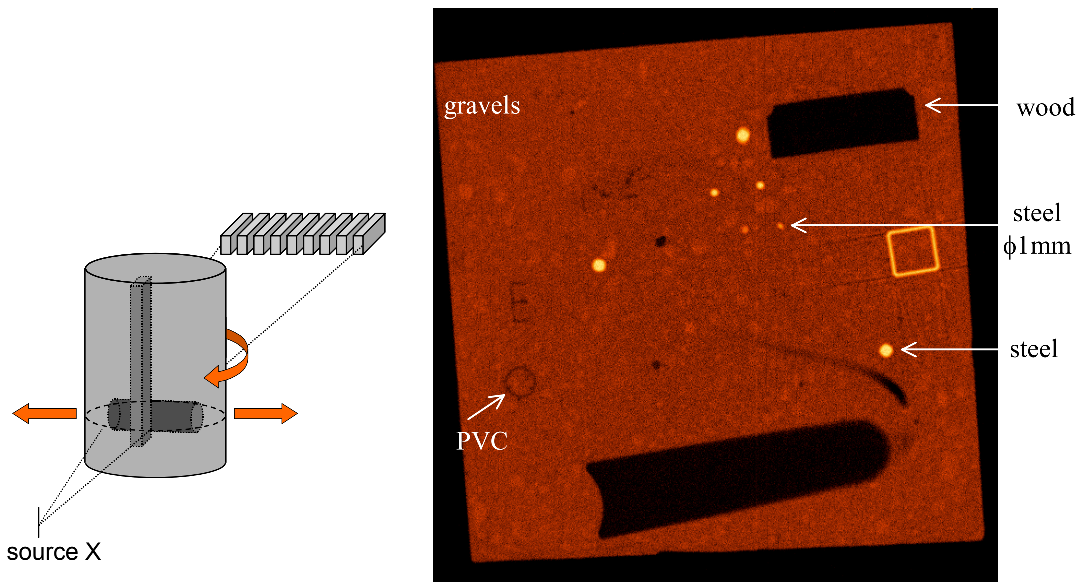


Figure 6: Tomography using translation-rotation, geometry (left) and result (right).

Notice that it is possible to use several levels of detectors, allowing to acquire several slices simultaneously. Of course the cost of the system is then multiplied by the number of levels.
This translation-rotation acquisition technique is highly time consuming. Our acquisition experiment with a 500 mm diameter drum takes 20 min, it could be as long as 1.5 hour for larger drums – and this only for an horizontal slice. A 3D tomography of the whole drum could not be considered. On the other hand, localized tomography can be easily implemented with this acquisition technique: a potentially suspicious or interesting area is previously localized, either using prior knowledge on the drum contents, or by analysis of 2D radiographs, or other sensor technique, and this area only is acquired. Dedicated algorithms allow to reconstruct correct volume from this partial information, and provide quantitative measures.
Consequently, tomographic techniques using unitary detectors are suitable for specific and thorough examination, but not for systematic control.

Another possible type of detector for tomography is a set of linear array detectors. Due to the drum size, a unique linear array should be at least one meter long, and would often be too long to fit inside the accelerator's conic flux. One solution is to use several small linear arrays, and apply a sequence of translations of the object. The result is a segmentation of the usual fan-beam in subsets, each one corresponding to an acquisition. Notice that the algorithm used for reconstruction is the conventional one. Collimation may be applied in one direction, thus quantitative measurements are still possible. Compared to the mono-detector presented just above, the acquisition time gain is 5 (for equal SNR), and the complete tomographic acquisition of a slice of a 1,400 mm diameter drum requires about 8 min.

Discussion: Using a high energy (8MeV) experimental set-up, we have studied and validated different modalities for X-ray inspection of attenuating drums. Digital radiography allows quick projection acquisition of a large part of the drum, possibly the entire drum. Time acquisition could be about 1s using a 2D scintillator screen imager, and a few tens of seconds using a linear array combined with a translation of the drum. A 2D detector allows other modalities: radioscopy and tomosynthesis. The use of a linear array for radiography is more restrictive than a 2D imager, since dynamic acquisition as shown above is no longer possible, but the image quality is greatly better, thanks to the strong stopping power of deep pixel made of convenient material such as CdZnTe, and to the fact that efficient collimation may be applied.
Radiography may be sufficient for some checks, as for instance numbering the compacted drums inside a drum as illustrated in Figure 2. But if the examination purpose is the detection of small structures in a complex drum, or local density estimation with sufficient accuracy, then tomography technique is required. It is a very powerful technique, but more time consuming than radiography. Different types of detectors can be used. A 2D screen imager allows to perform a several centimetre high slice tomography, though linear array or mono-detector of appropriate material such as CdZnTe provides high quality images, but makes complete control of the drum impossible, due to the huge acquisition time. Partial tomography is possible, either of a thin slice (2D tomography) or of a region of interest. Radiography and tomography (and their variants) make use of the same detectors. It is then possible to design a set-up, composed of a high energy source and several detectors, to perform different inspection modalities.
Multi-level strategy control could then be applied to waste drums, based on these complementary modalities. Radiography can be performed systematically on all the drums, radioscopy is an intermediate control, though tomography could only be applied for partial check because of the acquisition time. The part to inspect by tomography can be chosen thanks to radiography results, but also by prior knowledge, for instance the potential presence of air cavities just under the drum cap. Tomosynthesis is dedicated to periphery control. Specific constraints may influence the choice of modalities: inspection time, required space, known heterogeneous distribution of object attenuation.
Other techniques could be studied. Dual energy techniques, either for radiography or tomography, are well-known techniques at low energy. Based on the different components of X-ray-matter interaction, they provide information on the chemical nature of the present materials. For drum check, they could be used for material identification and matrix correction for spectroscopy. But at high energy fields, the main components of X-ray-matter interaction are different, and Compton effect and pairs creation are preponderant. The border between both is about 3 - 4 MeV , thus the source required should be very energetic (15 MeV). Data Fusion of active and passive detection systems is promising, especially with tomography, and could greatly increase results interpretation and reliability. It should be considered in a global inspection strategy.
Notice that the development of new detectors architecture will allow new sampling methods, and consequently reduce corresponding time acquisition.

Conclusions: Different checks based on X-ray techniques may be applied to highly attenuating drums. They imply a high energy linear accelerator (>6 MeV) and detectors adapted to this X-ray flux. These detectors can be unitary, linear array, or 2D imagers. Combined with different acquisition geometries, they allow several inspection modalities: radiography, radioscopy, tomosynthesis, 2D tomography, localized tomography, 3D tomography. Combined within a multi-level strategy, and possibly associated to other checks based on passive systems, they allow to reach the final objective of non-destructive drums inspection, which could be sorting the waste before packaging, physical characterization prior to radiological characterization, quality control before storing, transport, or storage. Notice that this inspection approach may also be suitable for other attenuating objects.

This work has been partially funded by CEA/DEN. The authors are grateful to JL.Pettier for his collaboration.

References:

[WIT01] U.S. Department of Energy, Innovative Technology summary report, Waste Inspection Tomography, OST/TMS ID 259, April 2001, http://ost.em.doe.gov.

[BERN95] R.Bernardi and H.Martz, Nuclear waste drum characterization with 2 MeV x-ray and gamma-ray tomography, Proc. of the SPIE, The International Society of Optical Engineering, 1995, 2519:140-8.

[PURS02] M.Purschke, IQI-sensitivity and applications of flat-panel detectors and x-ray image intensifiers – a comparison, Proc. 8th ECNDT, Barcelona, 2002.

[THAL01] Thales Electronic Devices, Flat panel imaging System Flashscan 35 & 33, User's Manual, V4.20.0, TIV/1M.6403/01.

[ANTO02] M. Antonakios, G. Sanchez, F. Sauvage, V. Moulin, Large Field CCD-based detector devoted to High Energy X-ray Digital Radiography, ECNDT02, Barcelona, Spain, june 2002.

[XTEK] http://www.oisel.co.uk.

[GLAS01] F.Glasser, V.Gerbe, P.Ouvier-Buffet, M.Accensi, JL.Girard, M.Renaud, JL.Gerstenmayer, CdZnTe high-energy radiography detector, Nuclear Instruments and Methods in Physics Research A458 (2001) 544-550.

[GLAS03] F.Glasser, P.Villard, JP.Rostaing, M.Accensi, N.Baffert, JL.Girard, Large dynamic range 64-channel ASIC for CZT or CdTe detectors, Nuclear Instruments and Methods in Physics Research A509 (2003) 183-190.

[ANTO00] M.Antonakios, P.Rizo, P.Lamarque, Real time digital tomosynthesis system dedicated to industrial solid rocket motor examination, 15th WCNDT, Rome, Italy, october 2000.

[REBU03] V.Rebuffel, S.Pires, A.Caplier, P.Lamarque, Automatic delamination defects detection in radiographic sequences of rocket boosters, Int.Symp.on Comp.Tomography and Image Proc. for Ind.Radiology, Berlin, Germany, june 2003.

[GLAS92] F.Glasser, G.Thomas, M.Cuzin, L.Verger, Application of cadmium telluride detectors to high energy computed tomography, Nuclear Instruments and Methods in Physics Research A322 (1992) 619-622.

[PETT04] JL.Pettier, V.Moulin, Une imagerie très haute energie pour la gestion des déchets radioactifs, to be published in Revue Contrôle et Essais, 2004.