X-Ray, Digital Imaging with Volumetric Density Measurement and Profiling, Applied to the Characterization of Waste Drums

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ABSTRACT

The European Commission's Joint Research Centre Ispra Site (JRC-Ispra) has initiated a decommissioning and waste management program that will span about two decades. The program includes a requirement to characterize the contents of about 6,500 radioactive, 220 litre waste drums whose documented history is incomplete. To render the characterization process more efficient, the drums will be initially divided into homogeneous groups, an activity that will be based on existing documentation and non-destructive examination (NDE) by x-ray digital imaging. This paper describes the x-ray imaging techniques chosen, and the planned performance validation of the equipment.

INTRODUCTION

The 6,500, 220 litre waste drums at the European Commission's Joint Research Centre Ispra Site contain low and very low-level waste in the form of miscellaneous waste objects (ρ~1500-6000kg/m^3), compacted drums (ρ~500-1500kg/m^3), and solidified sludges. Bitumen (ρ~1000kg/m^3) was used as the embedding or solidifying matrix. The maximum line average density is 1500kg/m^3, while the maximum weight of a drum is 350kg. JRC-Ispra must perform a radiological characterization of all of the drums using a combination of non-destructive assay and destructive analysis techniques in combination with historical documentation to satisfy national legislation. The x-ray techniques chosen for the non-destructive examination utilize digital radiography (DR) and tangential computed tomography (TCT), operating at x-ray energies of up to 450kV to map all solid waste items and measure the density variations in 3 dimensions through the volume of each drum to identify the configuration and type of waste object(s) in each drum.

The selected system presents the processed data as a 2-dimensional image on which a vertical and a horizontal cursor are superimposed. The density measurements along the line of each cursor are displayed on the operator screen. The operator can move each cursor independently to view the density gradient across any vertical or horizontal path through the drum.

The importance of this is that the measured density information will enable non-destructive assay (NDA) measurement campaigns to be performed in the most optimized way. The resulting cost savings are expected to exceed the investment cost of the x-ray system.

The imaging results include 2-dimensional radiographs and 3-dimensional CT images viewed either as a plan view plus two orthogonal side view images of the drum, or as a single 3-dimensional representation of the drum and its contents. Volume-rendering presents the CT data in visually meaningful ways, showing what the object or phenomenon looks like, especially in terms of its interior structure, and does it fast enough for the user to interactively manipulate the images. The user can rotate the image, look through it by dissolving away opaque material, and take advantage of motion cues and lighting.

This information will be used to plan the required sampling campaigns, thus offering further cost and schedule savings in the overall program.

SYSTEM OPERATIONAL DESCRIPTION

The system consists of a drum conveyor subsystem, which provides input and output drum buffering to enable the temporary hold up of drums before and after scanning, and loads and unloads drums into and out of the x-ray booth. The complete operational cycle of the system is automated except for the loading and unloading of the drum conveyor subsystem, and is designed to examine twenty drums per day in a single, 20 hours cycle.

When the drum is inside the x-ray booth, its barcode identifier is read, and a drum location marker is fixed automatically to the drum. This sets the 0° rotational datum.

The imaging chain consists of a 450kV x-ray source, a linear detector array, and x-ray beam collimators.

Description of Imaging Chain Operation

The detector array is located parallel to the axis of rotation of the object, while all conventional type DR/CT Scanners use the detector array perpendicular to the axis of the object. An individual detector channel collects data mostly for one DR/CT slice. Consequently the tangential computed tomography (TCT) scanner simultaneously collects data for almost 384 individual DR/CT slices. The system scans an object as large as 660mm (26") diameter x 915mm (36") tall, as a true volume CT/DR scanner.
A diagram of the data collection method is shown in Figure1.

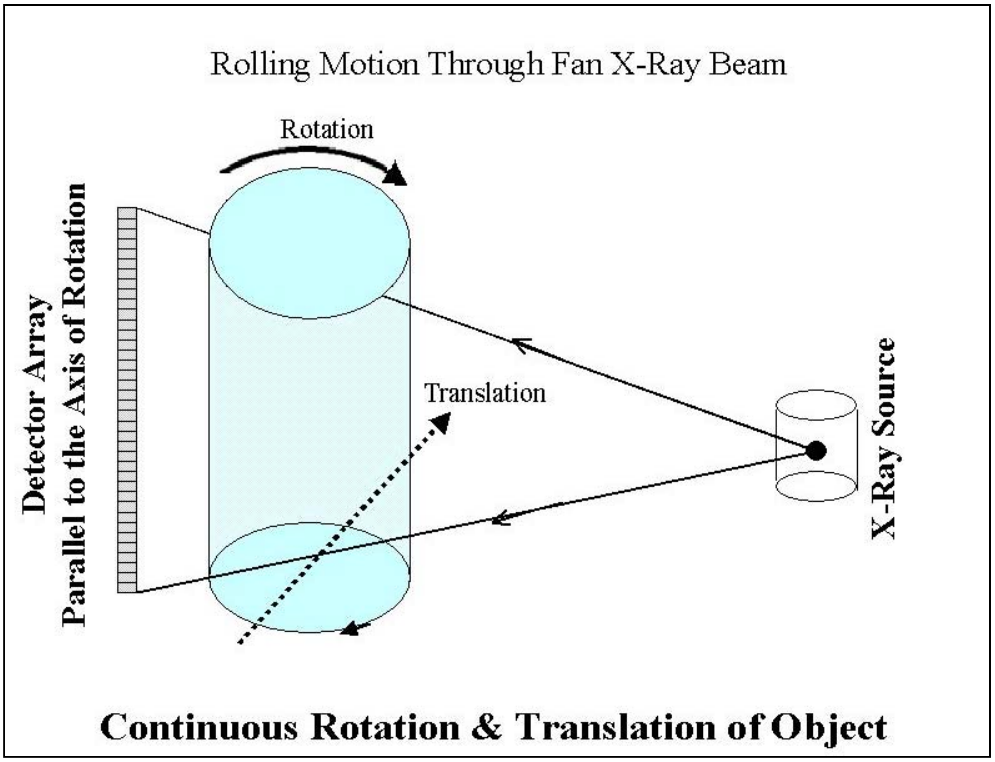

Fig. 1. Tangential CT data collection method

The Object Motion System

The motion system consists of heavy-duty linear motion system and a worm gear type rotary system (turntable). The linear motor has an accuracy and repeatability of 5µm at the maximum weight over the entire range of traverse distance. The rotary table has an accuracy and repeatability of 10 arc seconds at maximum load. The rotary table is mounted on the linear motor to provide the rotation-translation motion. The high rotational accuracy of the motion system enables use of the TCT system as a high spatial resolution system. A spatial resolution of over30 line pairs per centimeter over large field of view can be achieved. Until now, only microfocus x-ray tube based systems have achieved similar high resolution DR/CT scans. However, microfocus systems require large geometrical magnification and thus have extremely small field of view (area of scan). Also, microfocus x-ray tubes provide low (kV) energy and very small x-ray flux and hence can only penetrate very small components. The TCT system can penetrate 175mm (6.8”) of steel with energies of 450kV.

384 Channel Solid State Linear Detector Array

The detector array is the heart of any DR/CT system. In the early 1990’s, a breakthrough in the detector design, made it possible to reduce the electronic noise by several orders of magnitude. The TCT detector array exhibits over 20 bits (10^6) true dynamic range.

The 384 channel detector array of the TCT scanner is made of 6, 64 channel modules butted together to form a contiguous 384 channel detector array. Each 64 channel module has 64 scintillation crystals mounted on an array of 64 silicon photodiodes, together with 64 channels of analog circuits (amplifiers plus integrators), and eight 8:1 multiplexers followed by a line driver circuit. The entire detector array is housed inside an aluminum extrusion and environmentally sealed for long life. In the TCT system, the detector array is totally surrounded by a 6.35mm (¼") thick lead shielding from all sides for almost total x-ray scatter rejection.

The scintillation crystals are made from cadmium tungstate ($CdWO_4$) single crystals. The $CdWO_4$ scintillation crystals are 3mm wide (located at a pitch 3.30mm) in the long (vertical) direction of the detector array. The scintillators are 9mm long in the spatial resolution (horizontal) direction and 6mm deep in the x-ray beam direction. With 6mm depth, the $CdWO_4$ scintillation crystal detects (stops) >70% of the photons from the 450 kV x-ray source, even after the x-ray beam has been hardened by passing through 127mm (5") of steel.

Variable Width Detector Collimator for Adjusting Detector Aperture
A variable width collimator is mounted in front of the detector array. This collimator system is made out of 25mm thick lead sheet sandwiched between two 6.25mm thick sheets of steel. The collimator plates are mounted in parallel on a precision-machined sliding surface. The opening width between these two collimator plates can be adjusted to achieve any desired active detector width in the resolution direction.
With this parallel plate collimator system, the active width of the detector array can be adjusted from a very small value to up to 9mm. This parallel plate collimator provides a tremendous x-ray scatter rejection and the ability to achieve very high spatial resolution.

Variable Width Object Collimator System for Shaping X-ray Beam at the Object
The variable width collimator is mounted in front of the drum under investigation. This collimator system is made of 51mm thick lead plate sandwiched between two 1.5mm thick sheets of steel. These plates are mounted between the x-ray tube and the drum to provide best x-ray collimation and scatter rejection. The opening width between these two collimator plates can be adjusted to achieve any desired x-ray beam width exposing the drum. This allows the drum to be exposed only in the region of x-ray detection by the detector array. This reduces the unwanted production of x-ray scatter from the drum and thus provides the best image contrast.

These collimator systems substantially reduce the scatter and define the spatial resolution of the TCT system.

With the combination of the dynamic range (signal/noise ratio) of the detector array, the post gain amplifier and the parallel plate collimator, the system can scan 175mm (6.8") thick steel objects and achieve 2%-2T performance in radiography mode with 450kV x-ray energy, and can achieve 30 line pair per cm spatial resolution. To scan through this thickness of steel, would typically require several times the energy used, requiring a Linear Accelerator based x-ray source, while to achieve 30 line pair per cm spatial resolution, would require a microfocus x-ray tube system.

Multi Step Automated Detector Calibration System
Each detector channel of the 384-detector array has slightly different response from each other. It is almost impossible to fabricate a detector array to provide uniform x-ray response across the entire array and still have a very wide dynamic range. Hence, the response of each detector channel is determined and corrected within the system software. To determine the response of

each individual detector channel, the raw detector signal of each detector channel is measured as a function of x-ray signal.
A precision steel step wedge is used for these measurements. Under software control, a different thickness of the step wedge is introduced in front of the x-ray tube collimator. The software system automatically measures the output signal of each detector channel as a function of wedge thickness. After a series of these measurements, the software system computes correction coefficients (for a polynomial fit) for each detector channel. When these coefficients are applied to the raw detector signal, the system computes the equivalent material thickness in the x-ray beam for the entire data set of the CT/DR scan. After such a software correction, the response of all detector channels becomes uniform.

TESTS TO DEMONSTRATE DENSITY RESOLUTION

To demonstrate density resolution, solid conical shapes made of polystyrene foam and aluminum test phantoms were made. The height and diameters of each cone was chosen to enable the resolution to be demonstrated over a density range of 500 to 2000 kg/m3 when the phantoms were immersed in 220 litre drum filled with water. A photo of the aluminum and polystyrene phantoms is shown in Fig. 2.

Fig. 2. Aluminum and polystyrene phantoms

Each test was performed for measurement times of 5, 10, 15 and 30 minutes and for drum rotation angles of 0°, 90°, 180° and 270°. A summary of the tests together with the image reference number at each scan are provided in Table I.

Table I. Summary of Tests

Scan #	Scan Time (Min.)	Scan Angle	No. of Data Points	Scan Length	Averaging	X-ray kV	X-ray mA
102	5	0°	6000	600mm	1	400	10
104	5	90°	6000	600mm	1	400	10
106	5	180°	6000	600mm	1	400	10
108	5	270°	6000	600mm	1	400	10
111	10	0°	12000	600mm	1	400	10
112	10	90°	12000	600mm	1	400	10
113	10	180°	12000	600mm	1	400	10
114	10	270°	12000	600mm	1	400	10
121	15	0°	18000	600mm	1	400	10
122	15	90°	18000	600mm	1	400	10
123	15	180°	18000	600mm	1	400	10
124	15	270°	18000	600mm	1	400	10
131	30	0°	18000	600mm	2	400	10
132	30	90°	18000	600mm	2	400	10
133	30	180°	18000	600mm	2	400	10
134	30	270°	18000	600mm	2	400	10

Examples of the results are shown in Fig. 3 and Fig. 4.

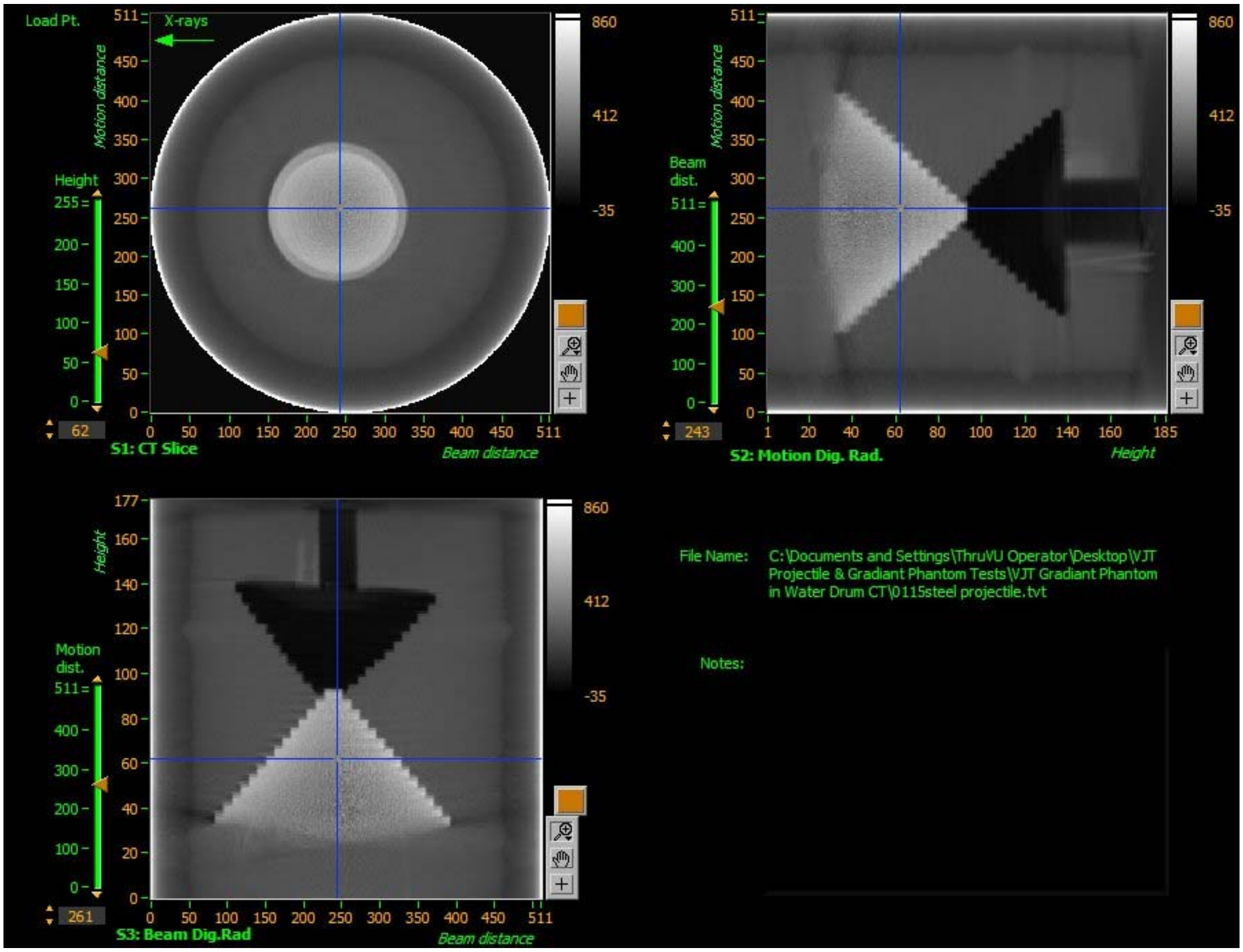

Fig. 3. Three orthogonal views

Three orthogonal views of the water filled test drum test containing the phantoms are shown in fig. 3, in typical CT format. The images are in "negative" form, with the aluminum phantom at the bottom and the polystyrene foam phantom at the top. The pressure required to hold down the Styrofoam phantom in the water has pressed the tip of the aluminum phantom into the Styrofoam phantom. The "cursors" show the chosen sections shown in the image. Density is represented by the image grayscale.

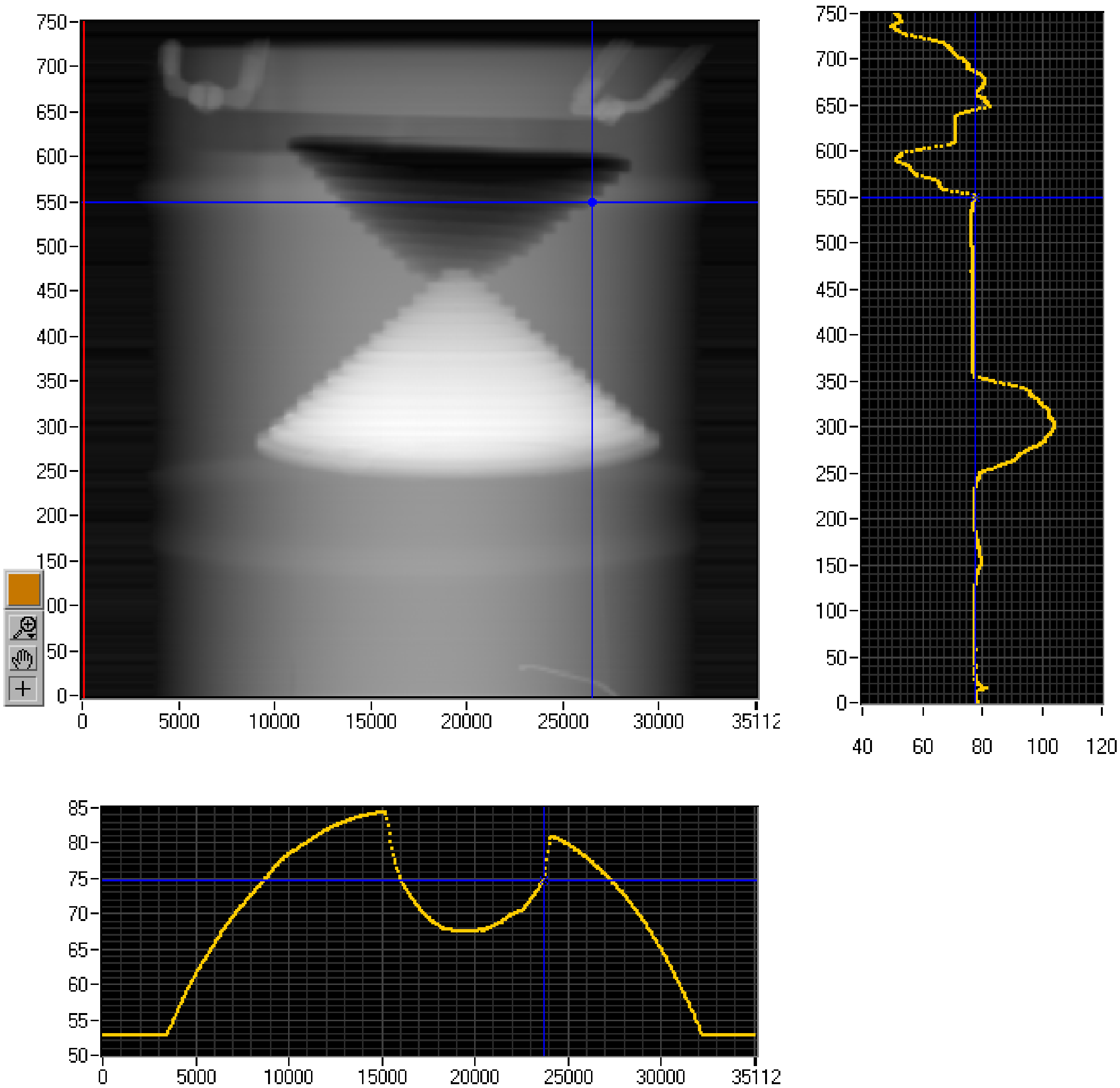

Fig. 4. Quantitative density data

A quantitative representation of density is shown in figure 4. The system presents the processed data as a 2-dimensional image on which a vertical and a horizontal cursor are superimposed. The density measurements along the line of each cursor are displayed on the operator screen. The operator can move each cursor independently to view the density gradient across any vertical or horizontal path through the drum. X-ray attenuation, which is proportional to density, is shown in "yellow" along the "cursor" lines shown in "blue". The chart on the right hand side shows the density change along the vertical blue line. The chart at the bottom shows the density change along the horizontal line.

Thus the system provides quantitative density data with respect to specific location in the drum.

CONCLUSION

Although the x-ray images of the drum shown in this paper are at specific rotation angles, the system allows images to be viewed at any rotation angle, continuously variable from 0° to 360°, and at any height continuously variable over the whole height of the drum to enable independent viewing and quantification of the density gradient across any vertical or horizontal path through the drum. The density measurement by volumetric location will be used to optimize non-destructive assay (NDA) measurement campaigns.

In addition the information will be used to plan the required sampling campaigns, thus offering further cost and schedule savings in the overall program.