RADIOACTIVE WASTE DRUM INSPECTION USING COMPUTED TOMOGRAPHY AND DIGITAL RADIOGRAPHY

John Steude, and Ed Strickland
Scientific Measurement Systems, Inc.
Austin, TX
Jeff Anders
Rockwell International Corporation
Canoga Park, CA

ABSTRACT

Vast quantities of radioactive waste materials have been generated as a result of the production of nuclear energy and defense materials for the past five decades. Regulatory requirements for the safe handling and disposal of these materials specify that waste forms meet stringent waste acceptance criteria. One such requirement is that free liquids in containers must be less than 1 percent by volume. Another requirement is that the contents of waste containers have an adequate inventory. This paper presents results demonstrating that digital radiography and computed tomography, using high energy x-rays (2.5 MeV), can assess compliance with maximum free liquids limits and can produce images that are useful for inventory purposes. The significance of these results is that the inspections can be applied to a wide variety of dense waste forms (e.g., soil, concrete, heavy metal objects) in a noninvasive manner. Opening containers to assess compliance is not desirable for both safety and economic reasons.

INTRODUCTION

There have been great quantities of radioactive waste generated as a result of the production of nuclear energy and defense materials over the past five decades. Data compiled from the DOE Integrated Data Base (1) and the Environmental Management Five-Year Plan (2) estimate that there are over 1.4 million drums of buried and stored, high and low level waste. In addition, there are 300,000 cubic meters of transuranic waste to be handled within the DOE Complex. There are also hundreds of facilities requiring decontamination and decommissioning that will require the processing of many more drums of radioactive materials. Rising to the challenge of safely handling these materials, the DOE has imposed strict guidelines on the acceptable forms of radioactive waste for storage and disposal.

To ensure that drums do not release radioactive liquids and vapors into the environment, regulations for low level waste (3) require that drums contain less than 1 percent free liquids. For transuranic wastes, the Waste Acceptance Criteria for the Waste Isolation Pilot Plant (4) require that any container, or container within a container, entering the facility must have less than 1 percent free liquid inside.

Additional waste acceptance criteria require that the contents of drums have an accurate inventory.

One practical way to certify that waste drums meet waste acceptance criteria is by non-destructive evaluation (NDE) methods. Opening drums for inspection and certification is not desirable from either a safety or a cost basis because it is labor intensive and additional wastes are generated in the hot-cell where the inspection takes place. The NDE method commonly used, real-time radiography with a 420 kV X-ray tube, has been successful for many waste forms, but it is widely recognized that there is room for improvement with many types of dense waste forms in drums. Examples of problematic waste forms include: cement-solidified wastes, compacted sludge, soil, and miscellaneous objects composed of thick, dense materials.

The objective of this paper is to present demonstration results of NDE methods that offer increased inspection capabilities for inspection of dense waste forms. The methods demonstrated here are digital radiography (DR) and computed tomography (CT) imaging utilizing a linear accelerator that produces 2.5 MeV x rays.

An inspection method* recently developed by Scientific Measurement Systems, Inc. (SMS) utilizes DR to quickly detect free liquids in waste drums. This quick screening method, along with quantitative CT density measurements, can be used to identify liquids and measure their volumes. This combined CT/DR approach has the potential to take the guesswork out of certification for meeting waste acceptance criteria.

Previous results (6) have demonstrated that the SMS screening technique with DR can detect free liquid volumes as small as 1 ml inside containers within drums having miscellaneous contents (i.e., glass and plastic bottles, fire extinguishers, paint cans, etc.). The results of CT measurements show that a residual water volume as small as 2.5 ml can be quantified with only 10% error. This volume of water represents 1% of the glass container volume, which was 250 ml. The screening technique was also shown to be effective at detecting slurry mixtures, as well as free liquids.

Prior results (7) with CT imaging measurements showed that fluid-filled voids in a cement-filled drum could be distinguished from air-filled voids over a wide range of sizes, including voids as small as 3 mm. Results also showed that CT measurements of drum wall thicknesses could be utilized to determine drum integrity.

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* Patent Pending

DIGITAL RADIOGRAPHY AND COMPUTED TOMOGRAPHY

An idealized radiograph (shadowgraph) is shown in Figure 1. This example shows how three-dimensional objects are projected onto a two-dimensional viewing plane with conventional radiography. Because the images of internal features overlap when projected onto the radiograph, it is difficult to distinguish between differences in shape, size, and density of objects inside a container holding many items.

When it is important to distinguish different objects and their internal features, CT imaging can be utilized to obtain spatially resolved internal maps of objects and their densities. These maps are independent of the sizes and shapes of the internal features, providing that the objects can be penetrated by the X-ray energy level utilized.

Figure 1 shows an example of a CT image. The CT image is obtained by taking attenuation measurements of an X-ray fan beam from hundreds of angles around the object. A computer is used to "backproject" the measurements onto a spatially resolved density map for a given cross-sectional plane of the object.

The numerous X-ray attenuation measurements are obtained with a CT/DR scanner such as the one shown in Fig. 2. This scanner is an SMS Model 201 designed for large aerospace and automotive components up to 6 feet in size and weighing up to 2,000 lbs. It can be equipped with a 420 kV X-ray tube or a linear accelerator that provides either a 2.5, 6, or 9 MeV X-ray source. The images presented in the following section were generated with an SMS Model 201 scanner equipped with a Schonberg 2.5 MeV linear accelerator.

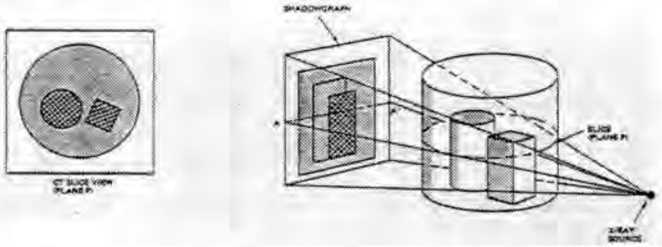

Fig. 1. Comparison of computed tomography (tomographs) and conventional radiography (shadowgraphs).

Fig. 2. SMS Model 201 Industrial Computed Tomography/Digital Radiography Scanner.

The dynamic range of the linear detector array provides X-ray measurements over several hundred thousand intensity levels. This wide range provides highly sensitive density measurements for exceptionally dense materials (e.g., iron, mercury, and lead) as well as very light materials (e.g., plastic, wood, and rubber).

METHODS AND MATERIALS

In designing the test drum, emphasis was placed on challenging the inspection techniques and finding the approximate detection limits of screening for free liquids.

To test CT and DR techniques for inspection of drums with dense contents, a standard 55-gallon drum was filled with cement from the bottom to a 6 cm height, and sand from 6 to a 70 cm height. Thin-walled plastic spheres (20, 38, 50, 70, 100, 150 mm diameters) half-filled with water were placed in the sand to simulate partially filled pockets of water in a drum filled with soil, compacted sludge, etc. Glass tubes (1.7, 2.2, 3.4, 4.1, 4.9, 6.0, 7.9, 9.8 mm diameters) were inserted into the cement before it hardened to simulate voids of known sizes. These tubes contained either air, water, or an aqueous solution of sodium nitrate.

The sodium nitrate solution was chosen for two reasons. First, this is a common liquid waste associated with spent fuel reprocessing. Sodium nitrate supernatant has been generated in large volumes and mixed with cement for disposal. Second, the density of the solution (1.3 g/cc) is closer to cement density (approx. 2.0 g/cc) than pure water density (1.0 g/cc). It is, therefore, more challenging to distinguish sodium nitrate solution from cement than water from cement with CT density measurements.

The drum was scanned with an SMS Model 201 scanner equipped with a Schonberg 2.5 MeV linear accelerator as the X-ray source. A linear accelerator is required to generate enough X-ray penetration for a drum filled with cement or soil. The aperture setting for the detector collimator was 2 mm by 2 mm.

The scan time was approximately 6 minutes for each image. Images of equal quality can be obtained in approximately 1 minute per drum, with minor modifications to the scanner (i.e., additional detectors that are more closely spaced and a shorter distance between the source and detectors).

To screen a drum for free liquids, SMS has developed a simple digital radiographic technique with two digital radiographs that is both fast and conclusive. This technique is: 1) radiograph the drum, 2) tilt the drum a few degrees, 3) radiograph the tilted drum, 4) digitally overlay and subtract one radiograph from the other. Because the liquid surfaces will move relative to their containers in the tilted drum, subtraction of the images conclusively identifies liquids in a drum with a positive/negative "fingerprint" where the liquids moved.

The DR screening technique is followed by quantitative CT scanning to determine if densities of common liquids are present at the location indicated with the screening technique. If desired, CT imaging can also be used to determine the volume of free liquid.

After the scanning demonstration for free liquid detection, miscellaneous items with a wide range of densities were placed in the drum for CT imaging of common objects. The items included: a rubber respirator mask, a rubber disk, a plastic bottle of water, graphite blocks, bags of soil and rocks,

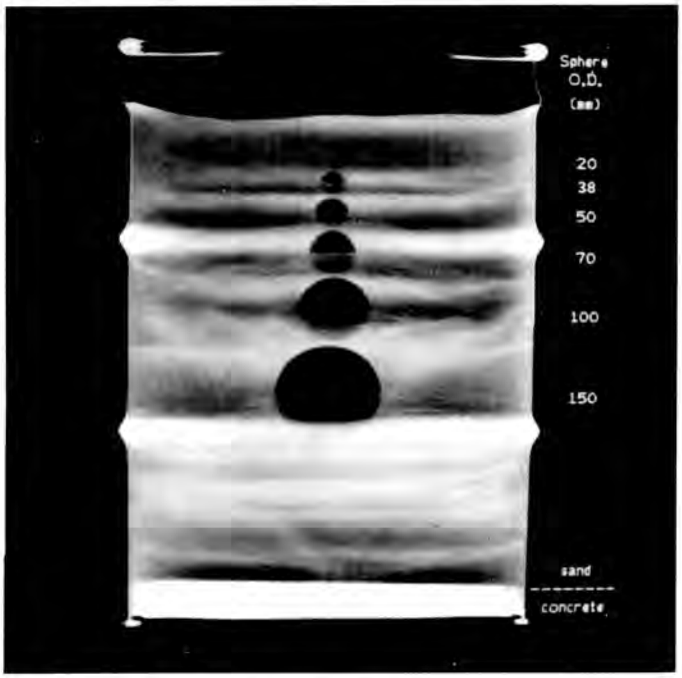

Fig. 3. DR of a sand-filled drum with hemispheres of water.

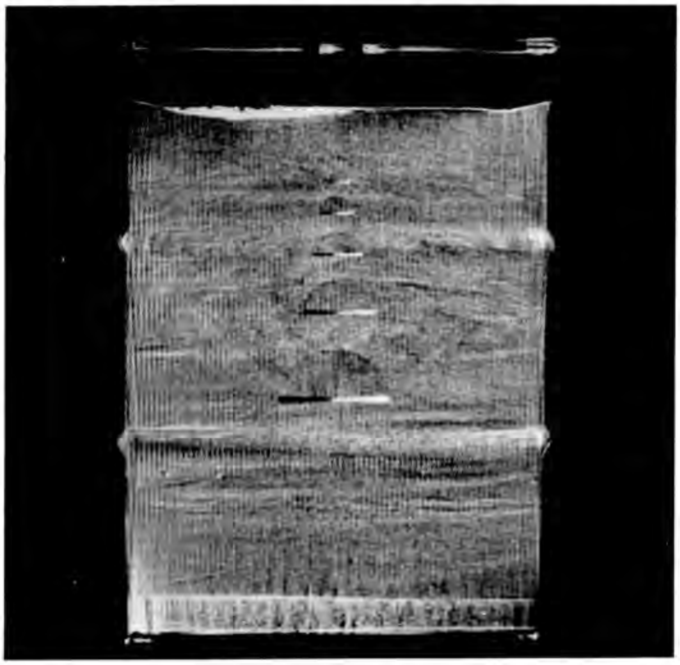

Fig. 4. DR of water surfaces in a sand-filled drum.

concrete rubble and core samples, batteries, a steel respirator tank, a steel ball valve, a jar of mercury, and a lead brick. These items were chosen to demonstrate the wide dynamic range of the CT imaging by showing all these items in the same image.

RESULTS AND DISCUSSION

For all images presented, higher density is indicated by white and lower density by black. Intermediate densities are displayed in corresponding shades of gray.

A digital radiograph of the sand-filled drum with a cement layer at the bottom is shown in Fig. 3. A review of the radiograph shows that there are a number of partially filled spheres in the drum. Although the single digital radiograph reveals the locations of the voids in the drum, it cannot by itself identify free liquids in a conclusive manner.

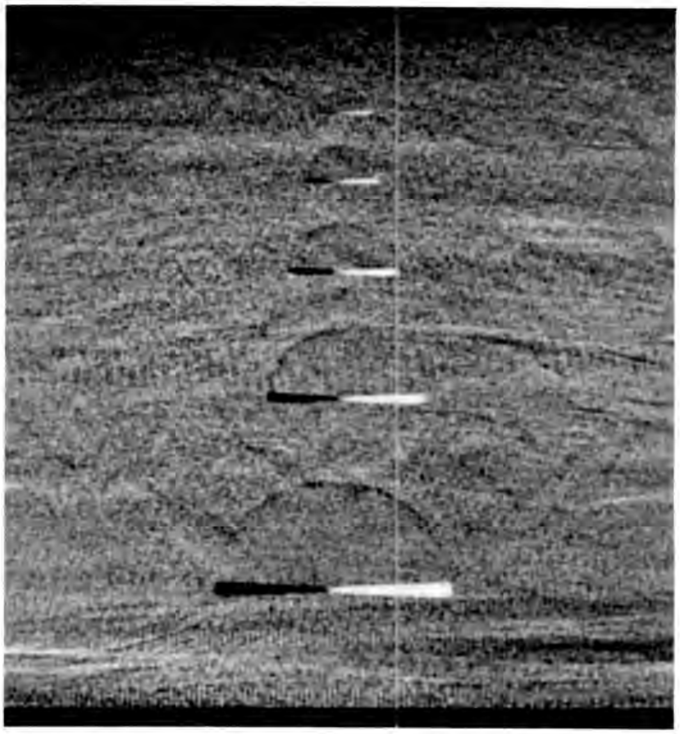

Fig. 5. DR enlargement of water surfaces in a sand-filled drum.

The result of using the tilted drum screening technique is shown in Fig. 4. The free liquid surfaces are clearly identified by a black and white bar where they shifted relative to their containers. Figure 5 shows an enlargement of the drum image in the vicinity of the hollow spheres. All but the smallest sphere shows the black and white signature of a free liquid surface. This result indicates that the detection limit of the screening, with the scanning parameters utilized, is approximately a 38 mm void. Longer scan times increase the signal to noise ratio in the image and would likely result in better detection limits.

The volume of water in the half-filled 38 mm sphere was 14.4 ml. The allowable free liquid in a 208 liter drum at the 1% level is approximately 2 liters. Therefore, the DR screening technique is capable of detecting 1% free liquid, even though the liquid may be dispersed in many smaller amounts.

A CT image of the drum at the height of the fluid-filled tubes in the cement is shown in Figure 6. The image shows the three sets of tubes as black dots in a circle half-way between the center and the outer edge of the drum. Natural voids are randomly distributed throughout the image.

Figure 7 shows a plot of CT densities measured inside the tubes. The plot shows that it is relatively easy to distinguish air-filled voids from fluid-filled voids that are 3 mm or greater. For example, a threshold could be set at a density of 0.5 g/cc. Any void 3 mm or greater in size having a density less than 0.5 could be considered to contain air, while those having a density greater than 0.5 likely contain a liquid.

Smaller voids can be imaged and measured with increasing statistical confidence by using a narrower setting on the detector collimator and increasing the scan time. For example, the collimator apertures could be set at 1 mm by 1 mm

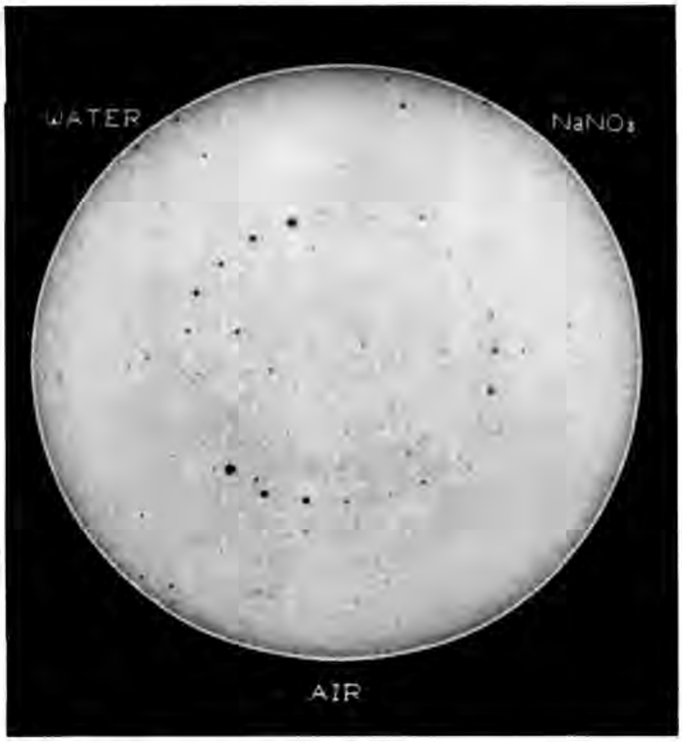

Fig. 6. CT image of fluid-filled voids in a drum of cement.

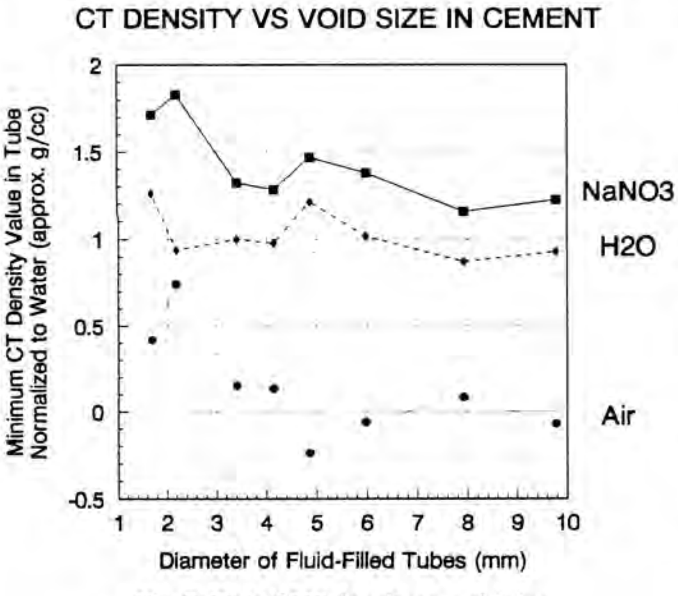

Fig. 7. Plot of CT density vs. void size.

instead of 2 mm by 2 mm. For these apertures, the scan time may have to increase by four times to attain a similar signal to noise ratio in the image.

Figures 8 and 9 show CT images of miscellaneous items with a wide range of densities. These images demonstrate the robust imaging capability of CT to inspect drums with confusing contents. Note that the rubber respirator mask (approx. 1.0 g/cc) is visible in the same image as a steel respirator tank (7.9 g/cc), a lead brick (11.4 g/cc), or a jar of mercury (13.5 g/cc). The overlapping images of these objects would cause the lower density items to be difficult to identify with other radiographic methods.

SUMMARY AND CONCLUSIONS

In presenting a new technique for certifying compliance with waste acceptance criteria, a method for rapid detection of small amounts of free liquids in a sand-filled drum was demonstrated. This digital radiographic technique depends on the shifting of liquids relative to their containers when a drum is tilted. Tilted and non-tilted drum images are overlaid, and the difference between the images identifies liquid surfaces with a conclusive black and white signature.

The ability to use quantitative CT measurements for distinguishing fluid-filled voids from air-filled voids as small as 3 mm was demonstrated.

Miscellaneous light and dense objects, representing confusing contents for other radiographic methods, were imaged with CT. The ability to nondestructively determine the identity of these confusing contents is extremely important for meeting waste acceptance criteria requiring inventories of drum contents.

Radioactive waste management is publicly perceived as a difficult problem demanding the best available inspection technologies to assure environmental and public safety. Digital radiography and computed tomography are exceptionally sensitive and applicable inspection technologies that are commercially available.

Existing CT/DR scanners offer increased capabilities for inspecting radioactive waste drums for free liquid content and other waste acceptance criteria. Minor improvements in the scanners, such as optimizing the number of detectors and the source to detector distance for scanning drums, will reduce the scan time from 5 to 6 minutes per image to approximately 1 minute per image.

With further study, knowledge specific to waste drum inspection will accumulate and lead to increased confidence in the CT/DR techniques and their unique quantitative capabilities. The support of applications research directed at waste drum inspection with a CT/DR scanner specifically designed for waste drum inspection will bring immediate results that will significantly advance the nuclear industry toward its goal of safe, long term management of radioactive waste.

ACKNOWLEDGEMENTS

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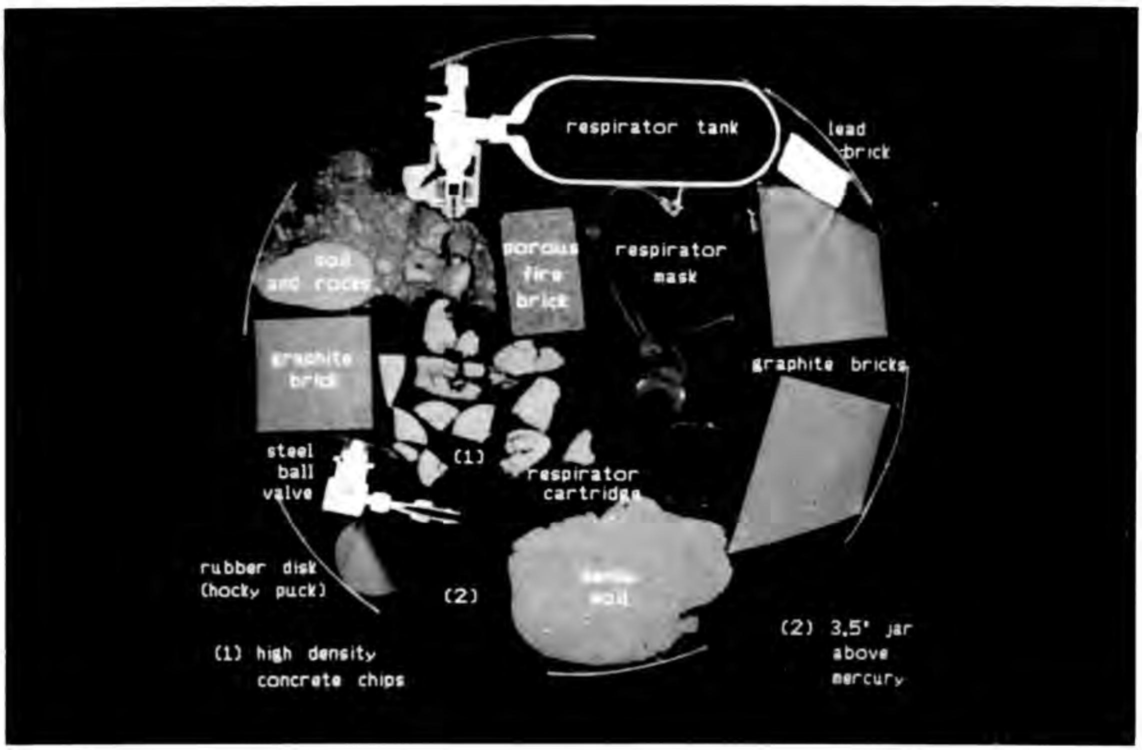

Fig. 8. CT image of a drum with miscellaneous contents.

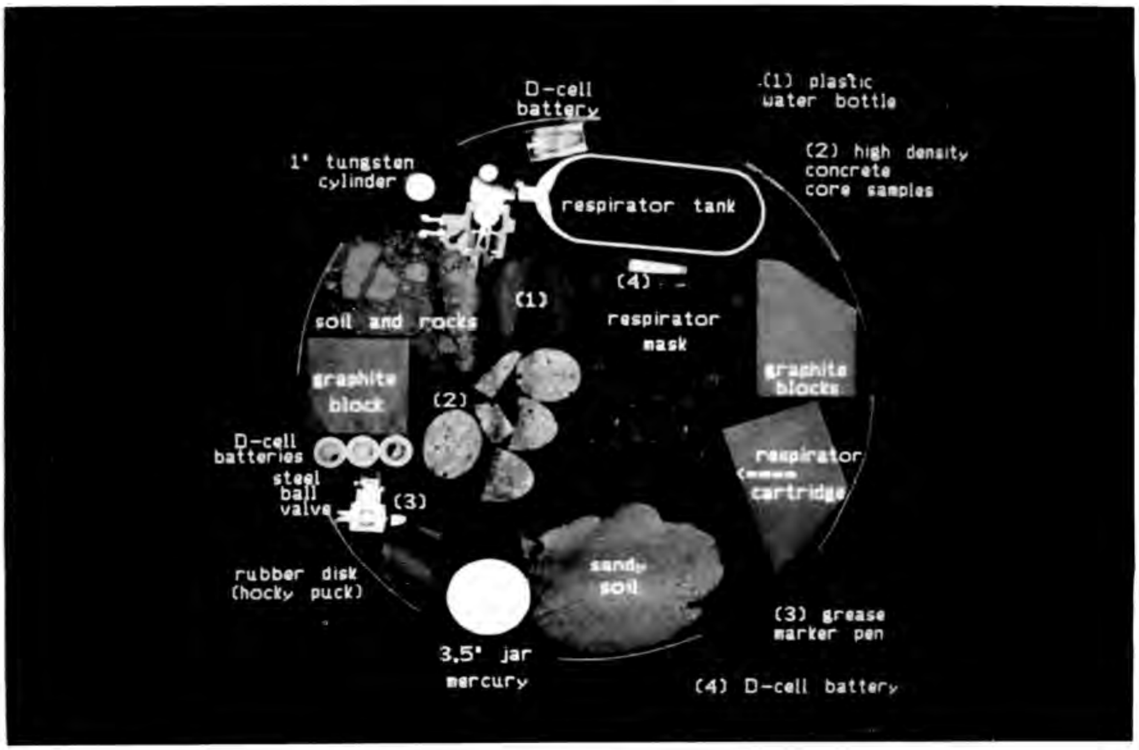

Fig. 9. CT image of a drum with miscellaneous contents.

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