FEASIBILITY AND APPLICATIONS OF CONE BEAM X-RAY IMAGING FOR CONTAINERIZED WASTES

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ABSTRACT

Large area scintillation screens coupled to video and scientific-grade CCD cameras allow high speed digital data acquisition for both single 2-D x-ray projections and tomographic data sets comprised of multiple 2-D projections. While the data acquisition may proceed more rapidly than data acquisition using a linear detector array, there are geometric distortions associated with the projection cone angle long processing times for 3-D tomographic data. This paper reviews issues associated with processing and interpretation of the data and approaches to resolving some of the problems for containerized waste inspection. Results obtained with the Idaho National Engineering Laboratory's Digital Radiography and Computed Tomography scanner are presented.

INTRODUCTION

Real time radiography (RTR) has been, and continues to be, the major radiographic method of waste container inspection throughout the DOE complex. For immediate, nonintrusive,

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qualitative inspection to verify the content code of a waste drum, RTR is presently the uncontested choice. Studies at the Idaho National Engineering Laboratory (INEL) demonstrate that RTR operators can successfully verify content codes, identify several waste categories, and estimate the weights of materials in homogeneous waste forms.[1] In addition, advances in real time digital processing of RTR data provide for greatly improved RTR images and allow for some quantitative estimation to be performed.[2,3] Estimation of weight in heterogeneous waste matrices, of layers of containment, and of chemical compositions remain difficult or nearly impossible (chemical composition) for RTR alone.

The current version of the TRU Waste Characterization Quality Assurance Program Plan (QAPP),[4] Section 10, addresses the requirements for radiographic inspection of waste drums. The description of radiography and a majority of the requirements listed lean towards RTR as the only method available, however, it is also implied that alternative radiographic methods may be allowed. For the reasons listed below, it is likely that digital radiographic or tomographic inspection methods (DR and CT), in addition to or in place of RTR, will be used by DOE sites in the future.

- The QAPP requires an estimate of several waste material parameter weights.

- Digital radiography and computed tomography offer objective, quantitative, repeatable results that are more defensible than subjective analyses currently allowed by RTR methods.

- The QAPP requires a visual examination be performed on a statistically determined subpopulation of waste containers to verify the results of RTR -- quantitative DR and CT could reduce the number of drums that need to be visually inspected by providing a very highly spatially resolved map of drum contents, greatly reducing the costs of statistical sampling.

- Digital storage is a more permanent and reliable method of data storage than the analog tape format currently used in RTR inspections.

- The quantitative nature of both DR and CT data for spatial positioning, dimensioning, and density estimations for waste container contents will provide significant, useful information in an integrated multiple measurement approach to waste assay.

- Automated pattern recognition and object identification are useful digital processing tools to assist operators in containerized waste inspections.

- DR and CT imaging can assist in verification of drum content integrity in the Performance Demonstration Program (PDP).[5]

- Increasing requirements for hazardous component identification will be occur in mixed waste applications.

The Digital Radiography and Computed Tomography (DRCT) of Waste Containers project at the INEL is developing radiography and tomography methods that will optimize the nondestructive evaluation of waste containers with respect to the points listed above. This paper addresses some of the issues associated with area detector scanning of drums. The next two sections introduce concepts associated with radiography and tomography of waste drums and describe the INEL DRCT scanner. Following these two sections, some of the key issues of area detector scanning for waste container inspection are described and some examples are provided. The last section discusses future plans for the DRCT project and provides a summary and conclusion.

RADIOGRAPHY AND TOMOGRAPHY OF WASTE DRUMS

X-ray techniques are nondestructive and nonintrusive--waste containers are unchanged and unopened during the x-ray process. X-ray imaging is advantageous because it can rapidly provide detailed information about the contents of the otherwise opaque containers. Radiography generates an image of container contents by a single projection of x-rays through an object onto a detector. The 3-D object information is compressed to a 2-D static image on film or a scintillation material. Features in the object overlap in the image and shadows result. RTR is similar to conventional radiography but the radiographic image is transferred to a live video display at real time rates (30 frames per second). The object can be rotated to provide a sensation of 3-D images generated mentally from a series of 2-D images. Scintillation screens that convert x-radiation to visible light in real time are most often used.

Figure 1 shows a collection of x-ray images using the DRCT scanner. An x-ray source produces a cone of radiation directed at the object of interest, in this case a 55-gallon drum. The radiation that passes without attenuation through the drum is detected by either the large area detector or the linear detector array, depending on the characterization requirements for the particular object and the time frame allowed for imaging. The large area detector supports real time radiography, digital radiography, 2-D tomography, or full 3-D tomography. The linear detector array supports digital radiography, 2-D tomography, and 3-D tomography by generation of a series of 2-D tomographic slices. A brief description of each of the methods is provided here. More complete descriptions of DR and CT can be found in References 6 and 7.

Digital radiography is essentially the process of converting analog radiographic information to a form that can be stored on a computer, and processed via computer algorithms. An analog radiographic image can be converted to digital form by digitizing the brightness values associated with each point or by sampling the analog electrical video signal. Various linear and area detectors also exist that more directly provide a digital output as part of the measurement. For example, scintillation materials such as gadolinium oxysulfide (GOS), some plastics, and cadmium tungstate convert x-ray energy to visible light. The intensity of the visible light is then measured by CCD cameras, photomultiplier tubes, or photodiodes and stored as digital data representing x-ray intensity as a function of position. DR may provide quantitative information but is limited by the shadowing of object features.

Computed tomography uses a large number of radiographic projections through an object combined with computer processing to generate a map of the spatially varying x-ray attenuation property of the object. The map is a point-by-point representation and does not suffer from the object overlap problems seen in radiography. Because the attenuation property depends on density and elemental content, a map of the interior of an object, representing a combination of these two features, is provided. Two-dimensional tomography (Figure 1, tomography display) provides a series of cross-sectional (image) slices that can be stacked to generate a 3-D image. Three-dimensional tomography provides a direct 3-D image data set that can be displayed (following substantial processing) as either a series of 2-D planes (i.e., slices of bread in a loaf) or directly as a 3-D volume.

Several of the methods described here have been investigated for waste drum inspection by industry and national laboratories,[8-11] but to date conventional RTR is the only method in routine use at waste characterization facilities throughout DOE.

INEL DRCT SCANNER

The INEL DRCT scanner is a combination of a Model 201 CITA™ linear-detector-based system from Scientific Measurement Systems, Inc (SMS), an area detector jointly designed and constructed by SMS and INEL, and several upgrades to both pieces of equipment (Figure 2). The Model 201 scanner was acquired from an unrelated government project via government excess in FY93. The scanner was refurbished, upgraded, and installed in FY94. The x-ray source, source and object positioning units, and motion controls for the original linear scanner are used with the area detector as well. The x-ray source is a Seifert 420 kVp with two spot sizes, nominally 1.8 and 4.5 mm diameter. A modified 4 MeV linear accelerator medical therapy source will be added to the system in FY96. The linear detector consists of a 125-element plastic scintillator/photomultiplier tube array and is capable of providing a maximum spatial resolution of 0.5 mm (1 lp/mm @ 50% modulation) and 0.5% density resolution in CT mode.

The area detector combines a large scintillator coupled optically to a CCD camera. The scintillation screen is comprised of a 3x3 planar array of gadolinium oxysulfide scintillators, each 14 in. x 17 in., yielding a 42 in. (W) x 51 in. (H) screen. Light output at the backside of the screen is projected via a large mirror to the CCD camera. The camera used depends on the application. A video CCD camera with electronic integration capability is used for RTR applications. For high-dynamic-range digital imaging, a 14-bit, 1024x1024 Photometrics (Model CH250) CCD camera is presently used. A 12-bit, 2048x2048 Photometrics (Model PXL-4200) camera is also being tested in the system.

The scanner presently operates either in linear detector or area detector mode with a two-hour turnaround time to exchange detectors and realign the system. During the next year, we intend to substantially reduce the turnaround time for changing detectors. Various methods of data acquisition possible with the scanner are described in the following sections.

The scanner is presently installed at a warehouse on the Idaho State University (ISU) campus in Pocatello, Idaho. Scanner development and tests with INEL calibration and Type A2 low level waste drums is ongoing. A more complete description of the scanner with early results using the linear detector array is provided in reference 12.

AREA DETECTOR SCANNING

The main attraction of an area detector system comes from more efficient use of the cone-beam x-ray source and is twofold: 1) the ability to view a complete x-ray projection of an object in real or near-real time, and 2) the potential for large improvements in throughput times for digital data acquisition. In the following paragraphs, we **briefly** and **generically** discuss differences in the hardware (x-ray source and detector), scanning protocols, and software (data acquisition and processing) between linear and area detector imaging methods. A discussion of some of the issues associated with the two methods with respect to waste drum inspection, and some examples, complete this section.

X-ray Sources and Detectors

The sources under consideration here are those commonly known as generator or accelerator sources that produce bremsstrahlung radiation from the slowing of electrons in a metal. For waste drum inspections, the most common sources used in the past have been 420 kVp or lower voltage. Newer research systems at Lawrence Livermore National Laboratories[9] and commercial systems from BioImaging Research[10,11] and Scientific

Measurement Systems[8] have employed 2 to 4 MeV linear accelerators on waste drums or surrogates. All of these sources produce a cone beam of radiation. When used for linear scanning, the source is highly collimated so that only a thin cross section of an object is illuminated by x-rays. Any radiation not emanating in the small angle allowed to escape the collimator goes unused. For area scanning, the source may be entirely uncollimated in the forward direction of the radiation or collimated only to the point that the cone of x-rays covers the full volume of the object.

Nearly all the x-ray detectors used in waste inspection employ a scintillator that converts x-radiation to visible light and a visible light detector that converts light to an electronic signal and ultimately to a digital value. Linear detectors consist of many (up to 1000) discrete detector channels whose signals are commonly isolated from each other electronically, and physically by x-ray collimators and optical shielding. The discrete detector channels provide for a line of digital samples (pixels) representing the x-ray flux at each detector pixel. Area detectors typically consist of a single large-area scintillator that provides a large-area optical image of the x-radiation pattern impinging on it. The visible light image is then projected to a (small-area) CCD camera either through a fiber optic bundle (for relatively small area detectors) or through an optical lens system. Depending on the type of camera used, the light-converted x-ray image is either seen in real time analog video or digitally captured and stored on computer.

Scanning Protocols

Several types of data can be obtained with linear and area x-ray detector systems, including single 2-D digital radiographs, 1-D slice projection data (for 2-D tomography), and multiple 2-D projections (for 3-D tomography). Since linear detectors can be scanned and area detectors can be collimated, linear and area detectors are capable of obtaining the same type of data with one exception, 2-D projection RTR is available only with area detectors. For radiography, a linear detector array is scanned vertically in tandem with a horizontally collimated x-ray source to acquire a series of line scans that are merged to create a digital radiograph, while an area detector remains stationary and simultaneously acquires a single projection radiograph (Figure 1).

In industrial computed tomography, the object is typically rotated in a series of discrete steps to acquire the set of angular projections required to adequately sample the object. Again, the linear detector would be translated vertically in tandem with the collimated x-ray source (following acquisition of a complete set of angular projections at each slice) to allow for acquisition of several horizontal (cross section) CT slices. Within each slice plane, the stationary source presents a fan of radiation to the object and detector called a fan beam.[7] The area detector remains stationary during 3-D tomographic data acquisition, collecting a 2-D projection image for each angular position of the object. These cone beam projection data are then processed with cone beam tomographic reconstruction algorithms.[13]

The single, circular orbit used in many cone beam tomography applications does not sample the object as uniformly as multislice linear tomography, and does not sufficiently sample the object to allow an artifact-free tomographic reconstruction. To compensate for this, more complex "orbits" to sample the object are employed.[14-16] One orbit being tested at INEL involves supplementing the usual circular orbit with projections taken along two vertical translations of the source, with the object rotated 180° between the translations.[17] This orbit is referred to as "c2l" for circle and two lines. An example of the improvement in the reconstructed image from this type of orbit is provided in a later section.

Two other methods of linear tomographic data acquisition are: parallel beam tomography[7], which requires translation of the source in a horizontal plane and is too slow to be useful for nondestructive evaluation of waste drums (except for attenuation corrections in nondestructive assays[18]), and spiral CT, which combines simultaneous object rotation with source translation (vertical) to acquire a 3-D data set.[19] The area detector may also be used to acquire data during synchronous motion of source and detector. This acquisition method is known as helical cone beam and is an area of interest in the DRCT project. Finally, note that when using a video camera for RTR, image data may be digitized rapidly enough that a cone beam data set could be acquired in real time. The dynamic range and spatial resolution of cone beam data acquired in this fashion would be poorer than that acquired with the higher dynamic range, higher resolution CCD cameras; however, there may still be sufficient quantitative information retained in this data to make it a viable drum inspection technique.

Data Processing

Single projection radiographs from either RTR or DR systems are conceptually simple but have complex images due to the overlap that occurs in compressing a 3-D object onto a 2-D image. In general, because of the overlap, it is difficult to derive quantitative information and so radiographs are most often used in a qualitative manner. Tomographs produced from multiple projections are, on the other hand, slightly more difficult to describe in terms of data acquisition and processing but produce images that are simpler to relate to object properties such as dimension and density. Data processing may be split into three areas for DR and CT: tomographic reconstructions (CT only), raw data/final image enhancement, and image analysis. Radiographs acquired with linear or area detectors are similar, so processing of their digital radiographs is similar. Also, image enhancement and analysis techniques are similar for DR and CT images. Thus, it is primarily the differences in tomographic data processing that are of interest here. Major differences do occur for tomographic processing of data acquired from linear and area detectors. Linear detector tomographic data is used to reconstruct 2-D cross sectional slices (from parallel beam or fan beam data) of an object (2-D CT) that can be "stacked" to create a 3-D image while area detector data may be used to directly reconstruct 3-D volumes using cone beam CT algorithms. In addition, area detector data can be acquired and resampled in such a way as to mimic linear detector data so that the same processing used for linear detector data may be applied to the (resampled) area detector data.

Issues and Examples

An area detector coupled with a cone beam radiation source offers the potential for a dramatic improvement in data acquisition times when compared to a linear detector array, but not without some sacrifice. The most immediate visual difference is illustrated in Figure 3, which shows a single projection radiograph of the INEL Graphite Calibration drum taken in area detector mode (left) and linear detector mode (right). The drum contains several layers of graphite bricks separated by lower density spacers and was chosen as a near-worst-case example. A vertical magnification occurs in the area view, as can be seen by the difference in vertical separation of the drum hoops. The graphite layers in the area view are vertically magnified and hence overlapping, while in the linear view the vertical layering shows through undistorted. The detector pixel resolution in both cases is approximately 1.3 mm. Note that although the picture on the right represents the type of image that can be acquired with a linear detector array, it was actually acquired by horizontally collimating and vertically scanning the x-ray source while exposing the area detector (i.e., the shutter on the camera was left open during the entire vertical scan of the source). Accomplishing equivalent spatial resolution and image contrast with a linear detector array would likely be faster than with this emulation, but would still be substantially slower than the area detector image acquisition. This qualitative comparison yields several considerations for digital radiography: area detectors are inherently faster at acquiring full 2-D projection data but yield a vertical distortion, linear detectors provide a more distortion free image, and the area detector can be used to acquire data that resembles the linear detector.

Another important factor affecting image quality is the dynamic range of the detector. Higher dynamic range allows for a higher variation in object density and distribution to be recorded and leads to an improvement in image contrast for both DR and CT images. The dynamic range of the area detector in the DRCT scanner depends on the camera used--the CH250 camera has a 14-bit dynamic range, the PXL-4200 has a 12-bit range, and video cameras are typically digitized to 8 bits. Frame averaging can increase the dynamic range slightly (1 to 2 bits) in these cameras at the expense of multiple exposures. Typical dynamic range in linear detectors is 17 to 18 bits. Thus the contrast provided by a true linear detector is likely to be better than that provided by the area detector.

The remaining issues addressed here involve cone beam CT and either pertain to the practical problems of processing very large data sets (200 to 500 Mbytes) or artifacts that occur due to insufficient sampling. Currently, using a dual processor, 75 MHz, Sun Sparc 20 workstation with 448 Mbytes of RAM, running the Feldkamp[13] algorithm, volume reconstruction times for data consisting of 180 angular projections, each at 640x1024 pixels, are on the order of 1 h for an image that is 200x200x200 voxels (representing an object sampling of about 0.5x0.5x0.5 cm). There are a variety of methods and hardware options available to speed up the reconstruction times if the quality of the image warrants the effort, so processing times are not a major issue. The issue of greatest interest, therefore, becomes the quality, quantitative accuracy, and usefulness of cone beam imaging for waste container characterization. We have recently verified that the traditional circular orbit and Feldkamp reconstruction will work well for a small volume of interest but fail when applied to an object as large as a drum. The region close to the horizontal plane that contains the x-ray source reconstructs very well but the off-axis regions develop severe artifacts, poor spatial resolution, and reduced quantitative accuracy. Any narrow horizontal section can thus be tomographically imaged with either fan beam or cone beam methods. We are currently exploring the range of applications that circular-orbit cone beam tomography has on waste drums (i.e., regions of interest) but, more importantly, we have begun developing data acquisition protocols and software to perform cone beam tomography on whole drums using improved sampling methods, commonly referred to as sufficient orbits.[14] A sufficient orbit (or complete data acquisition geometry) is defined by Smith[15] as follows: if on every plane that intersects the object there lies a vertex (source location), then one has complete information. Complete information implies that an artifact-free reconstruction of the object can be performed. Two sufficient, but impractical, orbits are the orthogonal circles and infinite vertical line. Orthogonal circles are impractical for drum imaging as they require either laying a drum on its side or an impossible motion for source and detector. Likewise, the infinite vertical line is impractical. An orbit that approaches the completeness condition and holds promise for drum inspection is described next.

The circle-and-two-line (c2l) orbit, mentioned in an earlier section on scanning protocols, provides a far better sampling of the whole drum than the circular orbit. In the c2l orbit, the standard circular orbit is supplemented with projections of the source along two vertical lines, 180° apart (Figure 4). The data acquisition along the two vertical paths adds little to the overall acquisition time. Reconstruction algorithms to process c2l data have only very recently been developed.[20] An example of the potential value of c2l cone beam tomography is provided in Figure 5. This figure shows the results of two simulations of data acquisition and processing of a drum phantom with characteristics similar to the INEL graphite drum. The phantom consists of a hollow closed cylinder (empty drum) 5 mm thick, 57 cm in diameter, and 90 cm high, containing four disks, each 5 cm thick and separated by 5 cm. Two 1-cm diameter spheres were located 30 cm above the top graphite layer. Line integral projections from source to detector through the object were analytically calculated. The simulation data is noise free. The detector is square, with 200x200 pixels, 7 mm per side. This coarse sampling on the detector plane was chosen because it is sufficient to demonstrate the effect of interest. The two reconstructed images shown represent a vertical plane of the object, normal to the source-detector axis, through the center of the object. Both images were reconstructed into a 100x100x100 volume, with each voxel 1 cm^3. For the reconstruction shown on the left, 180 angular projections were acquired and the Feldkamp algorithm was applied. A noticeable distortion of the graphite planes occurred. For the reconstruction on the right, an additional 36 projections were acquired, 18 on either side of the drum with the source stepped from a height of 41.65 cm above the central plane to 41.65 cm below (49 mm per step). The algorithm[20] applied to these data handles several orbits including the c2l. There is a dramatic improvement in the image resulting from the c2l method. The distortion seen in the circular-only process has been completely removed. Note that the small spheres appear brighter in the image on the left. This is in part due to the undersampling on the detector (i.e., there is a partial volume effect that is more prevalent in the c2l image). Note also that the top and bottom of the left reconstruction do not show at all. Thus, there is a large improvement in the resultant 3-D image from the use of the c2l method. The next step in investigating the c2l method is to apply the algorithm to real data. We are currently developing the capability to acquire and process c2l data.

While the primary interest in the area detector is for whole drum RTR and 3-D tomography, it is also capable of providing linear scans and 2-D cross-sectional images. An example using the INEL Valrath Can calibration drum is shown in Figures 6 and 7. As can be readily seen in the single projection radiograph (Figure 6), the Valrath Can drum is simply a set of empty cans stacked inside the drum. Also evident in the radiograph are three cylindrical tubes that are used to place plutonium sources at various positions in the drum when it is used to test gamma and neutron assay systems. In this drum, two plutonium sources were placed at different vertical levels in the same tube. The plutonium sources are roughly the diameter of a quarter and have a plutonium wafer approximately 175 μm thick sealed in a copper coating. Figure 7 shows a 2-D horizontal slice of a Feldkamp cone-beam reconstruction from circular-orbit data taken at the level of one of the sources. The results demonstrate the adequacy of the imaging process for locating and sizing plutonium sources in low-density drums.

SUMMARY AND CONCLUSIONS

The fields of radiography and computed tomography are mature, but new measurement methods and new applications are continuously being developed. The interest in DR and CT for the characterization of waste containers includes identifying, locating, and dimensioning objects; quantifying the weights of individual components of the waste matrix; conveying quantitative information to systems that perform nondestructive assays; and minimizing the need to perform intrusive visual inspections of drum contents. Nondestructive evaluation of waste containers has not been well covered by radiographic and tomographic methods to date, and thus will benefit from applications of traditional methods and from new methods. We have described DR and CT with an area detector recently developed by the INEL. There is additional development work to be performed to make the system easy to use and to optimize it for waste drum inspections. Understanding and resolving the critical issues in area detector scanning of waste drums will be a major source of activity in the DRCT project. The high spatial resolution of CT and its potential to characterize waste matrices by density offers promise as a useful tool for waste assay systems (neutron and gamma).

There are many applications for NDE of waste other than drums, including large-box and small-package inspection, and pretreatment and postprocess inspections. The DR and CT methods offer the potential to provide rapid quantitative information in many of these applications. DR and CT offer the highest attainable spatial resolution for waste container inspection. All other forms of "imaging", both neutron and gamma ray activities (passive or active), are extremely coarse in spatial resolution.

Area detectors allow for all modes of radiographic and tomographic imaging, but do not provide as high a degree of spatial resolution, dynamic range (contrast resolution), and processing speed of (more mature) linear detectors and their respective methods. An ideal DRCT system may be one that can provide several modes of operation--area detectors for rapid RTR, DR, and CT, and linear detectors for high resolution.

ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy, Assistant Secretary for Environmental Management, under DOE Idaho Operations Office Contract DE-AC07-94ID13223. The Digital Radiography and Computed Tomography of Waste Containers project is sponsored by the Office of Technology Development (EM-50) of the Department of Energy. The authors thank Gerry Streier (Lockheed Martin Idaho Technologies), George Schneider (DOE Idaho), Kevin Kostelnik (Lockheed Martin Idaho Technologies), and Frank Harmon (Idaho State University) for their continuing support of this project.

REFERENCES

1. S. M. Hailey, "A Comparison of Real-Time Radiography Results and Visual Characterization Results with Emphasis on WIPP WAC and TRAMPAC Compliance Issues," *Proceedings of the Nondestructive Assay and Nondestructive Examination Waste Characterization Conference in Pocatello, Idaho, February 14-16, 1994*, pp. 217-233.

2. T. J. Roney, R. T. Allemeier, S. G. Galbraith, D. M. Tow, "Developments in Radiography and Tomography of Waste Containers at the Idaho National Engineering Laboratory," *Proceedings of the International Topical Meeting on Nuclear and Hazardous Waste Management Spectrum '94 in Atlanta, Georgia, August 14-18, 1994*.

3. R. T. Allemeier, D. M. Tow, G. V. Miller, T. J. Roney, "Digital Image Processing of Real-Time Radiographic Images for Waste Characterization," *Proceedings of the 4th Nondestructive Assay and Nondestructive Examination Waste Characterization Conference in Salt Lake City, Utah, October 24-26, 1995*.

4. U.S. Department of Energy Carlsbad Area Office, *TRU Waste Characterization Quality Assurance Program Plan*, Rev. B, July 8, 1994.

5. U.S. Department of Energy Carlsbad Area Office, *Performance Demonstration Program Plan for Nondestructive Assay for the TRU Waste Characterization Program*, Rev. 0, December 1994.

6. "Radiography and Radiation Testing," *Nondestructive Testing Handbook*, Lawrence E. Bryant and Paul McIntire, Vol. 3, American Society for Nondestructive Testing, 1985.

7. H. H. Barrett and W. Swindell, *Radiological Imaging: The Theory of Image formation, Detection, and Processing,* Academic Press, 1981.

8. J. Steude, G. Perry, D. Wiese, "Visualization and Characterization of Objects and Free Liquids in a Drum Containing Mock TRU Wastes Using Computed Tomography," *Proceedings of the Nondestructive Assay and Nondestructive Examination Waste Characterization Conference in Pocatello, Idaho, February 14-16, 1994,* pp. 251-259.

9. H. E. Martz, D. J. Schneberk, G. P. Robertson, "Real-Time Radiography, Digital Radiography, and Computed Tomography for Nonintrusive Waste Drum Characterization," *Proceedings of the Nondestructive Assay and Nondestructive Examination Waste Characterization Conference in Pocatello, Idaho, February 14-16, 1994,* pp. 295-342.

10. R. T. Bernardi, R. E. Slocum, "Digital Radiography and Computed Tomography for Advanced Inspection of Solidified Nuclear Waste Containers," *Review of Progress in Quantitative Nondestructive Evaluation,* D. O. Thompson and D. E. Chimenti, Vol. 11, pp. 1893-1900, Plenum Press, New York, 1992.

11. R. T. Bernardi, H. E. Martz, Jr., "Nuclear Waste Drum Characterization with 2MeV X-Ray and Gamma-Ray Tomography," *Xray and Ultraviolet Sensors and Applications,* Society of Photo-Optical Instrumentation Engineers, Volume 2519, in print, SPIE, Bellingham, 1995.

12. T. J. Roney, S. G. Galbraith, "Digital Radiography and Computed Tomography (DRCT) of Waste Containers Status Report," Lockheed Martin Idaho Technologies Company Internal Report, INEL-95/0143, March, 1995

13. L. A. Feldkamp, L. C. Davis, J. W. Kress, "Practical Cone-Beam Algorithm," *Journal of the Optical Society of America*, Vol. 1, No. 6, pp. 612-619, 1984.

14. H. Tuy, "An inversion formula for cone-beam reconstruction," *SIAM J. Appl. Math.*, Vol 43, pp. 546-552, 1983.

15. B. Smith, "Cone-Beam Tomography: Recent Advances and a Tutorial Review," *Optical Engineering*, Vol. 29, pp. 524-534, 1990.

16. R. Clack, M. Defrise, "Overview of Reconstruction Algorithms for Exact Cone-Beam Tomography," *Mathematical Methods in Medical Imaging III*, Society of Photo-Optical Instrumentation Engineers, Vol. 2299, pp. 230-241, SPIE, Bellingham, 1994.

17. G. L. Zeng, G. T. Gullberg, "A Cone-Beam Tomography Algorithm for Orthogonal Circle-and-Line Orbit," *Phys. Med. Biol.*, Vol. 37 No. 3, pp.563-577, March, 1992

18. G. P. Robertson, H. E. Martz, D. J. Decman, D. C. Camp, S. G. Azevedo, E. R. Keto, "Characterization of Waste Drums Using Nonintrusive Active and Passive Computed Tomography," *Proceedings of the Nondestructive Assay and Nondestructive Examination Waste Characterization Conference in Pocatello, Idaho, February 14-16, 1994*, pp. 261-294.

19. W. A. Kalender, "Principles and Applications of Spiral CT," *Nucl. Med. Biol*, Vol. 21, No. 5, pp. 693-699, 1994.

20. M. Defrise, R. Clack, "A Cone-Beam Reconstruction Algorithm Using Shift-Variant Filtering and Cone-Beam Backprojection," *IEEE Trans. Med. Imag.*, Vol 13, pp. 186-195, 1994.

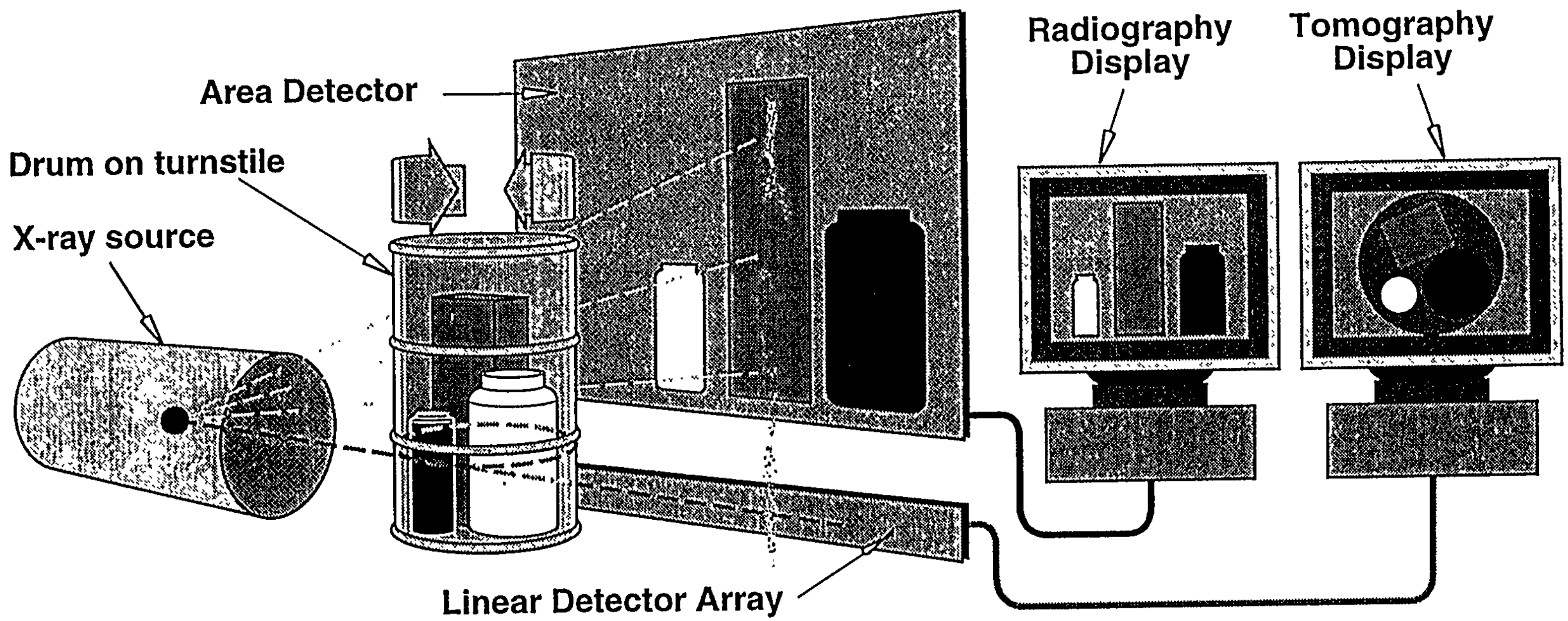

Figure 1. Digital Radiography and Computed Tomography Displays.

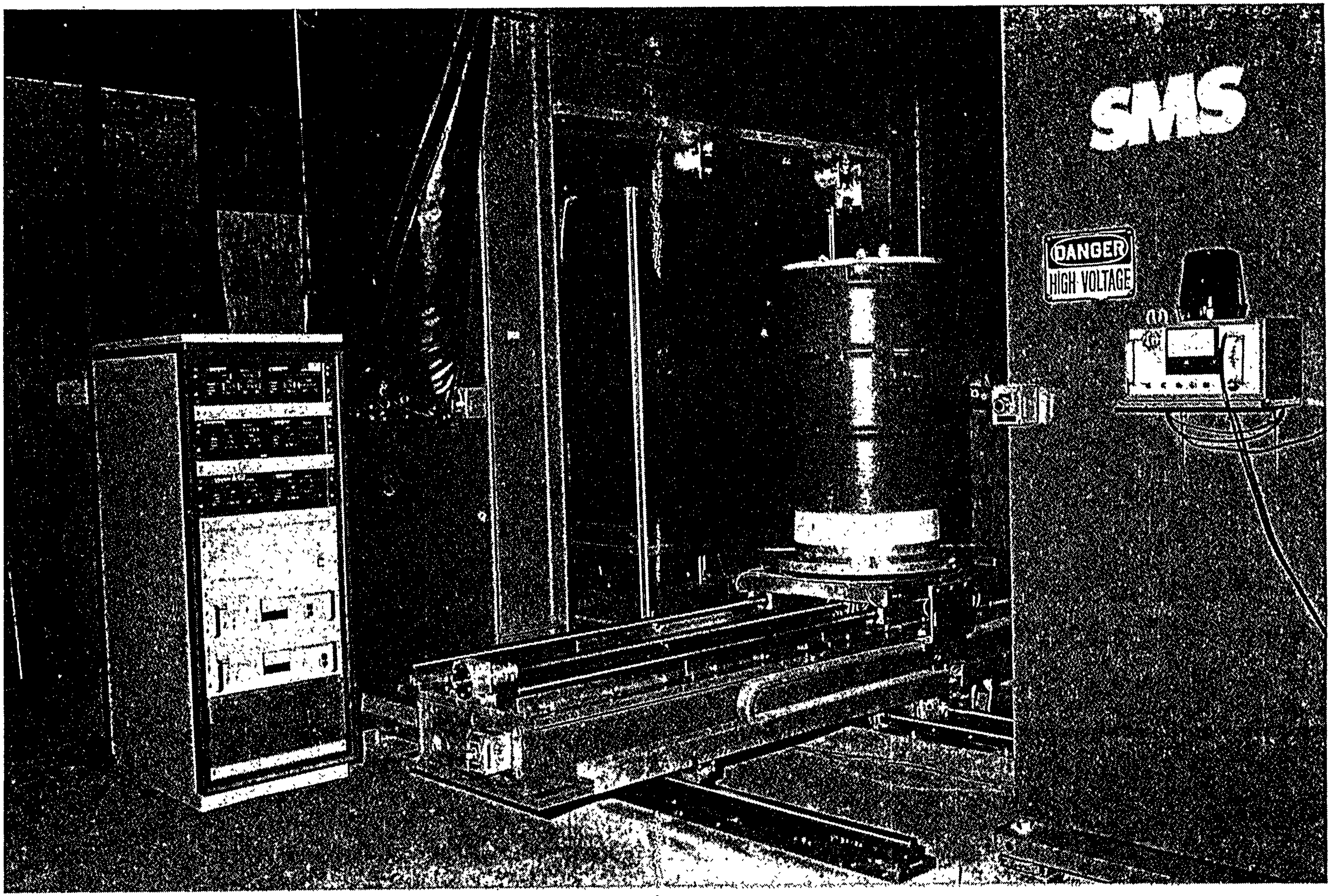

Figure 2. The INEL DRCT Scanner. Note the linear array has been translated up to leave room for the area detector.

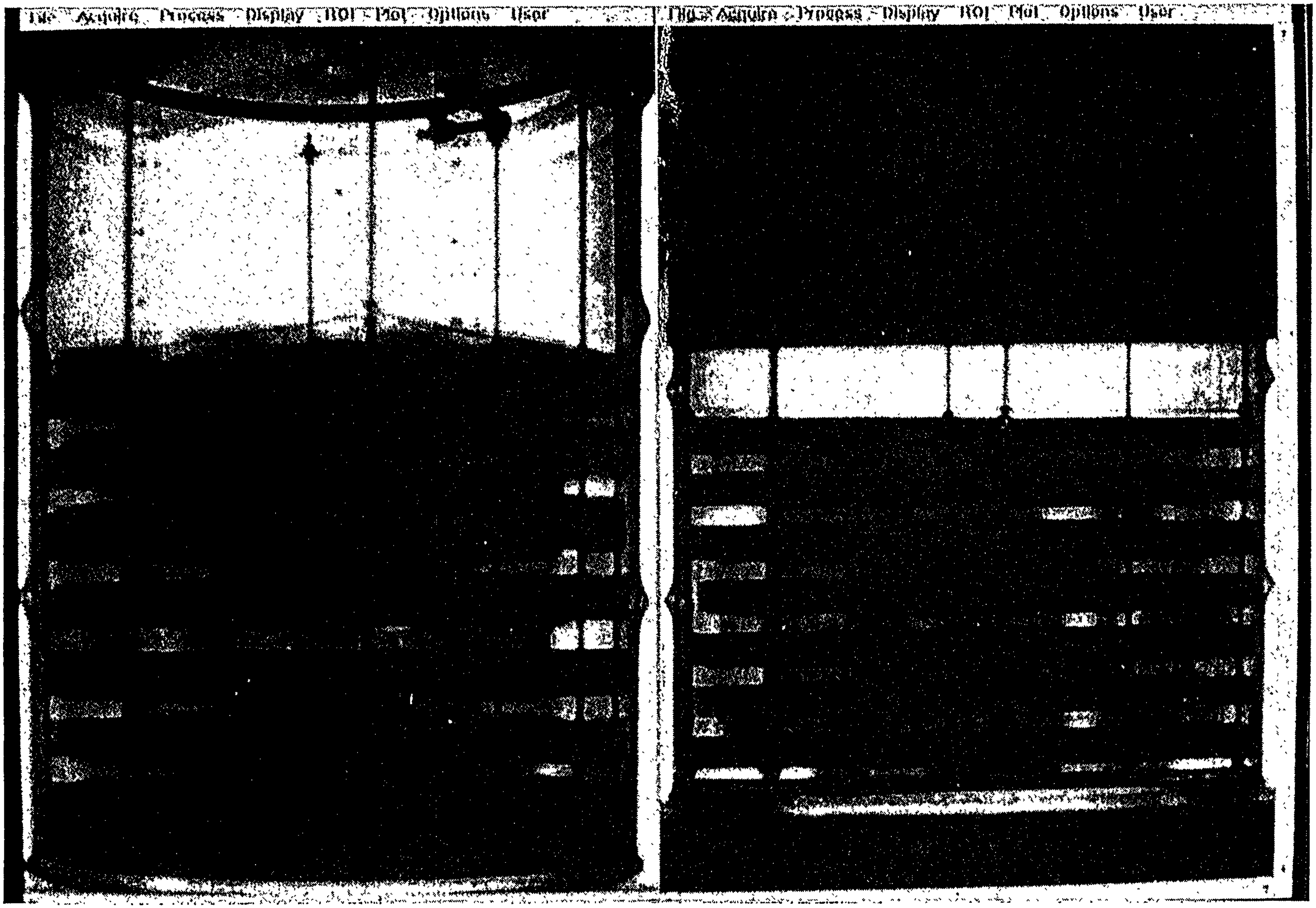

Figure 3. Comparison of cone-beam and linear fan-beam detector data for a single projection radiograph.

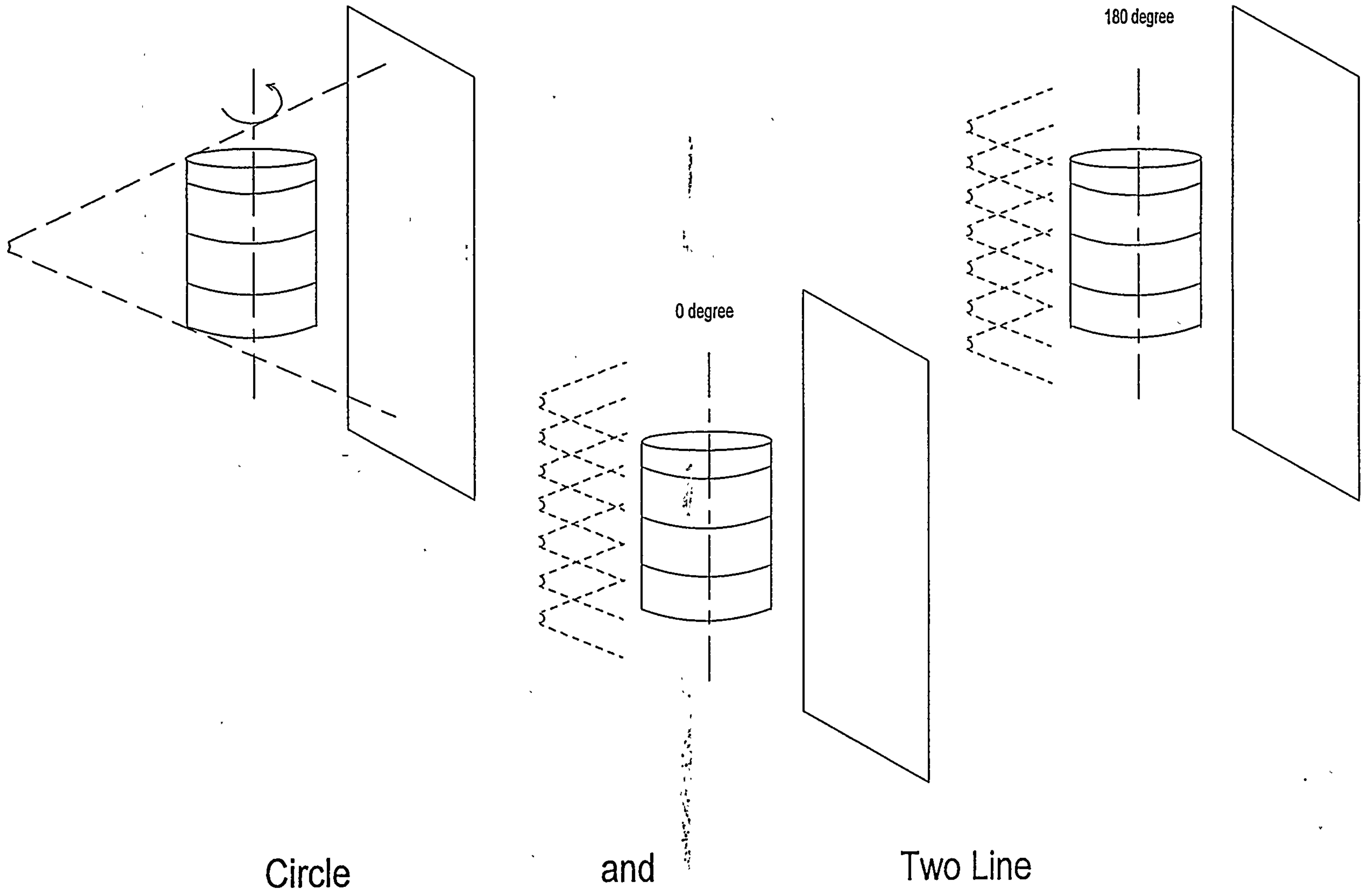

Figure 4. Circle and two vertical line data acquisition.

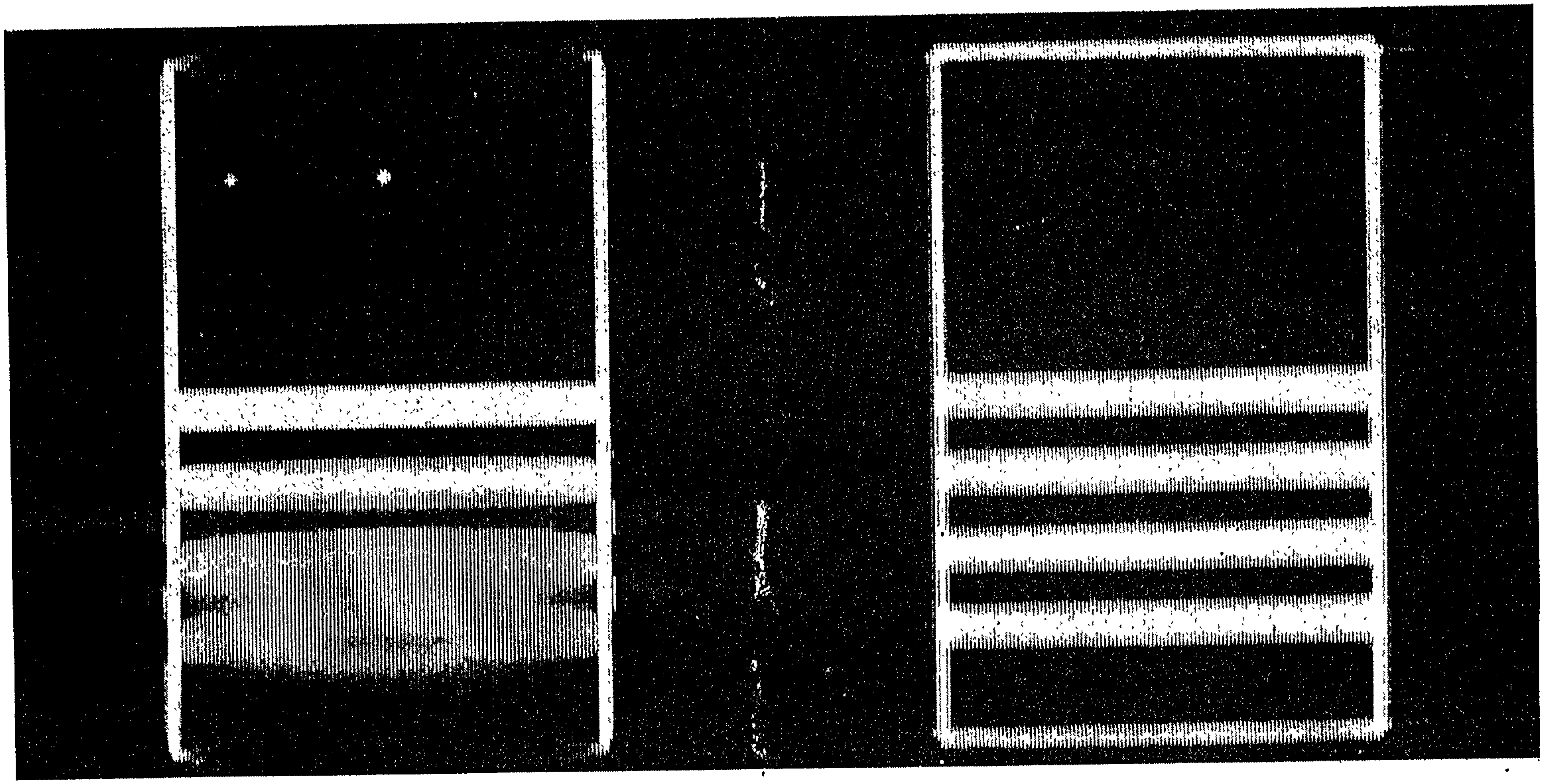

Figure 5. Comparison of tomographic reconstructions of simulated graphite calibration drum: circular orbit (left) vs. circle-and-two-line orbit (right) cone-beam data acquisitions.

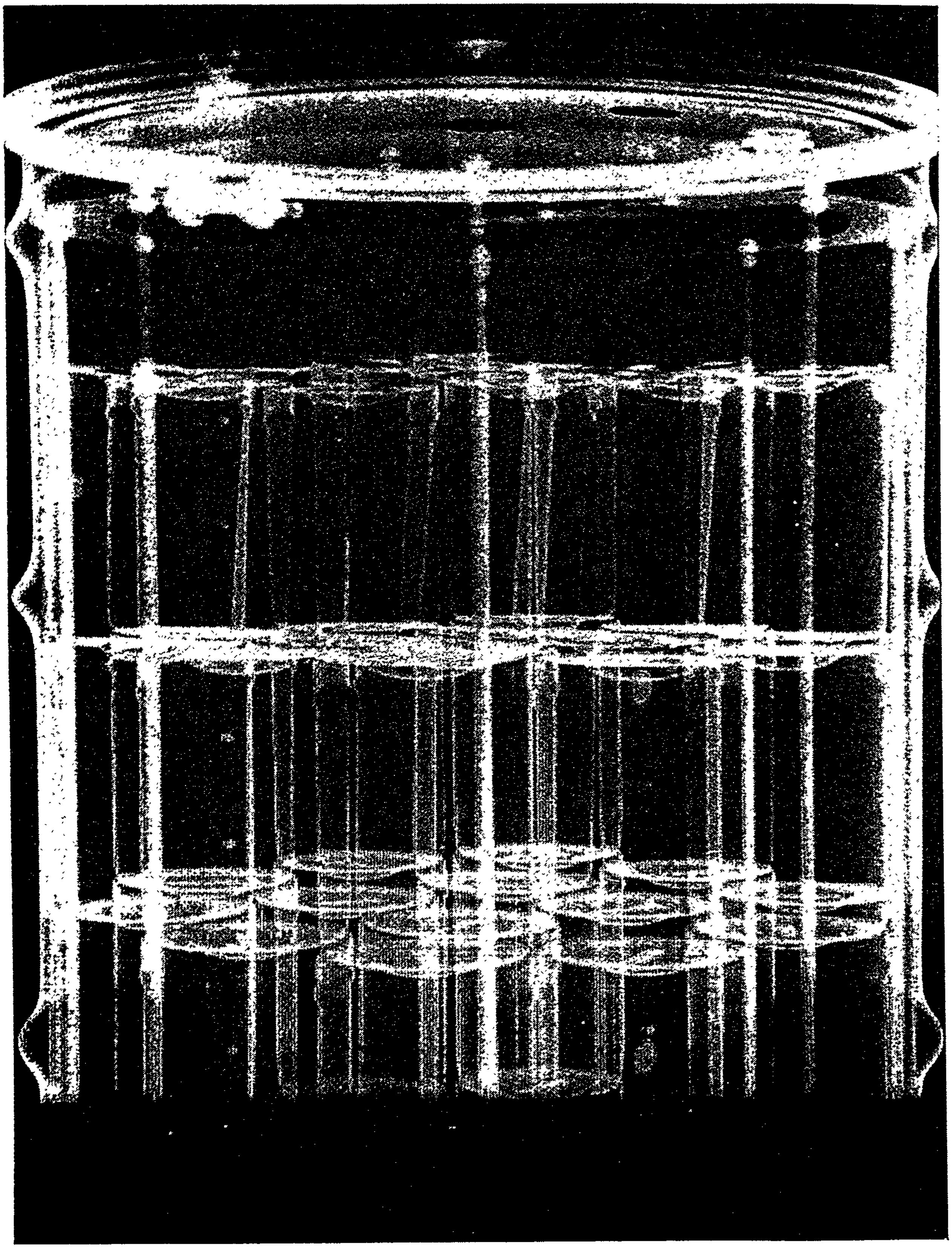

Figure 6. Digital radiograph of INEL Valrath Can Calibration Drum with two Pu NAD sources.

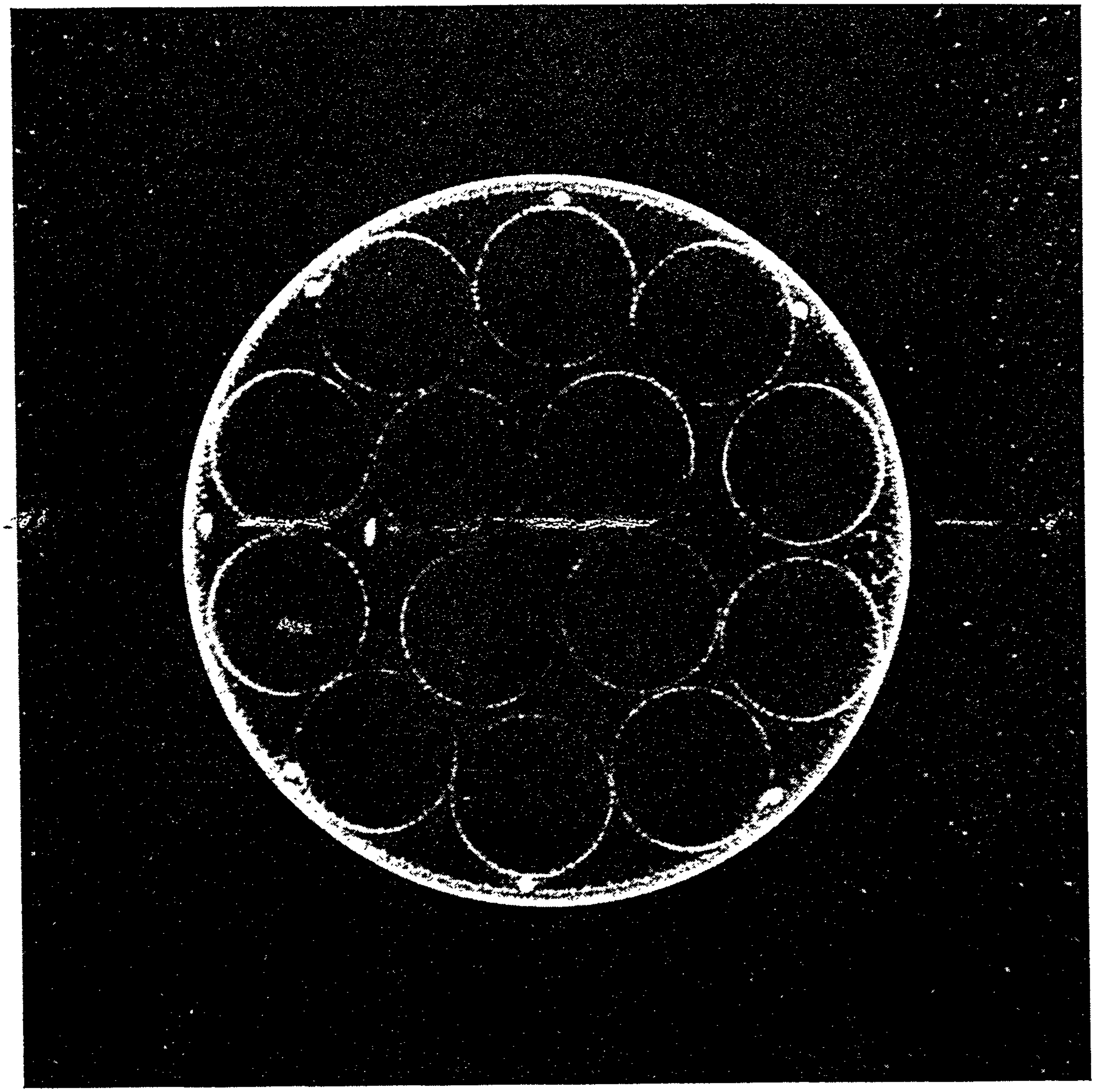

Figure 7. 2-D slice of a cone-beam (Feldkamp) reconstruction of the Valrath Can Calibration Drum, the bright line within one of the small tubes is a cross-section of a Pu NAD source.