CONF-900804--3
Received by OSTI
MAY 04 1990

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Submitted for presentation at the
1990 International Fast Reactor Safety Meeting
Snowbird, Utah

CONF-900804--3

DE90 010087

*Work performed under the auspices of the U. S. Department of Energy

Work supported by the U. S. Department of Energy Technology Support Programs Contract W-31-109-Eng-38.

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ABSTRACT

A series of CT codes is under development in the Reactor Analysis and Safety Division of Argonne National Laboratory for use as a post-test examination tool to analyze segments of the final fuel-bundle configuration of TREAT tests. This paper presents the results of CT analysis for fuel assemblies using neutron radiography. Fuel relocation following overpower transients in the TREAT reactor is examined for sections of the assemblies, and results are compared to metallographic sections. Further improvements are expected to increase the use and reliability of CT analysis as a standard post-test examination tool.

INTRODUCTION

The TREAT reactor is designed to study the effects of simulated reactor transients on prototypic fuel assemblies. Among the primary objectives of these tests is the definition of material movement during and after the simulation. During the actual test transient, a fast neutron hodoscope follows the motion of the fuel as it melts, is released from the fuel pins and relocates within the assembly.

Until recently, the standard technique used to analyze the final configuration of the relocated materials was destructive examination. The fuel assemblies are sectioned at multiple axial locations determined by a radiograph of the assembly. Sections are polished and examined to identify flow tube blockages, characterize the relocated material and determine metallurgical changes in the materials.

A computed tomography (CT) system is now being developed to complement the post-test destructive examination (PTE) and metallography that is normally performed on the test trains used in the experiments. CT will be used not only as a guide to locate optimal sectioning positions, but also to provide cross sectional images at more locations than would be possible with destructive sectioning. The package of codes has been used to analyze parts of the final configurations of PFR/TREAT tests L05, L06 and L07, seven-pin assemblies subjected to overpower transients in the TREAT reactor. While the CT system is still being refined, the results are sufficiently good at this stage to identify relocated fuel and steel, flow tube blockages and pin displacement.

COMPUTED TOMOGRAPHY TECHNIQUE

Computerized or computed tomography has gained increasing acceptance as a diagnostic tool in recent years. Medical applications include x-ray transmission, positron emission and nuclear magnetic resonance images of various organs. Industrial imaging systems use x-rays, gamma rays and particle beams to look for defects in items ranging from small turbocharger turbine blades to full-sized rocket boosters. The CT process used here is basically the same as that used in other diagnostic systems, but has been adapted for use with neutron radiographs of fuel bundles.

The underlying principle of CT is that a two-dimensional image of an object can be reconstructed from a number of one-dimensional rays or projections through the object. In medical CT imaging, these projections are often measured x-ray attenuation factors of a collimated beam at multiple angles around a specific axial location of the body. For the fuel bundle CT, the projections are the measured intensities (or equivalently, measured attenuation) of parallel neutron beams passing through the assembly at multiple viewing angles. Whereas x-ray systems use detectors to directly measure beam intensity, neutron CT as it is currently performed requires an intermediate step. A radiograph is made whose density at any spatial point is a measure of the neutron intensity at that point. A series of codes has been developed to run on a small Sun workstation with large data storage capacity, making it feasible to use CT as a routine part of the TREAT experiment analysis.

Neutron Radiography and Digitization

Radiography for the CT is performed at the Hot Fuel Examination Facility (HFEF) at Argonne-West using a water-moderated, enriched uranium fueled reactor. The beam port is aligned to enable a large percentage of epithermal neutrons to be used. The beam is shaped by a scraper to a rectangular opening of 432 by 254 mm. This results in a near-parallel beam configuration with only a 1.5% magnification factor at the image plane.

The fuel pin bundle to be examined is positioned between the reactor beam port and a neutron detector. The test object, typically near two meters long and 100 mm diameter, is suspended by a fixture capable of precisely rotating the large loops in small angular increments. The detector device consists of a package of two foils: a 0.5-mm thick cadmium foil to attenuate thermal neutrons and an indium foil to capture epithermal (1.45 eV) neutrons. After an exposure time of about 30 - 60 minutes, the indium foil is removed and placed in contact with a sheet of photographic film. After the decaying indium exposes the film, it is processed and prepared for digitization. This procedure is repeated for each angular position, normally 76 views over a range of 180 degrees.

Digitization is performed on a scanning micro-densitometer. In this system, the film is positioned on a moving stage which is accurately traversed over an adjustable aperture. Data is stored on magnetic tape as either density or transmission values with a resolution of 12 bits (1 part in 4096). These values are the attenuation data which are input to the CT reconstruction codes. The densitometer can scan one half of a radiograph, which then must be rotated on the stage and realigned before the second half can be scanned. Normally, only three radiographs can be scanned per day.

Adjustment of the aperture in the horizontal scanning direction and the number of angles at which the projections are made determine the final minimum spatial resolution of the reconstructions, while adjusting the vertical aperture determines the axial resolution of the sections. Apertures as large as 200 x 400 μm and as small as 50 x 400 μm have been tested, and ideal resolution parameters are still being studied.

Reconstruction Technique

The first major problem to be solved in the CT analysis is alignment of the views. In medical CT imaging, the patient is normally fixed in position while the source/detector system rotates as a unit in a well-defined pattern. Since the reactor is a fixed source, the detector is also fixed and the fuel bundle must be rotated.

The test train is inserted into an aluminum cylinder before being positioned in front of the foil cassette, and this entire assembly is rotated for each view. Since the large assembly cannot be rigidly fixed parallel to the axis of rotation, there is some wobble as the holder is rotated. The correction for this misalignment consists not just of a horizontal shift, but also a rotation. An edge finding routine determines the tilt of the test train for each view and rotates the image on a pixel-by-pixel basis so that all views are aligned to a common angle. In addition, any vertical misalignment of the foil cassette is included in the correction using a standard density wedge attached to the foil holding mechanism.

The mathematical formulation of CT reconstruction has been implemented using the filtered back-projection (FBK) method. Using the FBK method, the data from each axial elevation of each view (one digitized radiograph row) is Fourier transformed, multiplied by a filter, inverse transformed, then combined with geometric weighting factors to produce the transverse section data. When the filtering is done in frequency space, the filters become multipliers on the terms of the discrete transform, allowing variations to be easily studied for comparisons.

While the reconstruction step is numerically simple, and the fast Fourier transforms are standard, the selection of the appropriate filter is a critical part of the process and determines the quality of the reconstruction. The filter is needed to reduce slowly varying components such as non-uniform background, and reduce the noise caused by statistical fluctuations in the data. The ideal filter minimizes statistical noise (graininess) and artifacts without removing significant details. While filters tailored to the radiography data are still being compared, reasonable results have been obtained using a standard Butterworth filter with rollover frequency and filter order determined by the spatial size of the data pixels.

The FBK process produces a two-dimensional array of CT numbers (attenuation coefficients) describing the x-y distribution of material densities at a given axial elevation along the test section. When these CT numbers are mapped to either colors or grey scales and displayed, the result is a transverse section image. The transverse sections are useful for determining the mixture of fuel and steel debris, the extent of flow tube blockage and final fuel pin condition.

These transverse sections can be stacked to create a three dimensional array of data, containing a full description of the entire test assembly that was within the field of view of the radiographs. Vertical planes can be defined through the length of this region and the appropriate pixels (data points) can be selected to produce longitudinal slices at any azimuthal angle and any offset from the center of the assembly. In one image, a longitudinal slices reveals fuel pin bowing and dislocation, as well as voided and blocked regions in the flow tube, highlighting those axial locations where PTE would be useful for further analysis.

RESULTS FROM TREAT TESTS L05, L06 AND L07

Tests L05, L06 and L07 are three of a series of experiments designed to study the effects of transient undercooled overpower excursions on full-length mixed Pu-U oxide fuel pins. L05 and L07 used fuel pins that were irradiated to about 4 at-% burnup in the UK Prototype Fast Reactor (PFR), while L06 used fresh PFR fuel. Uranium oxide blanket pellets are contained in each pin above and below the fuel region. In each of the tests, seven pins were supported by grid spacers and installed in a flowing-sodium loop with stainless steel flow tube, outer wall and loop wall. Table I lists various dimensions of the fuel pins and test train components.

Table I. Fuel and Test Section Dimensions

Fuel Length (mm)	914
Fuel Pellet Diameter (mm)	4.95 / 5.00
Fuel Pellet Annular Hole Diameter (mm)	1.52 / 1.78
Cladding Dimensions	
Outer Diameter (mm)	5.84
Thickness (mm)	0.38
Loop Wall	
Outer Diameter (mm)	57.3
Inner Diameter (mm)	36.8
Outer Adiabatic Wall	
Outer Diameter (mm)	34.9
Thickness (mm)	0.89
Zirconia Insulator Insert	
Outer diameter (mm)	32.7
Inner Diameter (mm)	26.7
Tri-Fluted Flow Tube	
Outer Diameter (mm)	26.0
Thickness (mm)	0.89

Following each of the three tests, there are large voided regions near the center of the fueled section and accumulations of debris near the top and bottom of the original fuel column and near some of the grid spacers. Detailed examination of the pin remnants, voided regions and the refrozen fuel-steel mixture shows differences between the tests. Because of the time required to digitize the radiographs, only one elevation from each of the tests has been analyzed. In L05 and L07 the analysis region is near the bottom of the original fuel column while in L06 the region is near the top of the fuel column. Each region covered an axial range of about 400 mm. The L05 test train remained in the outer loop tube during radiography, but the L06 and L07 test trains were removed.

Since the CT analysis is still in the developmental stages, various configurations were used on each of the three assemblies. In each case, radiographs were made at 2.4 degree intervals through 180 degrees, for a total of 76 views per test section. The densitometer aperture was set to 0.2 x 0.4 mm for L05, 0.05 x 0.4 mm for L06 and 0.1 x 0.2 mm for L07. The data for L06 was later averaged to 0.1 x 0.4 mm.

Figure 1 shows one longitudinal reconstruction from L06 at 0 degrees. Figure 2 shows three longitudinal reconstructions of the L05 fuel assembly at 0, 60 and 120 degrees (pins 2-7-5, 1-7-4 and 6-7-3, respectively from the bottom of each frame). Figure 3 shows the 0, 60 and 120 degree longitudinal views of L07. The reconstructed density values have been binned into four shades of gray, with darker shades representing more dense material.

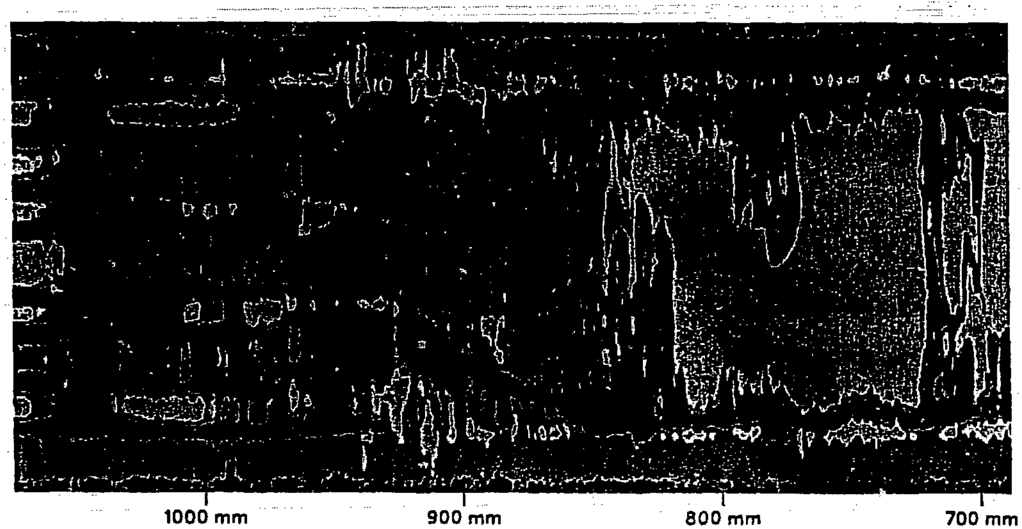

Figure 1. L06 Longitudinal Reconstruction at 0 Degrees Showing Pins 5 (top), 7 and 2 (bottom).

In each case the displacement and distortion of the remnants of the fuel pins is evident. Voided areas (light shades of gray) are interspersed in the debris consisting of refrozen fuel and steel. The L05 and L07 images show that melted material has flowed between the pins in the lower blanket regions, and the pins have tilted from their original vertical position. Figure 1 shows the upper limit of a large central void, just below a complete blockage of flow tube near the upper axial blanket region of L06. Figure 3 shows considerable pin distortion in the region from 0 - 200 mm, and a blockage with a large void fraction beginning at an elevation of about 200 mm in the L07 assembly.

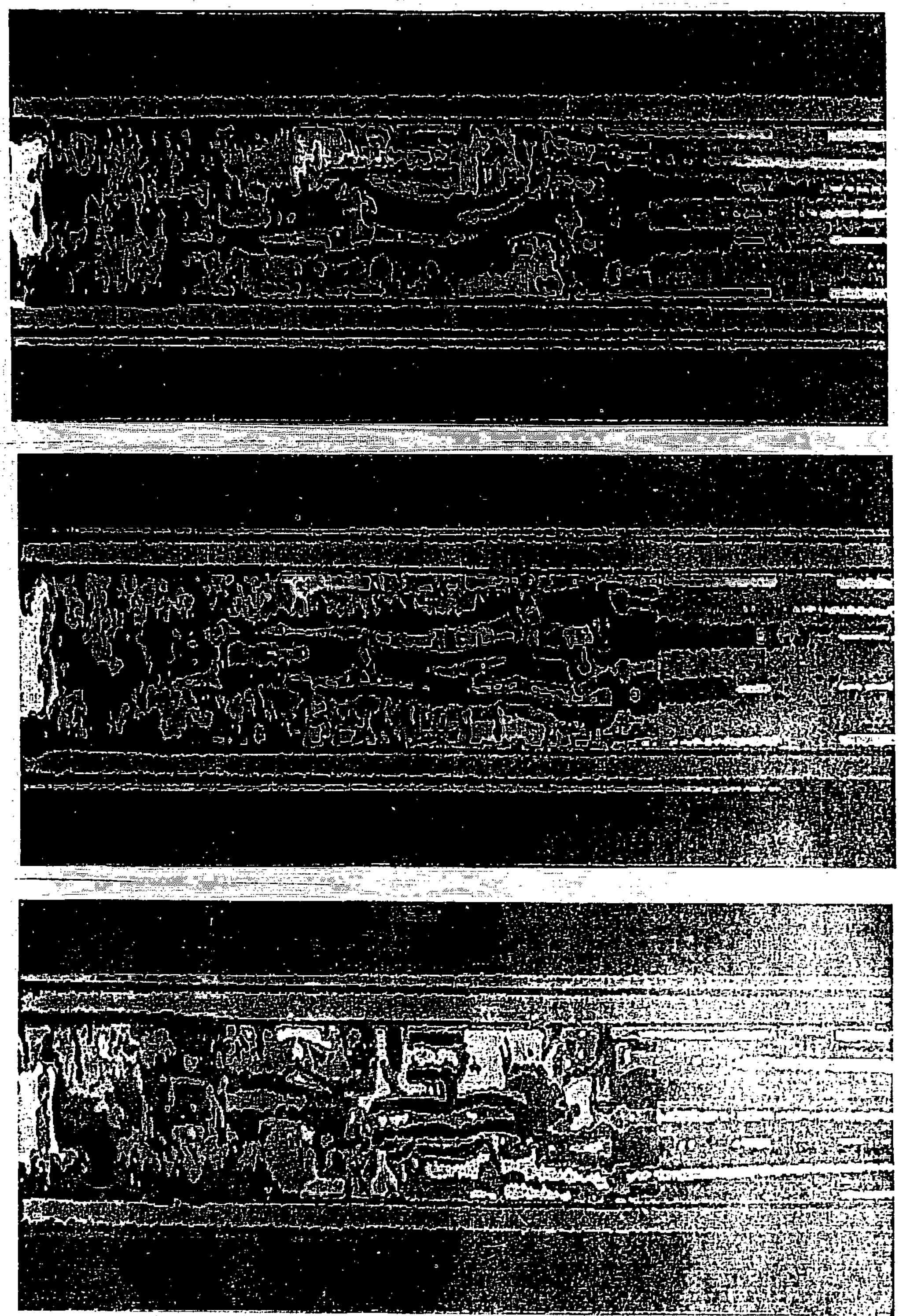

Figure 2. L05 Longitudinal Reconstructions at 0, 60 and 120 Degrees Showing Pins (5,7,2), (4,7,1) and [illegible]

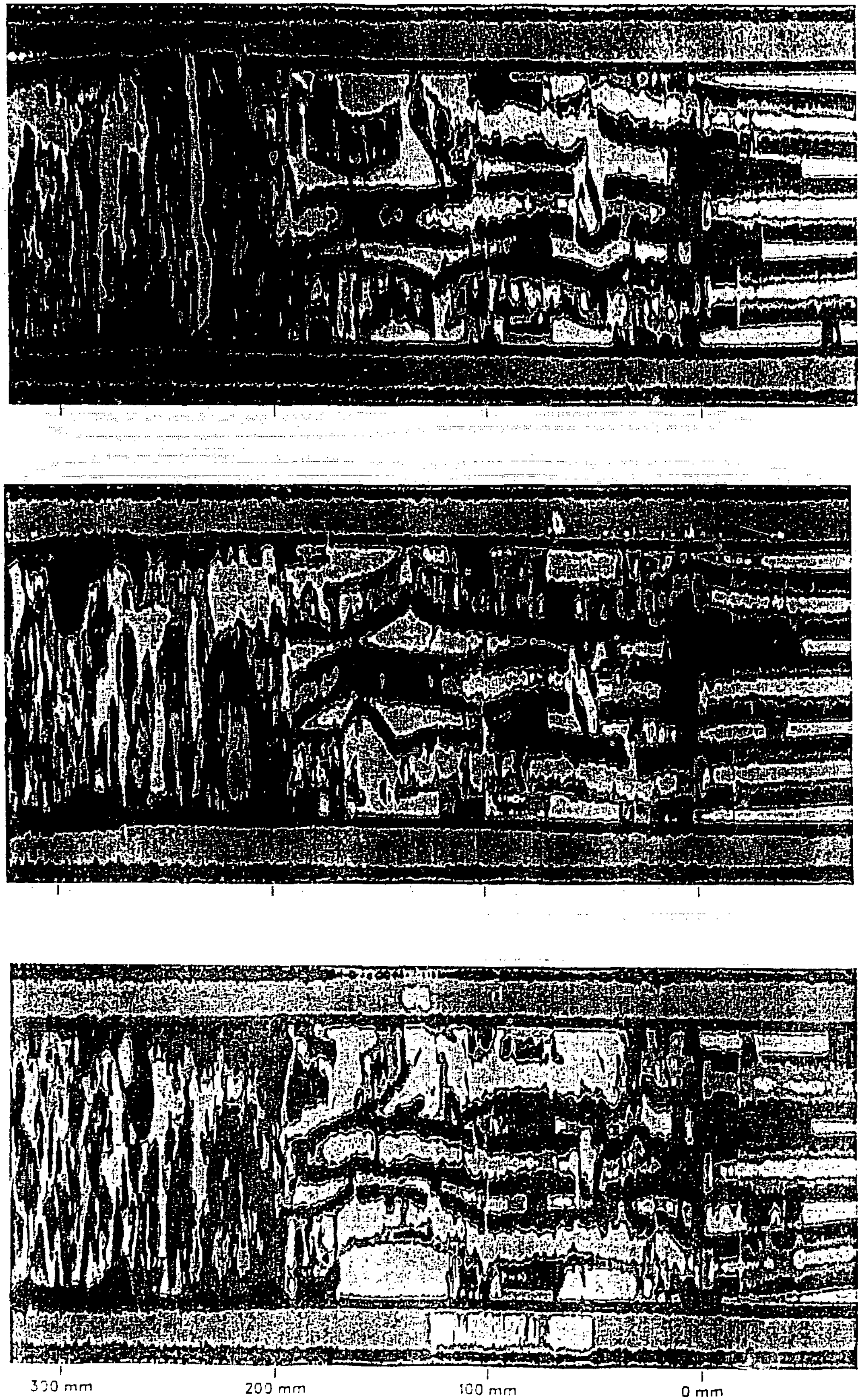

Figure 3. L07 Longitudin[illegible] ...tions at 0, 60 and 120 Degrees [illegible] (4,7,1) and (3,7,[illegible]

While the longitudinal slices are ideal for identifying the overall distribution of materials, the transverse section images show the amounts of fuel and steel than have refrozen along the flow tube wall and the pin fragments, as well as the configuration of the fuel pins at any given elevation. The transverse sections can be generated at intervals as small as the vertical aperture setting on the microdensitometer, providing detail not available through PTE sectioning operations. Figure 4 shows an example of two transverse sections from L05, where they are compared to the PTE sections near the same elevations. Figure 5 shows a similar comparison for two sections of the L07 test train. The comparisons are quite good, with all features of the PTE sections being seen in the CT reconstructions. In some comparisons, the CT images appear to retain details that have been lost in the PTE sections due to shipping and cutting processes.

SUMMARY AND FUTURE WORK

The results of the CT work to date, especially the comparisons with the PTE results, prove that computerized tomography using digitized neutron radiographs can now be considered a standard tool for the analysis of fuel bundles, to be used as a supplement to traditional PTE methods. At this stage of its development, CT analysis provides a good overview of the material relocation following the transient tests, clearly showing the accumulation of fuel and steel at the grid spacers and at the top and bottom of the fuel column.

Development work is now aimed at three specific areas: digitization, material recognition and quantitative analysis. Because of the number of radiographs needed to produce the required resolution, a faster digitization system is needed. State of the art imaging technology can be used to provide full-frame images of the radiographs while retaining the 12-bit density resolution needed to cover the wide optical density ranges of the radiographs. Characterization of the data in the transverse section images into fuel, steel, sodium and void regions is the next priority in the CT studies. Refinement of the filters used in the reconstruction method is needed to enhance the contrast between different materials without introducing edge effects and artifacts. Differentiation of materials depends on the macroscopic neutron cross sections of the materials in the test sections, which in turn depend on the spectrum of neutrons used to generate the radiographs. Further study will determine if filter refinement can extract enough information to identify materials, or if the absorption properties are too nearly then same to separate. Once separate materials can be identified, quantitative analysis programs will be able to determine void/fuel/steel fractions which will compare directly to fuel behavior models, and CT analysis will advance beyond qualitative material distributions to become a powerful tool for quantitative analysis of disrupted fuel elements.

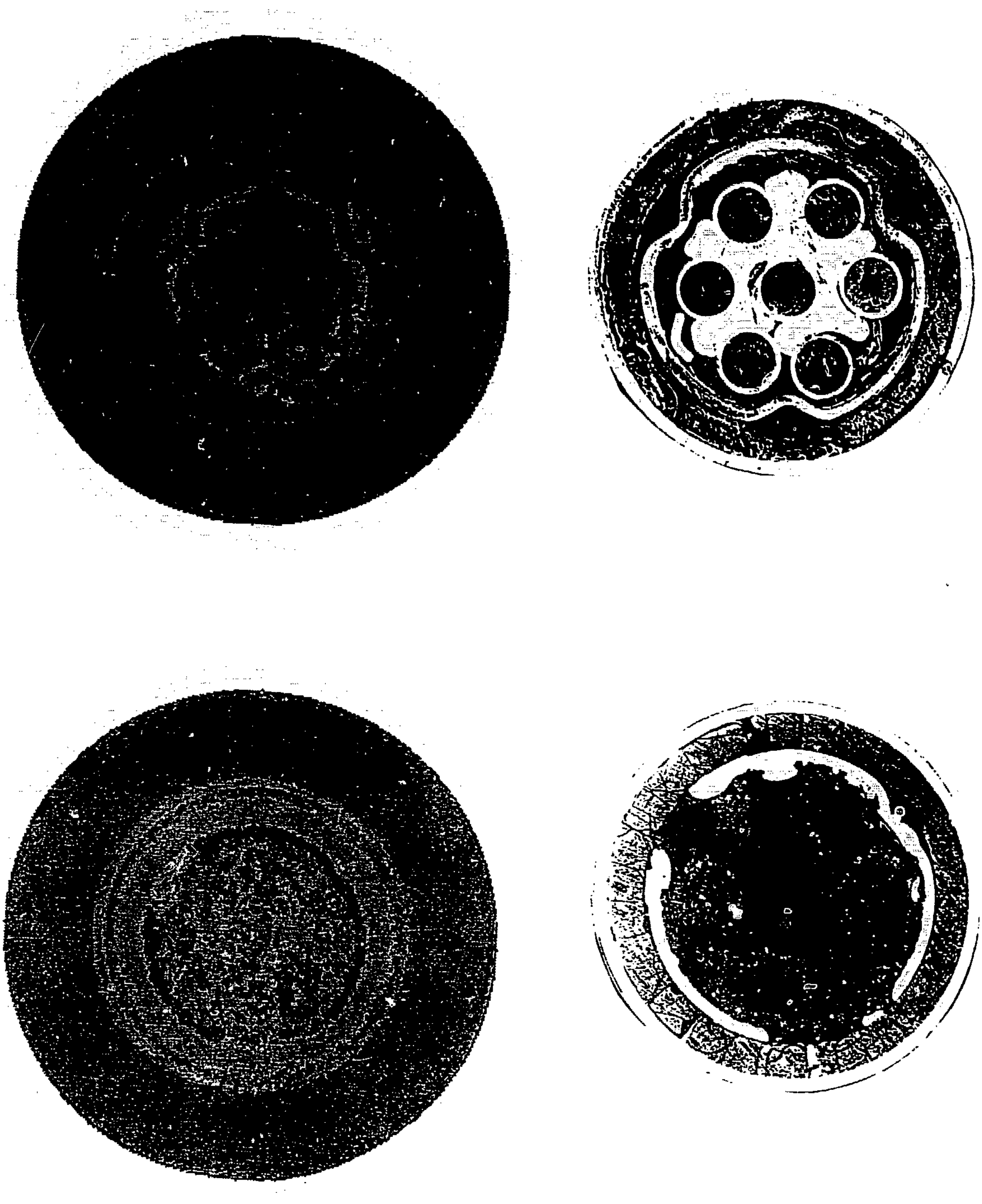

Figure 4. Comparison of L05 Transverse Reconstructions with Cut Sections at Elevations of -24 mm (top) and 189 mm (bottom).

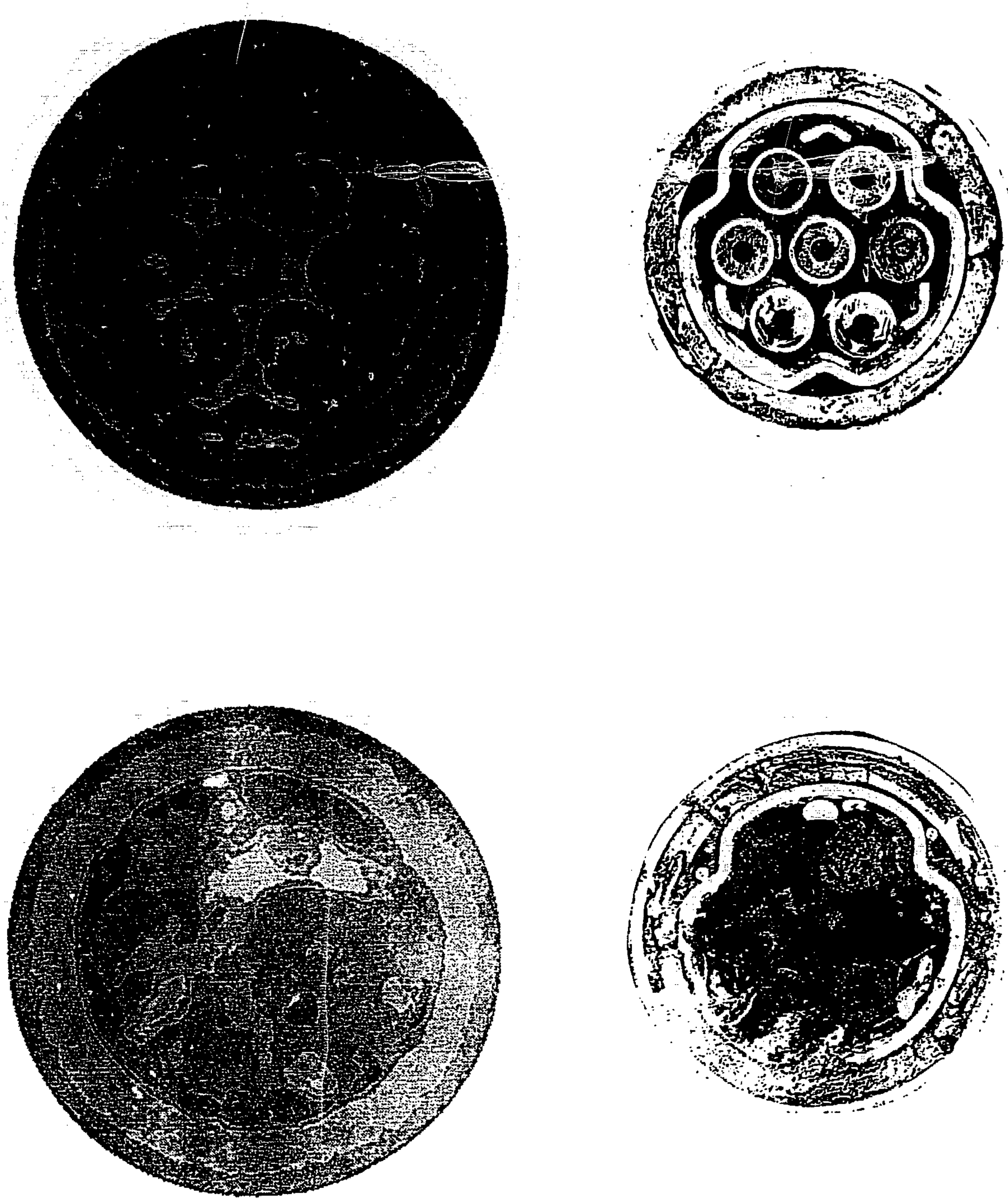

Figure 5. Comparison of L07 Transverse Reconstructions with Cut Sections at Elevations of 180 mm (top) and 247 mm (bottom).