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(Draft)

June 1984

FEASIBILITY OF USING NEUTRON TOMOGRAPHY TO EXAMINE TMI-2 FUEL ASSEMBLIES (DRAFT)

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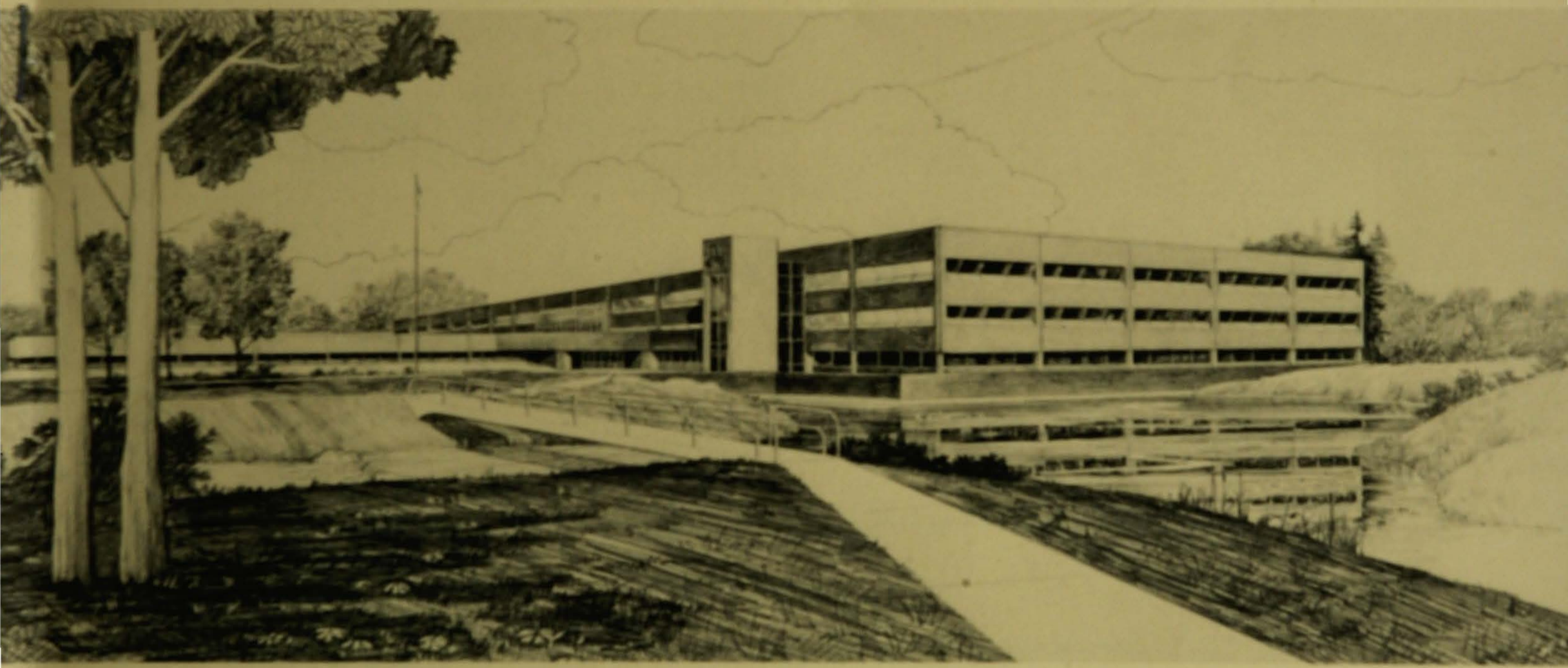
Operated by the U.S. Department of Energy



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EG&G Idaho

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ABSTRACT

This report presents results of a feasibility study for using neutron tomography (NT) to examine TMI-2 fuel assemblies. A fuel assembly mockup was constructed to simulate many of the conditions that may exist in actual TMI-2 fuel assemblies and was examined with NT techniques. This study demonstrated that useful and reliable information could be obtained regarding fuel assembly configuration, particularly the location and condition of the fuel and control materials within the assembly.

ACKNOWLEDGMENTS

Many people and organizations contributed to this task. Special thanks and recognition are extended to the following: K. G. Therp and staff at the Thermal Fuels Test Train Design and Assembly Section for fabrication of the fuel assembly mockup; M. L. Russell and T. E. Howell of the LOFT program for supplying many of the fuel assembly mockup components. A special thanks goes to the staff (especially G. McClellan) of the Argonne National Laboratory-West Neutron Radiography Facility for assisting in the total project from conceptual design through analysis of the final neutrographs. M. R. Martin and H. W. Reno assisted in analyzing the data and reviewing the manuscript.

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FEASIBILITY OF USING NEUTRON TOMOGRAPHY TO EXAMINE TMI-2 FUEL ASSEMBLIES (Draft)

INTRODUCTION

Neutron tomography (NT) is a nondestructive examination technique developed at the Idaho National Engineering Laboratory for examining irradiated fuel assemblies. NT provides a unique and powerful capability to examine an interior region of a specimen nondestructively without interference from surrounding regions. Adjacent regions may be excised mathematically so that the region of interest may be viewed separately, without having to "look through" other regions. NT has been used successfully to examine the fuel assemblies irradiated in the severe fuel damage tests. Other applications are planned for the near future.

This study was conducted to determine the feasibility of using NT to examine damaged TMI-2 fuel assemblies. Significant differences exist between TMI-2 fuel assemblies and fuel assemblies previously examined using NT. TMI-2 fuel assemblies have more than triple the cross-sectional mass of fuel than the assemblies examined in the past. The possible presence of control rods and water-saturated rods in TMI-2 assemblies would present conditions not encountered in previous examinations. Those differences would result in decreased neutron penetration of the TMI-2 fuel assembly and increased scattering of the neutron beam. This study was also designed to determine the effects of decreased neutron penetration and increased neutron scattering and to answer questions regarding optimal examination procedures. Of primary importance was the minimum number of angular views necessary to achieve acceptable examination results. As the number of views increases, image quality increases; but so does the cost of the examination. The study was to provide information concerning the suitability of existing radiography, digitization and data processing equipment, and procedures for use on TMI-2 assemblies.

DESCRIPTION OF TMI-2 FUEL ASSEMBLY MOCKUP

An important part of the feasibility study included the need to provide a fuel assembly mockup which would reasonably simulate some of the conditions that may exist in an actual TMI-2 fuel assembly. A fuel assembly mockup was designed and fabricated which provided many expected conditions. It is 9 in. high and consists of a standard 15 x 15 fuel rod array with guide tubes, control rods, and spacer grids. It is encased inside a 11-in.-high by 14-in.-diameter stainless steel housing which simulates the shipping/storage canister. Some simulated conditions of the individual components include:

Intact fuel rods (cladding with depleted UO^2 pellets)

2. Missing fuel rods

3. Offset and leaning fuel rod stubs

4. Empty cladding--no fuel pellets

5. Cladding containing borated water

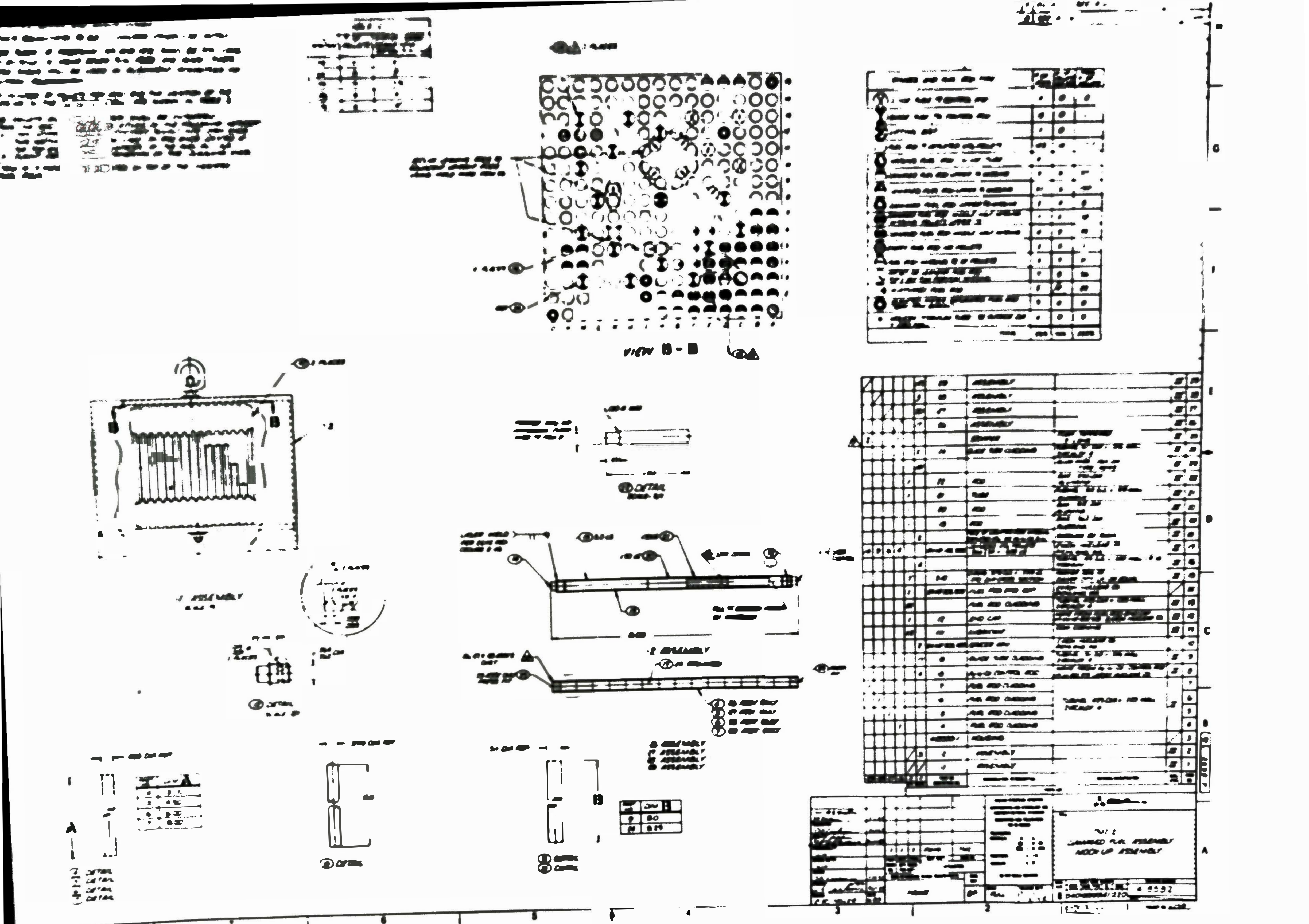
6. Ruptured and/or ballooned cladding

7. Chunks of previously molten core material (stainless steel, zircaloy-4, depleted UO_2, and Ag-In-Cd)

8. Zircaloy-4 guide tubes with Ag-In-Cd control rods

9. Zircaloy-4 guide tubes without control rods.

Figure 1 (EG&G Drawing 418532) shows the detailed configuration of the fuel assembly mockup. Figure 2a shows the mockup after fabrication. Figure 2b shows a closeup of the simulated damage zone. Figure 2c shows the simulated shipping/storage canister. The mockup is located inside the canister.



… 418522 TMI-2 damaged fuel assembly mockup assembly

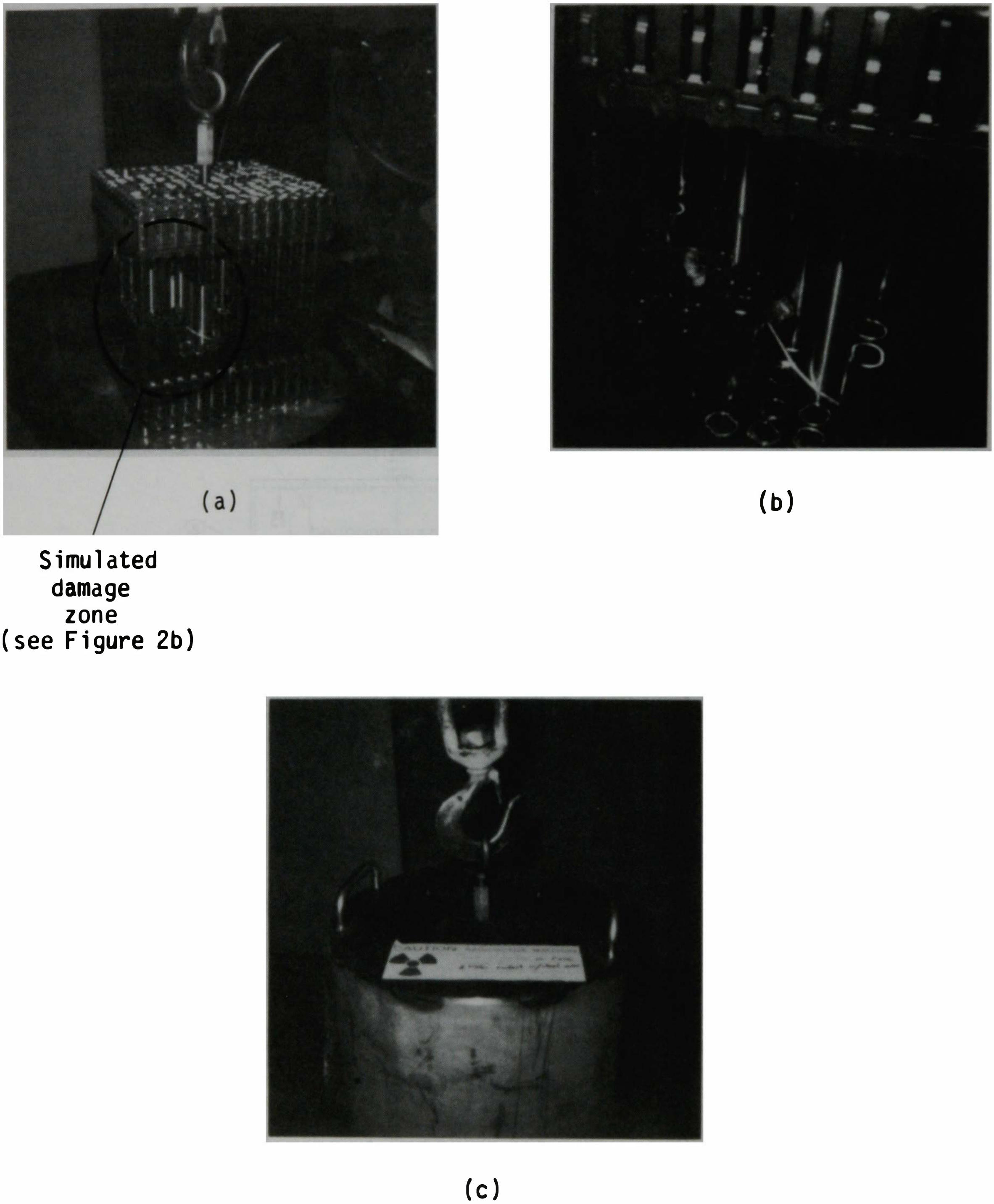


Figure 2. Photographs of mockup of the TMI-2 fuel assembly: (a) overall view, (b) closeup of the simulated damage zone, (c) simulated shipping/storage canister containing the mockup.

Rods saturated with borated water and the control rods were of particular interest. Water, boron, and control rod materials are strong neutron attenuators. It was unknown whether the neutron beam could adequately penetrate these materials. Insufficient neutron penetration adversely could effect results of the examination.

The randomness that probably exists in TMI-2 assemblies would be very difficult to accurately simulate in a mockup. It would be necessary to damage much of the cladding, fuel, and spacer grids to achieve such accuracy. This was not done in the TMI-2 assembly mockup. The majority of the rods in the mockup are positioned in a regular array. There was no crumbling or breakage of fuel pellets; only intact fuel pellets were used. These simulation inaccuracies might have cast doubt on the validity of this study had past experience in these matters been lacking. Experience has been acquired concerning the examination of simplified assembly mockups and how the examination results extend to actual test assemblies. For this reason, it was decided that this study would validly assess the suitability of NT for the examination of actual TMI-2 assemblies.

EXAMINATION AND ANALYTICAL TECHNIQUES

Examination of a specimen by NT yields cross-sectional images of the specimen. These are generated nondestructively from numerous views of the specimen in the form of neutron radiographs. In each of the radiographs, the specimen is rotated to present a unique angular view. The data contained in these radiographs are digitized for entry into a computer. Computer processing of the data yields the cross-sectional images. The examination technique can be viewed as a two-step process. The first step is the acquisition of the neutron radiographs. The process is depicted in Figure 3. The specimen is illuminated with a parallel beam of neutrons. Neutrons that penetrate the specimen impinge on a thin indium foil, creating a radioactive image of the specimen on the foil. The activated foil is removed from the beam and allowed to decay while in close contact with photographic film. This results in the transfer of the specimen image onto photographic film. The specimen is rotated radially to another preset angular position and the radiography process repeated. The angular rotation between each radiograph is called an increment. For purposes of NT, the process is repeated numerous times at equal increments until the specimen has been rotated through 180 degrees. The second step in NT, illustrated in Figure 4, is computer processing of the data contained in the neutron radiographs. The data (variations in the film density) are digitized by scanning each radiograph using a high resolution microdensitometer or similar digitizing device. The data are entered into a computer which manipulates the data using a mathematical reconstruction algorithm. The end result is a series of computer-generated reconstructions of cross-sectional images of the specimen. Cross-section images can be generated through the specimen at almost any angle and view. In addition, by using various filtering and color schemes in the computer, it is possible to accentuate or highlight different specimen materials by their unique neutron absorption characteristics, making identification of materials such as control rods, stainless steel, UO_2, and water much easier.

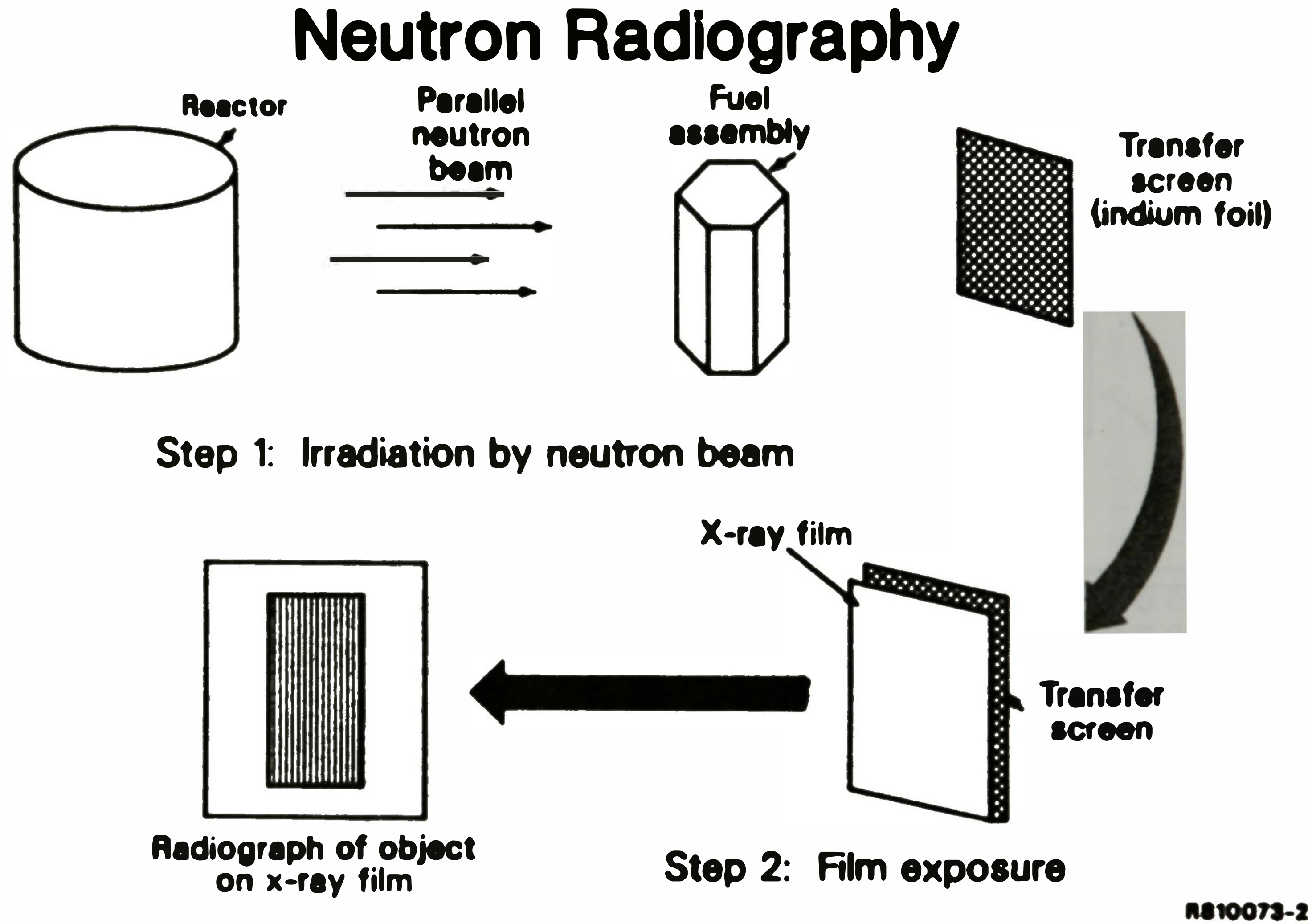


Figure 3. Schematic depicting the neutron radiography process.

Computerized Tomography Using Neutron Radiographs

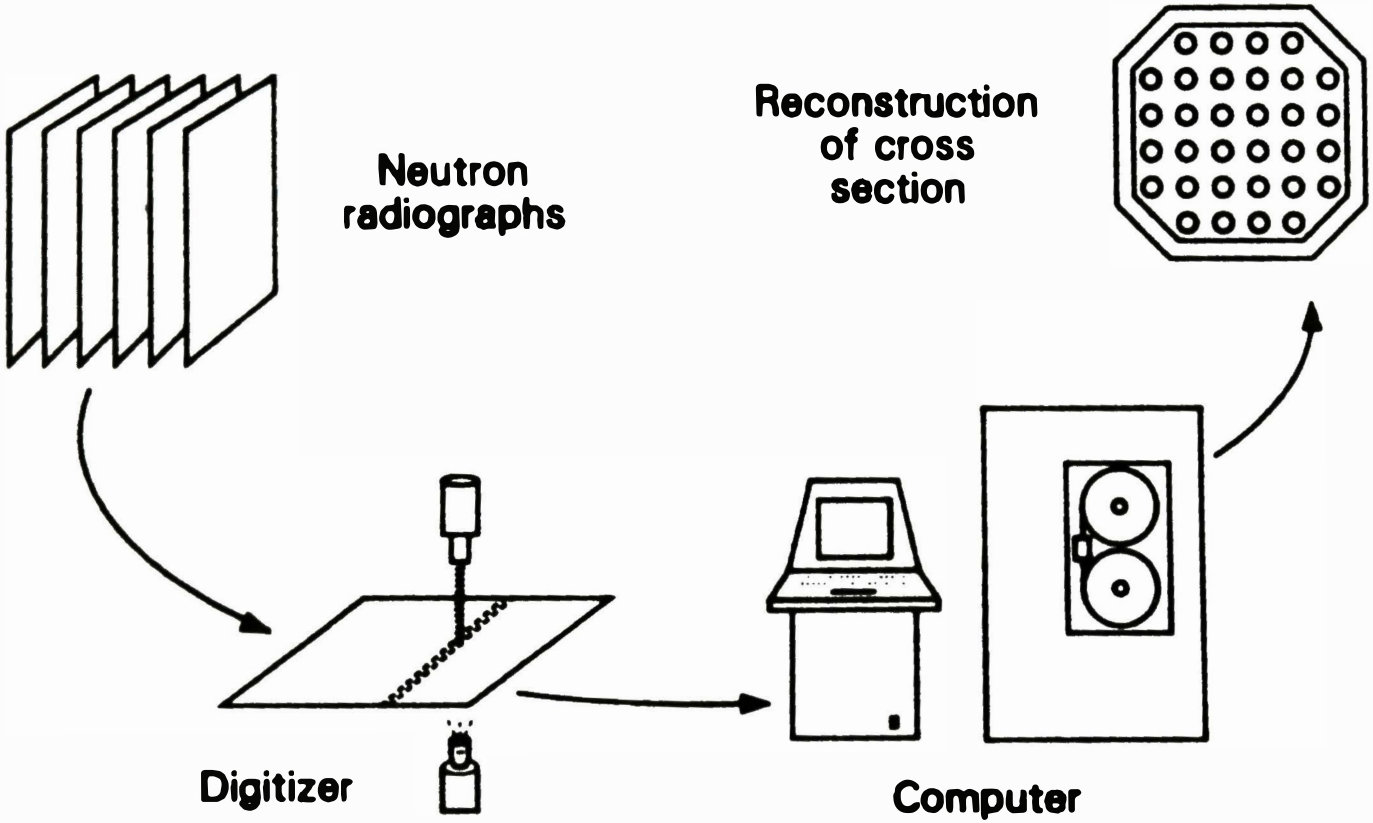


Figure 4. Schematic depicting the tomographic reconstruction process.

Ninety views of the TMI-2 assembly mockup were acquired for this study. The views were collected at two-degree increments. Cross-sectional images were generated from these 90 views as well as from smaller subsets. The smaller subsets contained 75, 60, 45, and 30 views. Interpolation was involved in generating the sets with 75 and 60 views. The two smaller sets were obtained by simply subsampling the original 90-view set.

The neutron radiography and digitization of the radiographs was performed at the Neutron Radiography (NRAD) facility at Argonne National Laboratory-West. The facility makes neutron radiographs suitable for NT examination of large irradiated fuel assemblies. The north beam of the facility is well suited to NT because the length of the beam tube (15 m) results in a highly parallel neutron beam. The exposure time of the neutron beam was 45 min for each radiograph of the assembly mockup. The image was transferred from the indium foil to Kodak Industrex AA film. Digitization of each radiograph took a little more than an hour. During an average eight-h shift, six radiographs of the assembly could be made and digitized.

Kodak Industrex AA film is a fast film that has not been used previously for examinations of the type used in this study. Past examinations have used Kodak Industrex T film, a slower, higher-resolution film. The concern with use of Type T film in this application is that a long exposure time (approximately 90 min) would be required. Longer than necessary exposure times are undesirable because of associated cost increases and fogging caused by neutron scattering[a] increases with exposure times. The choice to use the faster, lower-resolution Type AA film was based on the knowledge that the number of viewing angles, not the resolution of the radiograph, is the limiting factor in NT.

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a. Neutron scattering--A scattered neutron is one which arrives at the indium foil by way of an indirect trajectory. It does not approach as part of the parallel incident beam and pass straight through the specimen. Scattered neutrons impart a background fog to the neutron radiographs. This fog has a deleterious effect on the cross-section images generated by NT.

Considering the reduction in neutron scattering, it appears Type AA film resulted in negligible image degradation and substantially reduced costs.

EXAMINATION RESULTS

Twenty-four transverse (horizontal) and 30 axial (vertical) cross-sectional images of the assembly were computed using the set of 90 views. The computations were repeated for 75, 60, 45 and 30 views. The results using 90 views are discussed first.

Examination Using 90 Views

The performance of the examination technique (shown in Figures 5 through 13) in each of the following categories will be discussed separately:

1. Cladding and guide tubes
2. Spacer grid region
3. Missing fuel rods
4. Fuel rod condition (fuel geometry)
5. Water-filled rods
6. Irregularly shaped chunks
7. Control rods.

Cladding and Guide Tubes

The results of this study are consistent with previous NT work performed at the facility. Zircaloy cladding and guide tube materials are difficult to image using NT, because they are (by design) quite transparent to neutrons. Their presence, position, and condition are not reliably determined by NT using 90 views or fewer. In particular, the ruptured cladding included in the mockup is not apparent in the cross-sectional images. Some empty cladding and guide tubes are visible and some are not.

Spacer Grid Regions

In the upper spacer grid region (Figure 5a), most of the fuel rods are present and arranged in a regular grid pattern. There are a few missing rods, empty cladding, and empty guide tubes in this grid. There is also a few control rods and water-filled rods. As discussed above, the zircaloy elements

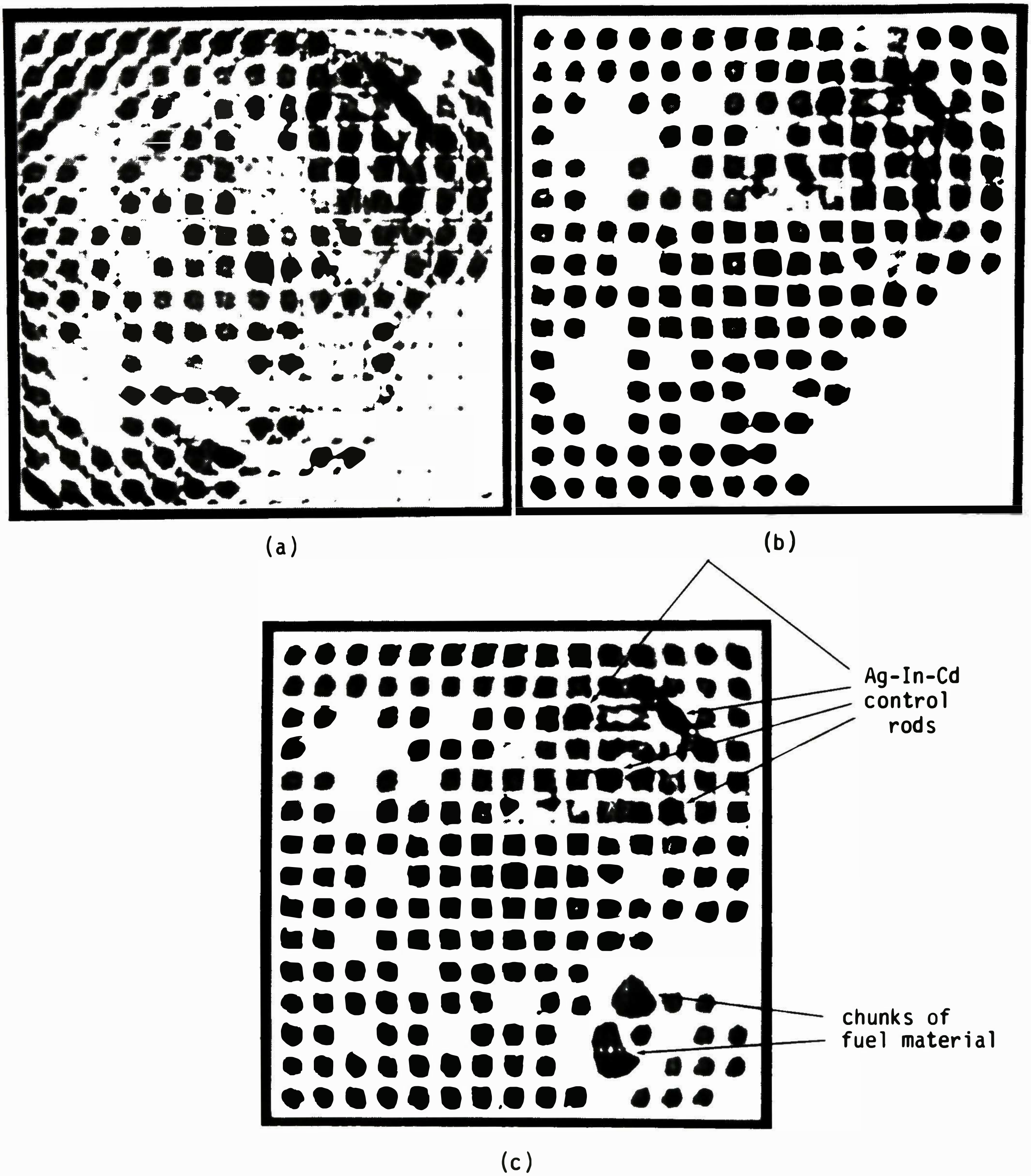
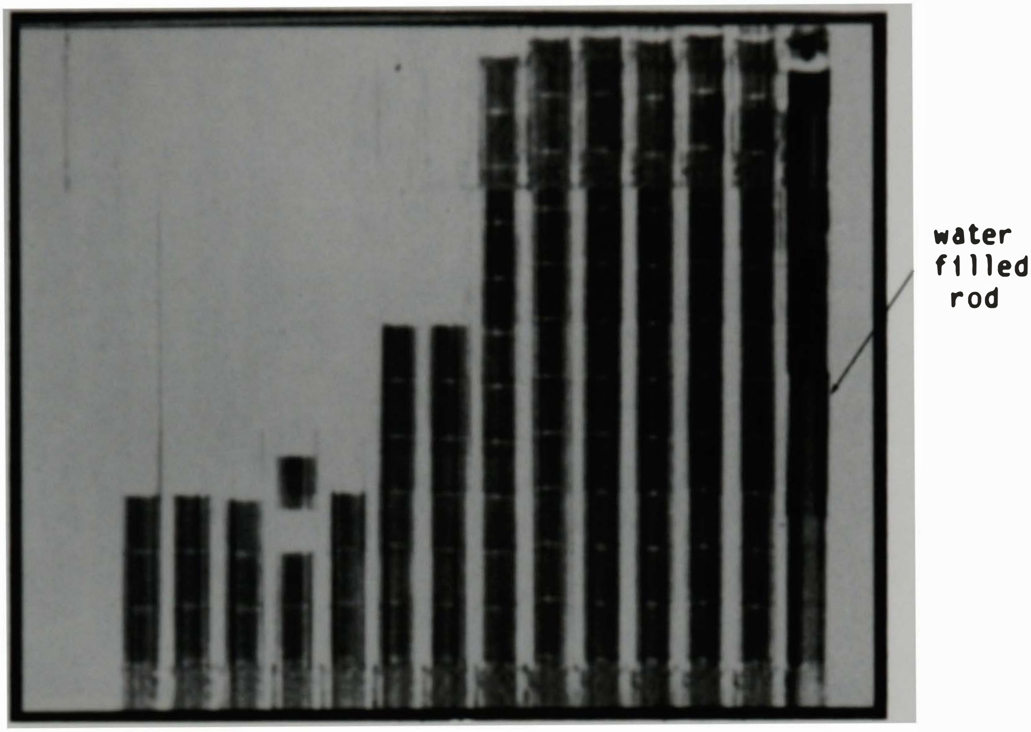
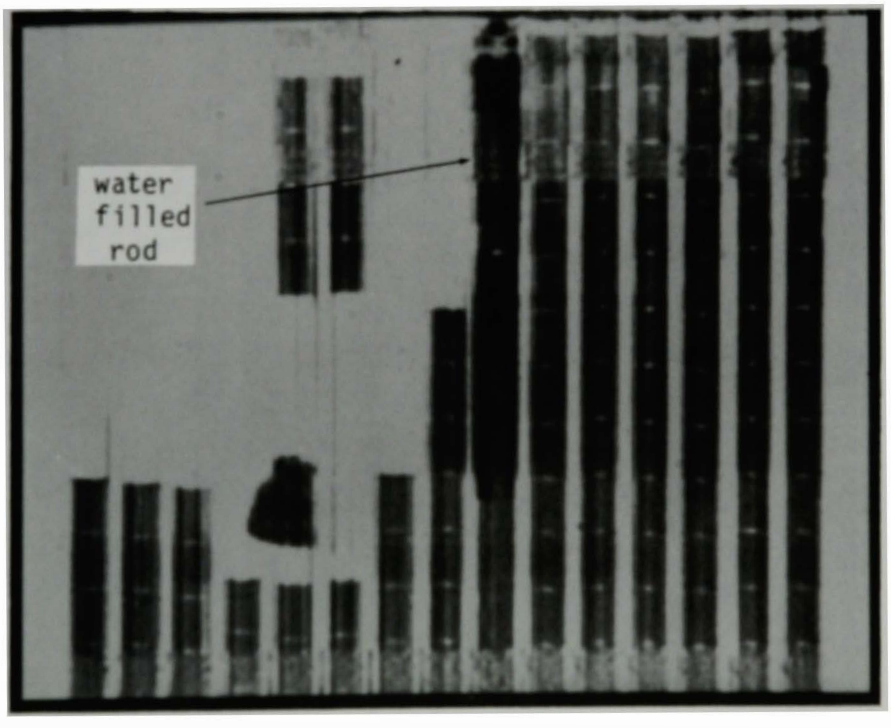


Figure 5. Transverse reconstructions using 90 views (a) within the upper spacer grid, (b) 11.2 cm below the top spacer grid, and (c) showing irregularly shaped molten chunks of previously molten core internal materials.

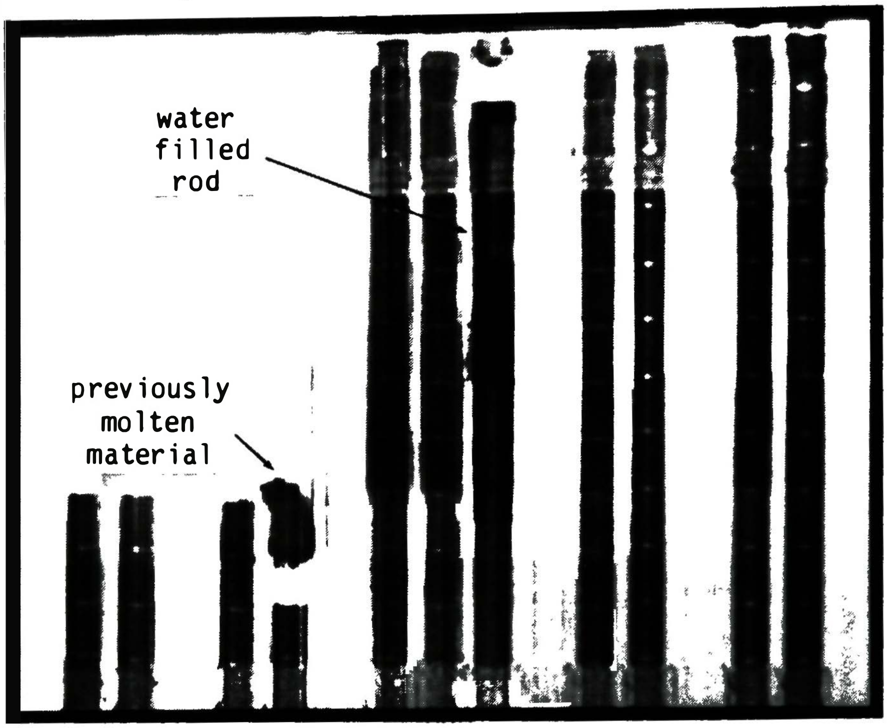


(a)



(b)

Figure 6. Axial reconstructions using 90 views (a) Row 1 of the TMI-2 assembly mockup and (b) Row 2 of the TMI-2 assembly mockup.



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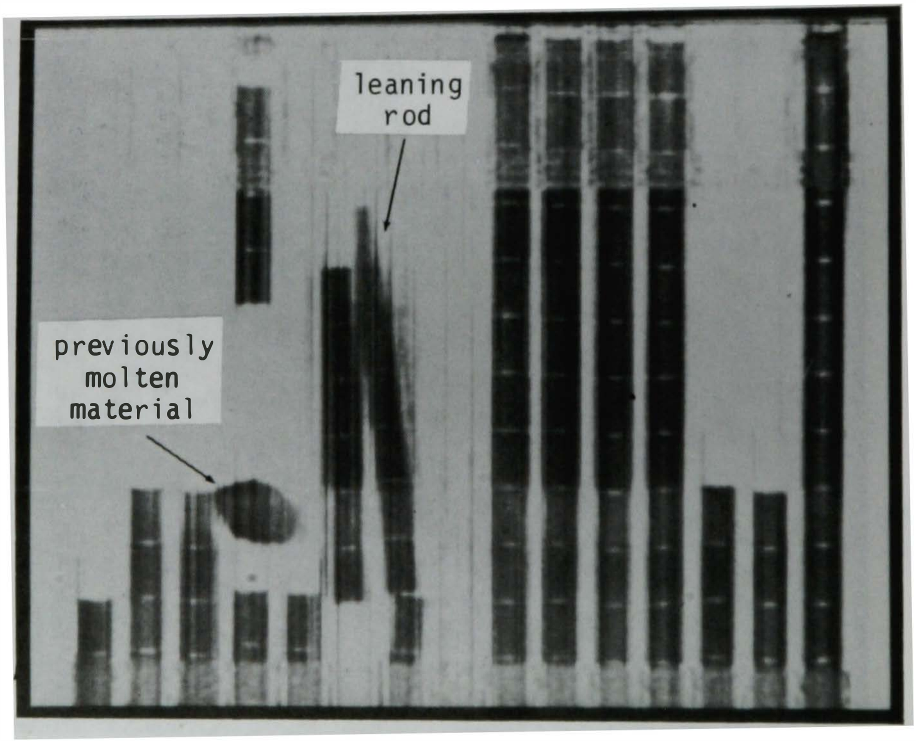
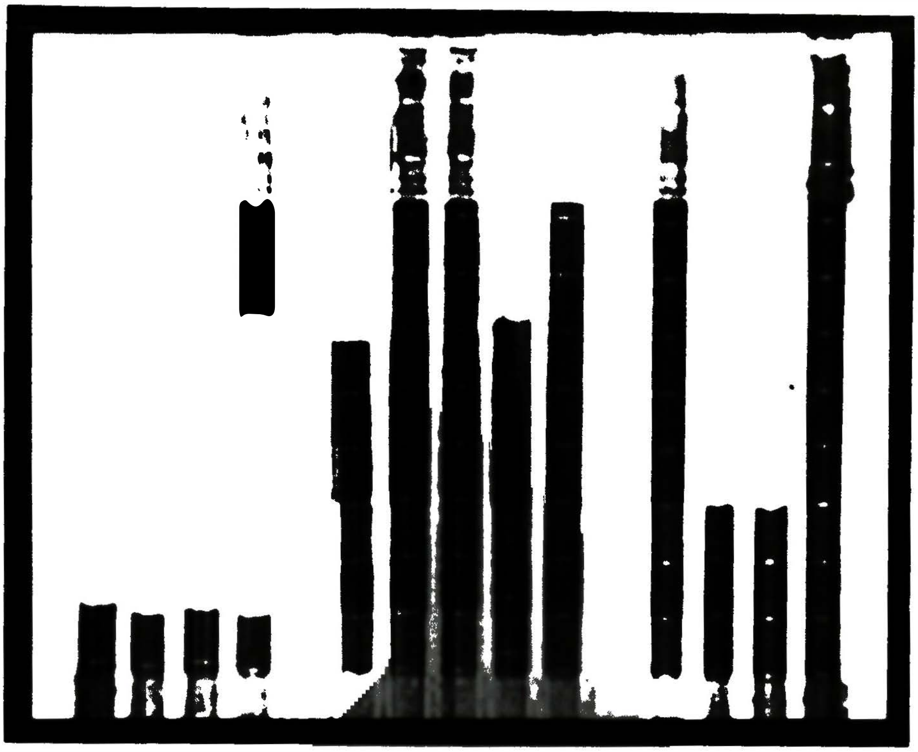
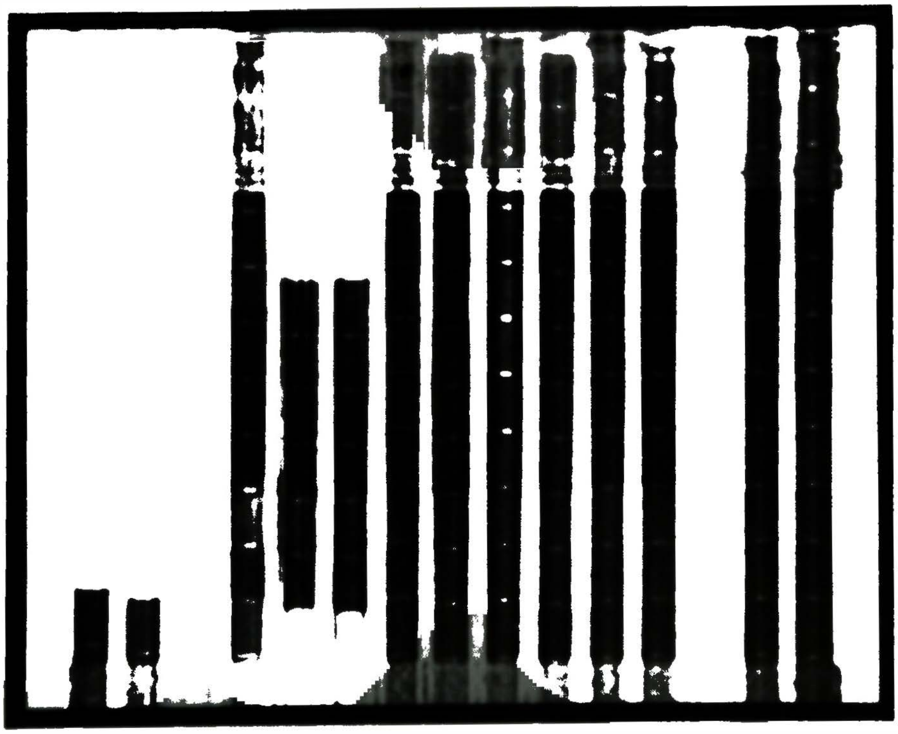


(b)

Figure 7. Axial reconstructions using 90 views (a) Row 3 of the TMI-2 assembly mockup and (b) Row 4 of the TMI-2 assembly mockup.

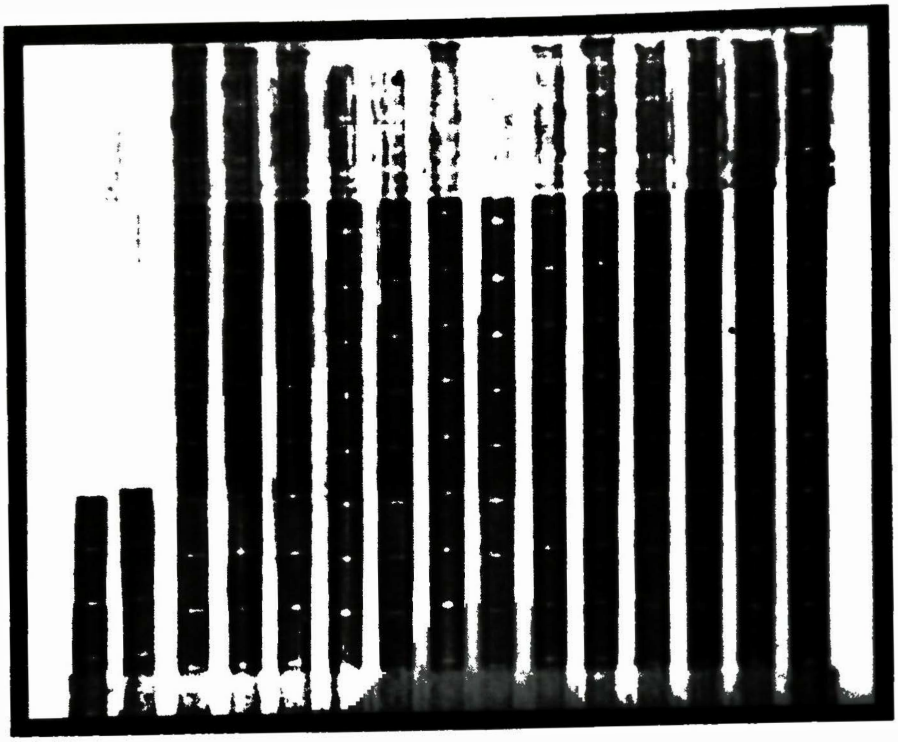


(a)



(b)

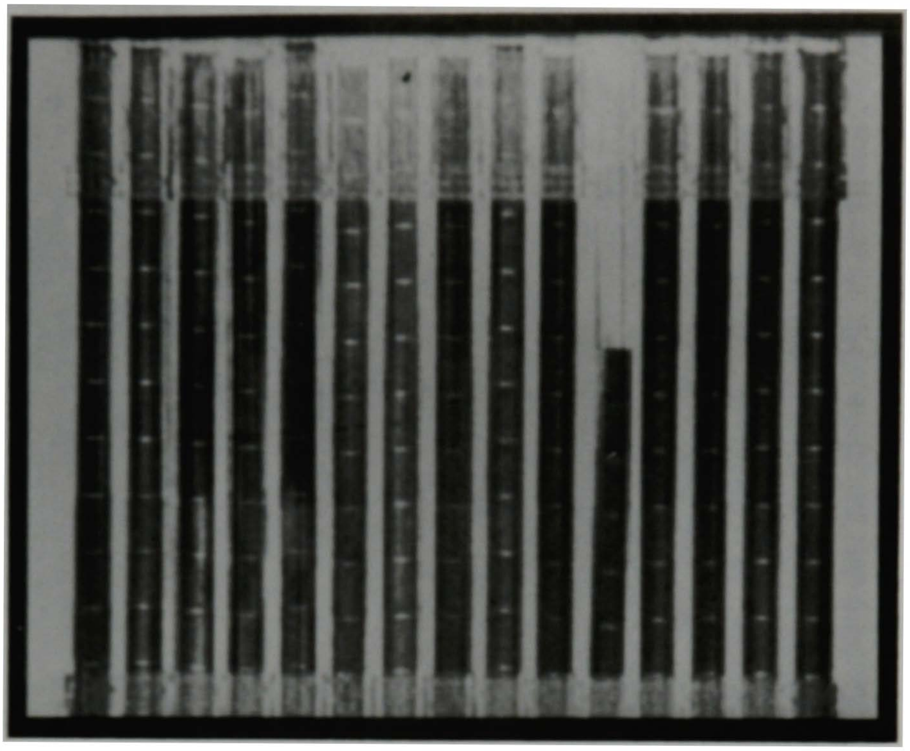
Figure 8. Axial reconstructions using 90 views (a) Row 5 of the TMI-2 assembly mockup and (b) Row 6 of the TMI-2 assembly mockup.



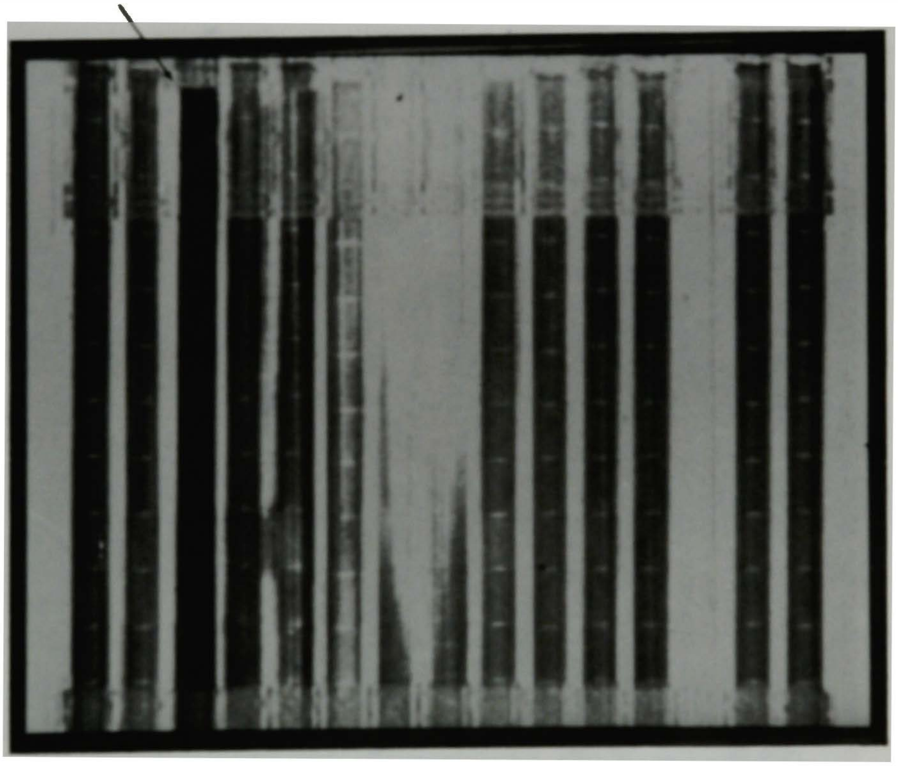
(a)

(b)

Figure 9. Axial reconstructions using 90 views (a) Row 7 of the TMI-2 assembly mockup and (b) Row 8 of the TMI-2 assembly mockup.

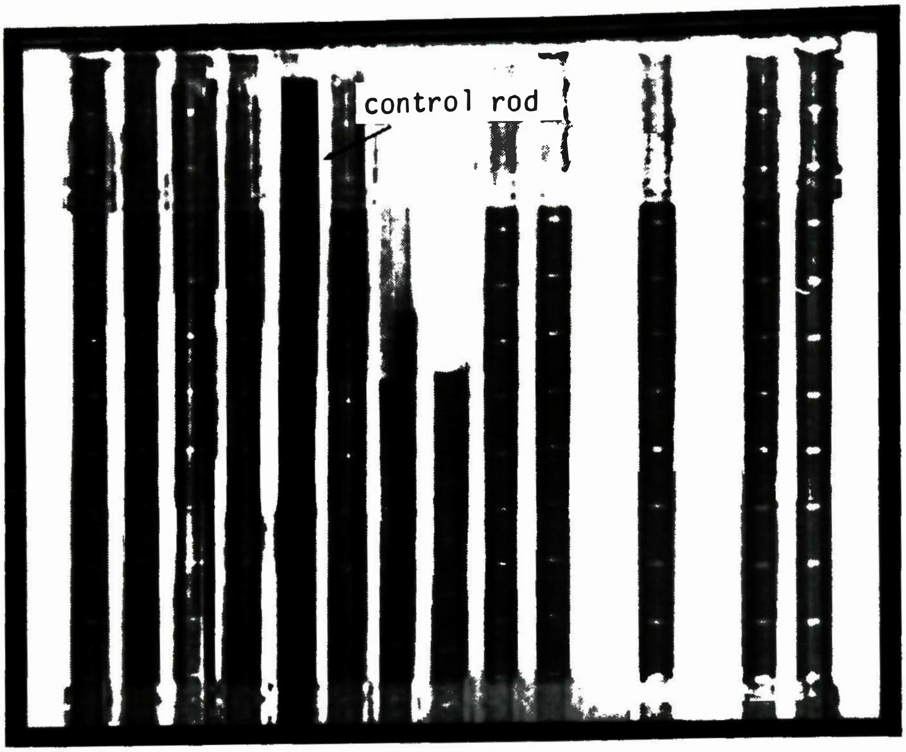


(a)

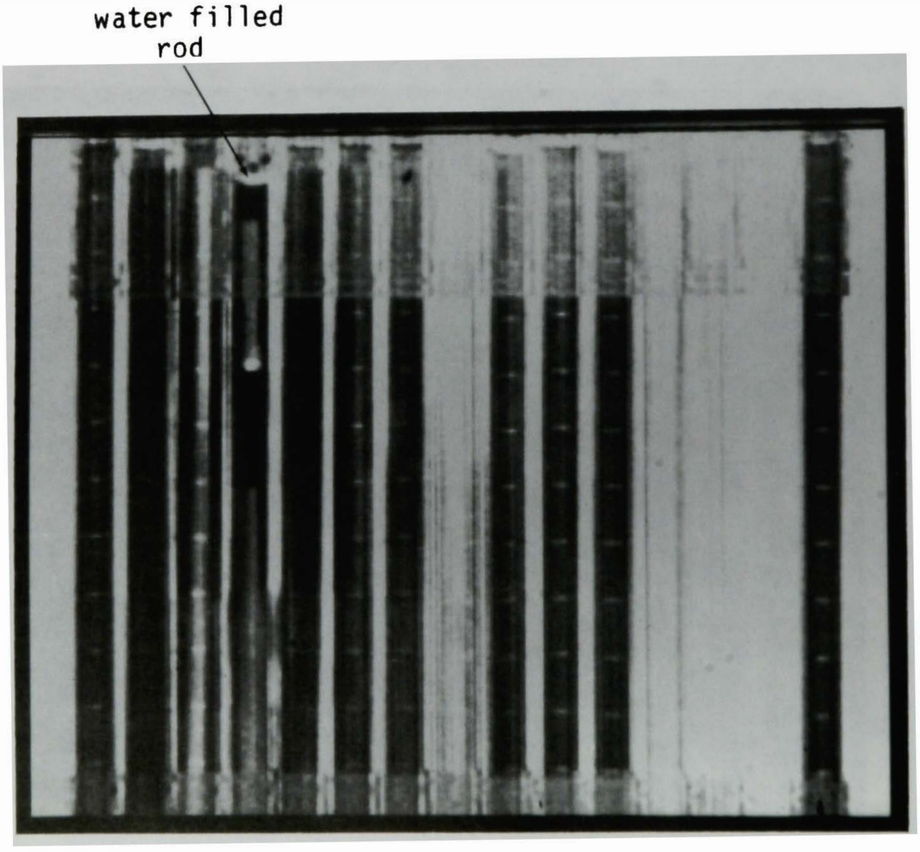


(b)

Figure 10. Axial reconstructions using 90 views (a) Row 9 of the TMI-2 assembly mockup and (b) Row 10 of the TMI-2 assembly mockup.

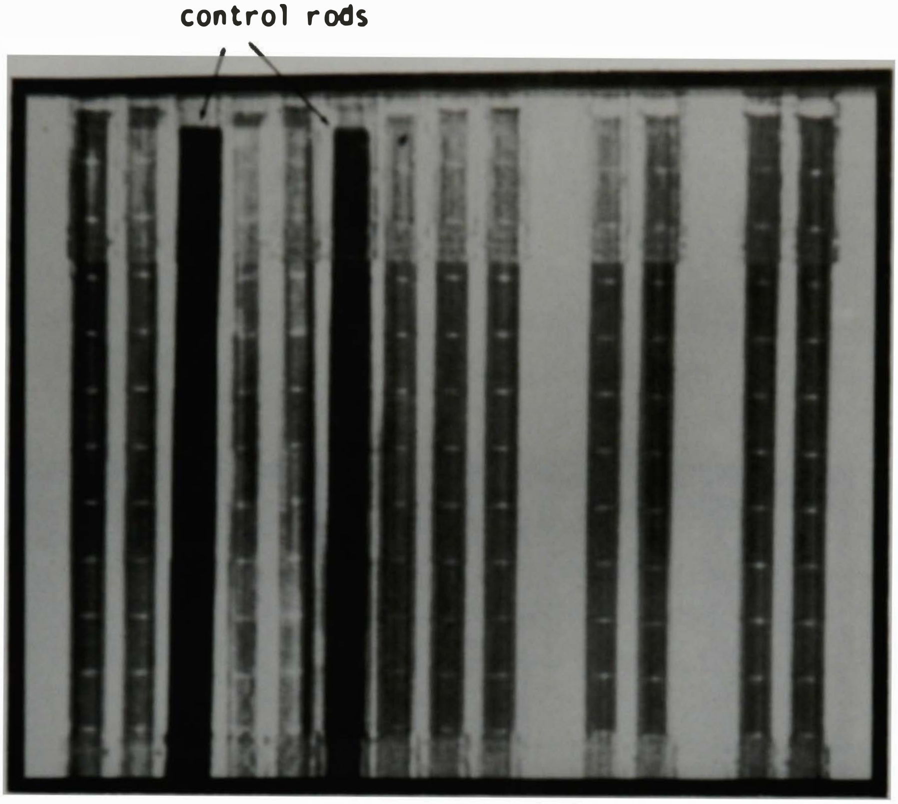


(a)

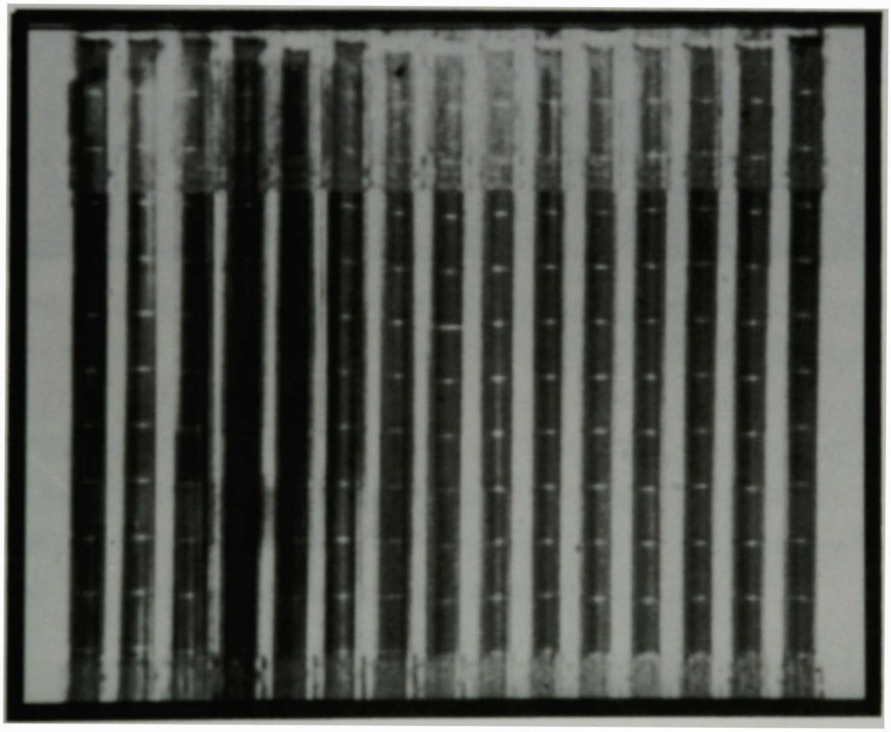


(b)

Figure 11. Axial reconstructions using 90 views (a) Row 11 of the TMI-2 assembly mockup and (b) Row 12 of the TMI-2 assembly mockup.



(a)



(b)

Figure 12. Axial reconstructions using 90 views (a) Row 13 of the TMI-2 assembly mockup and (b) Row 14 of the TMI-2 assembly mockup.

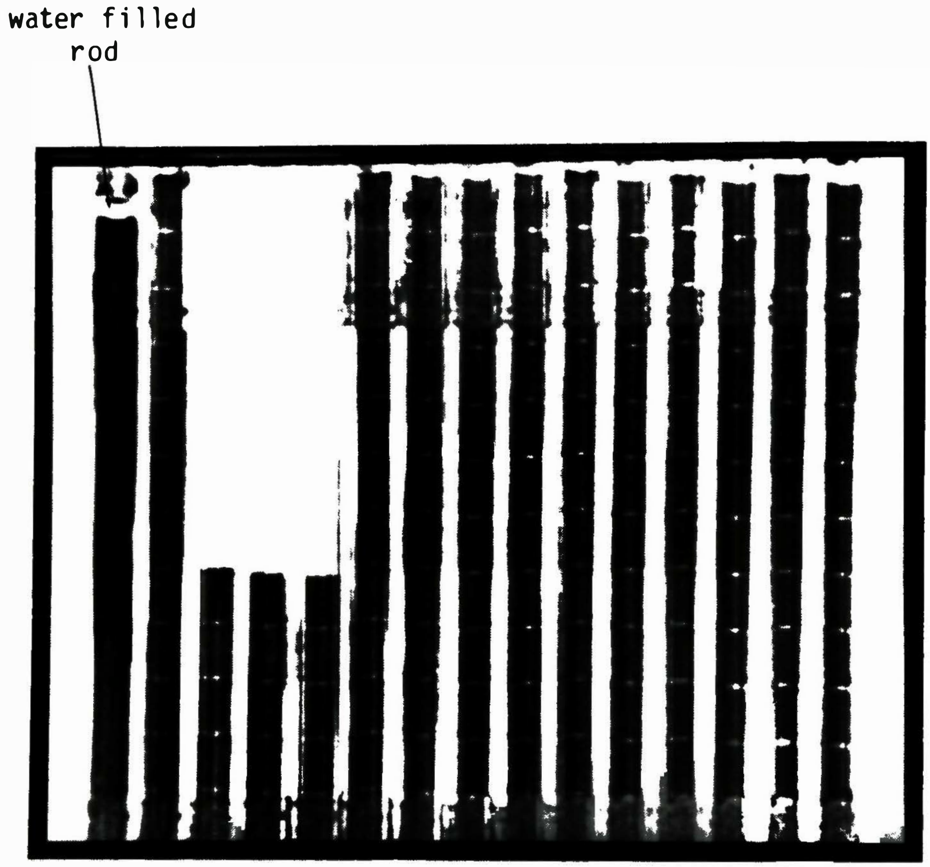


Figure 13. Axial reconstruction using 90 views for Row 15 of the TMI-2 assembly mockup.

are not reliably visible in the reconstructions. The transverse reconstructions reveal the remaining features with only a fair degree of reliability. The axial reconstructions provide a much better view. The transverse cross-sectional reconstructions are affected adversely by the great amount of detail (greater bandwidth) in the planes containing the spacer grid. Neutron scattering caused by the spacer grid may also have had an adverse effect.

The axial reconstructions seem less sensitive to the sources of impairment discussed above. Control rods and water-filled rods are clearly distinguished in the axial reconstructions. The alumina spacers in the water-filled rods are readily visible in the axial cross-sections. Those features are not as evident in the transverse images. From the transverse reconstructions, an inexperienced viewer might conclude that the fuel rods in the spacer grid regions are badly misshaped, especially in the region where four control rods are in close proximity to each other. The axial reconstructions provide higher resolution and a somewhat more accurate view. Although the roundness of the rods can not be seen in the axial views, these views more clearly indicate the actual configuration and show that the rods are in better condition than is indicated in the transverse views.

Missing Fuel Rods

Missing fuel rods can be reliably detected using NT. If not immediately apparent in the transverse cross-sections, the presence or absence of a fuel rod is obvious in the axial views. The transverse views outside the regions of the spacer grids indicate the presence or absence of such rods quite reliably. Within the spacer grids, transverse reconstructions are less reliable and the additional information contained in axial views is needed to make accurate determinations.

Fuel Rod Condition (Fuel Geometry)

Many fuel rods appear to be irregularly shaped in the transverse cross sections. Instead of being round, several have a square shaped appearance. This is a familiar phenomenon resulting from a combination of factors: the limited number of views (90), the square lattice arrangement of the fuel pins, and the particular reconstruction algorithm used to generate the cross-sectional images.

A few pins in the vicinity of the four close proximity control rods appear quite distorted in the transverse cross sections. Because the control rods are such strong attenuators of neutrons, the relatively transparent nearby fuel rods are somewhat masked from view. Consequently, insufficient information is available to accurately reconstruct these pins to the same detail as others are reconstructed.

Offset and leaning rods also appear rather distorted in the transverse cross sections. This is another familiar phenomenon. Irregular features, such as offset and leaning fuel rods, in otherwise symmetrical arrays of fuel elements are frequently inaccurately represented in cross-sectional reconstructions. This occurs when an insufficient number of viewing angles is used. In this case, 90 views is apparently insufficient to allow offset pins to be accurately visualized.

The axial cross-sectional images are valuable in determining the condition of the fuel rods. The axial images seem less sensitive to the sources of distortion just mentioned. They more clearly show the actual pellet cross section. The fuel pellets appear homogeneous in the axial cross sections, indicating no crumbling or other damage.

In summary, fuel rod condition can be determined with fair to good reliability by NT using 90 views. Both transverse and axial cross-sectional images are necessary to make such determinations.

Water-Filled Rods

Five water-filled rods were placed in the mockup at various locations to evaluate the effects of water saturation on the NT process. Instead of depleted UO_2 pellets, alumina rods and tubing of varying diameters were placed inside the cladding to provide variable (controlled) water layer thicknesses inside the rods. The rods were then filled with borated water and sealed closed. The configuration of those rods is shown in Figure 1. Water is known to be a high absorber of epithermal neutrons, and as such, could adversely affect the neutron tomography process.

The presence of these rods did not seem to seriously effect the cross-sectional images obtained by NT. The geometry and condition of the rods could be determined with good reliability by using a combination of the transverse and axial images. The various water layer thickness could be easily identified.

Irregularly Shaped Chunks

Two chunks of previously molten core material (stainless steel, zircaloy-4, depleted UO_2 and Ag-In-Cd) were included in the bundle. These chunks were on the order of one to three cm in diameter. During radiography, the chunks attenuated neutrons with about the same intensity as the fuel pellets. The shape and position of these chunks could be determined with good reliability in both the transverse and the axial cross-sectional images.

Control Rods

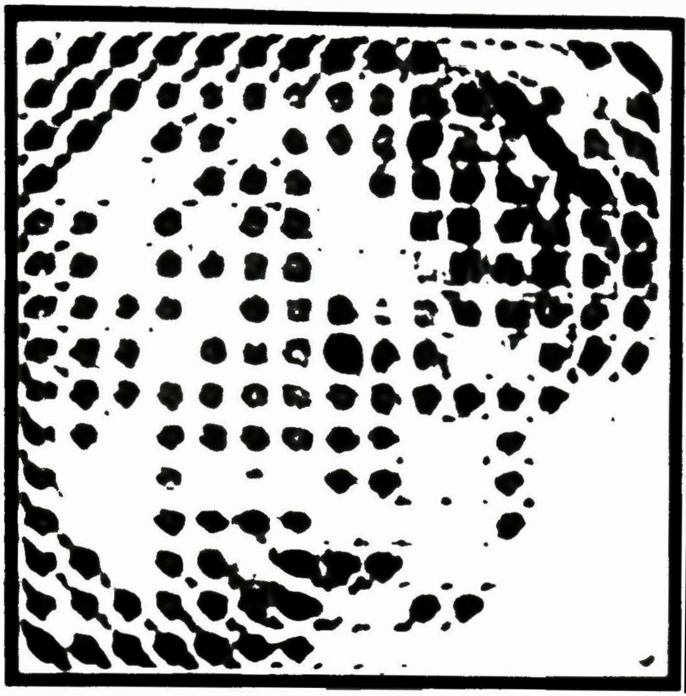
Ag-In-Cd control rod material is a strong attenuator of neutrons. Because of this, the positions and shapes of the control rods are accurately represented in both the transverse and the axial cross-sectional images. A negative consequence of the strength of this attenuation is the adverse effect on the cross-sectional images in the areas surrounding the control rods. Neighboring objects are relatively transparent and are masked in the radiographs by the images of these control rods. Consequently, neighboring objects are not as accurately represented in the cross-section images as similar objects which are further from the control rods. Fortunately, the axial cross-sectional images are less sensitive to the degradations caused by the control rods. Using these axial cross sections, the regions adjacent to the control rods can be viewed with reasonable accuracy and reliability.

Examinations Using Fewer Views

Cross-sectional reconstructions were computed using 75, 60, 45, and 30 views. Interpolation was necessary to generate 75 and 60 views from 90. No interpolation was required to pick 45 and 30 views from the original 90 as they are integer subsets of the 90 views (2 and 3). Figures 14 through 18 show comparisons of the same cross sectional views using 90, 75, 60, 45, and 30 views, respectively.

The accuracy and resolution of the reconstructed images decreases as the number of views is reduced. The resolution of the transverse cross-sectional images is roughly proportional to the number of views used, The axial cross sections are less sensitive to the number of views, but still suffer some impairment when the number is reduced.

It is concluded that 60 or more views are required to achieve the desired imaging accuracy.



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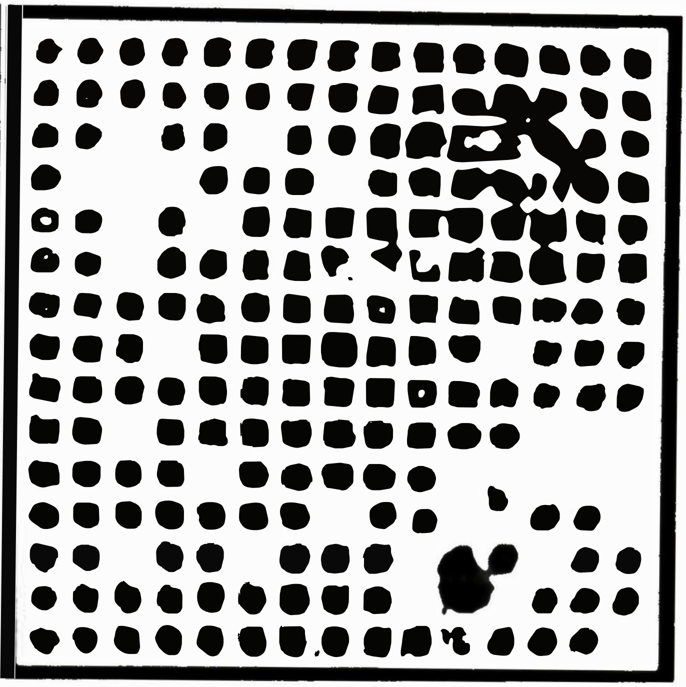

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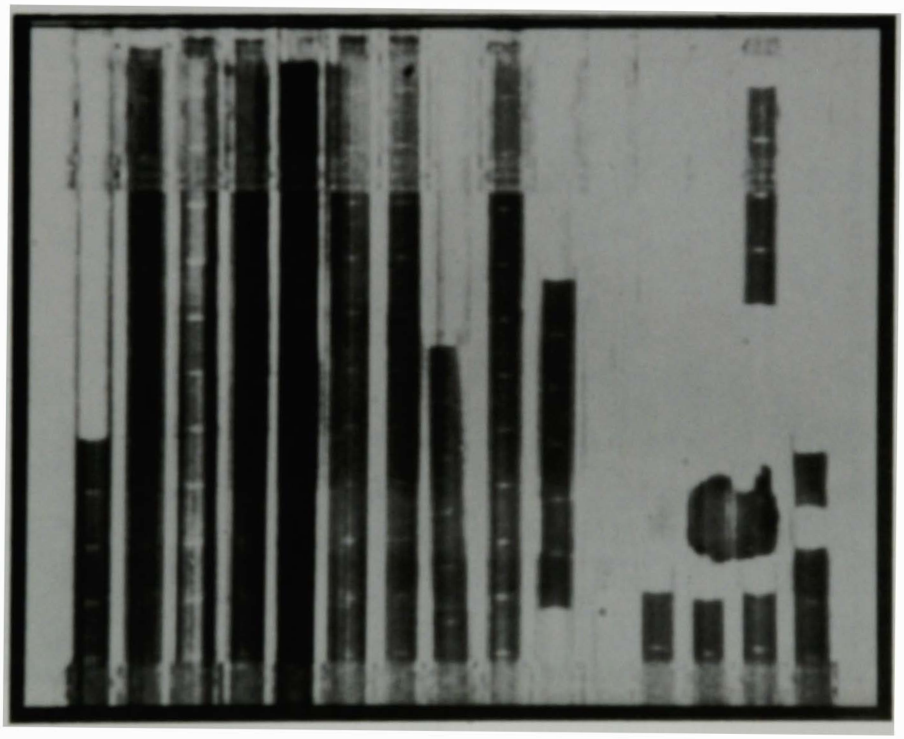
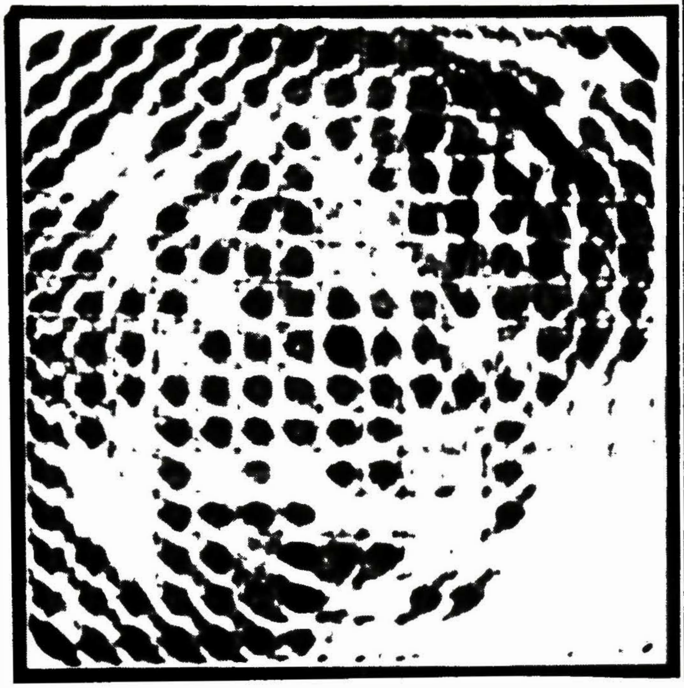


(c)

Figure 14. Reconstructions using 90 views (a) within the upper spacer grid, (b) 14.4 cm below the top of the spacer grid, and (c) Row E, axial view.



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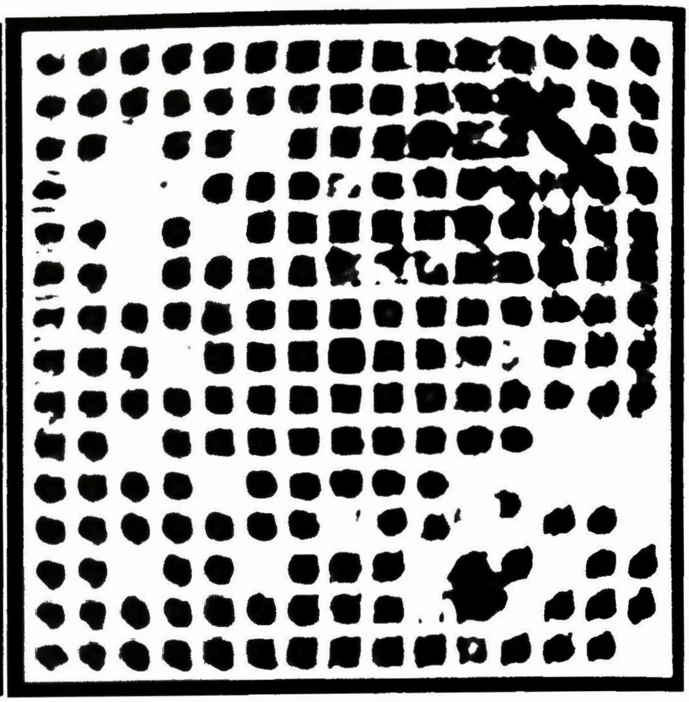

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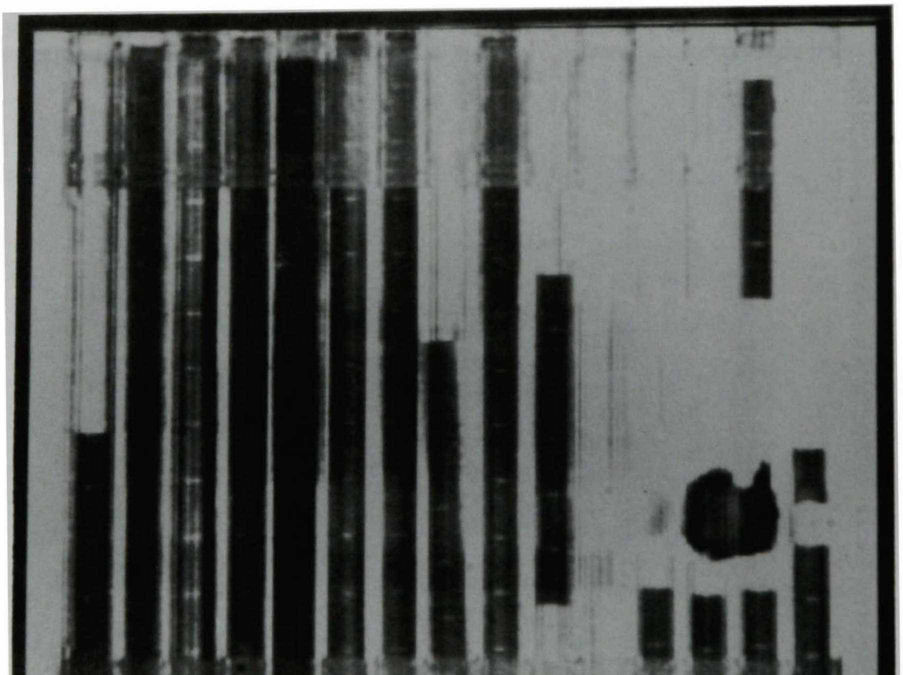
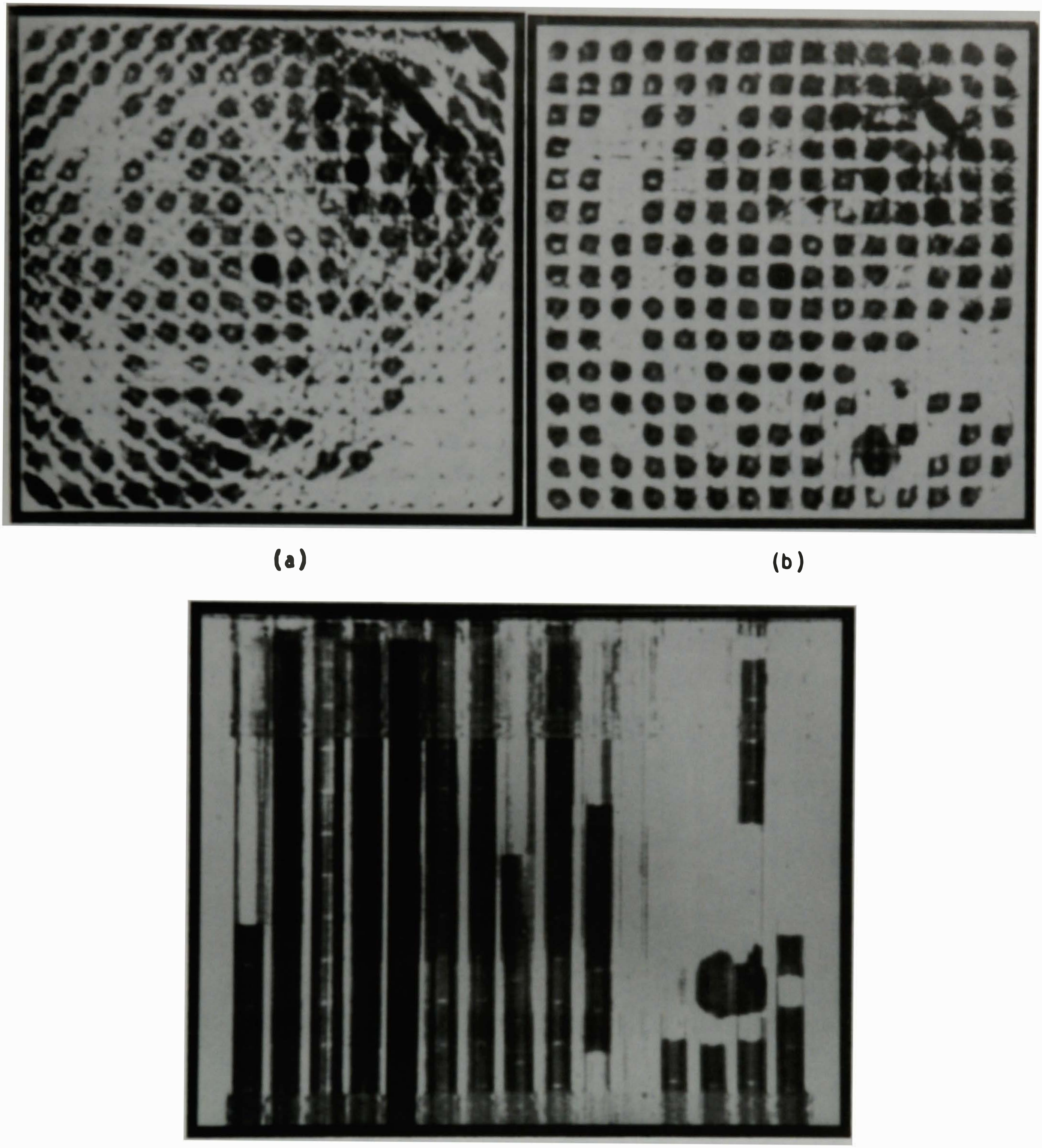


(c)

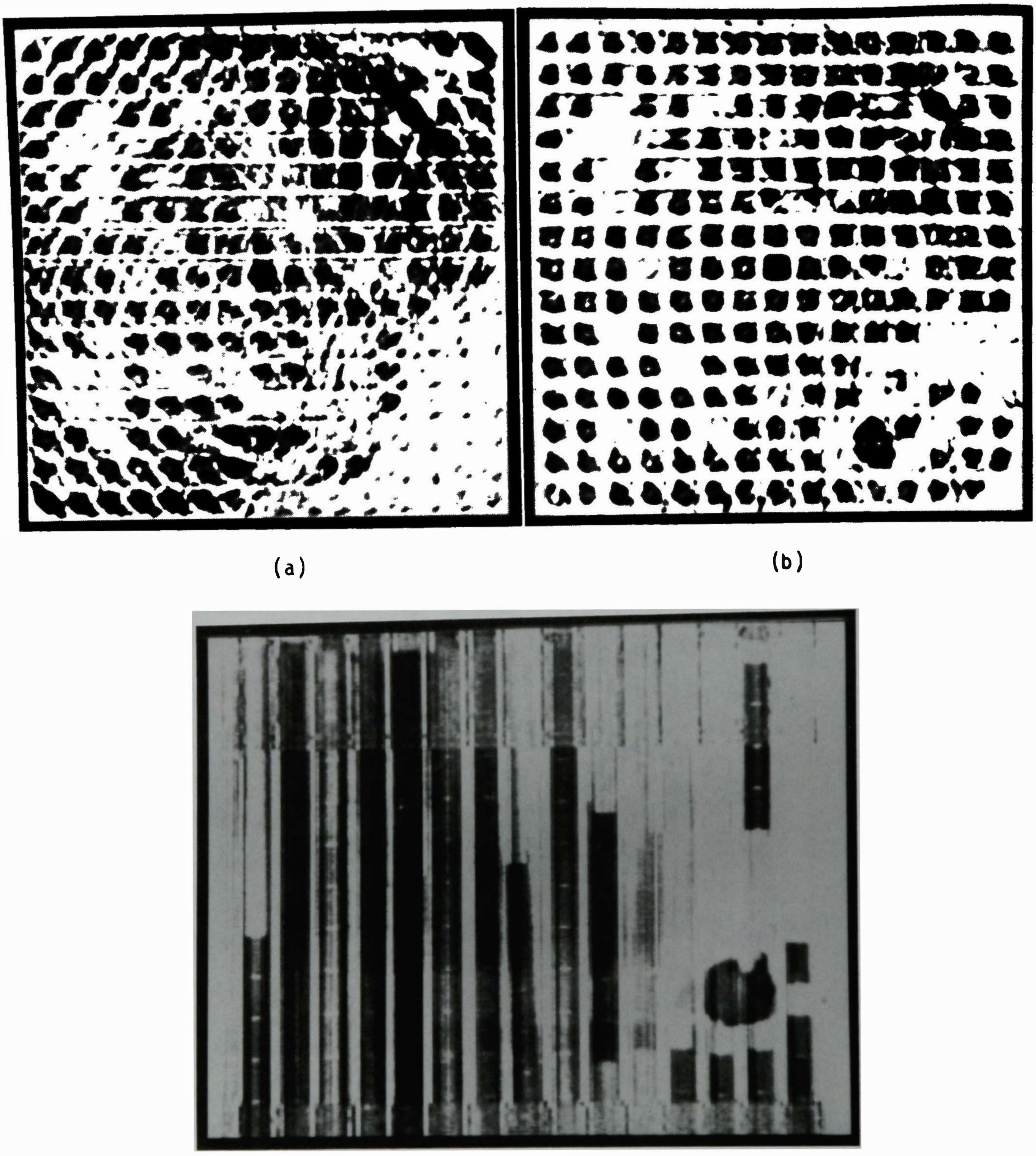
Figure 15. Reconstructions using 75 views--same cross sections as Figure 14 (a) within the upper spacer grid, (b) 14.4 cm below the top of the spacer grid, and (c) Row E, axial view.



(a) (b)

(c)

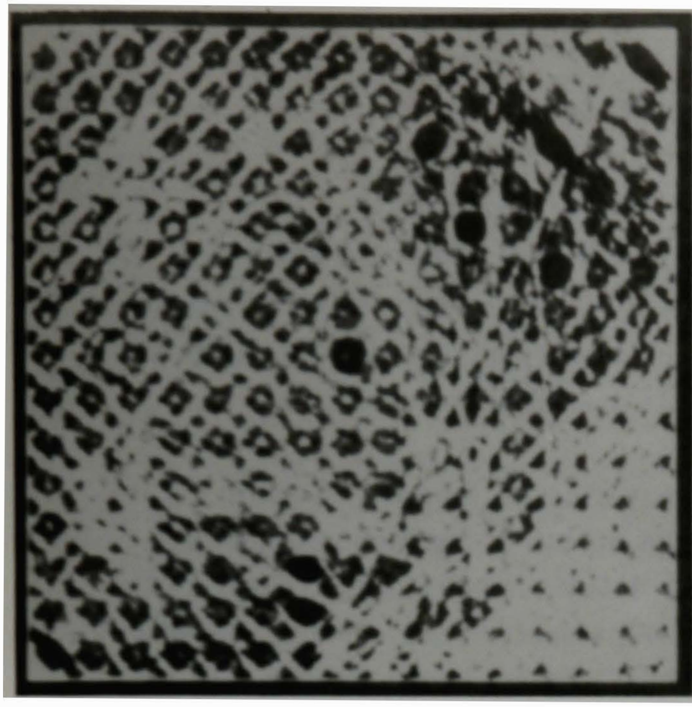
Figure 16. Reconstructions using 60 views--same cross sections as Figure 14 (a) within the upper spacer grid, (b) 14.4 cm below the top of the spacer grid, and (c) Row E, axial view.



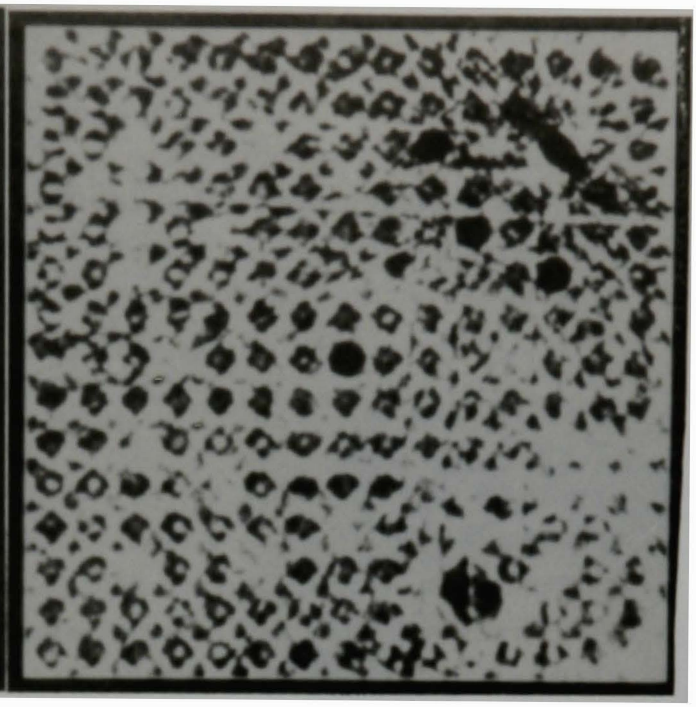
(a) (b)

(c)

Figure 17. Reconstructions using 45 views--same cross sections as Figure 14 (a) within the upper spacer grid, (b) 14.4 cm below the top of the spacer grid, and (c) Row E, axial view.



(a)



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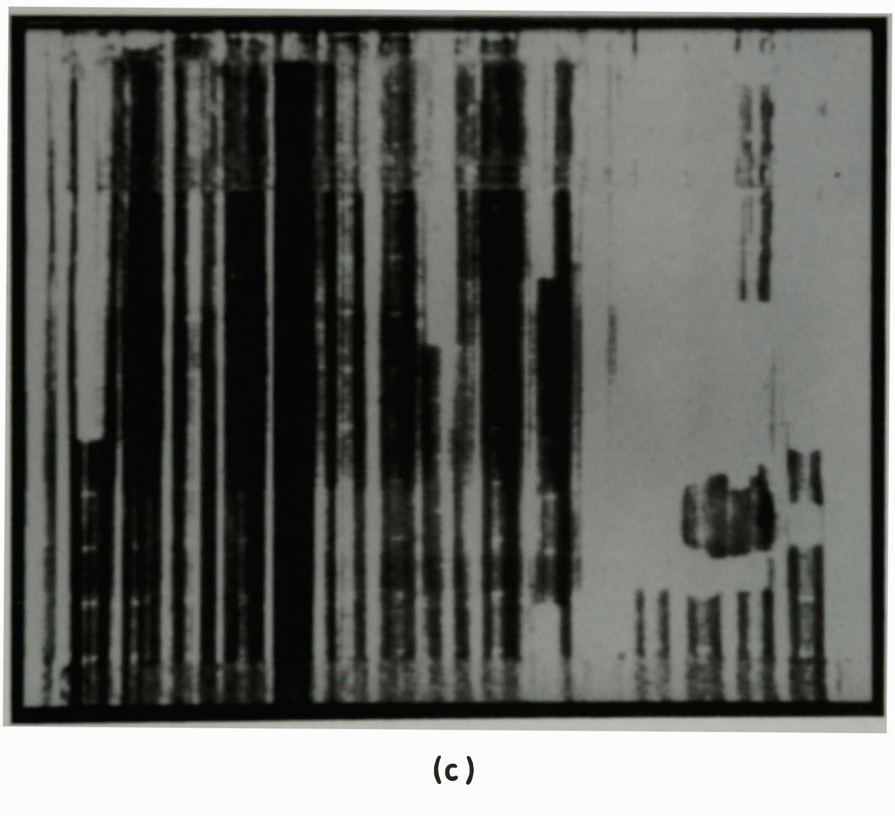

(c)

Figure 18. Reconstructions using 30 views--same cross sections as Figure 14 (a) within the upper spacer grid, (b) 14.4 cm below the top of the spacer grid, and (c) Row E, axial view.

CONCLUSIONS/RECOMMENDATIONS

This study demonstrated the feasibility of using NT to nondestructively examine a fuel assembly with mass and cross section similar to a TMI-2 fuel assembly. Useful and reliable information can be obtained regarding fuel assembly configuration, particularly the location and condition of fuel and control materials within the assembly.

One condition that was not adequately studied, and which could seriously affect the data results, is the effect of varying degrees of water saturation in the fuel rods. This study used five water saturated fuel rods only. If the quantity of water-saturated rods were increased to become a significant percentage (25 or more) of the total, NT may not be feasible due to total neutron absorption by the water. If NT becomes a serious consideration for use on TMI-2 fuel assemblies, this study should be expanded, varying the percentage of water-saturated rods within the fuel assembly. Additionally, if a neutron poisoning material is used inside the canister, the poisoning material likely will be detrimental to NT and should be included in additional studies.