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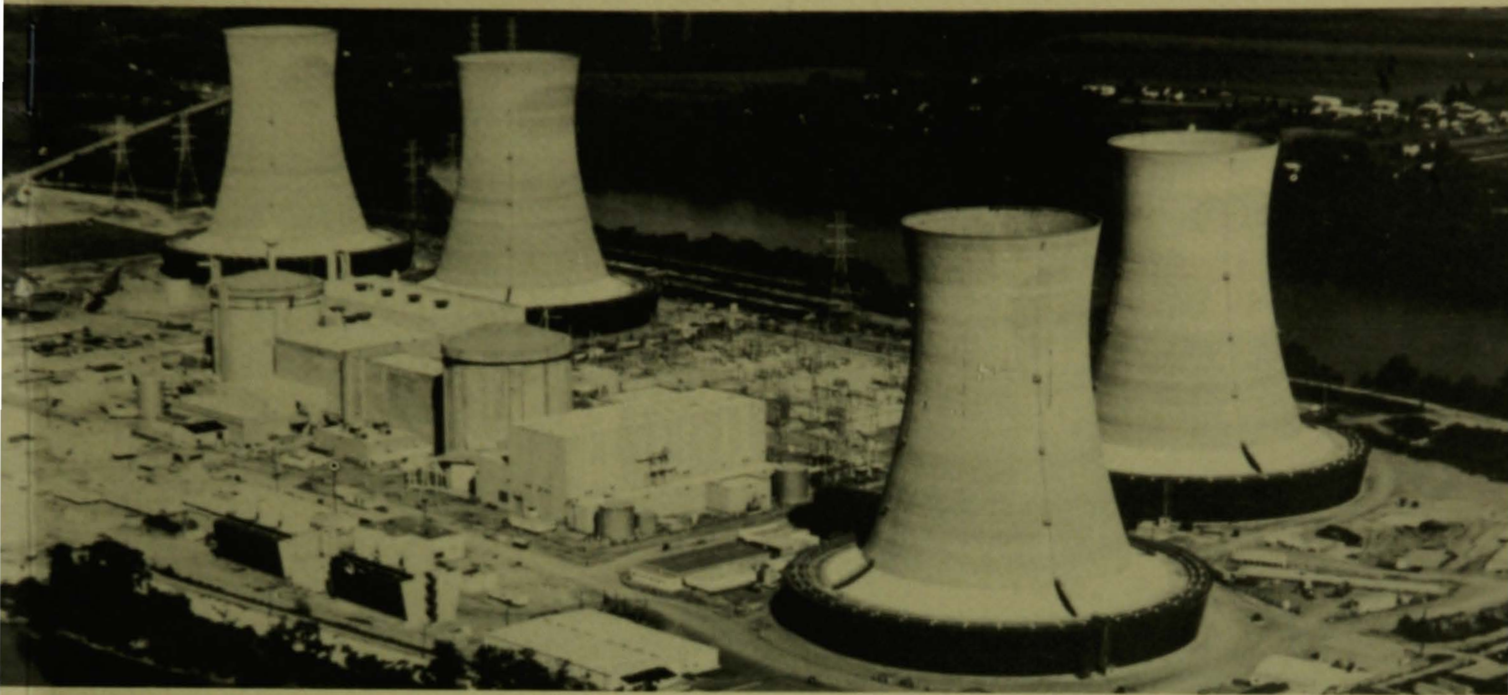

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TMI-2 CORE HORSESHOE RING EXAMINATIONS

M. L. Russell

Prepared for the
U.S. Department of Energy
Three Mile Island Operations Office
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ABSTRACT

A horseshoe-shaped ring of fused-together core material was uncovered by removal of loose debris from the TMI-2 core cavity floor between December 1985 and June 1986. The horseshoe ring is a possible source of clues to the TMI-2 core relocation scenario. Estimates of the location, dimensions, and surface appearance characteristics of the horseshoe ring were derived from limited data from video survey recordings and mechanical probing measurements for the sole purpose of furnishing information to the analysts who are reconstructing the TMI-2 core damage sequence scenario from the available known data and analytical predictions. The horseshoe ring location, dimensions, and surface appearance at accident termination are estimated to be as follows:

Location:	Extended from 50 to 110 inches above the fuel rod bottoms, and from 120° to 70° azimuth
Dimensions (average):	98 inches inside diameter x 27 inches high x 8.5 inches thick (radially)
Surface Appearance:	The upper surface contour was irregular and consisted of decomposed (fossilized-appearing) rod bundle remnants. The lower inside surface resembled cobblestone, and receded, cave-like, at the interface with the upper crust of the fused-together core region.

CONTENTS

FIGURES

TMI-2 CORE HORSESHOE RING EXAMINATIONS

1. INTRODUCTION

The purpose of this report is to provide a description of a horseshoe-shaped ring of agglomerate-appearing core material that was uncovered by removal of loose debris from the TMI-2 core cavity floor between December 1985 and June 1986. The information is intended for use by the analysts who are reconstructing the TMI-2 core damage sequence scenario from the available known data and analytical predictions. Closed-circuit television (CCTV) surveys in June 1986 discovered the ring of material (see Fig. 1) projecting inwards from the standing fuel rods and extending upwards from the upper-crust elevation (approximately 60 inches above the fuel bottoms) to approximately 90 inches above the fuel rod bottoms. The horseshoe opening was at the East side. This report also provides a still-image photograph album of views of the ring from CCTV surveys made in June, October, and December 1986.

The horseshoe ring configuration was altered by core boring and defueling activities and measurements were not attempted at any time. The horseshoe ring configuration is a possible source of clues to the TMI-2 core relocation scenario. This report provides an estimate of the horseshoe ring configuration from available (but imprecise) information.

1.1 Background

The examination of the TMI-2 core cavity sides and floor with the CCTV system is a small part of a large and complex effort described in Ref. 1.

Although the March 28, 1979, accident at TMI-2 involved severe damage to the core of the reactor, it had no observable effects on the health and safety of the public in the area. That such a severe core-disruption accident would have no consequent health or safety effects has resulted in the questioning of earlier light water reactor (LWR) safety studies and estimates. In an effort to resolve these questions, several major research programs have been initiated by a variety of organizations concerned with

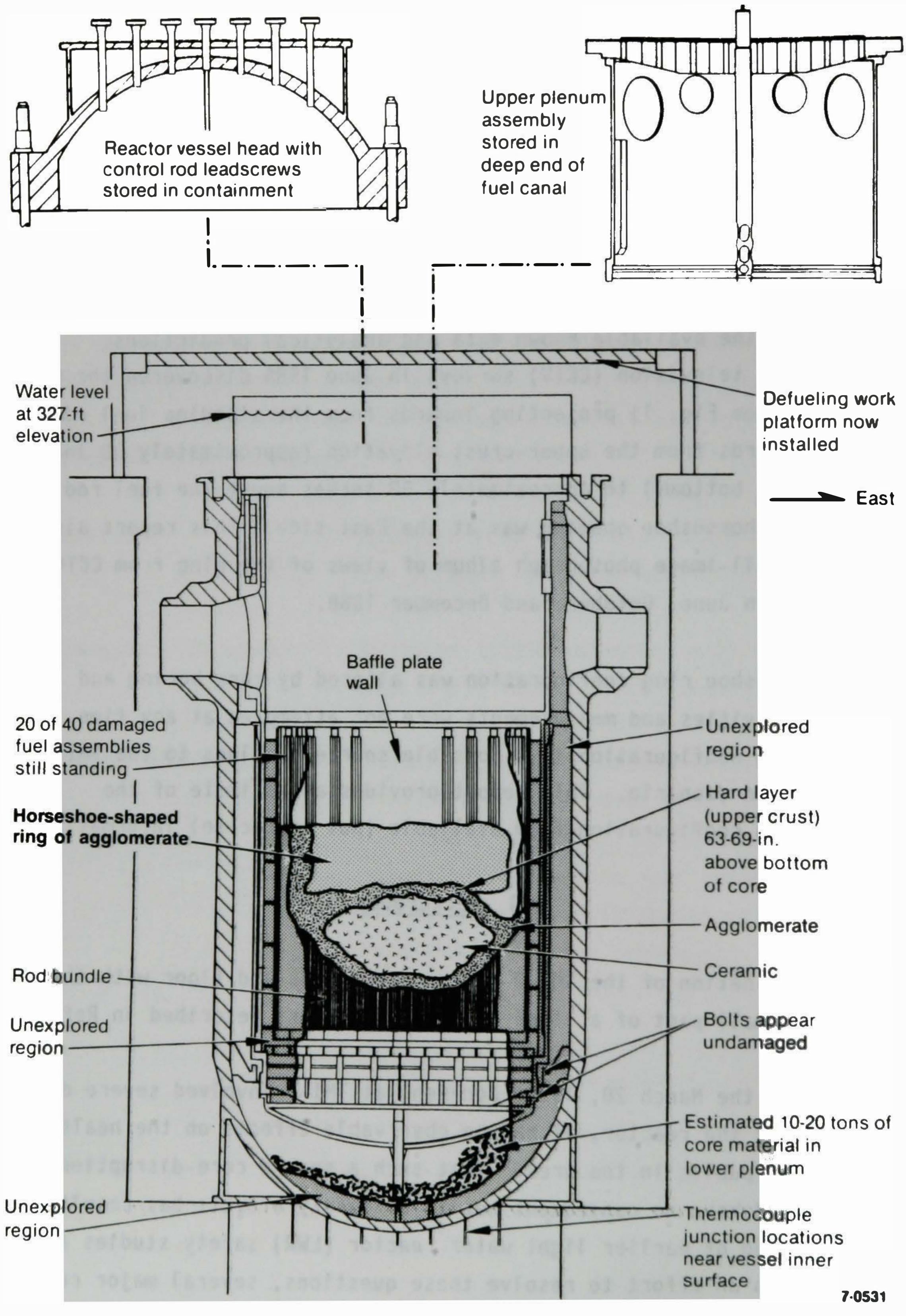

Figure 1. Estimated core and reactor vessel conditions in October 1986.

nuclear power plant safety. The U.S. Nuclear Regulatory Commission (NRC) has embarked on a thorough review of reactor safety issues, particularly the causes and effects of core-damage accidents. Industrial organizations have conducted the Industry Degraded Core Rulemaking (IDCOR) Program. The U.S. Department of Energy (DOE) has established the TMI-2 Program to develop technology for recovery from a serious reactor accident and to conduct relevant research and development that will substantially enhance nuclear power plant safety.

Soon after the TMI-2 accident, four organizations with interests in both plant recovery and accident data acquisition formally agreed to cooperate in these areas. These organizations, commonly referred to as the GEND Group--GPU Nuclear Corporation, Electric Power Research Institute, Nuclear Regulatory Commission, and Department of Energy--are actively involved in reactor recovery and accident research. At present, DOE is providing a portion of the funds for reactor recovery (in those areas where accident recovery knowledge will be of generic benefit to the U.S. LWR industry) as well as the preponderance of funds for severe accident technical data acquisition (such as the examination of the damaged core).

The EG&G involvement with the TMI-2 accident has been continuous, initially providing technical support and consultation from the Idaho National Engineering Laboratory (INEL). In 1979, EG&G received an assignment from DOE to collect, analyze, distribute, and preserve significant technical information available from TMI-2. This assignment was expanded (in 1981 and 1984) to include: (a) conducting research and development activities intended to effectively exploit the generic research and development challenges at TMI-2, and (b) developing an understanding of the accident sequence of events in the area of core damage and behavior of core radionuclides (fission products) and materials.

The <u>TMI-2 Accident Evaluation Program</u> report[2] defines the program required to implement the DOE assignments and contains the guidelines and requirements for TMI-2 sample acquisition and examinations.

The already-completed portion of the Sample Acquisition and Evaluation (SA&E) Plan includes in situ measurements and sample acquisition and examinations involving private organizations and state and federal agencies. It has provided the postaccident core and fission product end-state data that indicate the following:

- The current EG&G estimate of damage and reconfiguration of the core is as follows:

Core Region	Percent of Core Material	
Still standing rod bundle geometry	42	
Loose debris (unmelted and previously molten core material mixture) below the cavity in the upper core region (the cavity was 26 percent of the original core volume)	23	
Previously molten core material:	35:	
retained in core boundary		19
escaped from core boundary		16

- Some uranium dioxide fuel melting occurred indicating temperatures reached at least 3100 K.

- Between 10 and 20 metric tons of core and structural materials relocated into the space between the reactor vessel bottom head and the Flow Distributor.

- Most fission products were retained in the core. Most of the fission products that escaped from the core were retained in the reactor coolant system water or in the reactor building basement water and concrete.[3]

Significant consequences resulting from these findings include: (a) increased technical interest in the TMI-2 accident because it represents a full-scale severe-core-damage (SCD) event, (b) a reconsideration of the plans and equipment for defueling the TMI-2 reactor, and (c) an expansion in the TMI-2 accident examination plan to determine the consequences of high-temperature interactions between core components and to determine the amount of release from the fuel of the lower volatility fission products.

The CCTV examinations are part of the Reactor Vessel Internals Documentation portion of Ref. 1. This part of the SA&E Plan also included ultrasonic scanner surveys[a] for precise topographical mapping of the various regions that may be encountered during the exploration of the core and subcore regions. The SA&E Plan requirements and/or objectives for the CCTV and ultrasonic scanner examinations are as follows:

> "Continued use of these <u>in situ</u>, nonintrusive data-recording techniques at well-planned intervals during the defueling program will provide data from which: (a) core debris volume measurements can be inferred, (b) visual indications of the extent of liquefaction and core material relocation to the lower plenum can be obtained, (c) confirmation of the degree of damage to peripheral core support structures, including the reactor vessel, and (d) decisionmaking for further incore sampling plans and bulk defueling can be carried out."

1.2 TMI-2 Core History

The history intervals of interest for the TMI-2 core horseshoe ring characterization are: (a) the core loading and operation before the accident, (b) the accident sequence that damaged the core components and created the cavity in the upper core region, and (c) the post-accident reactor vessel internals disassembly activities that have caused further relocation and separation of core components. Appendix B is a summary of the TMI core history that highlights; (a) the core geometry and materials from which the horseshoe ring evolved, and (b) the events that may have affected the horseshoe ring composition and geometry.

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a. Additional ultrasonic scanner surveys are no longer included in the SA&E plan.

2. EXAMINATION METHODS

The location, dimensions, and surface appearance characteristics of the horseshoe ring were derived from video survey recordings and mechanical probing measurements. A specific program plan to determine the horseshoe ring characteristics was not developed.

2.1 Video Surveys

The examination method was to obtain a tape recording of the signal from the GPUN video camera surveys at TMI-2 and generate still-image photographs at INEL from the tape recordings using a special electronic image enhancement and production system.

2.2 TMI-2 CCTV System

The CCTV system used by GPUN at TMI-2 to examine the reactor vessel internals consisted of the following:

- An underwater video camera,
- A camera manipulator system to provide camera support and articulation,
- A 6-MHz bandwidth AMPEX VPR-80 video recorder, Synair video distribution system, and Quantex video quantitizer,
- The TMI-2 defueling platform for support and azimuthal positioning of the camera manipulator system.

Camera positioning is estimated from commentary on the tape recordings and the occasional sighting of known landmarks inside the reactor vessel. The azimuthal position of the images is probably accurate within 20° when landmarks are not nearby.

2.3 Mechanical Probing

Mechanical probings were conducted by GPUN in March,[4] July,[5] November,[6] and December 1986,[7] and February 1987[7] in the vicinity of the horseshoe ring to determine the height of the core debris. The March, December, and February probings included a tool with a 20-lb slide-hammer. The July and November probings were made with the core bore drill string.

The usual procedure with the slide-hammer tool was to record the elevation of the tool lower extremity at the following events:

- When the tool first touched the debris,
- When the tool settled under its full weight,
- When maximum penetration was obtained by the operator pushing downward and twisting the tool, and
- When maximum penetration was obtained by the operator pounding downward with the slide hammer.

The March 1986 mechanical probing was conducted with high water turbidity which probably accounts for some of the inconsistencies in data from the outermost (56-inch radius) locations. The inconsistencies include indications of the presence of standing fuel assemblies at known vacant locations.

3. EXAMINATION RESULTS

3.1 Video Surveys

The video survey information is presented in the form of eight plates of still-image photographs (see Appendix A). The video surveys were made in June, October, and December 1986 by GPUN to support defueling.

The June survey was conducted to determine the conditions at the planned core bore drill sites. Water turbidity was high and, for most of the tape recordings, image quality was too poor for still-image production.

The October survey was conducted to determine the conditions of the core cavity floor and sides before conducting the overlapping hole drilling into the region of fused-together core material. Water turbidity was improved from the June conditions.

The December survey was conducted to determine the conditions of the core cavity floor and sides after completion of the overlapping hole drilling. Water turbidity was improved still further.

Both the October and December surveys were incomplete due to the presence of fuel rods in the core cavity which prevented video camera access to the west wall.

The eight plates of still-image photographs reveal the following:

1. In June, a horseshoe-shaped ring of fused-together core material was observed. It projected inwards from standing rod bundles from 120° to 50° azimuth as shown in Fig. 2. The average inward projection of the ring is estimated to be 49 inches from the core centerline. In several locations, the visible bottom edge of the ring receded, creating a cave-like geometry (see Plates A-2, A-4, A-5, and A-7).

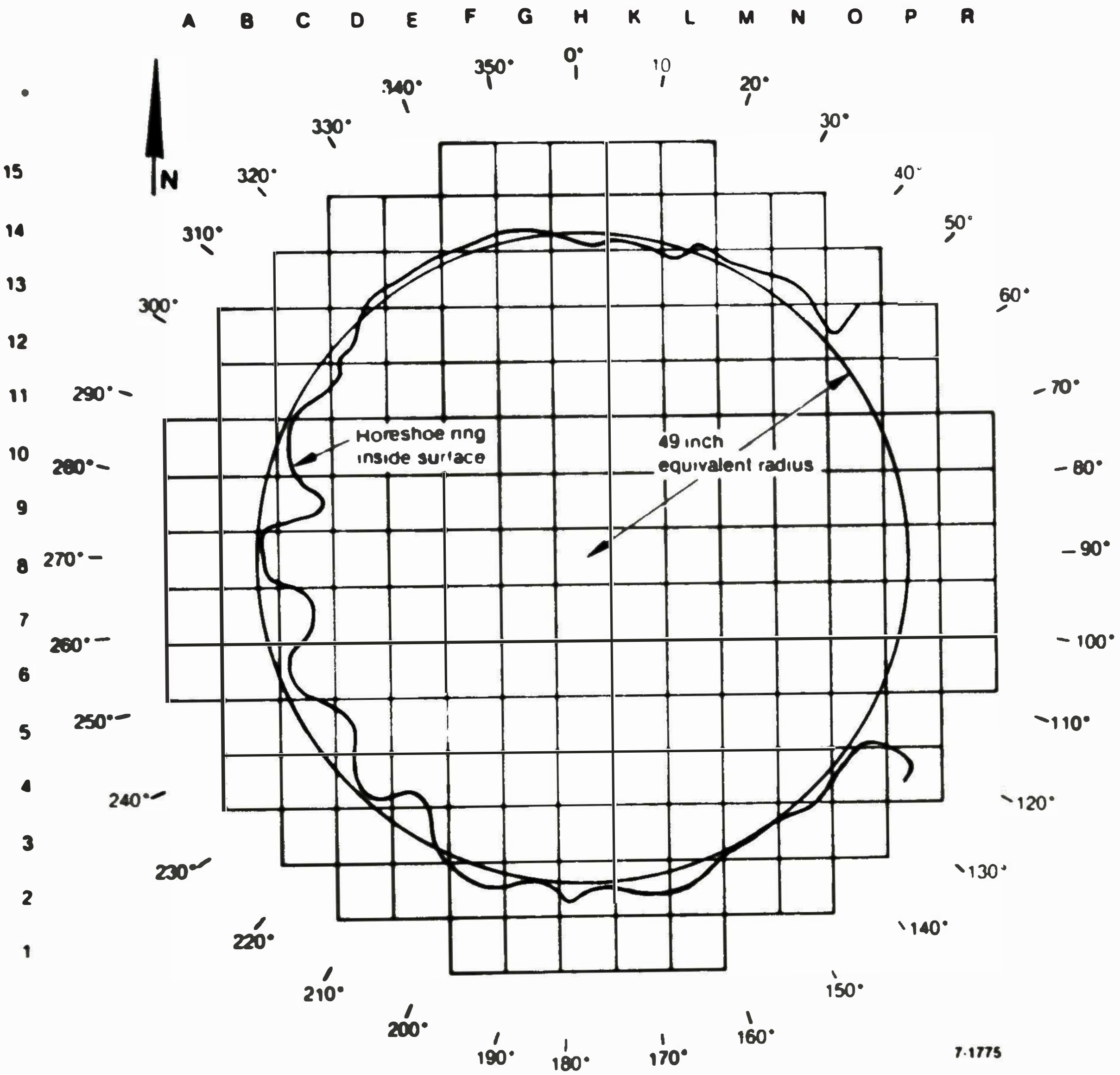

Figure 2. Estimated radial configuration of horseshoe-shaped ring of agglomerate core material.

2. The top surface of the ring consisted of clusters of decomposed (fossilized appearance) rod bundle remnants projecting upwards from the fused-together core materials (see Plates A-1, A-2, A-3, A-6a, A-6b and A-7).

3. The inside wall of the ring appeared to have an uneven, cobblestone-like surface (see Plates A-1, A-2, A-3, A-4, A-5, A-6a and A-7). After core boring and overlapping hole drilling operations, the inside wall had a "fossilized" rod bundle appearance (see Plates 6a and 6b) where spalling or drilling tool abrasion may have occurred.

4. In December, ring discontinuities had developed between 10° and 50° azimuth, and in the northwest, southwest, and south regions.

3.2 Mechanical Probing Results

A summary of mechanical probing data is shown in Fig. 3. Figure 3 also shows locations of core bore and overlapping hole drilling which may have affected the elevation of the hard stop. There are many cases of data inconsistencies such as:

1. Indications in March 1986 that (a) a fuel assembly was located at known vacant core positions F15, H1, and P11, and (b) no fuel assembly was located at known occupied core positions, L1 and O3.

2. Indications in February 1987 that the hard crust level has risen from 9 to 23 inches at core positions C11, H2, H14, L14, N12, N4, P10, and P6.

There are specific pieces of data from the probing that are consistent with the video survey data and are believed to provide reasonable approximations of the location and size of the horseshoe ring:

1. The July core boring at core position D4 where the hard-crust was first contacted near 84 inches above the fuel rod bottoms.

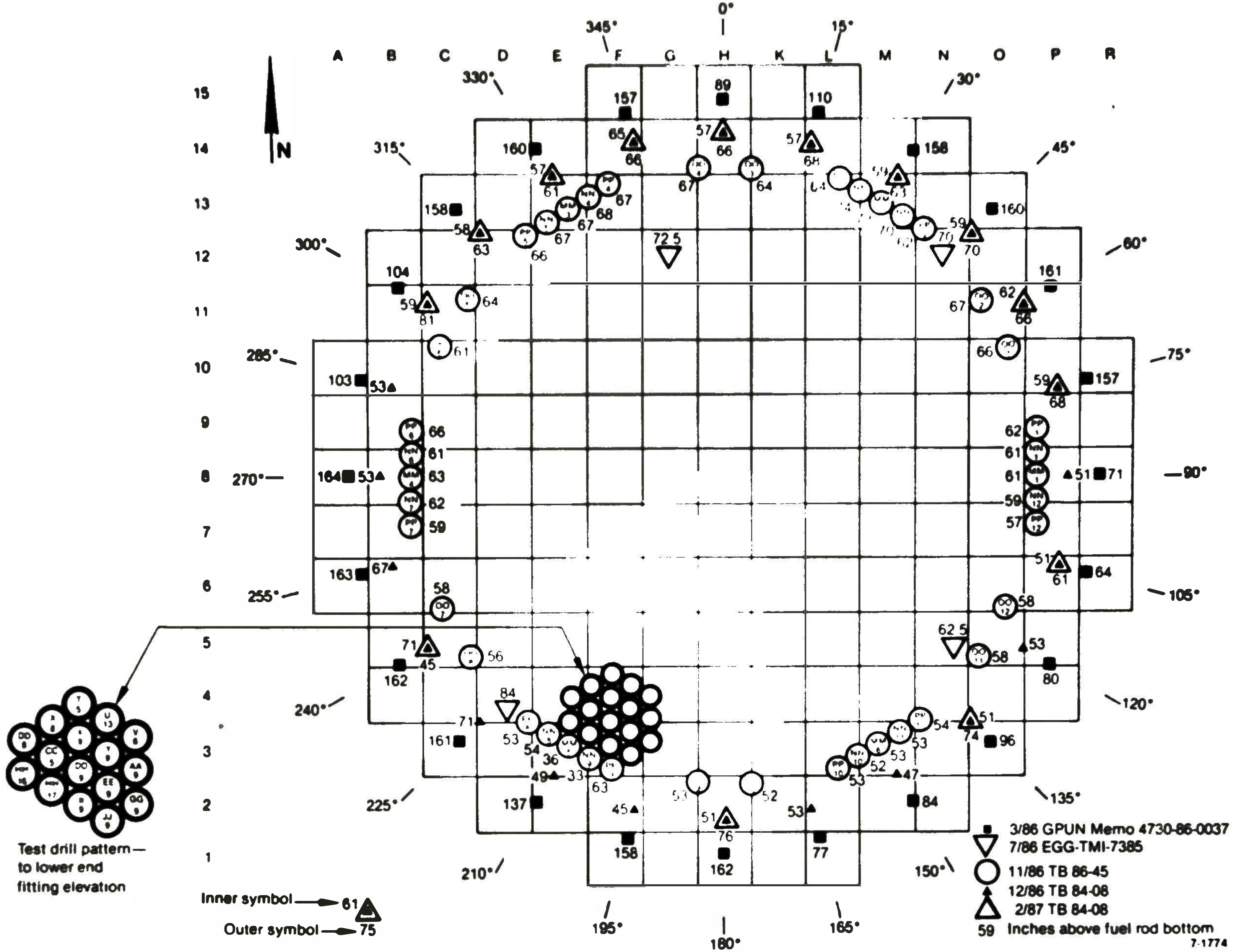

Figure 3. Hard-stop locations from mechanical probing measurements.

2. The March 1986 probing data at core positions B10, B11, H15, L1, M2, O3, and P5 that indicate a hard stop at 110 to 77 inches above the fuel rod bottom, which is consistent with some of the video survey data both in elevations and irregularity of the ring upper surface contour.

The February 1987 probing data at core positions C11, H2, N12, and N4 indicated a hard stop at 70 to 82 inches above the fuel rod bottom (compared to the December 1986 probing indications that the hard stop was at 50 to 59 inches above the fuel rod bottom). This data inconsistency may indicate the horseshoe ring inside wall location at those core positions.

4. DISCUSSION

The location and apparent composition of the horseshoe ring, in combination with the observed existence of core material outside the core boundaries, has caused some speculation that (a) the horseshoe ring upper surface represents the upper surface level of the fused-together core material at some time before the escape of molten core material from the core boundaries, and (b) the now-empty region inside the ring and the ring discontinuity on the east side (between 50 and 120° azimuth) may be equivalent to the mass of molten core material that relocated downward in the core region or escaped from the core boundaries.

The average height of the horseshoe ring is estimated to be 24 to 30 inches from the following observations and/or measurements:

- The mechanical probing data which indicate (a) the upper surface of the fused-together core material in the central 96 inches of the core was 50 to 70 inches above the fuel rod bottoms and the upper surface of the horseshoe ring was 70 to 110 inches above the fuel rod bottoms.

- Estimated[8] sizes of three large rocks, believed to be pieces of the horseshoe ring because of their size and surface appearance (fossilized rod bundle). The rock sizes were

	Dimensions (inches)		
Rock Number	Length	Width	Height
A	30	12	7
B	24	8	5
C	24	7	5

  The width and height dimensions (5 to 12 inches) are consistent with the estimated width of the horseshoe ring at 250 to 260° azimuthal where the peripheral (core positions A6 and A7) rod bundles were intact (8.5 inches wide) (see Fig. 2).

The mass of molten core material which would have been located in the empty region between the horseshoe ring upper and lower surface, including the 70° horseshoe opening, is calculated to be approximately 65,000 lb using the following dimensions:

- The horseshoe ring dimensions are roughly 98 inches inside diameter, 115 inches outside diameter, and 27 inches high.

- The fused-together core material density is 8.25 gm/cm^3.

5. CONCLUSIONS

Estimated location, size, and surface appearance of the horseshoe-shaped ring are based on imprecise and incomplete information. The information used was obtained between March and November, 1986; before March the ring was at least partially covered with loose debris, and after November large pieces of the ring may have been dislodged by defueling activities. From this limited information, the horseshoe ring location, dimensions, and surface appearance at accident termination are estimated to be:

Location:	Extended from 50 to 110 inches above the fuel rod bottoms, and from 120° to 70° azimuthal.
Dimensions (average):	98 inches inside diameter x 27 inches high x 8.5 inches thick (radially)
Surface Appearance:	The upper surface contour was irregular and consisted of decomposed (fossilized-appearing) rod bundle remnants. The lower inside surface resembled cobblestone, and receded, cave-like, at the interface with the upper crust of the fused-together core region.

6. REFERENCES

1. M. L. Russell et al., TMI-2 Accident Evaluation Program Sample Acquisition and Examination Plan for FY-1987 and Beyond, EG&G Idaho Inc., EGG-TMI-7521, February 1986.

2. E. L. Tolman et al., TMI-2 Accident Evaluation Program, EG&G Idaho Inc., EGG-TMI-7048, February 1986.

3. S. Langer et al., TMI-2 Fission Product Inventory Program FY-85 Status Report, EG&G Idaho Inc., GEND-057, November 1986.

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5. E. L. Tolman et al., TMI-2 Core Bore Acquisition Summary Report, EG&G Idaho Inc., EGG-TMI-7385, Rev. 1, February 1987.

6. S. Bokharee, Crust Breaking via Core Drilling, GPU Nuclear Corp., TB-86-45, Rev. 0, December 1986.

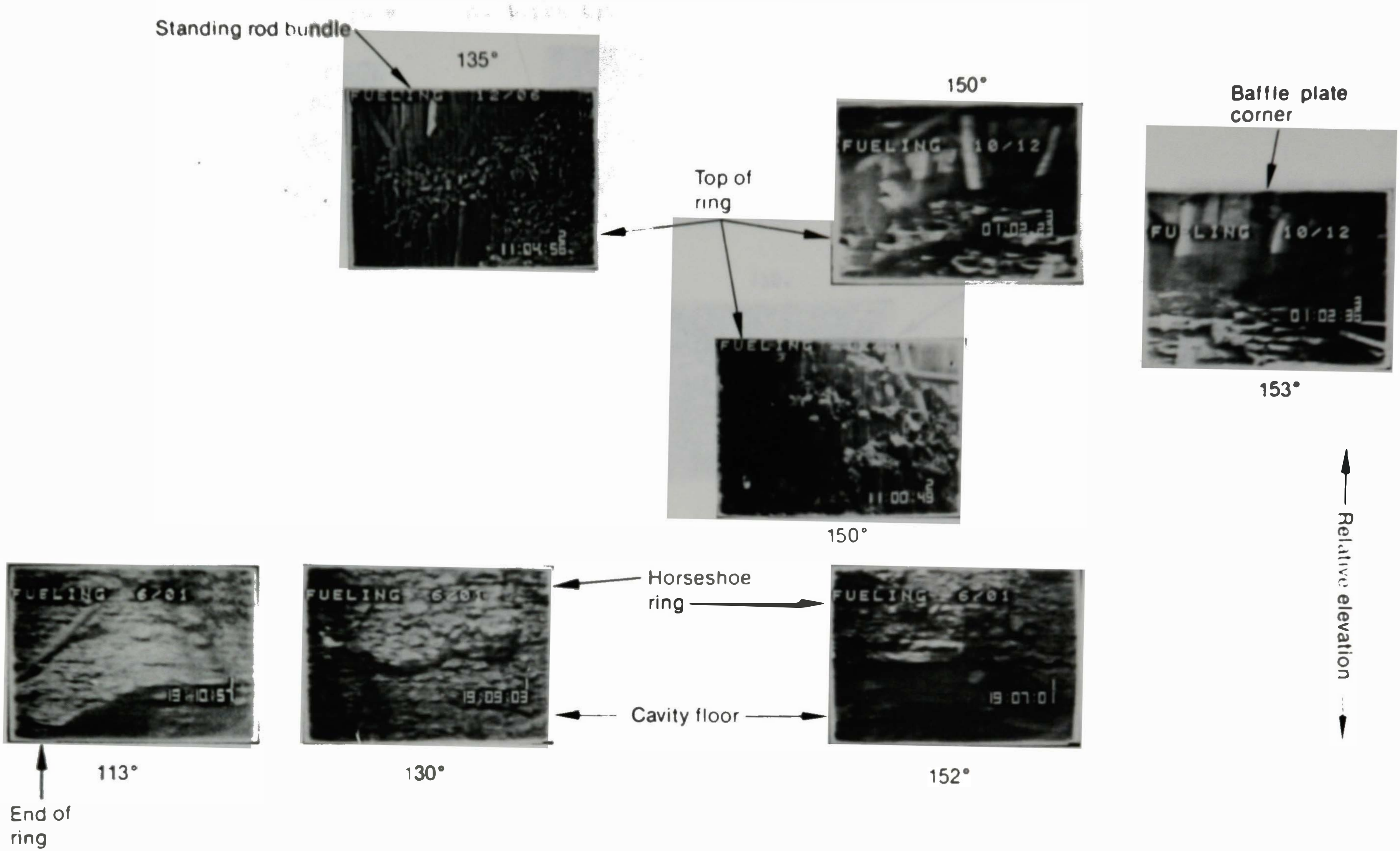
7. V. R. Fricke, Contour Map of Debris Bed as of February 8, 1987, GPU Nuclear Corp., TB-84-08 Rev. 3, February 1987.

8. M. Tanaka, Surface Condition of Debris Bed, February 8, 1987, GPU Nuclear Corp., TB-87-3, Rev. 0, March 1987.

APPENDIX A

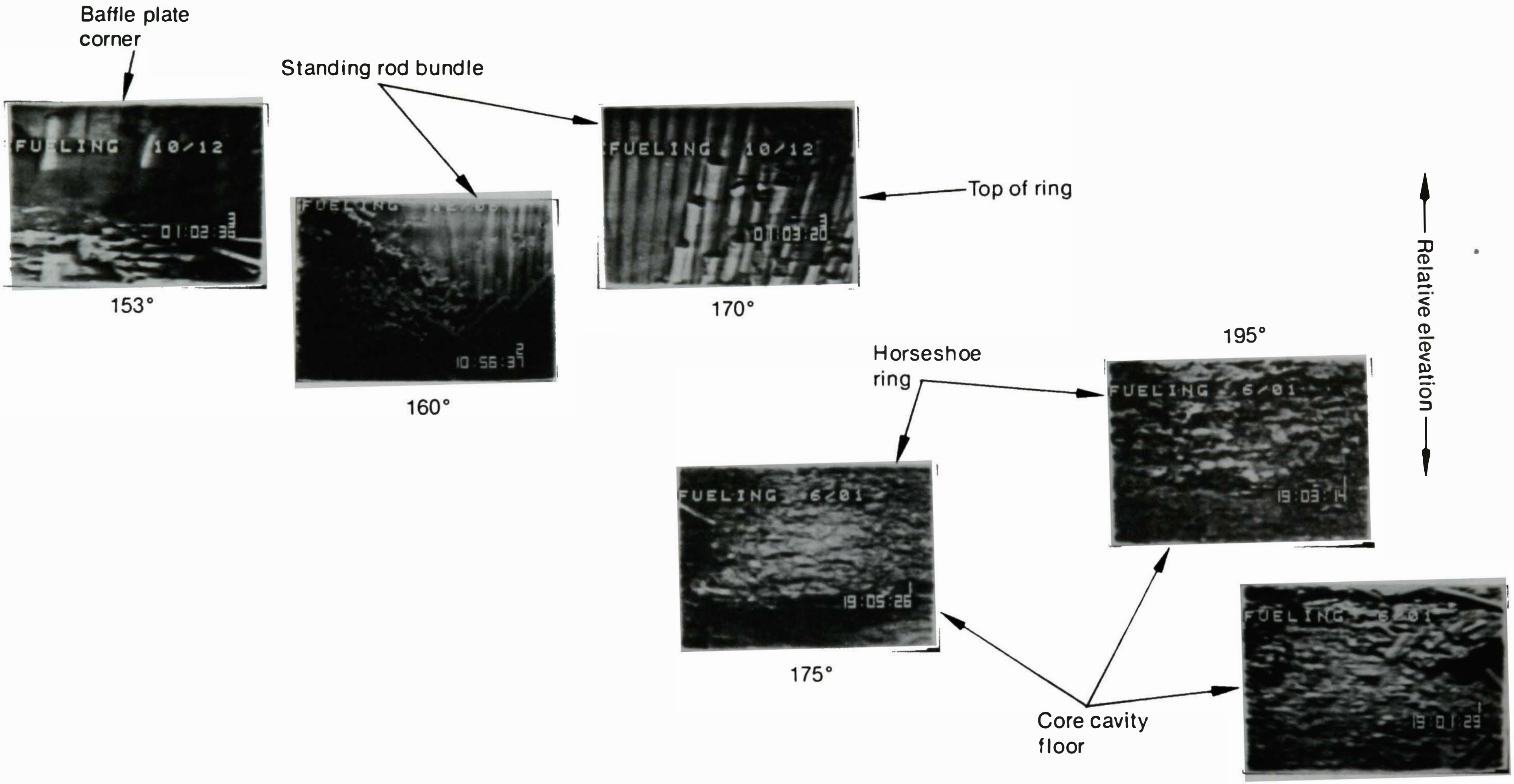
STILL-IMAGE PHOTOGRAPHS FROM VIDEO SURVEYS

PLATES



7-1767

Plate A-1. Horseshoe ring between 110° and 155° azimuth (Southeast).



7-1766

Plate A-2. Horseshoe ring between 153° and 200° azimuth (South).

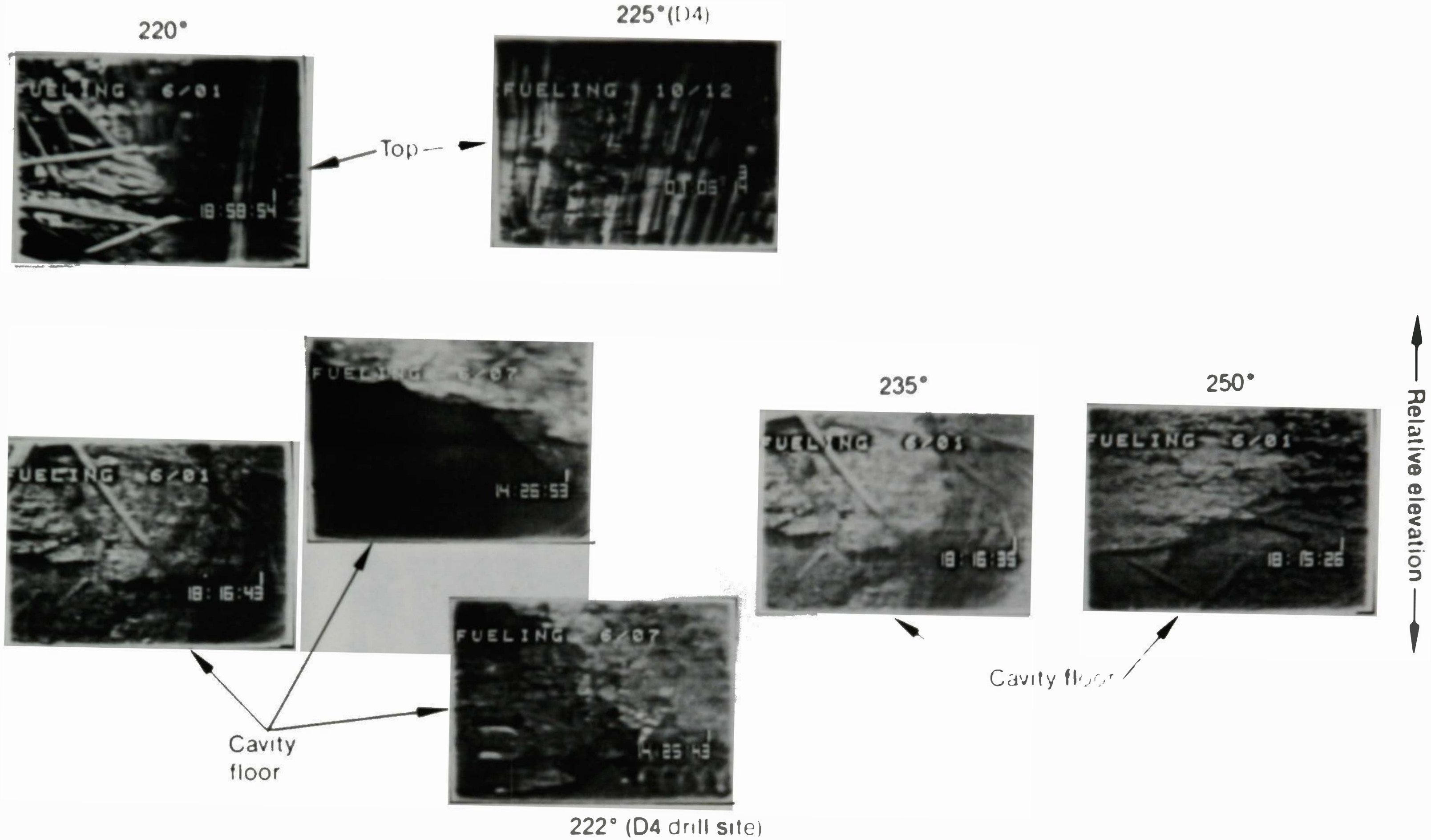
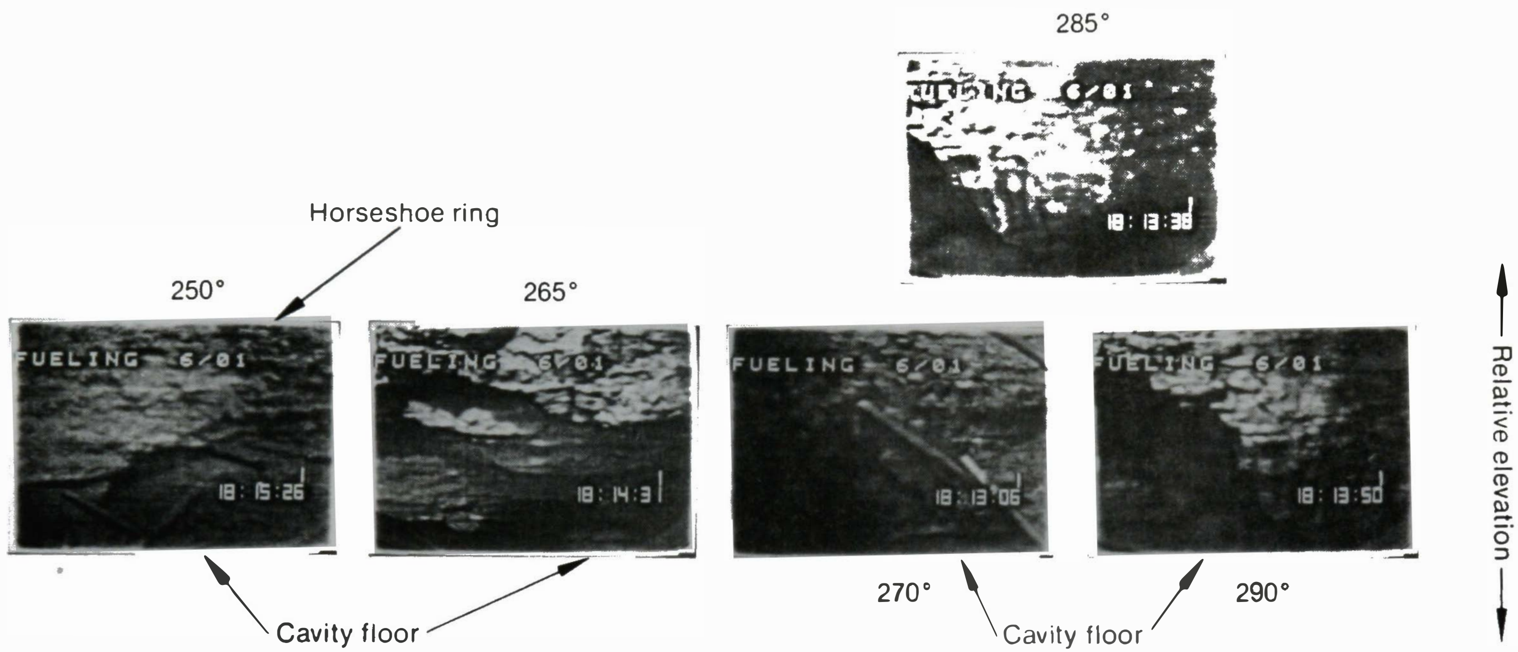


Plate A-3. Horseshoe ring between 200° and 250° azimuth (Southwest).



7-1768

Plate A-4. Horseshoe ring between 250° and 290° azimuth (West).

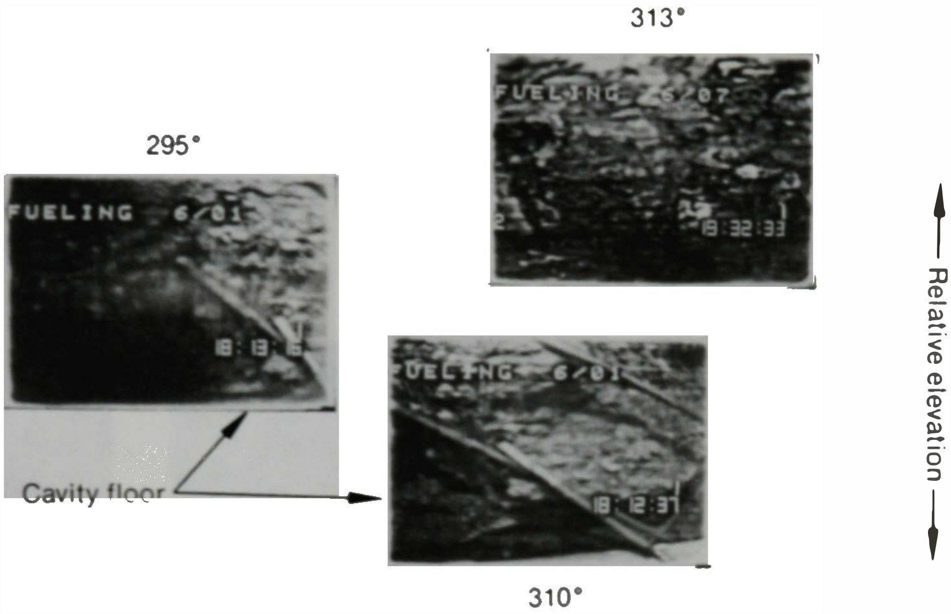


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Plate A-5. Horseshoe ring between 290° and 335° azimuth (Northwest).

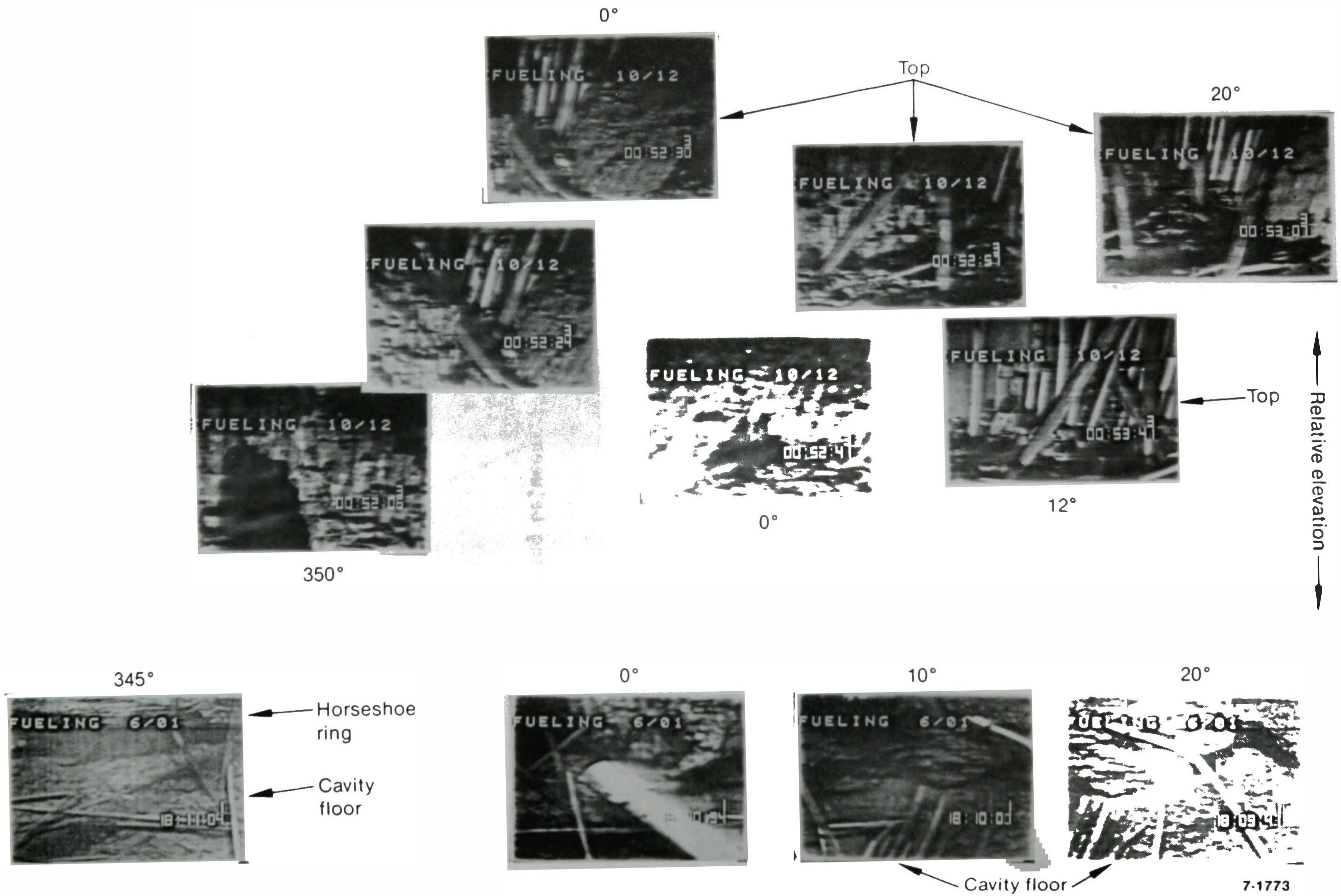


Plate A-6A. Horseshoe ring between 335° and 25° azimuth (North) before (06/01) and after (10/12) core boring.

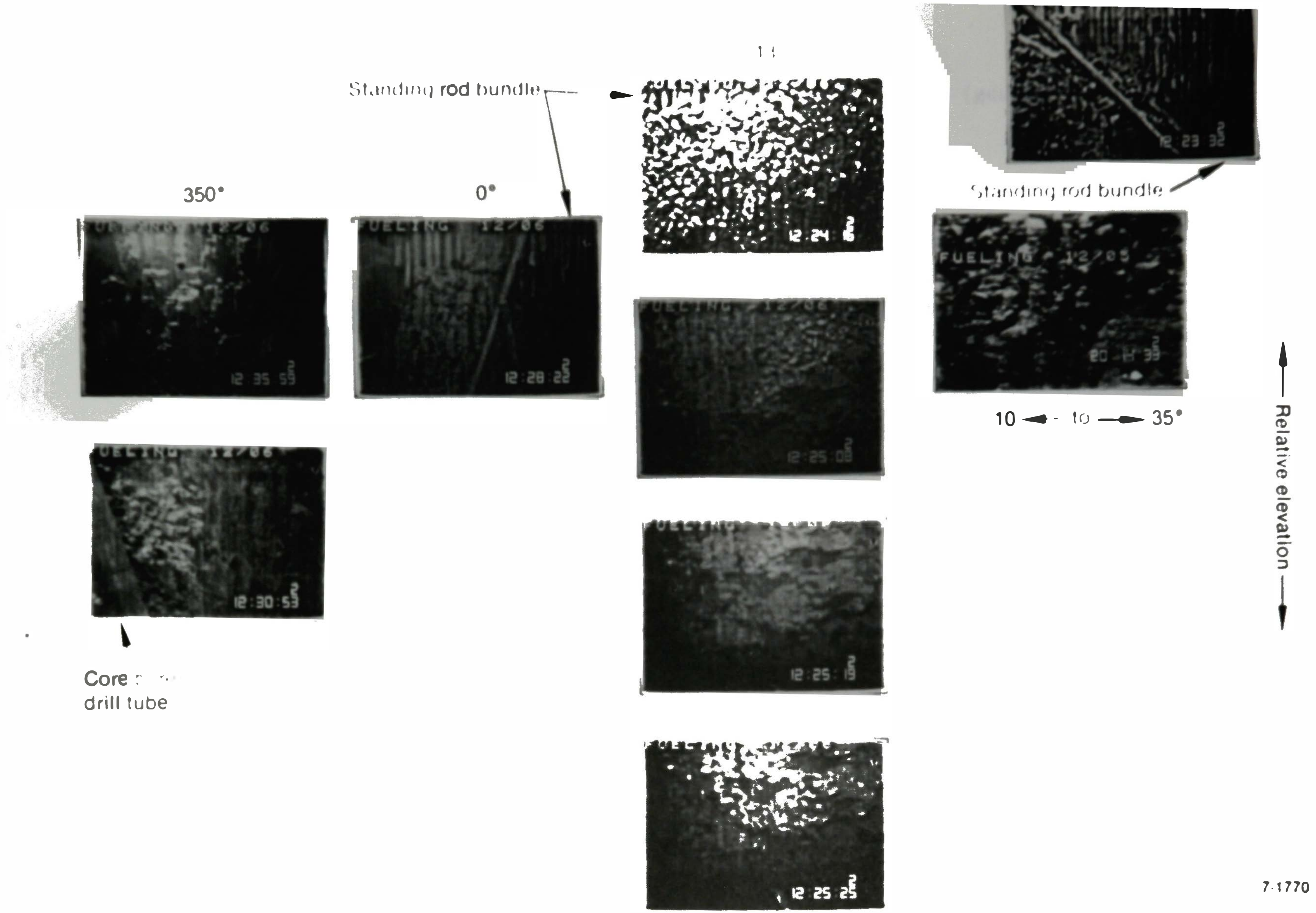
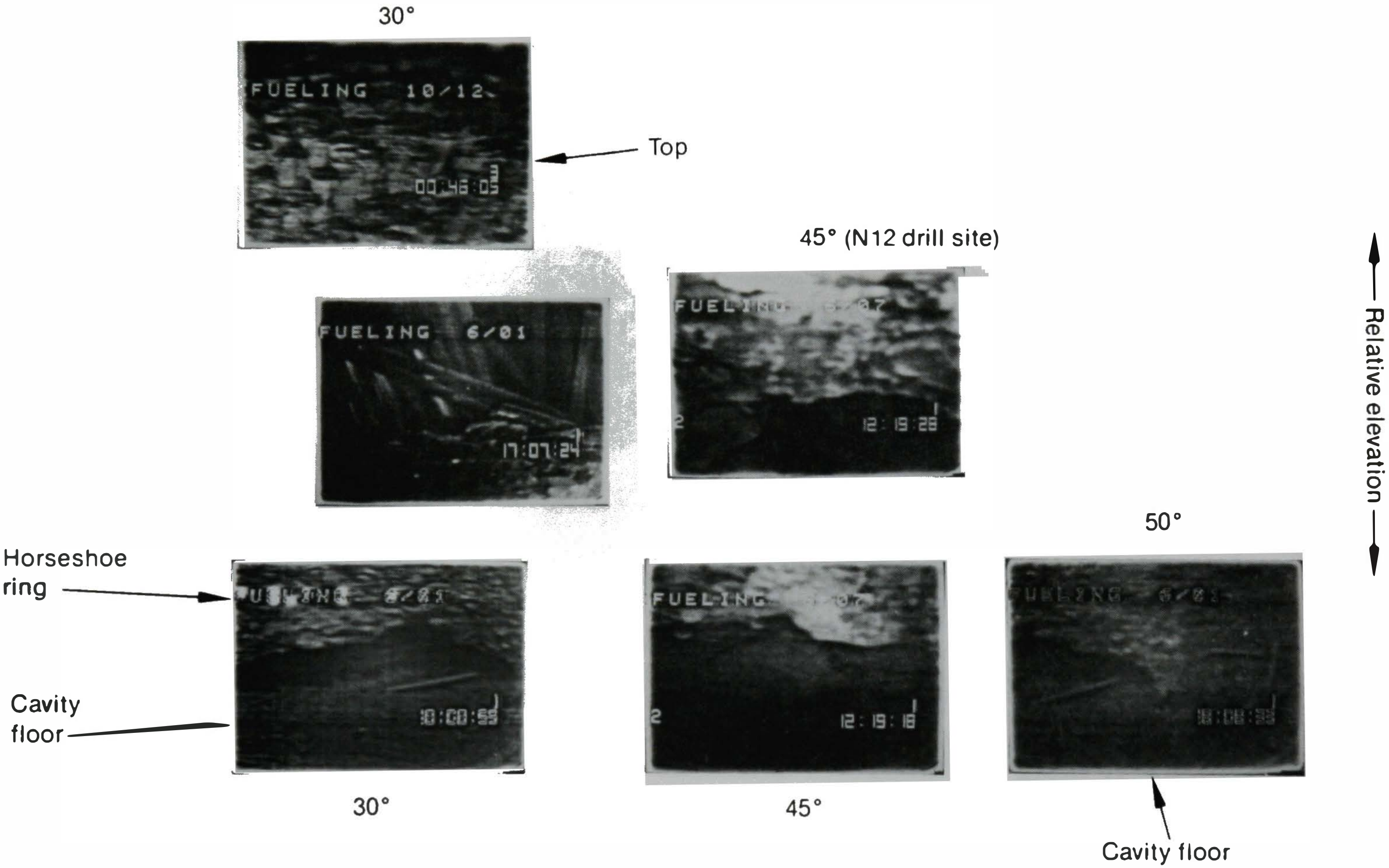


Plate A-6B. Horseshoe ring between 335° and 25° azimuth (North) after overlapping hole drilling.



7-1772

Plate A-7. Horseshoe ring between 25° and 70° azimuth (Northeast).

APPENDIX B

TMI-2 CORE HISTORY

FIGURES

APPENDIX B

TMI-2 CORE HISTORY

INTRODUCTION

This appendix provides a summary of the TMI-2 core history that is of interest in the evolution of the horseshoe ring. The summary is divided into three parts: (a) the core loading and operation before the accident, (b) the accident sequence that damaged the core components and created the cavity in the upper core region, and (c) the post-accident reactor vessel internals disassembly activities that caused further relocation and separation of core components.

PREACCIDENT OPERATIONS

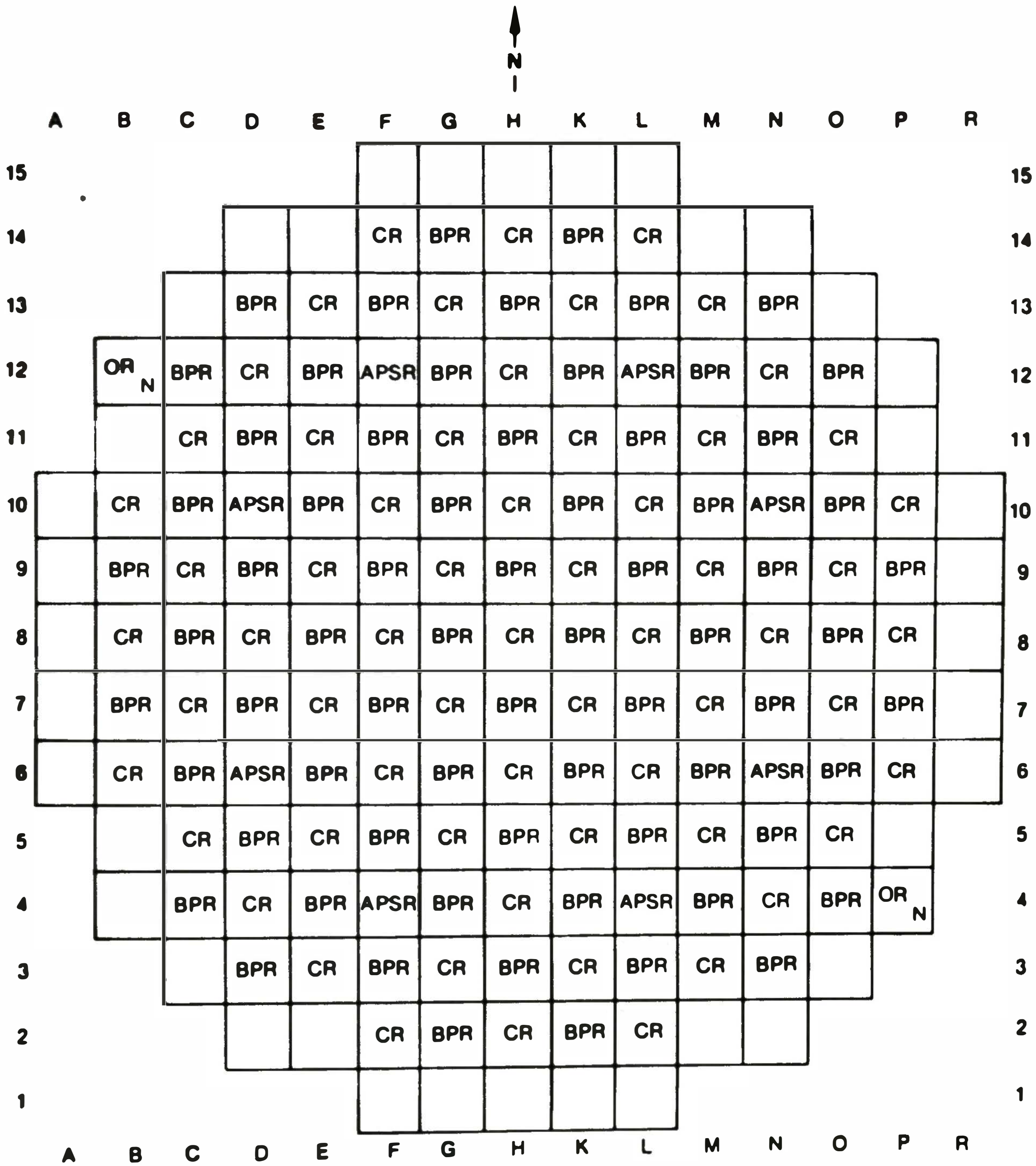
At accident initiation, the TMI-2 core was in the initial fuel cycle at 95% of full power with 3175 MWD/MTU average core burnup. The core loading consisted of 177 fuel assemblies and 139 rod assemblies arranged in the core positions as shown in Fig. B-1.

Each of the fuel assemblies (see Fig. B-2) was a 15 x 15 array of 208 fuel rods, 16 zircaloy guide tubes, and 1 center-position zircaloy instrument tube. The entire array was connected to and supported by eight Inconel spacer grids and 304L stainless steel upper and lower end fittings. An Inconel, coil-type holddown spring was located in the upper end fitting.

All interior and two of the 40 peripheral core positions also had rod assemblies consisting of 16 rods connected together at the top by arms extending from a central hub. The rods fit into the fuel assembly guide tubes. The two peripheral fuel assemblies (core position B12 and P4, next to the core former wall) contained a stationary orifice rod assembly with 12-in.-long stainless steel rods extending into the guide tubes to restrict coolant flow, of which one in each assembly is assumed to be modified to include a neutron source rod. Interior fuel assemblies contained one of three types of rod assemblies as follows:

- Burnable Poison Rod (BPR) Assembly (see Fig. B-3)--The stationary burnable poison rod assemblies were located in 72 core positions as show in Fig. B-1. Each BPR rod contained a 126-in.-long stack of Al_2O_2 (0.95)-B_4C (0.01)-impurities (0.04) ceramic pellets clad in zircaloy, except for core position N13, which is assumed to have contained 8 rods with boronated graphite instead of Al_2O_3-B_4C.

- Control Rod (CR) Assembly (Fig. B-4)--The CR assemblies were located in the 61 core positions shown in Fig. B-1. The rods



OR Orifice Rod Assembly

CR Control Rod Assembly

BPR Burnable Poison Rod Assembly

APSR Axial-Power-Shaping Rod Assembly

N Primary Neutron Source

6 4690

Figure 8-1. TMI-2 core loading diagram.

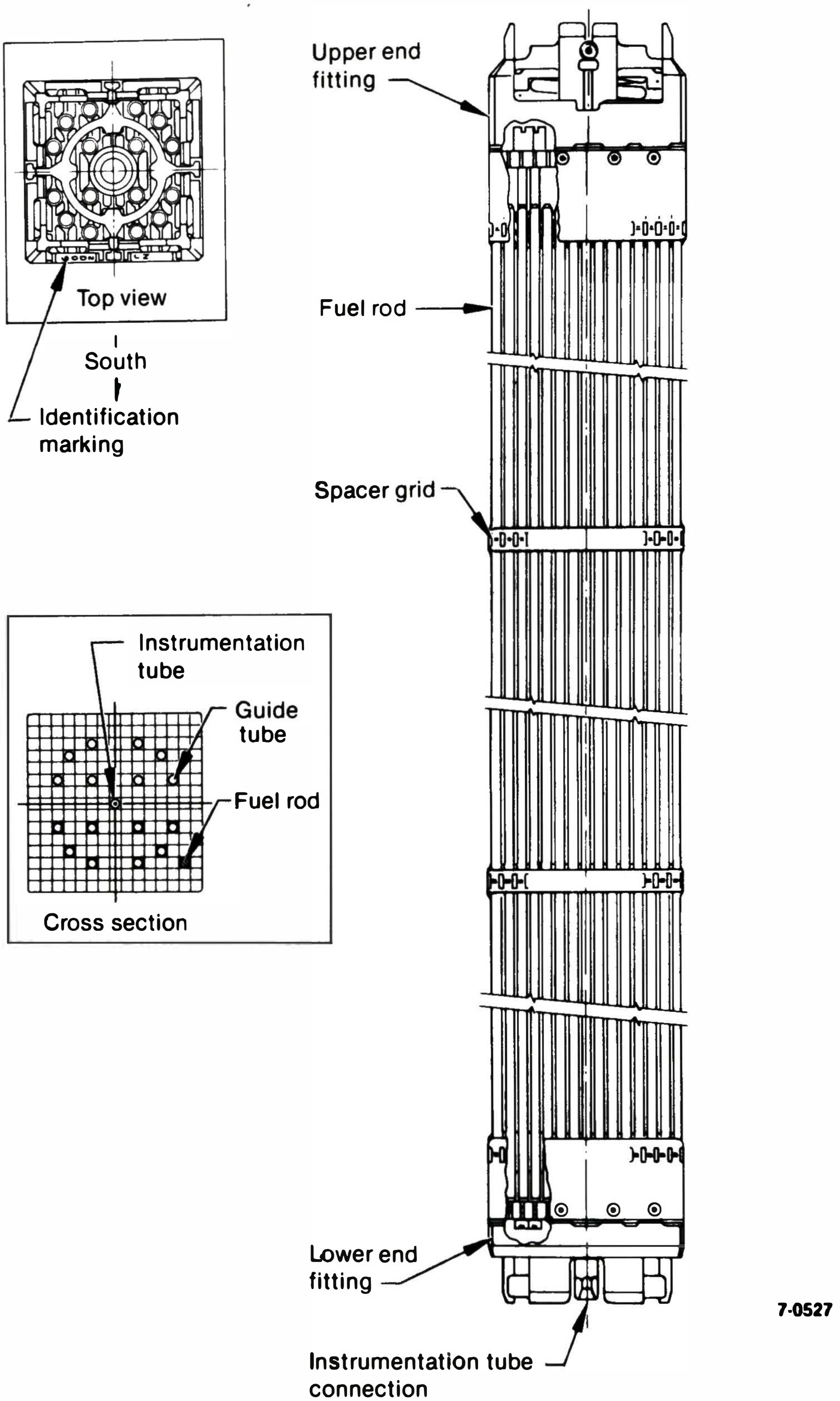


Figure B-2. Side, top, and cross-sectional views of TMI-2 fuel assembly (from Ref. B-1).

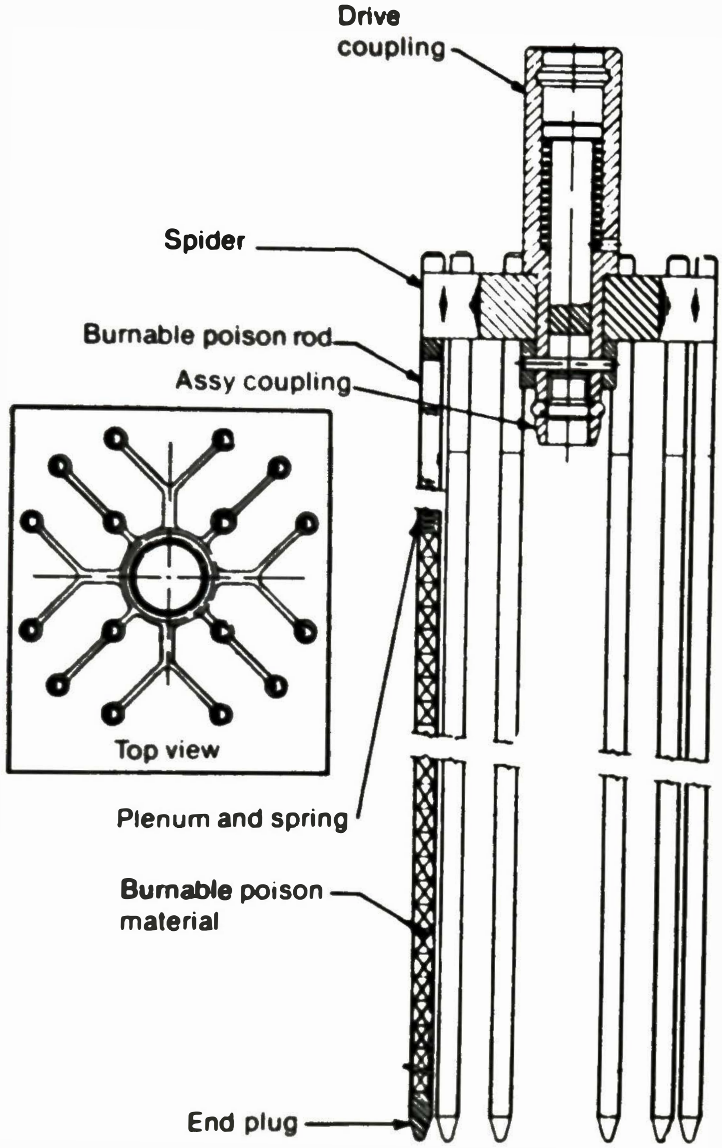


Figure B-3. Burnable poison rod assembly (from Ref. B-1).

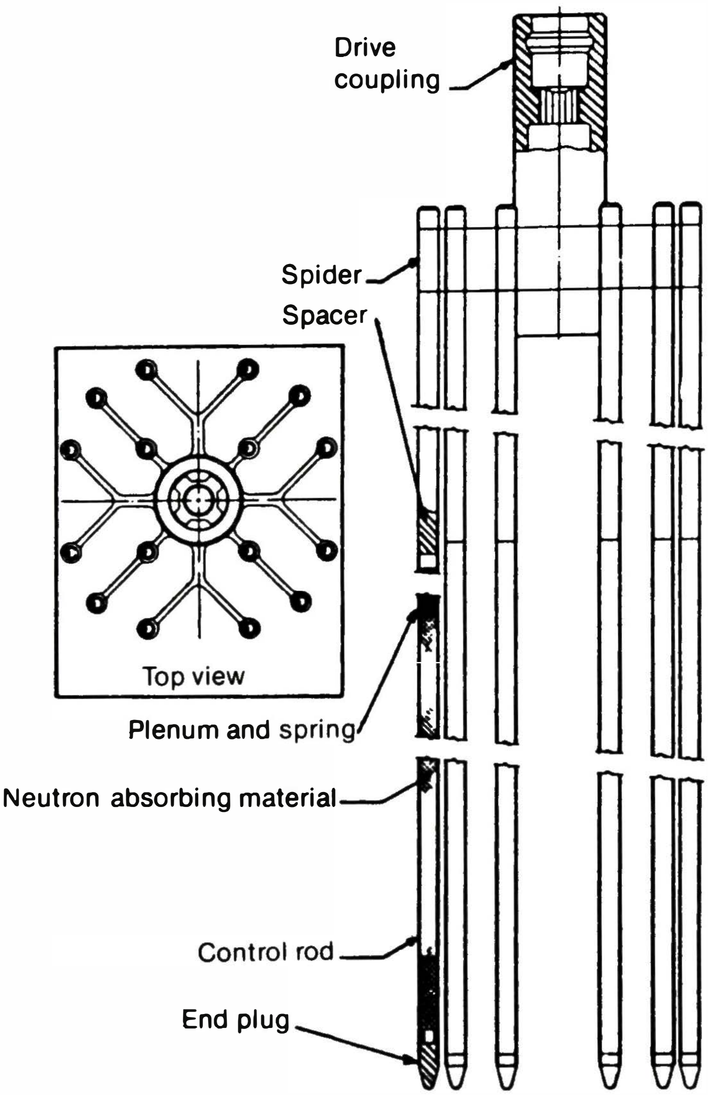


Figure B-4. Control rod assembly (from Ref. 8-1).

contained 134-in. lengths of Ag-In-Cd clad in Type 304L stainless steel. The CR assemblies were fully inserted during the accident sequence.

- Axial Power Shaping Rod (APSR) Assembly (Fig. B-5)--The APSR assemblies were located in the eight symmetrical core positions shown on Fig. B-1. Each rod contained a 36-in. length of Ag-In-Cd material clad in stainless steel. The APSR assemblies remained withdrawn at 37 in. during the accident sequence.

TMI-2 ACCIDENT SEQUENCE

Reference B-2 includes the current theory of the TMI-2 core damage progression. A summary of this theory is as follows:

"The accident was initiated by cessation of secondary feedwater flow. The steam generator boiled dry, and the resultant reduction of primary-to-secondary heat exchange caused the primary coolant to heat up, surge into the pressurizer, and increase the primary system pressure. The pilot-operated relief valve (PORV) opened to relieve pressure but failed to close when the pressure decreased. The first 100 min of the accident can be characterized as a small break loss-of-coolant accident (LOCA) with resultant loss of primary coolant and decreasing pressure. It differed from the scenario expected during such a LOCA in that the pressurizer liquid level remained high. This was interpreted by the reactor operator as indicating that the reactor coolant system (RCS) was full of water when in fact, the RCS was continually voiding. Up to 100 min, the core was covered with sufficient water to be cooled.

The reactor coolant pumps were turned off at 100 min, and core heatup was initiated as the water level stratified and decreased below the core top. By 150 min, a zircaloy-steam exothermic reaction was initiated, dramatically increasing the core heatup rate. As a result, zircaloy melting temperatures were exceeded, resulting in relocation of the molten zircaloy and some liquefied fuel to the lower core regions, solidifying near the coolant interface. This continued until 174 min, when a large region of consolidated, degraded core material existed in the lower, central regions of the core. Coolant flow through this consolidated core region indicate that the lower 0.5 m of the core remained cool.

A reactor coolant pump was turned on briefly at 174 min, and coolant was pumped into the reactor vessel. The resultant thermal-mechanical forces generated from the rapid steam

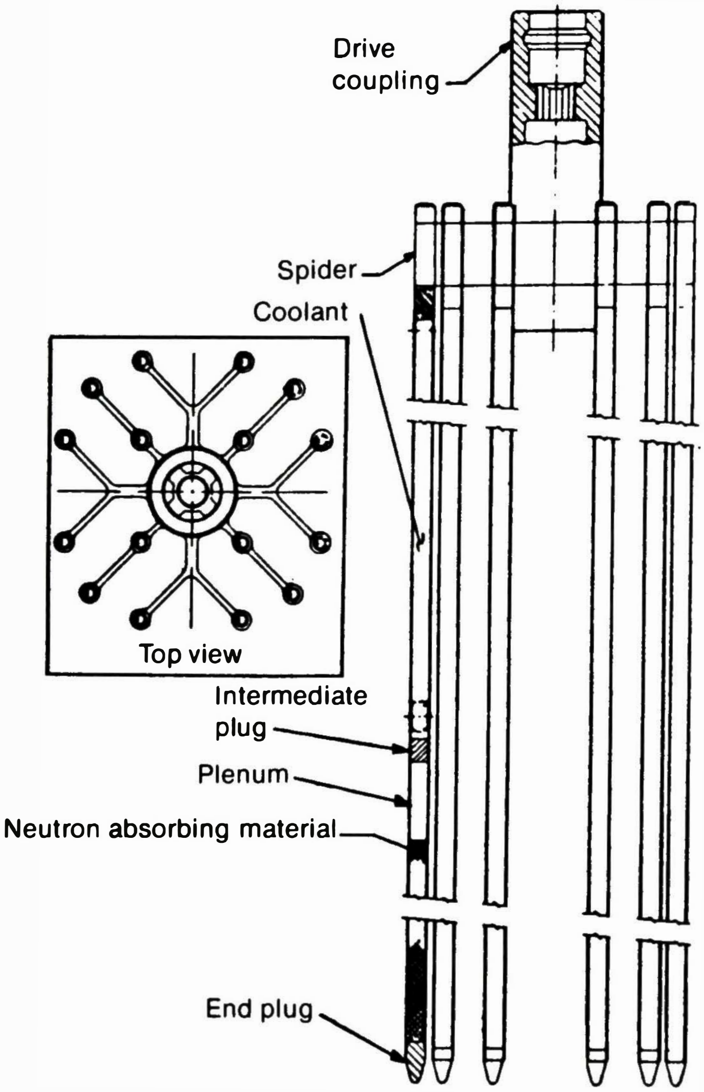


Figure B-5. Axial-power-shaping-rod (APSR) assembly (from Ref. B-1).

formation are believed to have shattered the oxidized fuel rod remnants in the upper regions of the core, forming a rubble bed on top of the consolidated core materials. The consolidated core materials continued to heatup during the next 50 min (174 to 224 min), even though coolant delivery to the reactor vessel from the pump transient and emergency core cooling injection is estimated to have covered the core by approximately 210 min. By 224 min, much of the consolidated region had reached temperatures sufficient to melt the U-Zr-O ternary mixture.

On-line TMI-2 data recorded during the accident indicate that the crust surrounding the consolidated core failed and some of the molten core material relocated to the lower plenum between 224 and 226 min. Based on the end-state core and core support assembly (CSA) configuration and supporting analysis of the degraded core heatup, it is believed that the crust failure occurred near the top of the molten core region in the southeast quadrant of the reactor vessel. Limited damage to the CSA occurred as the core material flowed to the lower plenum. Estimates of the maximum pressure vessel wall temperatures indicate that the melting point of stainless steel was not exceeded, even at the inside surface of the pressure vessel liner. The instrument assemblies, however, may have melted in the lower plenum above the vessel penetration weld. If this occurred, freezing of the molten material is predicted to have plugged any holes in the instrument assembly tubes."

Since the accident, the core components have remained at ambient temperature and pressure and are submerged in treated water with the following target specifications:

- pH: 7.5 to 7.7
- boron: >4350 ppm
- buffer: NaOH.

POSTACCIDENT REACTOR VESSEL INTERNALS DISASSEMBLY ACTIVITIES

A series of disassembly activities (including precursor examinations) have been accomplished since the accident-sequence termination. No activities or examinations were attempted until personnel access inside the reactor building was reestablished in 1981. A summary of significant examination and disassembly events that have occurred is as follows:

Quick-Look Video Surveys

In 1982, control rod leadscrews from core positions H8, E9, and B8 were removed for possible CCTV access to the core area. The CR spider was still in place at B8, but was missing at core positions H8 and E9. The CCTV survey discovered a large, empty region (core cavity) in the upper core region.

APSR Assembly Insertion[B-3]

In the first quarter of CY 1983, an attempt was made to insert all eight APSR Assemblies which, if successful, would relocate the APSRs 34 in. downward into the core cavity (see Fig. B-1 for APSR core positions). Insertion depths achieved were as follows:

Core Position	Insertion Depth (in.)
D6	0
D10	4
F4	30
F12	35
L4	8
L12	31
N6	0
N10	37

Ultrasonic Scanner Survey[B-4]

On August 31, 1983, an ultrasonic scanner survey was made to determine the shape and dimensions of the core cavity. Figures B-6 through B-9 are the resulting topographical maps of the core cavity. The core topographical features included the following:

- The cavity extended from the bottom of the upper grid-plate downward to approximately 7.5 ft above the core bottom and radially to the core baffle plates in some places

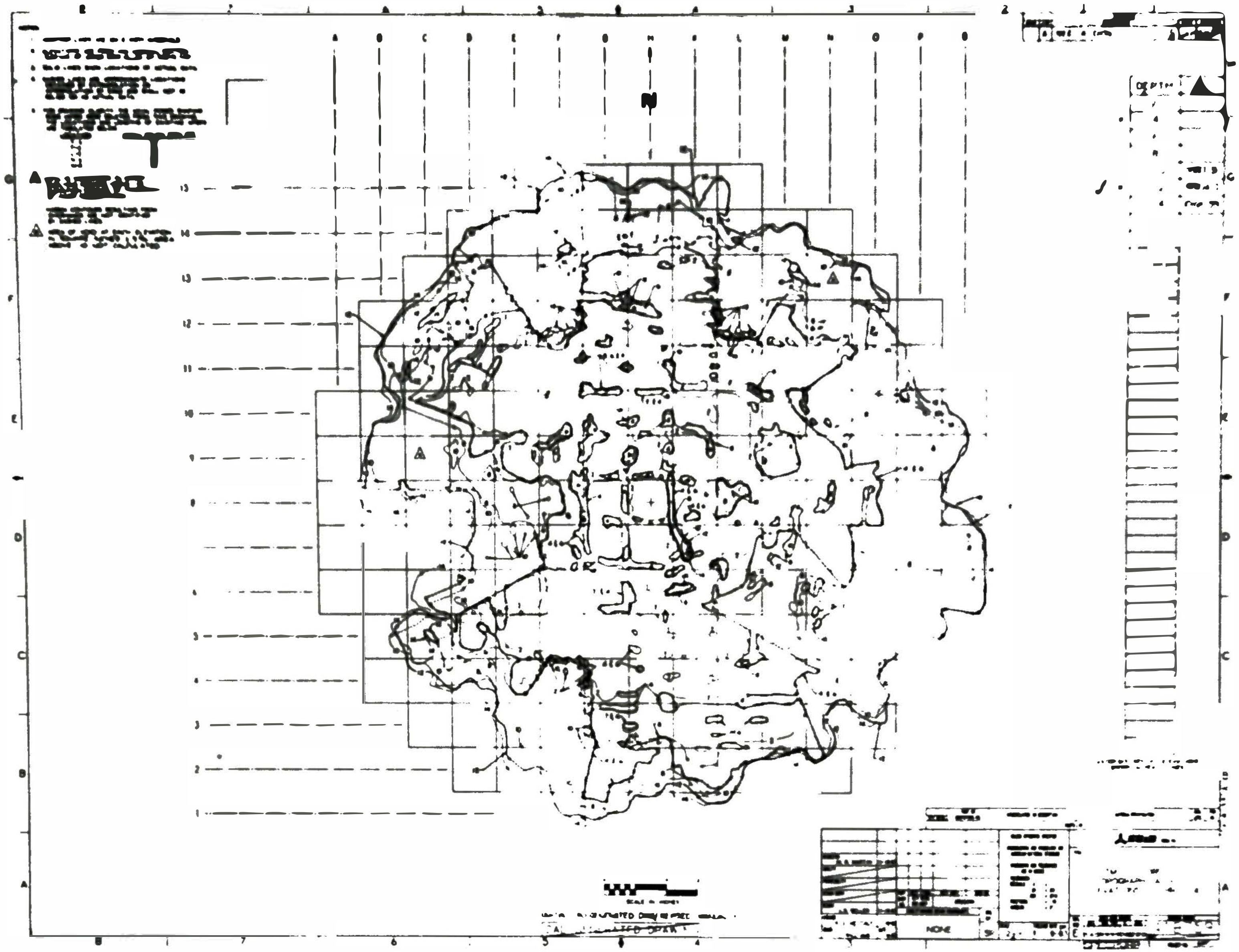


Figure B-6. TMI-2 core void topographical plot elevations -2 through -14.

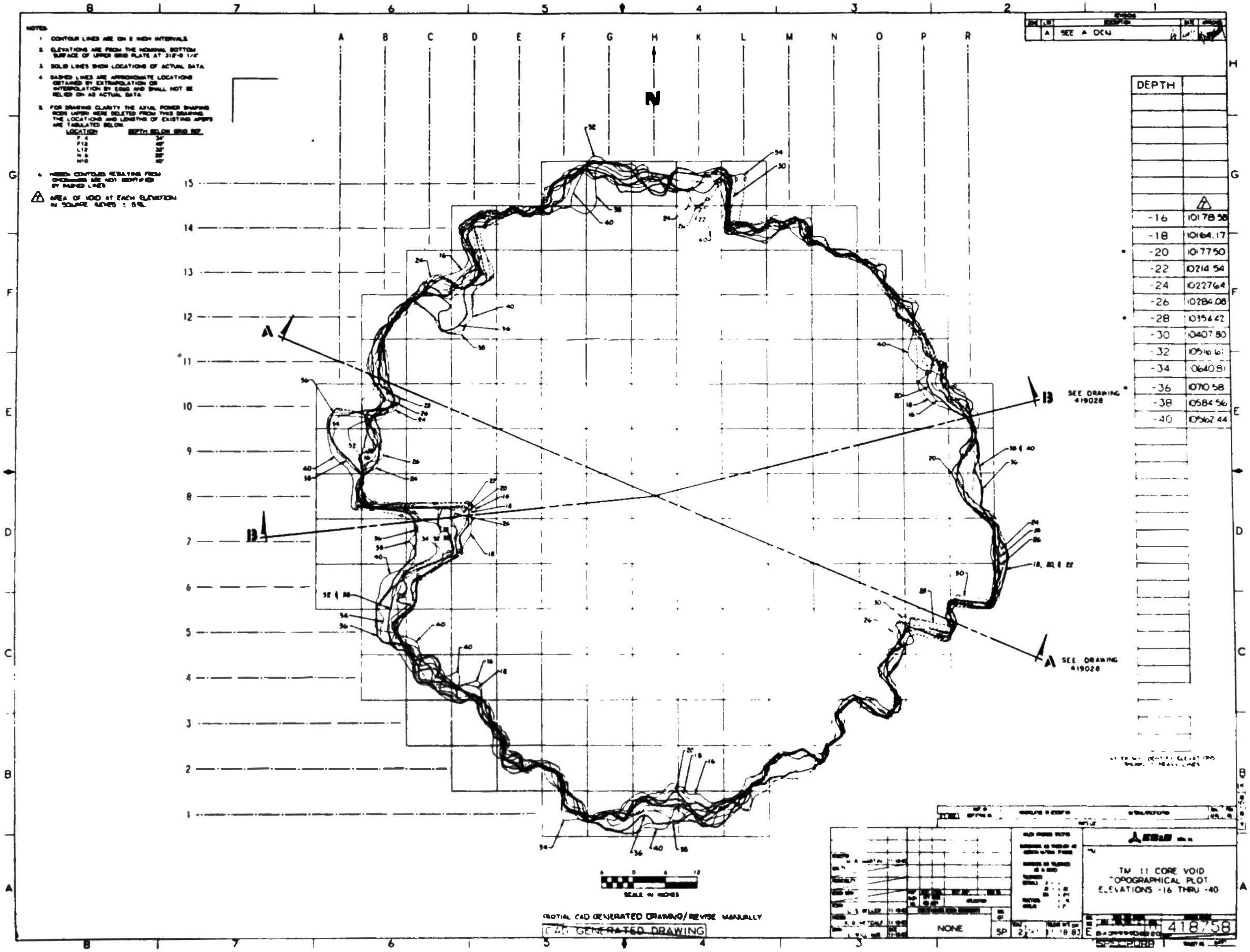


Figure B-7. TMI-2 core void topographical plot elevations -16 through -40.

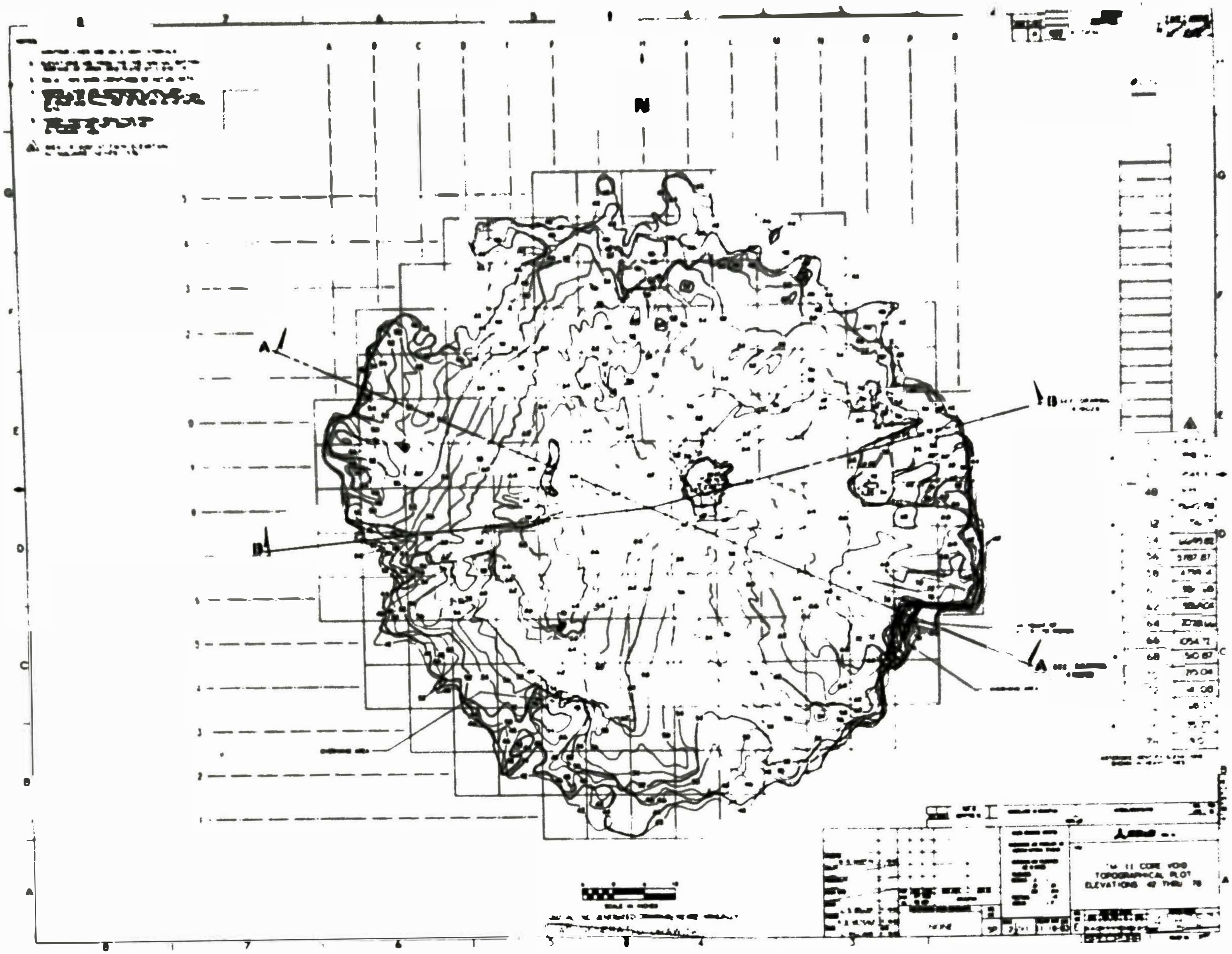


Figure B-8. TMI-2 core void topographical plot elevations -42 through -78.

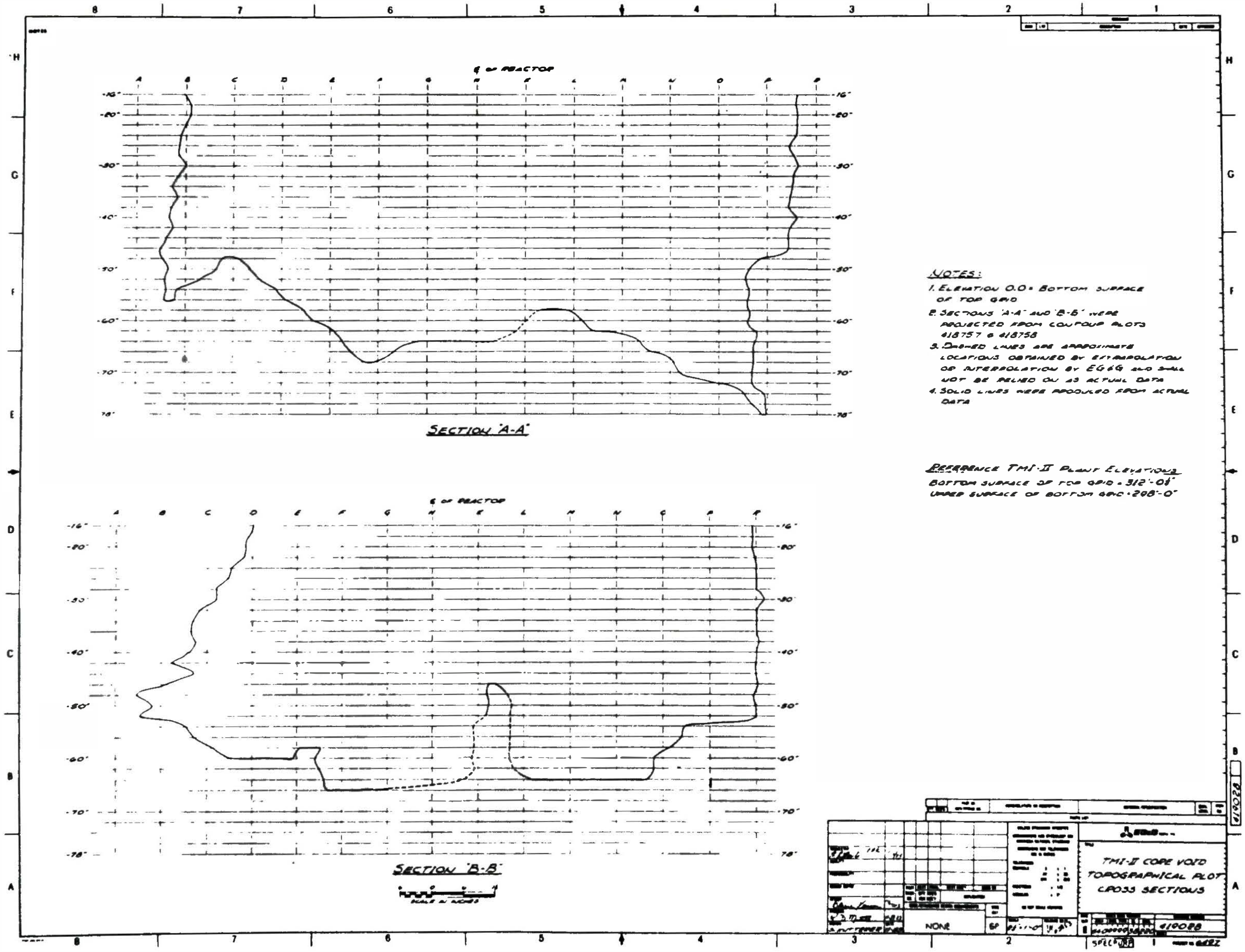


Figure B-9. TMI-2 core void topographical plot cross sections.

- The core cavity volume was equivalent to approximately 26% of the original core region

- Fuel assembly remnants appeared to almost completely encircle the core cavity toward the upper grid plate; the maximum fuel assembly damage appeared to be on the core East side, and the least fuel assembly damage on the core West side

- The ASPRs that had been inserted earlier projected from the cavity ceiling and interfered with ultrasonic-scanner measurement of topography in the cavity upper regions.

<u>Reactor Vessel Head Removal</u>[8-5]

In July 1984, the reactor vessel head was removed. Prerequisite work included uncoupling of the leadscrews from the CR assemblies and raising the leadscrews into the control rod drive mechanism (CRDM). The leadscrew uncoupling indicated the following:

- Thirty CR spiders were supported by the fuel assembly upper end fittings,

- Twenty-three CR spiders appeared to be unsupported by the fuel assembly upper end fittings, or were missing, and

- Four CR spiders became supported by the fuel assembly upper end fittings when lowered a small distance (less than 2 in.).

<u>Plenum Assembly Removal</u>

In May 1985, the plenum assembly was removed. Prerequisite work included dislodging of fuel assembly upper end fittings[8-6] and water-jet flushing of loose debris from horizontal (upward facing) surfaces.[B-7] The dislodging of fuel assembly upper end fittings indicated the following:

- Four upper end fittings (core positions O5, F3, F13, and K14) could not be dislodged,

- Ten upper end fittings (core positions E4, G14, K6, L2, L13, O3, O8, O11, P8, and R6) could only be partially dislodged,

- All other end fittings were missing, dislodged, or attached to their respective fuel bundles.

The water-jet flushing removed loose debris "ranging in size from very fine particles to nearly fuel pellet size" (Ref. B-7) from the plenum assembly upward-facing, horizontal surfaces. Post-flushing CCTV inspection indicated "some of the debris actually adhered to the plenum and could not be removed" (Ref. B-7).

The CCTV examination revealed probable damage to the plenum assembly lower surface as depicted in Fig. B-10.

Reactor Vessel Lower Head Region Video Surveys

In February and July 1985, the reactor vessel lower head region was partially surveyed with a CCTV camera lowered through the downcomer annulus at 13°, 63°, 167° and 245° (hole numbers 1, 4, 7, and 11, respectively) azimuthal positions. Samples of the loose debris deposited on the reactor vessel lower head were collected with a remote manipulator lowered through hole numbers 7 and 11. The surveys indicated the following:

- Some ten to twenty tons of core debris had collected in the region between the reactor vessel lower head and the Flow Distributor,

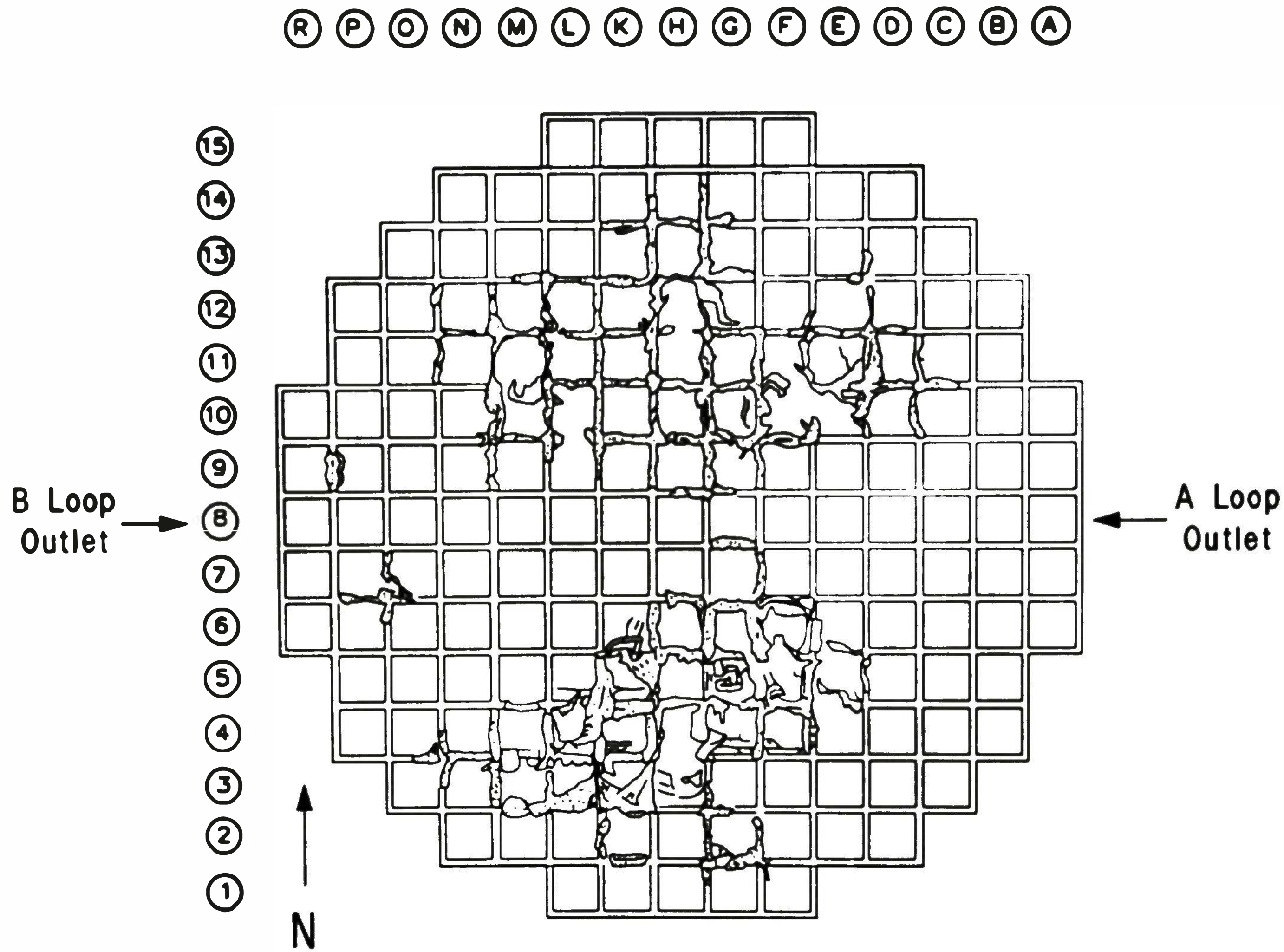


Figure B-10. Damage map of the TMI-2 fuel assembly upper grid plate.

- The core material form ranged from coffee-ground-sized particles to a vertical-curtain-appearing wall extending toward the Flow Distributor and appearing to be lava-like (previously molten),

- Previously molten material was hanging or attached to the Flow Distributor below core positions L2, L14, and N3.

The central and eastside regions between the reactor vessel lower head and the Flow Distributor were not surveyed.

Fuel Removal

Core debris removal commenced on November 12, 1985. In CY 1985 and 1986, debris removal was limited to the core cavity walls and floor and consisted of upper end fittings from fuel, control rod, and burnable poison rod assemblies, partial fuel assemblies, and unsegregated loose debris. By January 1987, a total of 51,000 pounds of the 300,000 pound core had been removed. The early debris removal included toppling standing peripheral fuel assemblies onto the core-cavity floor to provide clearance for the fuel debris canisters, occasional unaided toppling of unstable standing peripheral fuel assemblies onto the core-cavity floor, and shear-tool sectioning of some partial fuel assemblies lying on the floor of the core cavity.

Video surveys of the core cavity walls and floor were made in December 1985,[B-8] January 1986,[B-8] and June 1986. Six fuel rod segments were cut from standing fuel rods at the core south (core position L1) and southeast (core positions M2 and N2) sides in December 1985.[B-9]

Debris removal activities in CY 1985 and 1986 made the following changes to the core cavity.

- The fuel assemblies still standing (June 1986) at the core periphery were reduced to 21; 15 (A6, A7, A8, A9, A10, B4, C3, 02, 014, E2, L1, L15, N14, O12 and O13) with upper end fittings and 6 (B12, E2, L1, N2, O3 and R10) without upper end fittings.

- Sufficient loose debris had been removed from the core cavity floor to expose (a) the hard crust near the 70-in. elevation above the original core bottom, and (b) the horseshoe-shaped ring of agglomerated (cemented-together rod bundle remnants) core material projecting inwards from the standing fuel rods above the hard-crust surface. The ring extended from the hard crust to around the 100-in. elevation above the fuel rod bottoms. The ring receded near the hard crust creating a cave-like geometry.

- GPUN reported using, for defueling purposes, an impact chisel during May, June, August, September, and October 1986, and a crust impact tool during August, September and October 1986. Both tools may have been capable of altering the configuration of the horseshoe ring of agglomerated core material.

Biological Growth

In January 1986, reactor vessel water turbidity began increasing from a biological (microorganisms) growth in the water. The source of the microoganisms was believed to be the river water, which became mixed during the accident with reactor coolant in the reactor building basement and was subsequently introduced into the RCS after the contaminated basement water had been purified by the TMI-2 water cleanup system. The growth of the microorganisms was believed to be caused by (a) spillage of defueling tooling hydraulic fluid into the reactor vessel, and (b) other secondary events such as increased lighting, aeration, and oxygen dispersion of the reactor vessel water. Both aerobic and anerobic microorganism types were identified in the colony that evolved.

Water turbidity prevented identification of most material which was loaded into the fuel debris canisters after January 1986. It also prevented clear video surveys of surfaces and objects exposed by removal of the loose debris.

In April 1986, a biological-growth cleanup program began. It consisted of chemical (hydrogen-peroxide) addition to the water to kill the organisms and water filtering and feed-and-bleed operation to decrease the water turbidity. The biological-growth condition continued to be a problem during the remainder of the year as hydraulic fluid spillage continued. By early 1987, the addition of a polymer coagulent improved water clarity to normal visibility levels.

Core Boring

In July and August 1986, approximately 60 holes were drilled through or into the lower core region.[B-10]

The July drilling was for the purpose of (a) acquiring lower core and reactor vessel lower head region core material samples in the as-stratified condition, and (b) making visual (CCTV) inspections of the exposed lower core and core support assembly regions and lower head region core material upper surface. Holes of 3.65-in. diameter were drilled through the lower core region at the 10 core positions (D4, 08, G8, G12, K6, K9, N5, N12, 07, and 09) shown in Fig. B-11 and 1.26-in. diameter holes were drilled into the lower head core material to 8 in. above the reactor vessel lower head below core positions D4, K9, and N12. Core position D4 was the only drilling location where the horseshoe ring interfered with the drilling. The drilling data indicate that the horseshoe ring upper surface was at least 85 inches above the bottom of the fuel rods.

The August drilling consisted of using an approximately 2-in. diameter solid-faced bit at 48 locations within the 6 ft (73.2 in.) diameter central core region to make the removal of fused-tobether core material in the lower core region easier.

The core boring program produced the following information about the condition of the lower core region, the core support assembly region, and the core material deposited on the reactor vessel lower head.

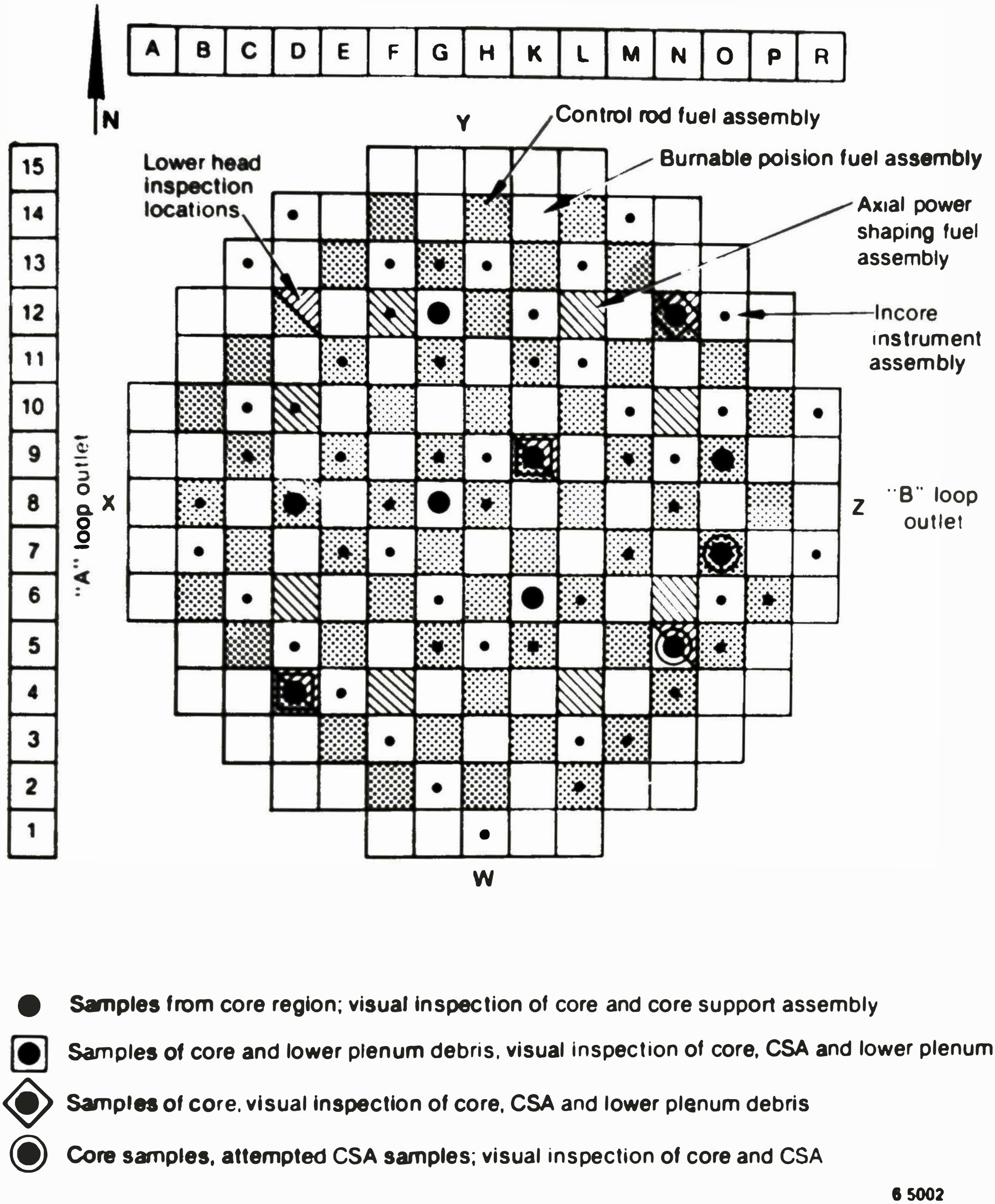


Figure B-11. TMI-2 core bore locations.

- A region of previously molten core materials estimated to be approximately 122 ft^3 (about 10% of the original core volume) was confirmed to be in the lower, central region of the core. This solid structure is approximately 4-ft thick in the center of the core, 1- to 2-ft thick near the core periphery, and is roughly shaped like a bowl extending down toward the bottom of the core. Intact rod stubs exist from the bottom of the core up to the previously molten material.

- At several core bore locations, metallic inclusions appear in the upper portion of the solid, previously molten material, while at other locations metallic inclusions are observed near the center and/or bottom of the previously molten regions. The shapes of the metallic inclusions vary widely.

- The primary migration path of the previously molten material into the lower plenum appears to be located on the east side of the core near the periphery, primarily at assemblies P-5 and P-6.

- The CSA appears to be undamaged in those areas where previously molten ceramic materials have frozen in place between the CSA structural members. However, one core instrument guide tube is damaged near the Lower Grid Distributor Plate and two others were missing or covered by solidified material below the lower grid.

- The fuel debris resting on the bottom vessel head near the center of the reactor vessel appears to be loose and relatively fine as compared with the large agglomerated debris existing near the edge of the reactor vessel in the lower plenum. The depth of vessel bottom head fuel debris was estimated to be as follows:

Core Position	Depth[a] (in.)
D4	18
K9	30
N12	12

- The core boring produced cutting debris including sand-like material, shards of fuel rod material, and fuel assembly lower end fitting plugs that (a) settled into the standing rod bundles and onto the horizontal surfaces of the lower core support assembly and reactor vessel lower head core debris, or (b) obstructed holes in the core support assembly plates. Future acquisition of core material samples from below the core must be accomplished carefully to avoid or segregate the core material which relocated during the core boring campaign.

A video survey of the core cavity walls and floor was conducted in October 1986. The estimated state of the TMI-2 reactor vessel internals in October 1986 is shown in Fig. 1.

Core Pulverizing[B-11]

In November 1986, after unsuccessful attempts to remove the previously molten core material from the core central region with available defueling tools, GPUN deployed the EG&G-furnished core boring equipment[B-10] as a milling device to loosen and/or pulverize the fused-together material in the 8.5-ft diameter central core region with a 4.5-in. diameter solid-faced bit. The planned milling pattern is shown in Fig. B-12 and the actual milling was accomplished at 409 of the 421 overlapping locations. The drilling data indicate that the horseshoe ring was not encountered by the drill except possibly near 25° azimuth. A core cavity video survey and mechanical probing[B-12] to determine the hard crust elevation were conducted in December 1986.

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a. Depth measured after boring with possible overlay of boring debris.

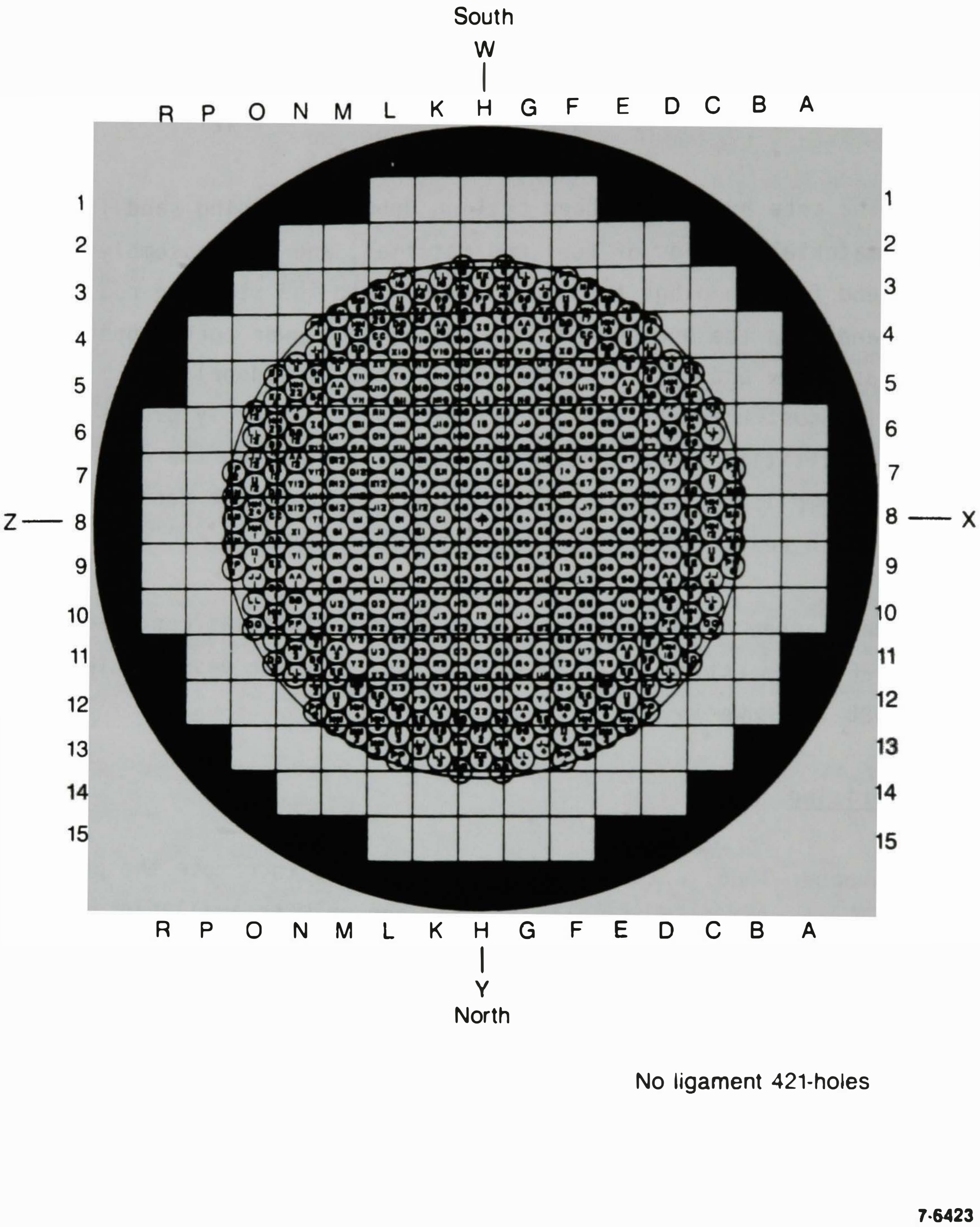

Figure B-12. Planned milling locations.

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