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# AN ASSESSMENT OF THE TMI-2 AXIAL POWER-SHAPING-ROD DYNAMIC TEST RESULTS

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## ABSTRACT

The Three Mile Island-Unit 2 (TMI-2) nuclear power reactor contains 61 control rod assemblies and 8 axial power shaping rod assemblies (APSRs). The APSRs are positioned symmetrically, forming a ring approximately mid-radius around the core. The APSRs do not perform a safety or control function, but are used only to flatten the axial power distribution within the core.

All control rod and APSR drive leadscrews must be uncoupled and removed prior to vessel head removal. Leadscrew removal is facilitated by having the rod assemblies inserted to a down hard-stop position. Following the TMI-2 accident, the eight axial power shaping rods were in a partially withdrawn position (∿25% of their full travel). Therefore, a test was performed to attempt to insert the APSRs to the fully inserted, or at least a hard-stop position. In addition, accelerometers were mounted on the drive mechanisms of all the APSRs in an attempt to obtain acoustical signals that would provide some information about the physical condition of the APSRs and of the damaged TMI-2 reactor core. The acoustical data obtained were analyzed independently by the Babcock and Wilcox Company (B&W) and by Science Applications, Incorporated (SAI). In addition to the APSR Insertion Test results, information obtained from the postaccident in-core instrumentation evaluation and "Quick Look" closed-circuit television camera pictures of the damaged core was used to interpret the physical condition of the TMI-2 core. This report describes the TMI-2 APSR Insertion Test performance and results, and presents an evaluation of correlations between APSR insertion information and other available information on the condition of the TMI-2 reactor.

## SUMMARY

When the TMI-2 accident occurred, the eight APSRs were all at approximately the 37-in. (25%) withdrawn position. Since they perform no safety or criticality control function, these rods were not inserted during reactor shutdown and remained at the partially withdrawn position throughout the duration of the accident. Uncoupling the APSR leadscrews from the APSR assemblies is essential to head removal prior to defueling the reactor, and uncoupling is facilitated by having the APSRs in the fully inserted, or at least a downward hard-stop position.

An APSR Insertion Test was performed in an attempt to move each APSR leadscrew to its fully inserted position. In addition to positioning the leadscrews for easy uncoupling and removal, the insertion test also provided an opportunity to obtain information on the physical condition of the leadscrew drive motors, the APSR rods themselves, the upper plenum guide tubes, and possibly the core itself. Accelerometers were attached to the top of the drive mechanism of each of the eight APSRs to provide acoustical data related to drive motor functions, leadscrew movement, and possibly resistance to APSR movement in the fuel assembly and upper plenum areas, due to distortion or blockage of guide tubes. Specific objectives of the TMI-2 APSR Insertion Tests were (a) to insert the APSRs as fully as possible to facilitate later uncoupling of the leadscrews, and (b) to obtain electrical and acoustical signatures, insertion distance data, and as much insight as possible into the extent and location of damage to the core and upper plenum.

The acoustical signals obtained from the TMI-2 APSR Insertion Test were evaluated by comparison to acoustic signals obtained from APSR movement in the identical, but undamaged, TMI-1 reactor, and from APSR mockup tests performed at the Diamond Power Specialty Company. The acoustic signals were analyzed independently by the B&W and by SAI. Results from these independent analyses are included and the analyses are provided in their entirety as Appendixes B and C of this report.

Two of the APSRs were able to be fully inserted, two were inserted to the approximately 5% withdrawn position, one was inserted to approximately the 18% withdrawn position and, for all practical purposes, the other three could not be moved at all. The acoustic signals representing the drive motor functions of "latch," "jog," and "pole slip" were all distinctive and easily recognizable. Based on the movement of the leadscrews and the acoustic signals, it was determined that the drive motors of all eight APSRs functioned properly, that the leadscrews were intact, and that the upper plenum guide tubes were not severely damaged since most of the APSRs moved to some degree. The acoustic and electrical signature data obtained on the APSRs may also be of generic benefit to other commercial reactors of similar design. The signatures may help in the diagnosis of system condition during the periodic surveillance of the APSR and control rod drive systems conducted at these plants.

The APSR movement results were also compared with in-core instrumentation (thermocouples and self-powered neutron detectors) damage evaluations and "Quick Look" television camera insertion results. The ability to move some of the APSR drives to essentially the fully inserted position correlates well with data from the in-core instrumentation and television inspection. Nonmovement of Rods 64, 68, and 69 correlates with other data indicating lesser core damage in these areas, which suggests that restrictions to rod movement may be due to movement interference in the core area or at the fuel assembly upper end fittings rather than in the plenum area.

# ACKNOWLEDGMENTS

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# AN ASSESSMENT OF THE TMI-2 AXIAL POWER SHAPING ROD DYNAMIC TEST RESULTS

## INTRODUCTION

The accident at Three Mile Island-Unit 2 (TMI-2) provides a unique opportunity to investigate severe accident damage and advance the knowledge of light water reactor safety. Recognizing these facts, four organizations joined together after the accident to acquire technical data during reactor recovery. These organizations, commonly referred to as the GEND group (General Public Utilities, Electric Power Research Institute, Nuclear Regulatory Commission, and the Department of Energy) are conducting a variety of data acquisition and reactor recovery tasks. Recently, the Department of Energy sponsored a study to assess the extent of damage to the TMI-2 axial power shaping rods.

In addition to 61 control rods assemblies, the TMI-2 reactor contains eight axial power shaping rod assemblies (APSRs) that are used to adjust the axial power shape for efficient fuel utilization throughout core lifetime. The APSRs are distributed symmetrically around the reactor core in the positions numbered 62 through 69, and are located as shown in Figure 1. Each APSR assembly contains 16 stainless steel clad silver, indium, cadmium shaping rods attached to a common spider, as shown in Figure 2. Each APSR is inserted into a fuel assembly through guide tubes located within the assembly.

The eight APSRs were all approximately at the 37-in. (25%) withdrawn position immediately prior to the TMI-2 accident. That is, the bottom ~111 in. (75% of their length) remained inserted in the fuel assemblies. The APSRs are not automatically inserted during a shutdown. Hence, when the accident occurred and the reactor scrammed, the APSRs were left in their partially withdrawn position. However, prior to head removal and core defueling, it is desirable that the APSRs be either fully inserted, or at least inserted to a hard-stop position, to provide vertical and torsional stability during the uncoupling of the drive leadscrews from the rod spider hubs.

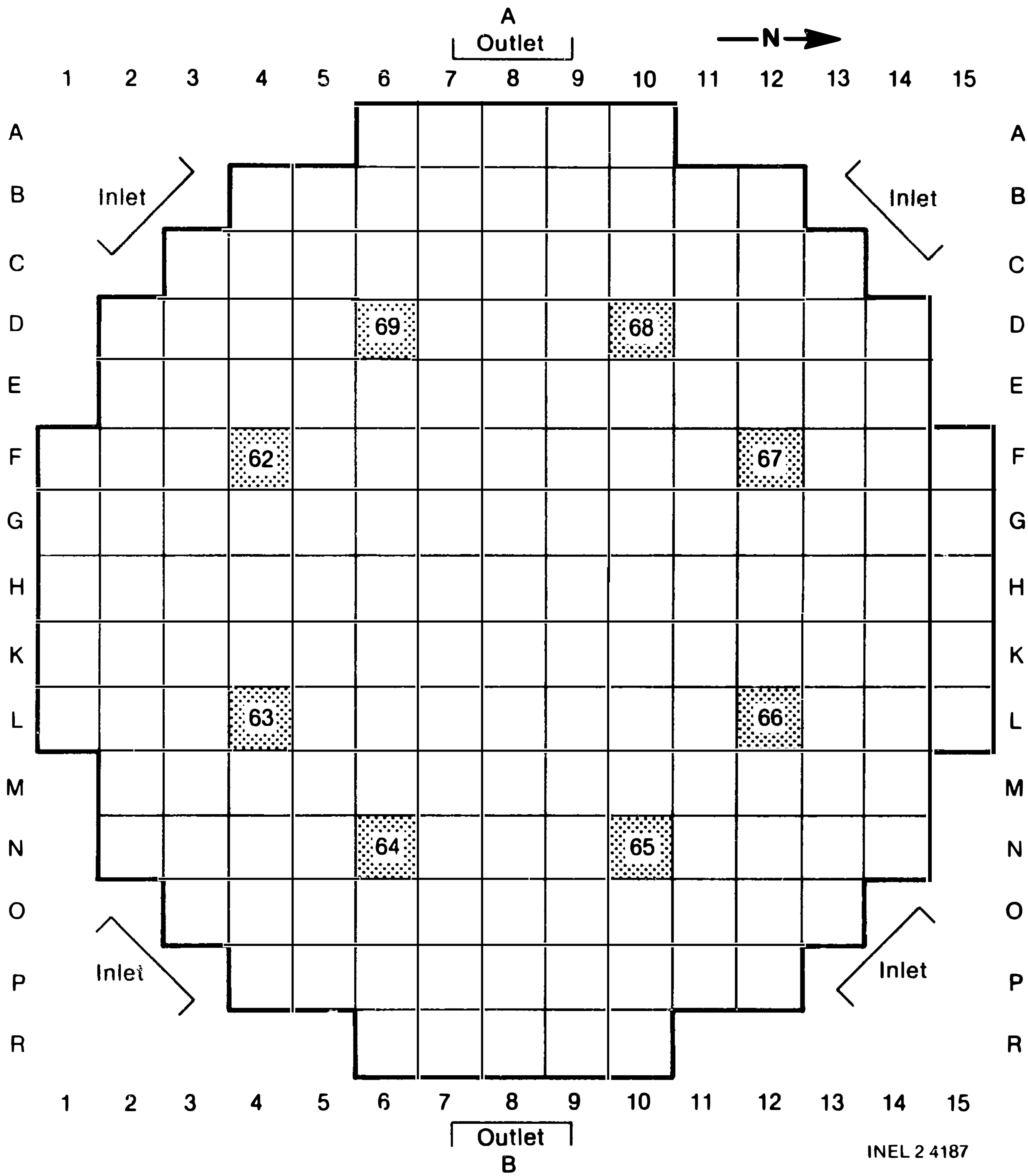



Figure 1. Diagram of TMI-2 core cross section, showing grid locations of the eight axial power shaping rod assemblies.

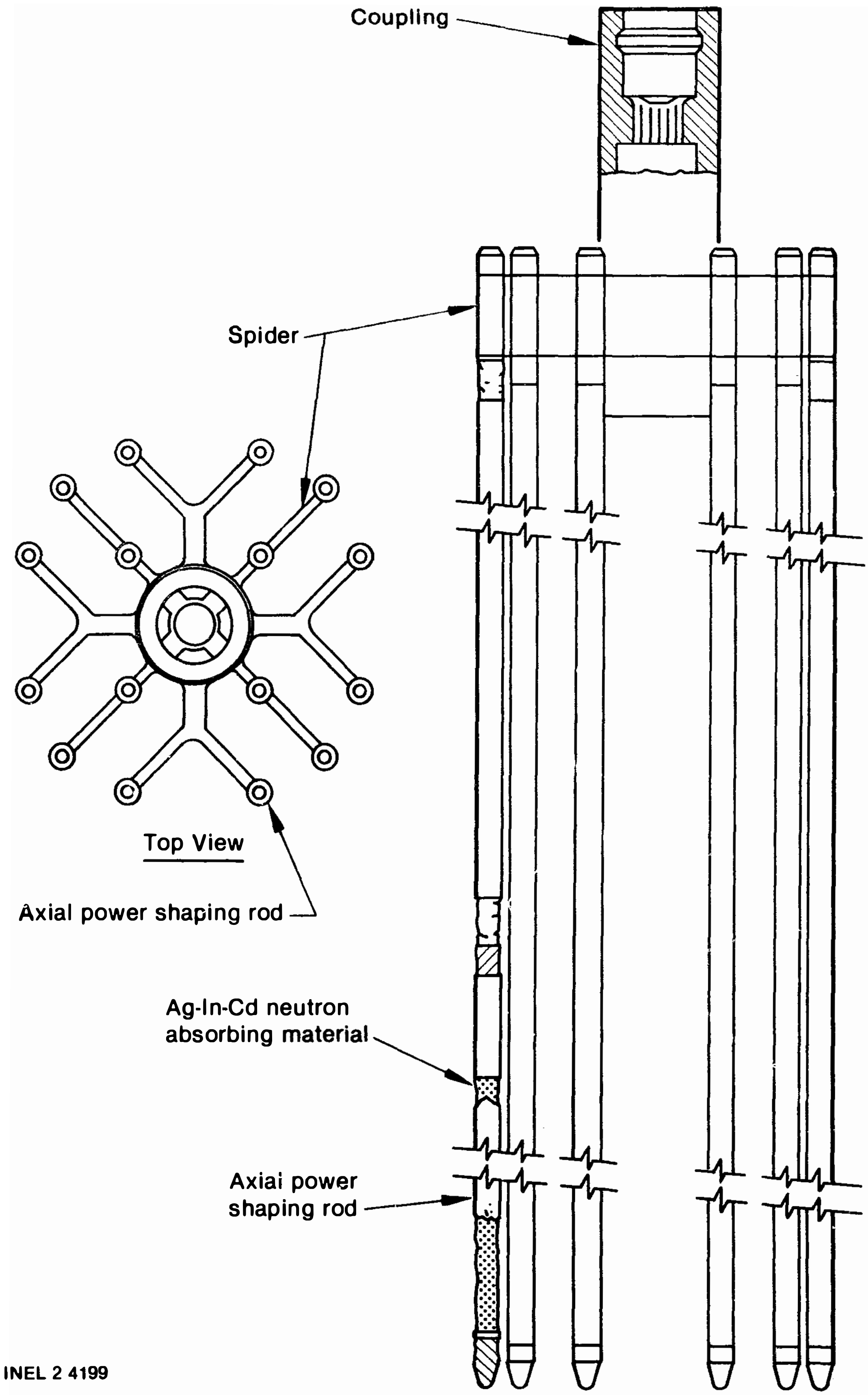



Figure 2. TMI-2 axial power shaping rod assembly.

Since the attempt to move the APSRs would be the first operation inside the reactor vessel following the TMI-2 accident, the operation could provide an opportunity to obtain information on the physical condition of the upper plenum region, and possibly even the core region itself. Movement of the APSRs would itself provide useful information, but the recording and analysis of electrical and acoustic signals from events occurring both internally and externally to the APSRs might provide additional insight as to the condition of the core. Thus, the specific objectives of the APSR Insertion Test were as follows:

1. Insert each APSR as fully as possible to facilitate later uncoupling of the leadscrews

2. Gather electrical and acoustical signatures, insertion distance data, and as much insight as possible into the extent and location of damage to the reactor core and the upper plenum.

Acoustical data were obtained from accelerometers that were attached to the top of the drive mechanism motor tubes of each of the eight APSRs as shown in Figure 3. To identify the APSR mechanical functions that can be detected acoustically, tests were performed on ASPR mockups at the Diamond Power Speciality Company (Lancaster, Ohio). Details of these tests are described in Reference 1. The Diamond Power tests demonstrated that the following mechanical functions could be detected acoustically:

- Latching (defined below)

- Movement of the leadscrew

- Drive motor pole slipping (defined below)

- Unlatching (defined below).

To provide a basis for evaluating changes in acoustical signals due to the conditions within the TMI-2 reactor, similar signals were obtained during an acoustically monitored insertion test of APSR No. 68 in the undamaged

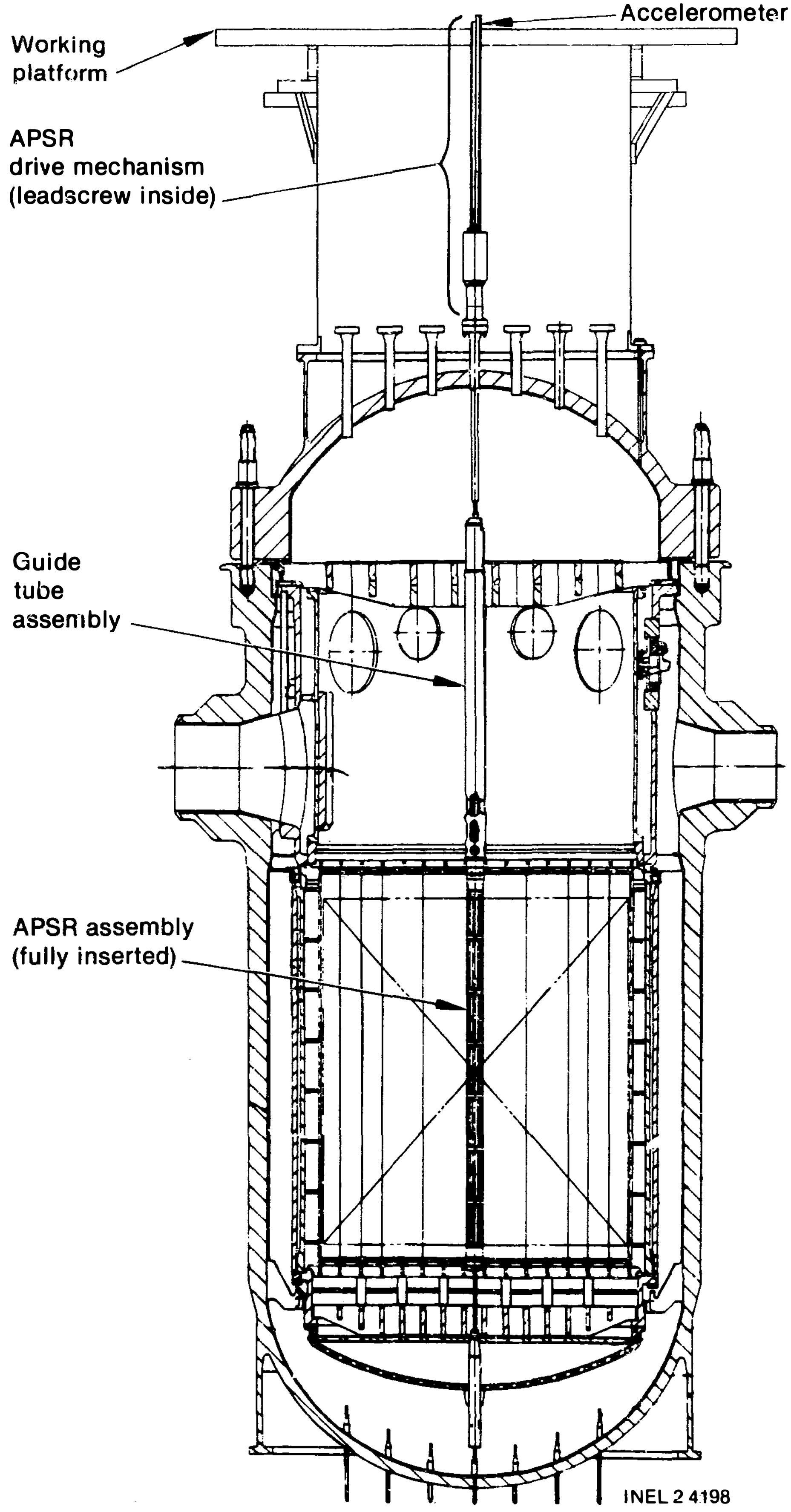



Figure 3. Cross section of TMI-2 reactor vessel, showing typical axial power shaping rod assembly.

TMI-1 reactor (a reactor that is identical to the TMI-2 reactor). However, because the water level for the TMI-2 tests was above the control rod drive mechanism (CRDM) motors, and the water level for the TMI-1 test was well below the drive mechanism (at the reactor vessel primary coolant loop penetrations) and, furthermore, flowing lubrication water was artificially introduced into the motor tube of the Unit-1 mechanism, the signals are not expected to be identical, even for mechanically identical functions.

Interpretation of the APSR Insertion Test acoustic data requires an understanding of the APSR drive mechanism, shown in Figure 4. The axial power shaping rod drive mechanism is an electromechanical device consisting of an electrically driven, rotating nut assembly (rotor) within a pressure vessel; a four pole, six-phase stator; a translating leadscrew that converts rotary motion of the nut to linear travel of the leadscrew and APSR cluster; and a brake that prevents motion of the APSR assembly when power is interrupted to the stator. When power is off (or interrupted), the rotor assembly segment arms pivot until contact between buttons on the lower end of the segment arms contact a rotationally fixed cylinder (motor tube). Contact of the buttons with the tube prevents complete disengagement of the roller nuts from the leadscrew while imparting a friction force that prevents rotor movement and thus leadscrew translation.

The drive mechanism control system inputs a sequentially programmed direct current to the four-pole, reluctance-type drive motor that incorporates a six-coil, star-connected winding. The stator coils are sequentially energized in a unique 3-2-3-2 progression, producing a rotating magnetic field around the rotor assembly. When power is applied to the stator, the magnetic field established by energizing the stator assembly acts as a magnetic coupling through the motor tube wall to pull the upper portions of the rotor segment arms outward. Due to the pivoting action, the lower portions of the segment arms move inward, causing the brake buttons to lose contact with the motor tube and the roller nuts to complete engagement with the leadscrew. As the stator coils are progressively energized, the rotor rotates (steps) to orient itself to the new positions. Basic functions of the drive mechanism are described by the following terminology, which is used throughout this report and supporting documents:

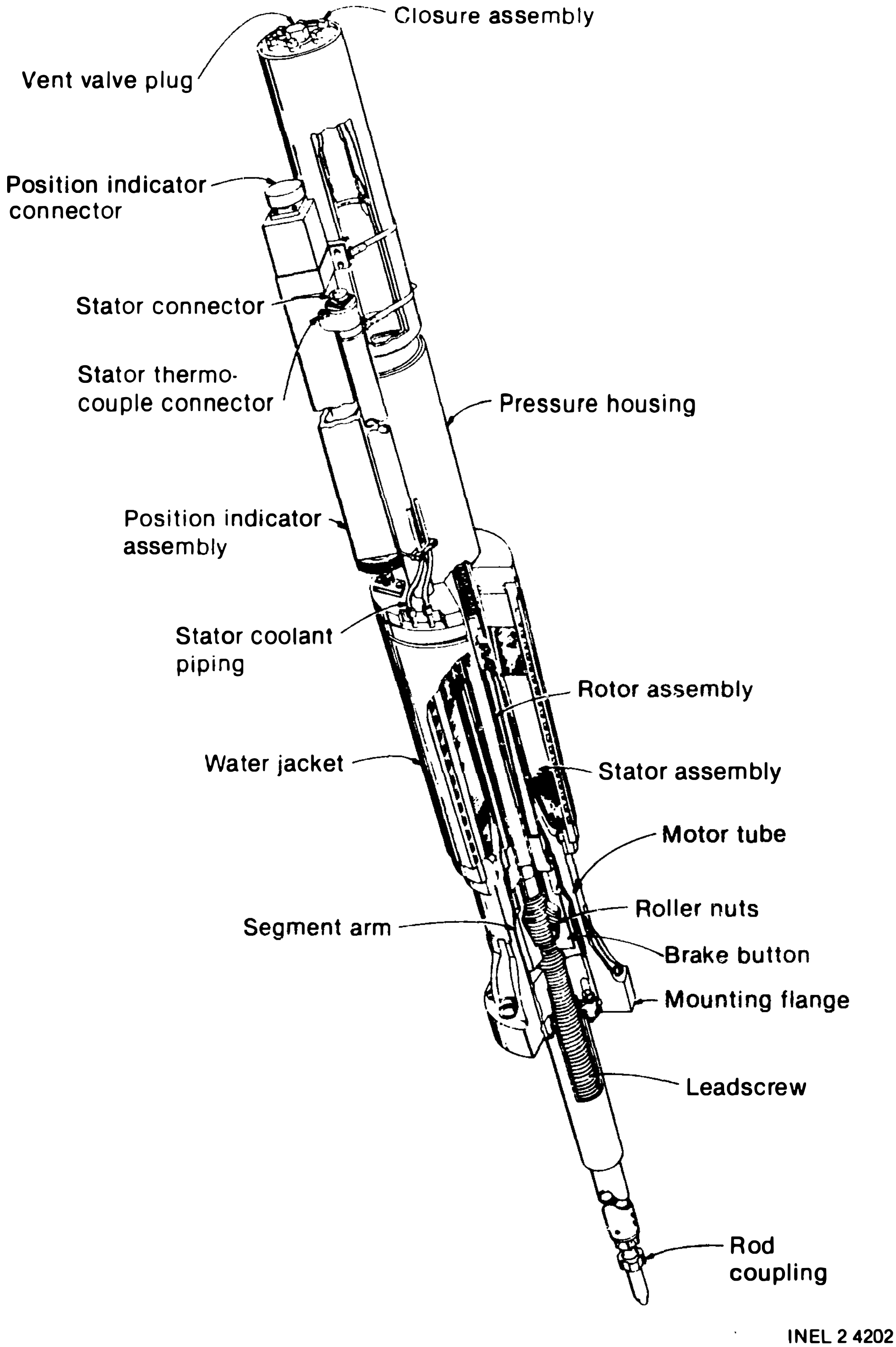



Figure 4. TMI-2 axial power shaping rod drive mechanism.

Latch — The action by which the rotor is aligned with the stator magnetic field, releasing a mechanical brake and locking the rotor into synchronization with the active magnetic poles of the stator windings. This is accompanied by a radially outward motion of the two rotor arms and inward travel of the roller nut elements, thus providing tight engagement of the four nut rollers with the leadscrew.

Single step — A single incremental advance (or retreat) of the stator field. This represents 15 degrees of mechanical rotation, which translates to 0.079 cm (1/32 in.) of axial linear movement of the leadscrew.

Jog — Continuous sequential step advance (or retreat) of the stator field. This represents 96 steps per minute or four full revolutions per minute and translates to 7.62 cm (3 in.) of linear movement per minute.

Pole slip — The action wherein the rotor fails to advance in response to the advance of the stator field. On the fourth such zero movement step, the rotor will reverse direction and move backwards the equivalent of two steps and again lock into synchronization, representing a 90-degree phase slip with respect to the field advance. This produces an audible noise. One must then step forward twice in order to get to the starting point. Thus, pole slip represents a loss in actual movement of six steps, when considered in terms of "applied" steps.

In addition to the APSR Insertion Test data, other information is available that provides insight into the physical condition of the TMI-2 upper plenum and reactor core. Perhaps most informative are the video tape "Quick Look" pictures that have been obtained by a closed-circuit television camera that was inserted down the leadscrew paths of core positions H-8 (central core position), E-9 (half-radius position), and B-8 (near periphery position). These pictures indicate a gradation of damage occurred to the core, varying from total absence of the upper portion of the fuel and control rods and formation of a rubble bed at ~150 cm (5 ft) below the top of the original core height at the center position, to observable fuel rod and control rod stubs at the E-9 position, to possibly intact fuel assemblies and control rods at the B-8 peripheral position. The "Quick Look" camera insertion information correlates well with core damage profiles obtained from analysis of the in-core instrumentation (thermocouple and self-powered neutron detectors).

The data obtained from the APSR Insertion Test were analyzed independently by SAI and the B&W. The purpose of this report is to summarize the performance and results of the APSR Insertion Test, to provide in a single document the analyses of the data by SAI and B&W, and to factor in other data relevant to interpretation of the physical condition of the TMI-2 core.

The following section, "Test Procedures and Measurements," briefly describes the APSR Insertion Test, identifies the acoustic and other measurements, and summarizes the analysis techniques used to help evaluate the plenum and core conditions. "Test Results Correlation with Other Data" describes the test results and summarizes interpretations of the acoustic data. This section also correlates the APSR movement data with other data, to aid in evaluating the plenum and reactor core conditions. The "Conclusions" section is based on the results of the APSR Insertion Test and related data. The appendixes are provided on microfiche attached to the inside of the back cover.

## TEST PROCEDURES AND MEASUREMENTS

The planned procedure followed during the TMI-2 APSR Insertion Test was to withdraw each APSR assembly individually, six steps (0.467 cm or 3/16 in.) in the single-step mode, then insert each assembly 12 steps (0.952 cm or 3/8 in.) in the single-step mode. If the 12-step inward motion succeeded, the rods were to be moved farther inward in the faster "jog" mode until the fully inserted position was reached or until pole slip occurred. The initial drive motor current to be used was 9 amps, and if pole slip occurred prior to full insertion it was planned to increase motor current in 1-amp steps, up to the maximum available of 14 amps. If 14 amps would not move a given assembly, testing would be discontinued and the assembly would be considered stuck. Once an assembly had reached its lowest position (whether it was fully inserted or stuck), its position would be determined by the absolute position indicator (available as a readout in the reactor control room) or by limit switches.

The APSRs were operated from the TMI-2 relay room, using a portable service power supply. The service power supply was instrumented to record voltage and current supplied to each drive mechanism stator winding, and was connected to each APSR individually at the CRDM cabinets in the relay room. The mechanisms were run without the normal stator cooling water, and stator temperature was limited by monitoring stator thermocouples, if they were available, and by limiting the time power was applied to the stator.

Data obtained during the TMI-2 APSR Insertion Test were categorized into two groups. Group 1 includes all of the electrical and acoustic data necessary to analyze operation of the APSRs. These data were recorded on magnetic tape for later analysis, and, in most cases, were recorded on strip charts for real-time analysis. Group 2 includes data that were beneficial to the conduct of the test, such as stator temperature and absolute position information, but were not essential to APSR movement analysis. Group 1 data are presented and discussed in this report, and a complete description of the Group 1 data obtained is provided in Appendix A. Group 2 data are not provided in this report, but are available from test files, GPU Job Ticket C-9631.

Analysis of the data included reduction of the real-time strip charts and test logs to arrive at event logs and movement summary plots for each APSR; analysis of stator coil voltage, current, and temperature data to evaluate drive motor performance; and comparisons of acoustic signals for each APSR with the Diamond Power and TMI-1 test signals to identify latching, unlatching, jogging, and pole slip events.

## TEST RESULTS AND CORRELATION WITH OTHER DATA

### APSR Insertion Data

Data obtained from strip charts and test records provided detailed event logs for each APSR movement, which include the following:

- The beginning and ending time of the insertion test for each APSR
- The total net motion of each APSR
- The mode of movement as a function of time (single step or jog)
- Rod movement direction (in or out)
- Specific comments on the mechanical and acoustic activities taking place during rod movement.

A detailed event log for each of the eight APSRs is provided in Appendix A. In addition to the event log, a movement summary plot was developed for each APSR. The movement summary plots relate APSR position (in terms of percent withdrawn) to the number of service power supply steps, and identify the locations at which pole slips occurred, which may be indicative of increased resistance to APSR rod movement or even total blockage of movement. A sample movement summary plot for APSR 65, which was inserted to the full-in position, is shown in Figure 5. Movement summary plots for all eight APSRs are also provided in Appendix A. Table 1 describes the initial position, final position, and inches of absolute movement of all eight APSR assemblies during the test.

Acoustic phenomena, as measured by the accelerometers attached to the top of the drive mechanism of each APSR, were recorded on magnetic tape during the entire movement sequence for each APSR. The significant APSR acoustic signals, indicating latch, unlatch, pole slip, and running motor noises, were observed. A few miscellaneous metallic impact noises were detected that had low amplitude and were associated only with the drive

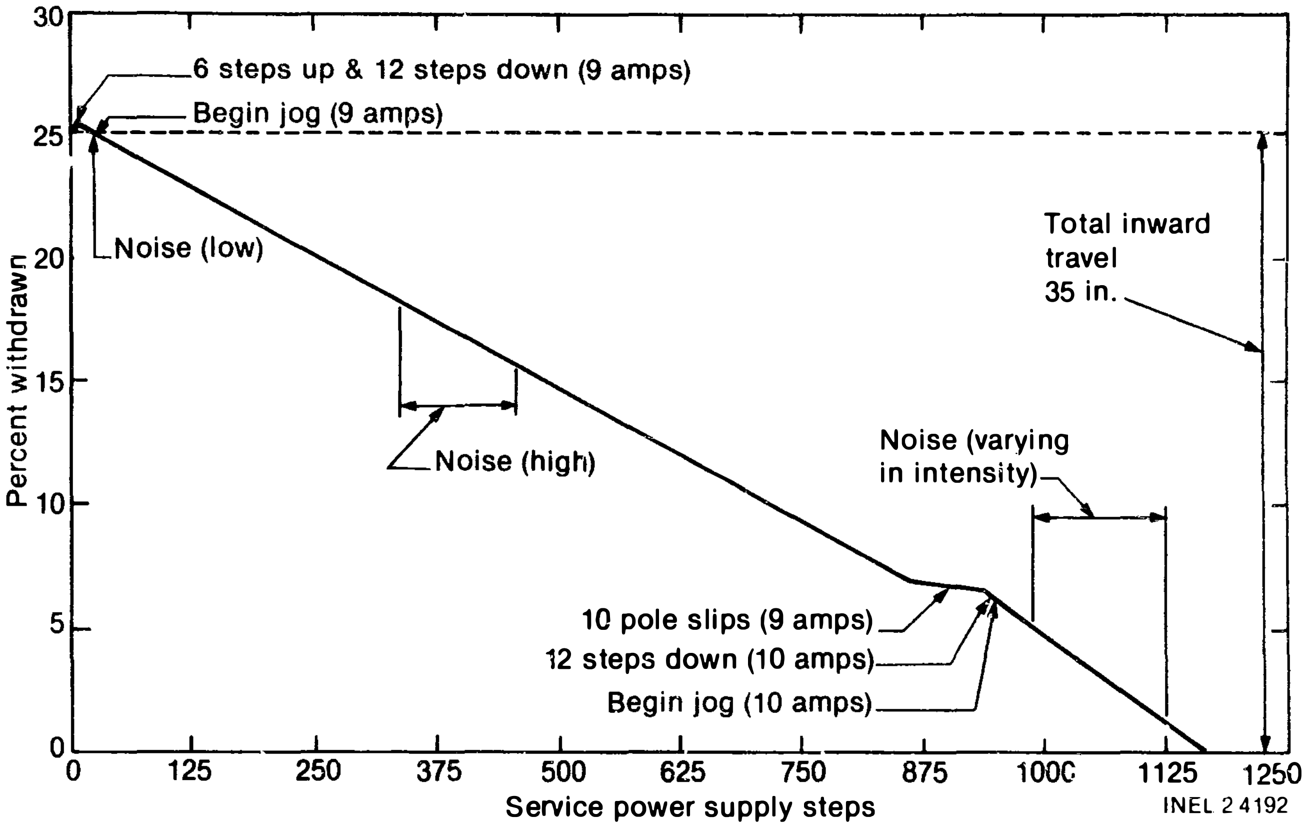



Figure 5. Movement summary diagram for APSR 65, during the TMI-2 APSR Insertion Test.

TABLE 1. APSR POSITION DATA

| APSR | Position (% withdrawn) Initial | Final | Absolute Movement (in. inward) |
|---|---|---|---|
| 62 | 26 | 5 | 29.72 |
| 63 | 25 | 19 | 8.31 |
| 64 | 25 | 25 | 0.31 |
| 65 | 25 | 0 | 37.16 |
| 66 | 25 | 4 | 30.9 |
| 67 | 26 | 1 | 35.22 |
| 68 | 25 | 23 | 3.63 |
| 69 | 26 | 26 | 0.25 |

under test (i.e., were not detected by the accelerometers on the other rod drives). Time-dependent plots of the acoustic signals for the various rod movement events were developed. Sample signatures obtained for APSR Rod 65 are shown in Figures 6a through 6f to illustrate the unique acoustic signatures associated with APSR movement events.

Individual APSR insertion event diagrams were developed, based on the acoustic signals (see Appendix B), which relate observed rod motion noise to rod position (percent withdrawn) during the insertion test. Based on the insertion event diagram, the diagram shown in Figure 7 was developed to compare rod motion noise levels (pole slip, running noise, quiet motion, and end of motion) at different rod positions for all the APSRs. Figure 7 clearly illustrates how each APSR assembly moved and identifies the major acoustic features associated with that movement.

Figure 7 reveals that although none of the insertion acoustic profiles are exactly alike (with the exception of the rods that did not move at all), there are similarities between several of the rods at specific locations. For example, Rods 62, 63, 65, and 66 all exhibit a high noise level (Rod 63 actually stopped) at about the 19 to 20% withdrawn level. Also, Rods 62, 65, 66, and 67 all exhibit a high noise level over the region from the 10 to 7% levels, Rods 62 and 66 stopping completely at the 5 and 4% withdrawn levels, respectively. It appears, then, that at specific elevations the resistance to rod movement increases. In some cases the increase is sufficient to stop rod motion, whereas in other cases the resistance decreases after movement past these locations.

In addition to the TMI-2 APSR Insertion Test data, other data were available that provided additional information on the physical condition of the core. These data were obtained from postaccident analyses of core instrumentation (thermocouples and self-powered neutron detectors) and from pictures taken by closed-circuit television camera insertions at different radial positions in the core. These data and their interpretations are described in the sections below. The implications of these data on the conclusions drawn from the APSR Insertion Test are also discussed.

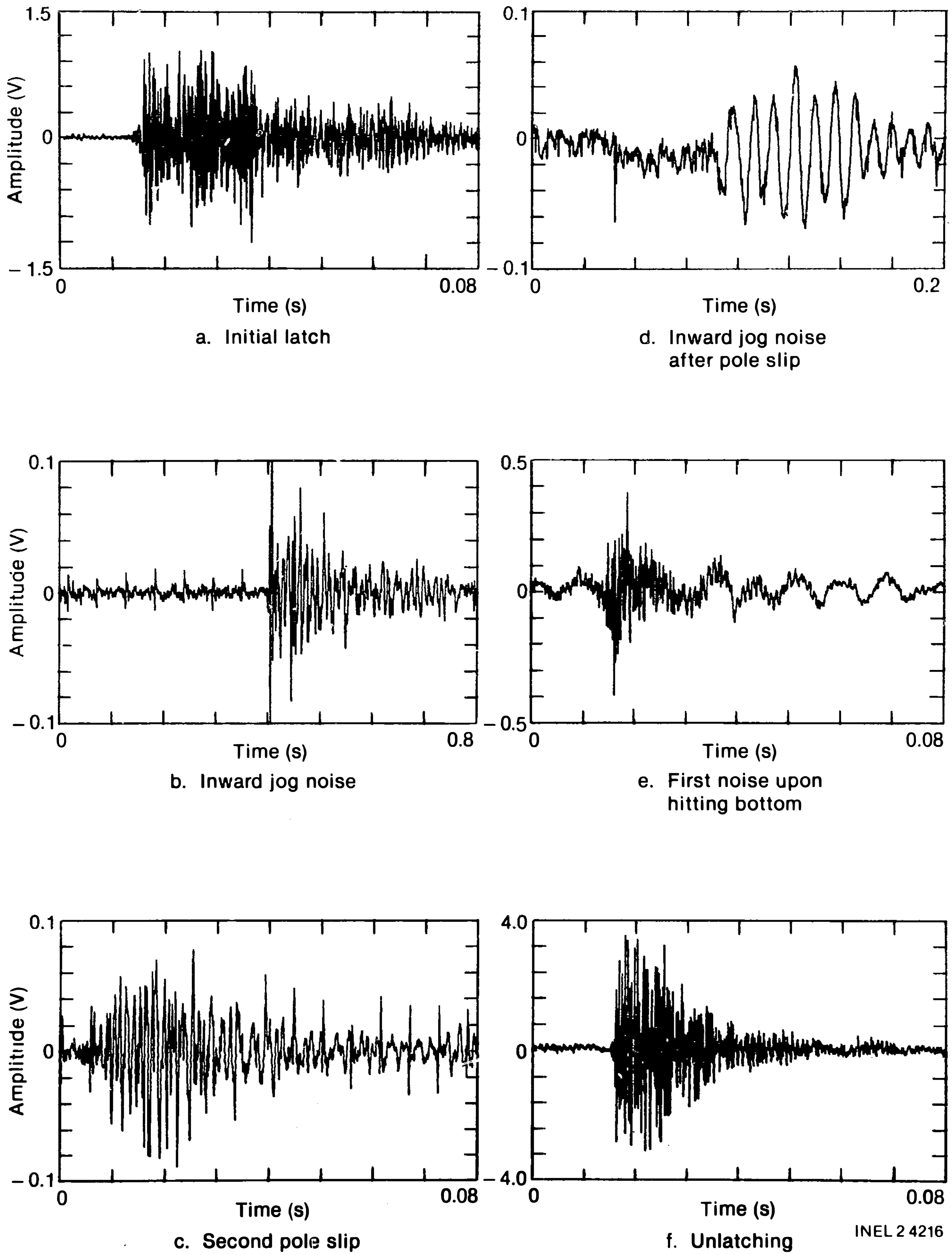



Figure 6. Acoustic signature of selected significant APSR rod movement events, as recorded on APSR 65 during the TMI-2 Insertion Test.

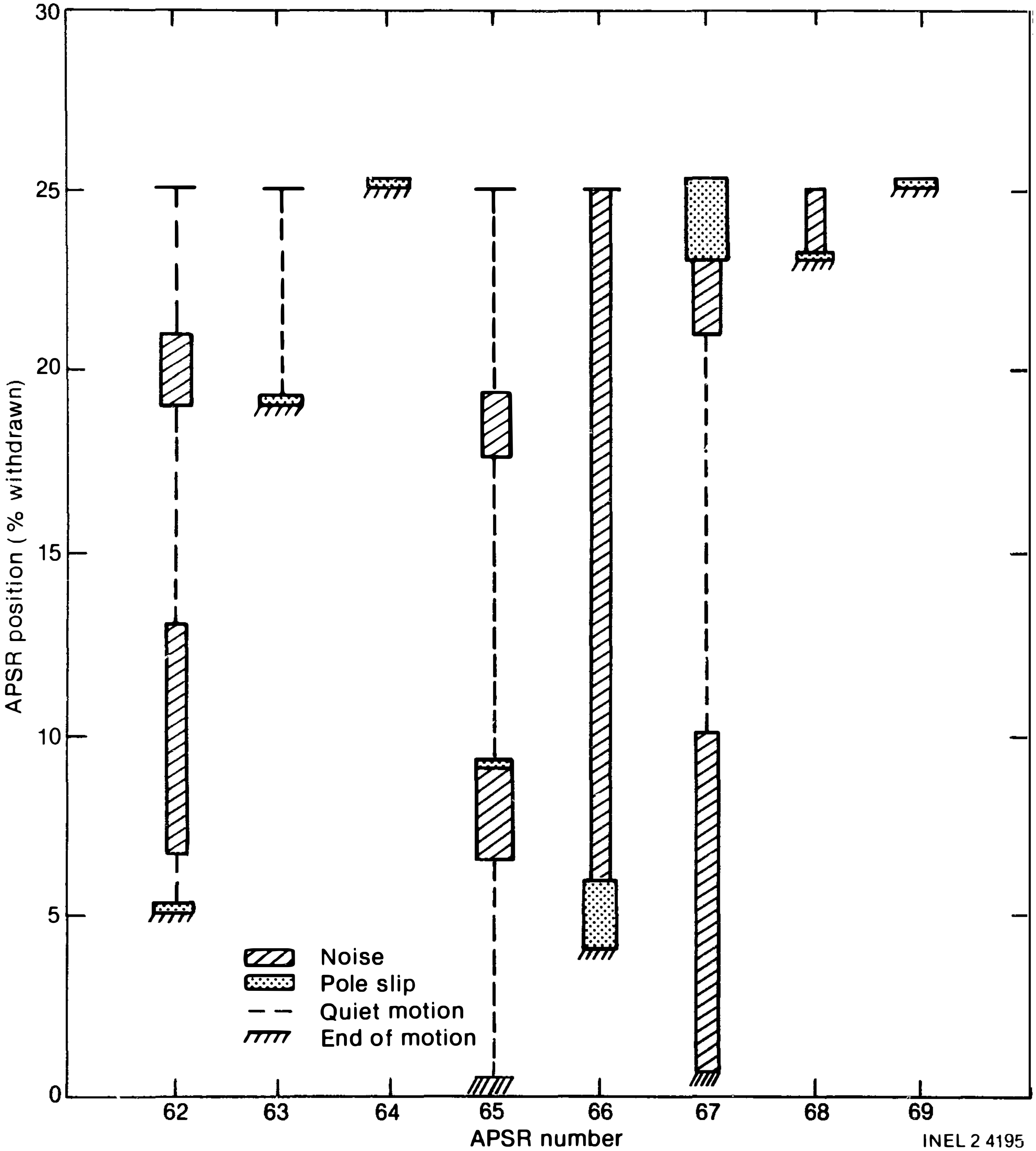



Figure 7. Comparison of rod motion noise levels at different rod positions for all APSRs during the TMI-2 APSR Insertion Test.

## In-Core Instrumentation Interpretations

Of the 177 fuel assemblies in the TMI-2 core, 52 are instrumented with a string of 7 self-powered neutron detectors (SPNDs), one background element (BE), and one thermocouple, located vertically along the length of the core, as shown in Figure 8. When the core was initially instrumented, resistance measurements were made on all in-core thermocouples, BEs, and SPNDs. Following the TMI-2 accident, resistance measurements were again made on all thermocouples, and the results were compared with the original measurements to obtain estimates of changes in the lengths of the thermocouple wires as a result of damage during the accident. Measurement of the postaccident thermocouple resistances revealed three distinct groups: Group 1 averaged a reduction corresponding to an apparent average reduction in length of 19 ft; Group 2 averaged a reduction in resistance corresponding to an apparent average reduction in length of 9 ft; and Group 3 consists of thermocouples for which the data, and consequently the thermal damage estimates, were inconsistent. These three statistical groups of thermocouple damage are located on the core map shown in Figure 9, "1" for Group 1, "2" for Group 2, and "3" for Group 3. As would be expected, the thermocouples that experienced the highest degree of apparent damage are generally located in the central core region.

Statistical analyses of the insulation resistance measurements on each of the 364 SPNDs and 52 BEs were also performed. Under normal conditions, the SPNDs and BEs exhibit an insulation resistance of $\geq 10^{10}$ ohms, representing essentially an open circuit. Lower resistance would indicate some type of cable failure or damage. The data indicate that some of the SPNDs and BEs are badly damaged, as evidenced by an electrical short between the center conductor and sheath. These damaged elements can be further categorized by fuel assembly location and SPND vertical position. Category A includes locations at which only SPNDs above the second level (see Figure 8) were considered failed. Category B includes locations at which essentially all SPNDs at all levels had failed. Locations of the Category A and Category B SPNDs are identified on the Figure 10 core map. Again, the area of apparently more severe damage is the central core region.

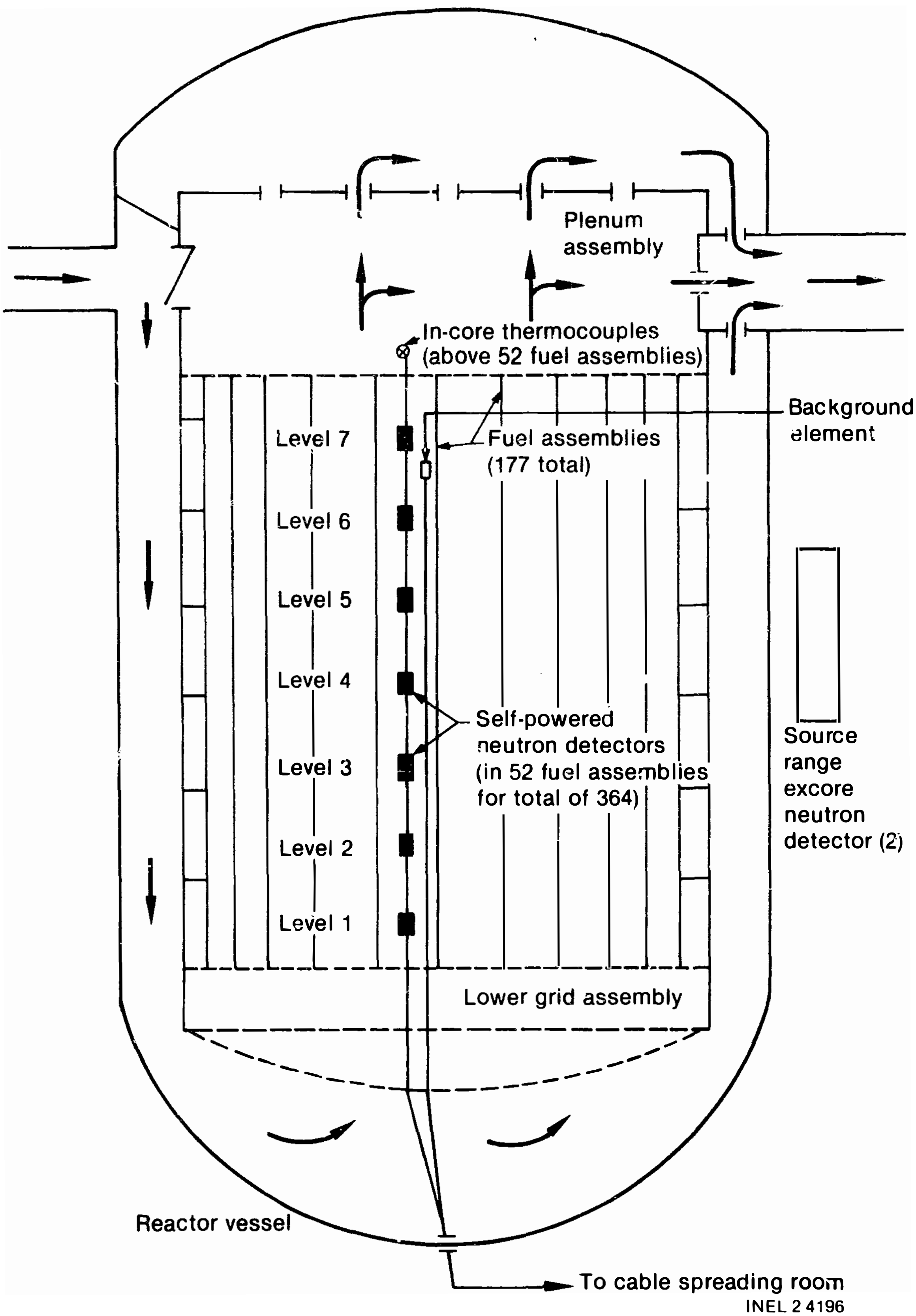



Figure 8. Cross section of TMI-2 core, showing relative vertical locations of in-core self-powered neutron and background element detectors and thermocouples in the 52 instrumented fuel assemblies.

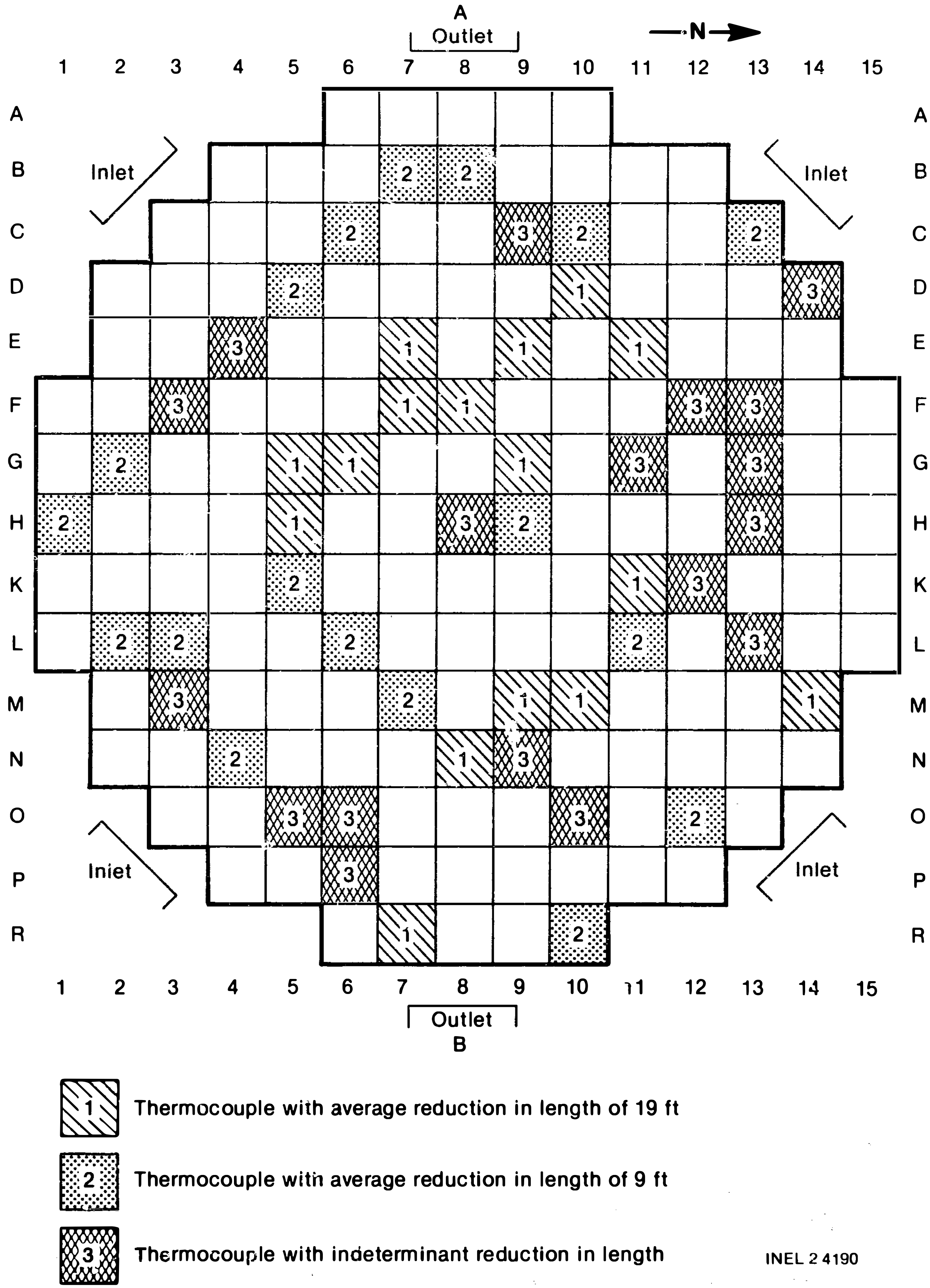



Figure 9. Thermal damage estimates for TMI-2 in-core thermocouples.

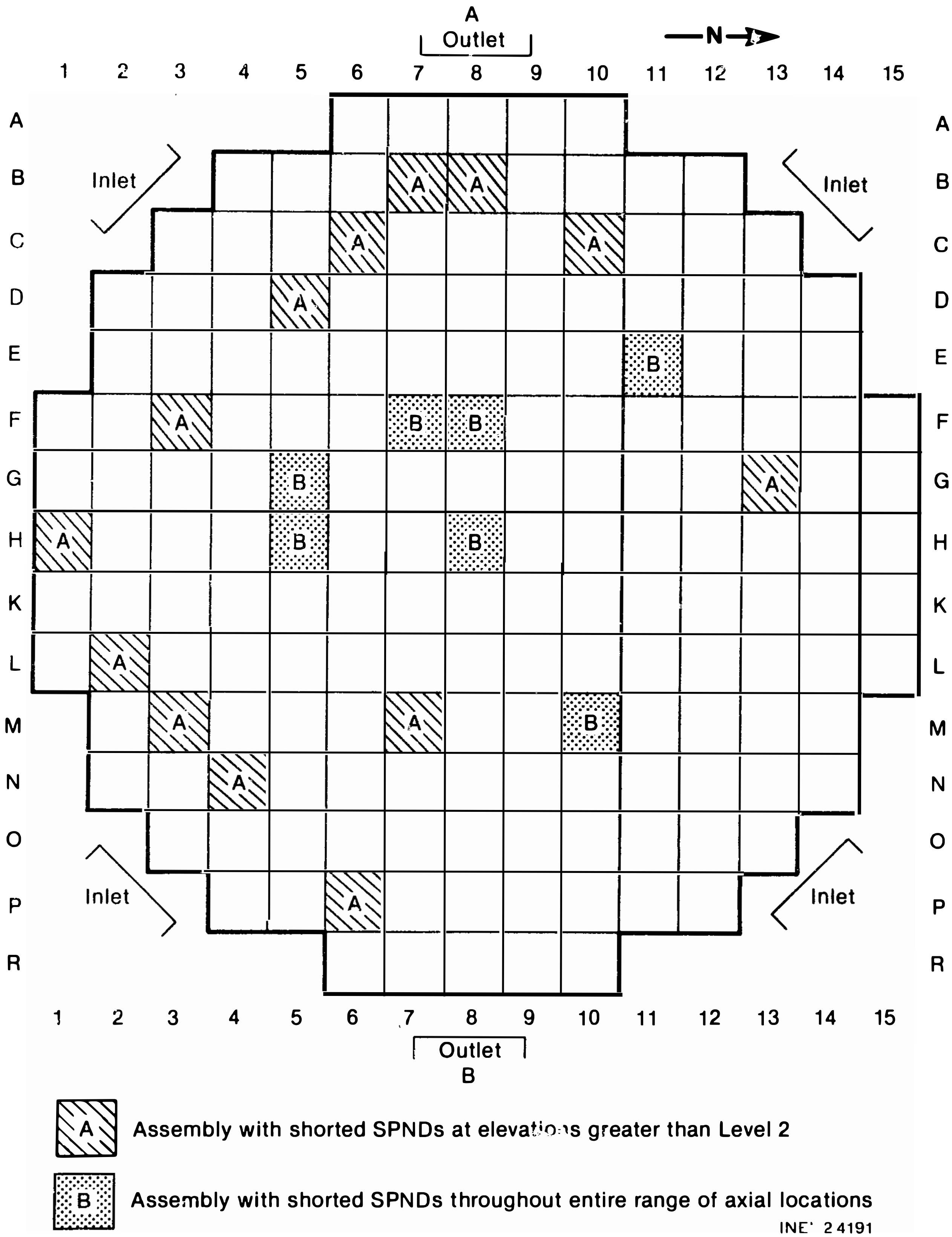



Figure 10. Thermal damage estimates for TMI-2 in-core SPNDs.

For comparison, Figure 11 shows the distribution of the final positions of all eight APSR assemblies, as determined from the APSR Insertion Test. The data shown in Figure 11 can be interpreted in two ways. The ability to drive APSRs numbered 62, 65, 66, and 67 to essentially the fully inserted position means that either, (a) core damage at these locations was severe enough that the control rods of these APSRs are virtually missing, and, therefore, there was no resistance to movement of the leadscrews to their fully inserted positions, or (b) that core damage at these locations was minor and that the APSR control elements can move freely in the fuel assembly guide tubes.

Assuming that complete or nearly complete APSR insertion means that these locations experienced severe core damage, one can outline this area of the core. A comparison of the areas of probable severe damage to the in-core instrumentation (the Group 1 locations in Figure 9 and the Category B locations in Figure 10) with the outline of essentially complete APSR insertion is also provided in Figure 11, and shows a high degree of correlation. From these data one would conclude that it is likely that the APSRs (with the exception of Numbers 63 and 64) are severely damaged and probably no longer attached to their leadscrews. It is, therefore, highly unlikely that resistance to APSR movement results from interference with in-core features such as fuel assembly guide tubes and spacer grids.

## Television Camera Examinations

Early in 1982, the DOE-sponsored TMI-2 Technical Assessment and Advisory Group (TAAG) suggested that a relatively simple "Quick Look" examination of the TMI-2 core could be performed by inserting a miniature television camera through a leadscrew support tube. This technique would involve removing a control rod leadscrew and lowering the camera down the control rod drive mechanism (CRDM) guide tube to examine the presumed damaged core.

### Sequence of Television Camera "Quick Look" Examinations

On July 21, 1982, after previously removing the control rod leadscrew, the first "Quick Look" Inspection (QL-1) was initiated at the H-8 (center

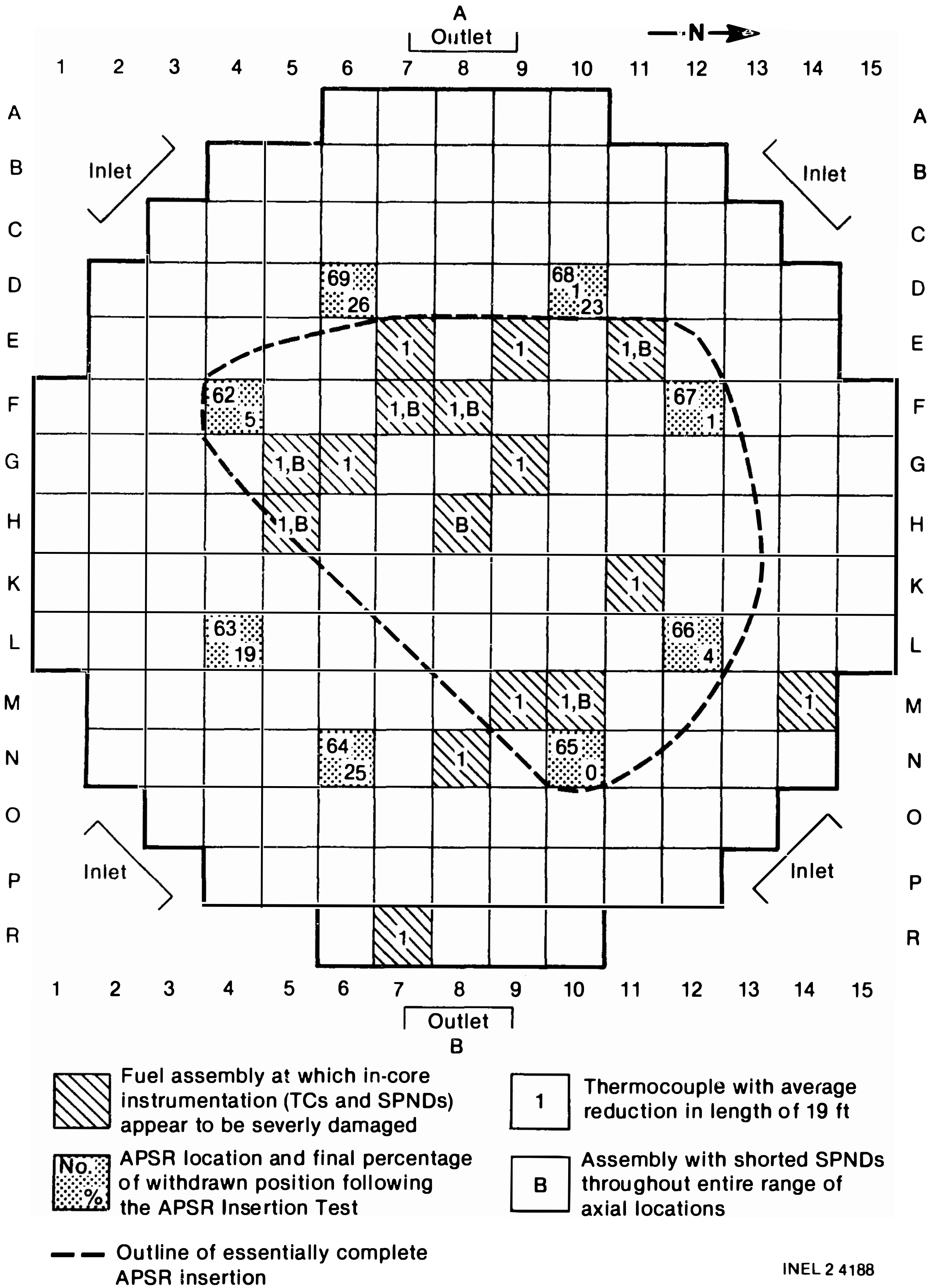



Figure 11. Areas of TMI-2 core damage based on APSR movement and in-core instrument analyses.

core) location. The camera was lowered down through the leadscrew support tube into the CRDM guide tube. Next, the camera was lowered down into a large void in the region where the core was originally located. At that location the void extended about 150 cm (5 ft) below the nominal top of the core. The debris bed was examined, and then the camera was rotated to view upward, and raised to examine the underside of the plenum assembly.

On August 5, 1982, after trying several locations, the leadscrews were removed at Locations E-9 and B-8 (see core position numbering diagram in Figure 11.) On August 6, the second "Quick Look" Inspection (QL-2) was performed at both locations. The control rod spider assembly was still in place at the B-8 location, which is near the core periphery, and the camera could not be lowered beyond that point. The camera was moved to the E-9 location, which is midway between the H-8 and B-8 positions and, as before, the CRDM guide tube, the void and debris bed, and underside of the plenum assembly were examined. Variations if lighting using the on-camera and auxiliary lights were tried.

On August 12, 1982, the third and final "Quick Look" Inspection (QL-3) was performed, again at Location E-9. Besides additional examination of the debris bed, two other activities were added to the inspection. The debris was probed for depth and degree of compaction with a stainless steel rod, and a right angle viewing lens was mounted on the camera to enhance the horizontal viewing.

## Summary of Observations During TV Camera Insertions

Many hours of video tapes from the three "Quick Look" examinations were reviewed and evaluated. Summary descriptions of the camera insertion information are provided in this section, as they relate to the core void, the debris bed, the plenum assembly, and the CRDM guide tubes.

## Core Void

There is a void in the upper central portion of the core, as shown schematically in Figure 12. At the core center, the H-8 location, the void

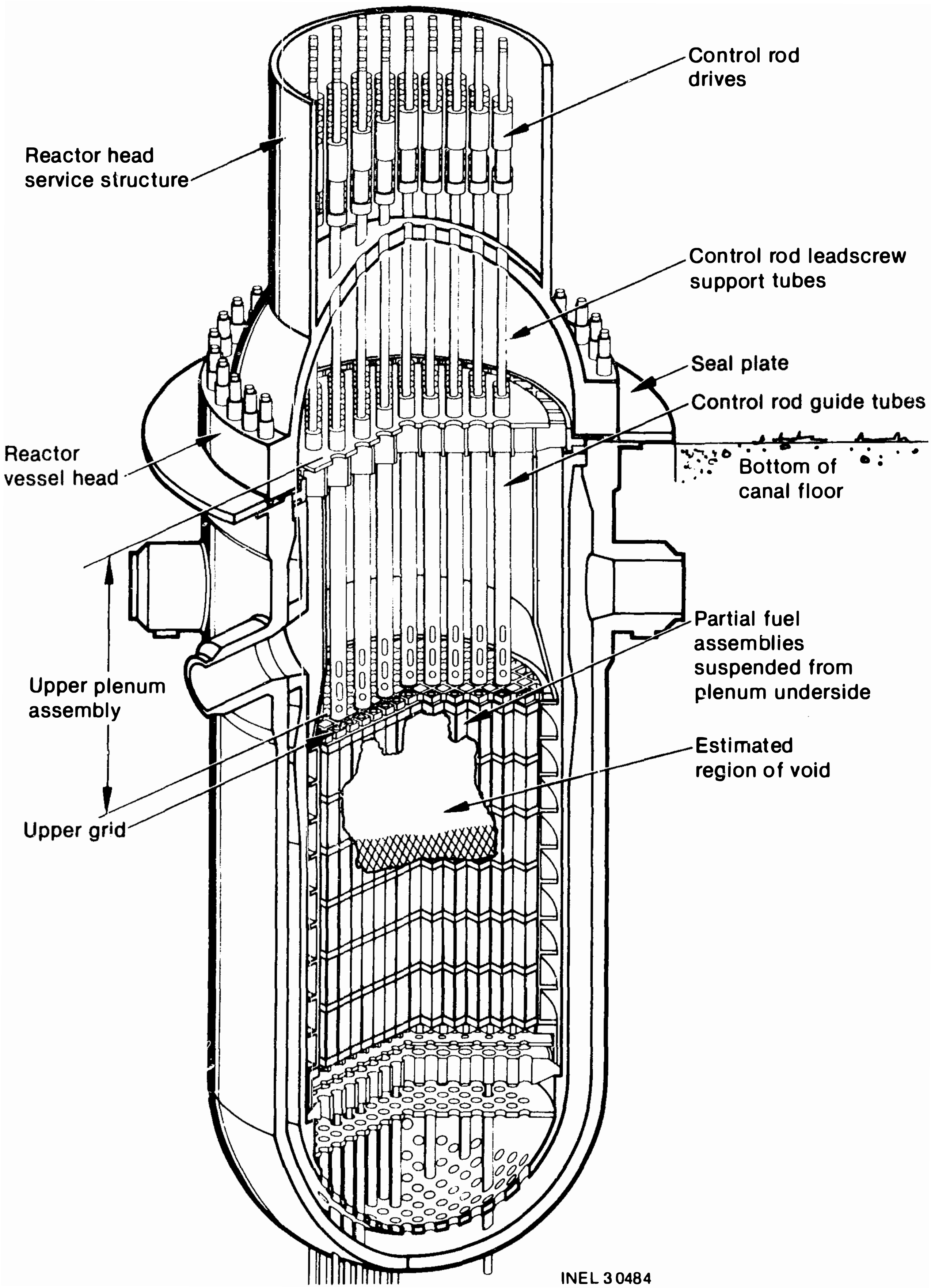



Figure 12. Void in the upper central portion of the TMI-2 reactor core.

extends downward from the bottom of the plenum to a debris bed whose top surface is about 150 cm (5 ft) below the plenum lower surface. The void also extends down to about 150 cm (5 ft) below the top of the core at the E-9 location. In addition, several fuel rod stubs extend vertically upward from the debris bed at E-9. Adjacent to the E-9 location, the remains of the upper ends of some severely damaged fuel assemblies are suspended from the bottom of the plenum.

When the camera with the right-angle viewing lens was inserted at the E-9 location, a panoramic scan was made at an elevation about 75 cm (2-1/2 ft) below the top of the core. An array of vertically oriented rods or tubes could be discerned when the camera was pointing toward the periphery of the core, although indistinctly. Based on their apparent size and the known magnification characteristics of the lens, the tubes appear to be 30 to 60 cm (1 to 2 ft) away from the camera. During the remainder of the scan, the picture was dark and detail was not discernible. Therefore, it is believed that the limit of the core void in this sector extends approximately to where indicated in Figure 12, and the void includes 45 or more full assemblies.

The control rod spider assembly was encountered at its expected location at B-8, as well as at one adjacent location. This indicates that the fuel bundles in these peripheral locations are either intact, or suffered minor damage.

Debris Bed

The debris bed was probed by lowering a 0.64-cm diameter (1/4-in.) stainless steel rod until it penetrated the debris by the force of its own weight (about 30 lb). The probe penetrated easily to a depth of 35.5 cm (14 in.), and then stopped. The probe penetrated to the same depth at Locations H-8 and E-9, indicating that the surface of the debris bed at both locations is loose and granular.

The debris bed appears relatively flat and level at the center location (H-8), and appears to consist of small granular fuel pieces whose average size is ~0.32 cm (1/8 in.) or less. A few very small particles that appear to have once been molten were also observed. A photograph taken of this material appears as Figure 13. The debris bed is more irregular at location E-9; the pieces are larger and many identifiable components, such as fuel rod cladding pieces, broken cladding shards, and $Al_2O_3$-$B_4C$ burnable poison rod pellets, are present (Figure 14).

Plenum Assembly

The underside of the plenum assembly appears to be in the normal configuration at the H-8 location. Two of the pressure pads were seen, and appear to be normal, except for linear surface patterns. These patterns could be either cracks in a surface coating of fine debris, or fracture marks associated with spalling of the pad surface.

Four adjacent fuel assembly upper end-fittings could be seen suspended from the underside of the plenum at location E-9. The four end-fittings suspended from the grid plate have been identified as belonging to the fuel elements located at grid points D-9, D-8, and E-8. Protruding downward from these fuel assembly upper end-fittings were, at various locations, damaged control rod stubs, fractured fuel rods, and portions of a damaged top-most fuel assembly spacer grid. Also, the grillage on the bottom of the stainless steel upper end-fittings was eroded or melted in several locations (see Figure 15).

It is considered highly likely that the high temperatures that caused severe damage to the fuel assemblies and control rods could also have melted and fused the stainless steel cladding of the APSRs to the associated fuel assembly upper-end fittings. If the upper end-fittings in turn were distorted or fused to the upper plenum support plate, APSR motion would have been prevented.

CRDM Guide Tubes

The C- and split-tubes, which guide the control rods and APSRs when they are withdrawn into their guide tubes (shown in Figure 16), are intact

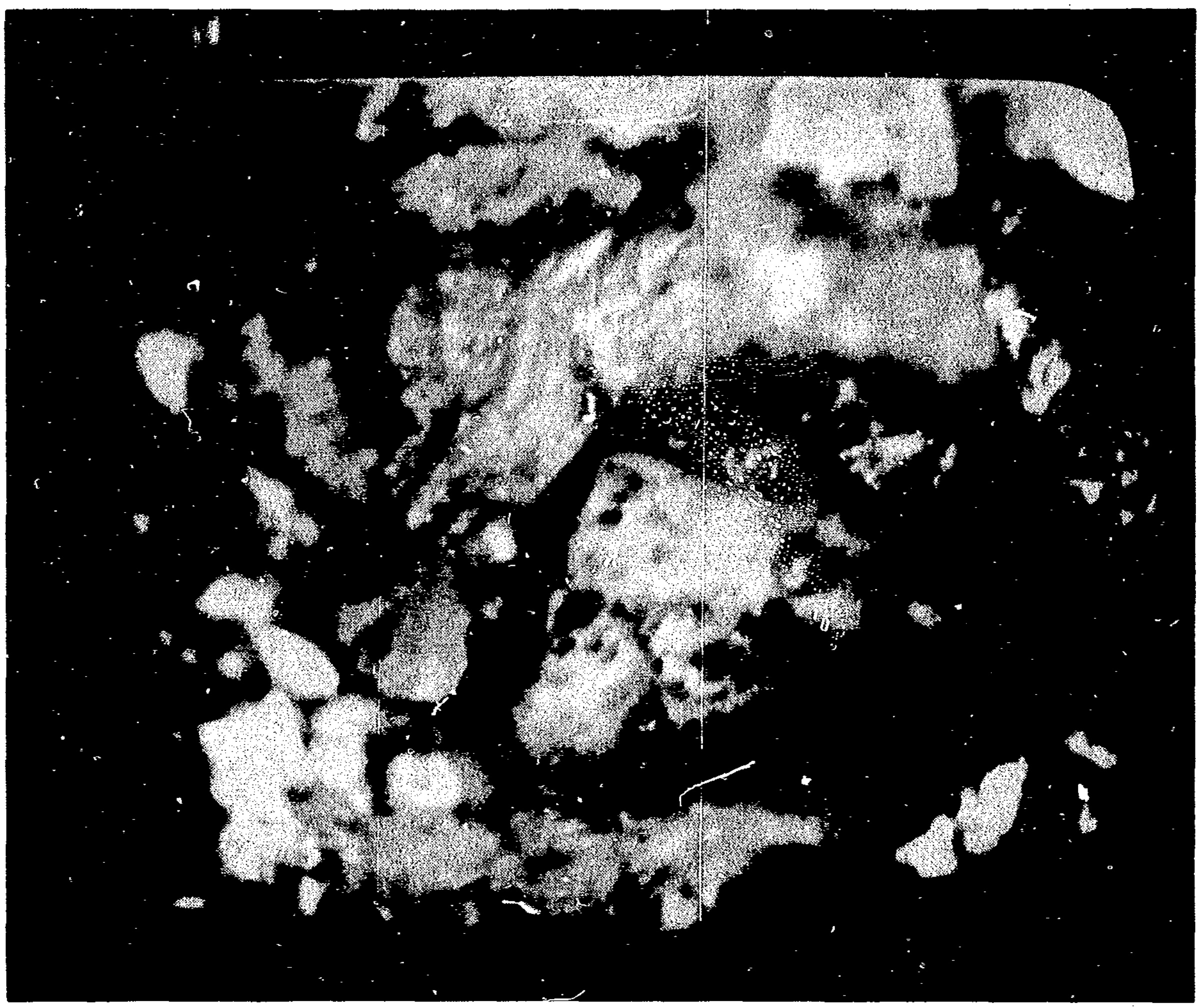


Figure 13. Photograph of debris bed at location H-8, showing a small particle that appears to have been molten and resolidified.

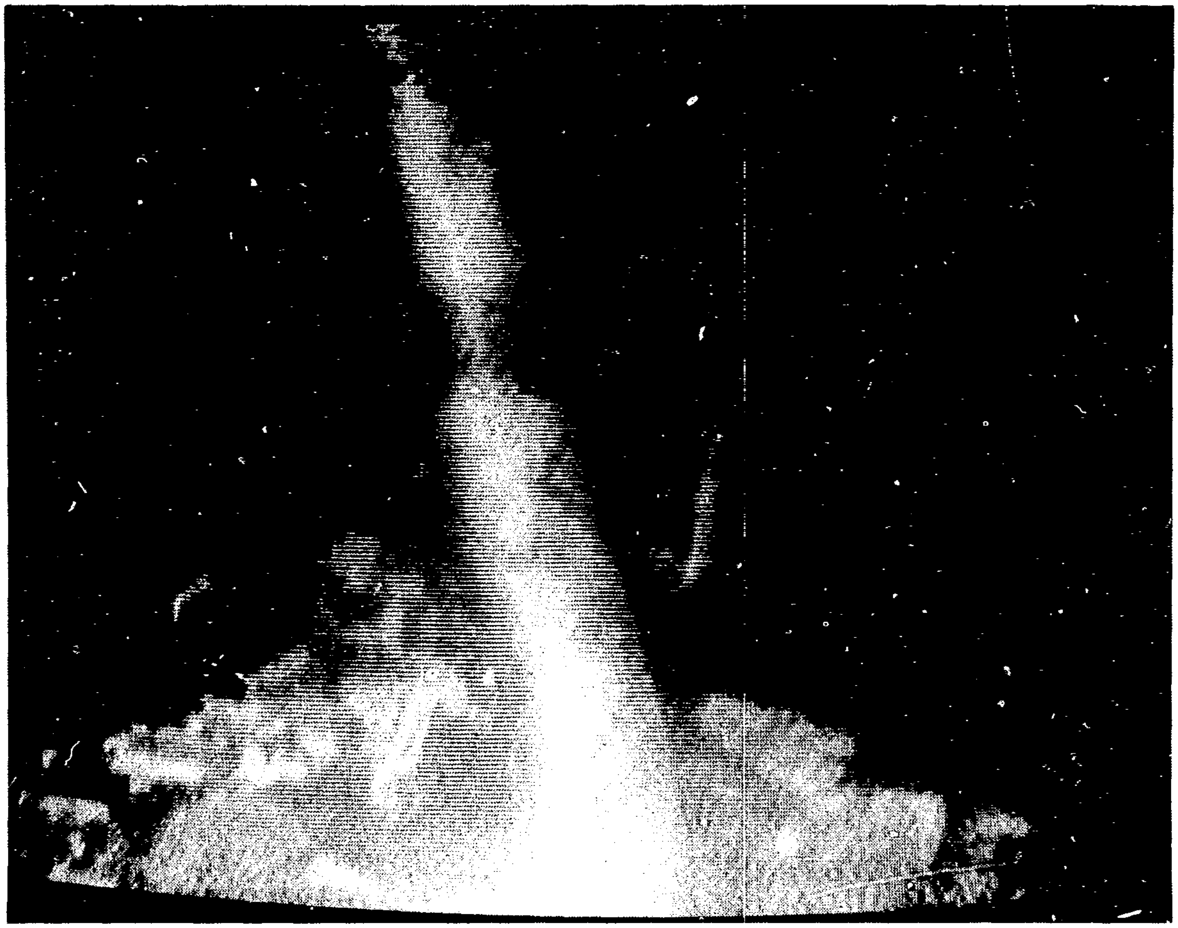


Figure 14. Photograph of debris bed at location E-9, showing larger recognizable pieces.

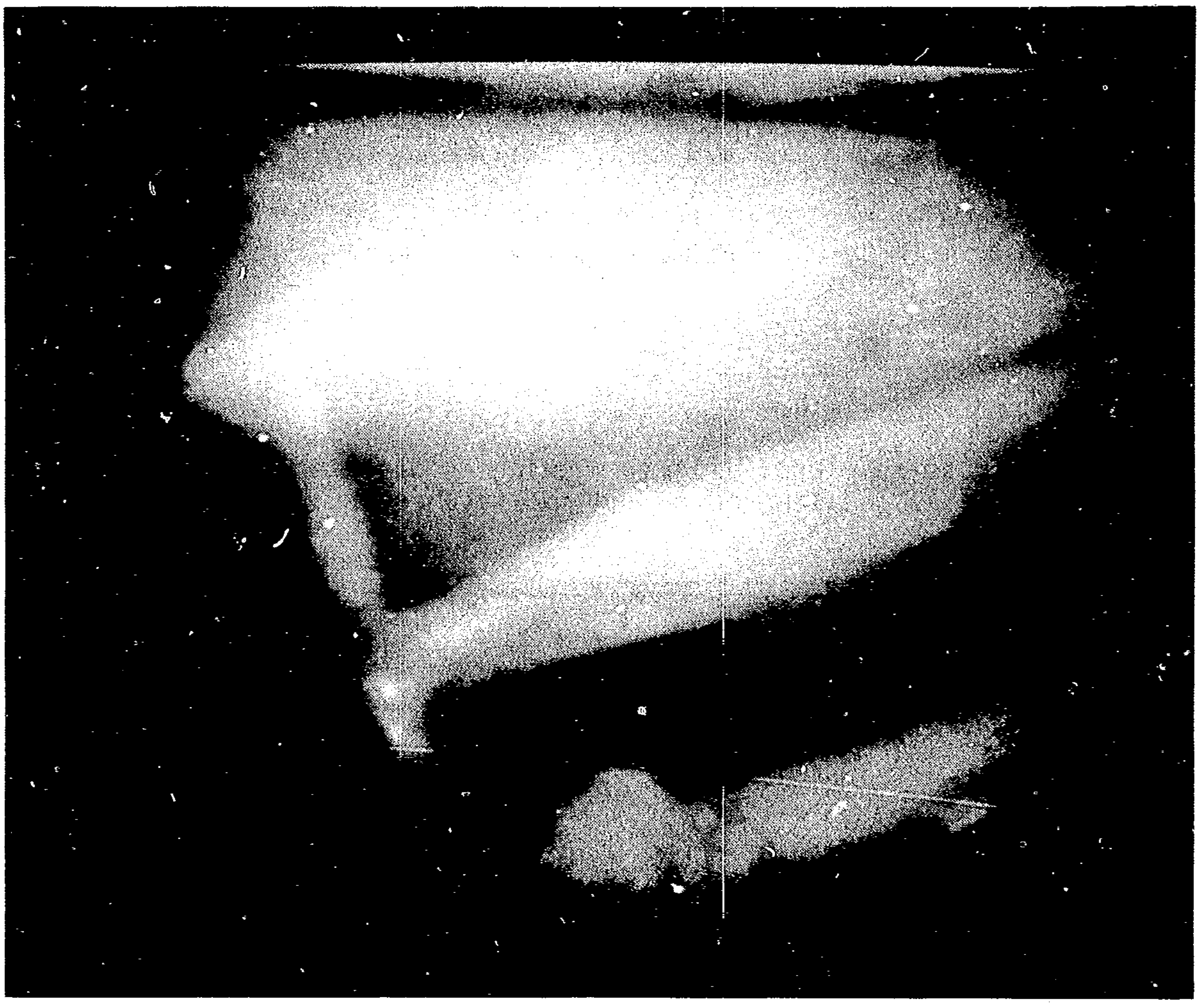
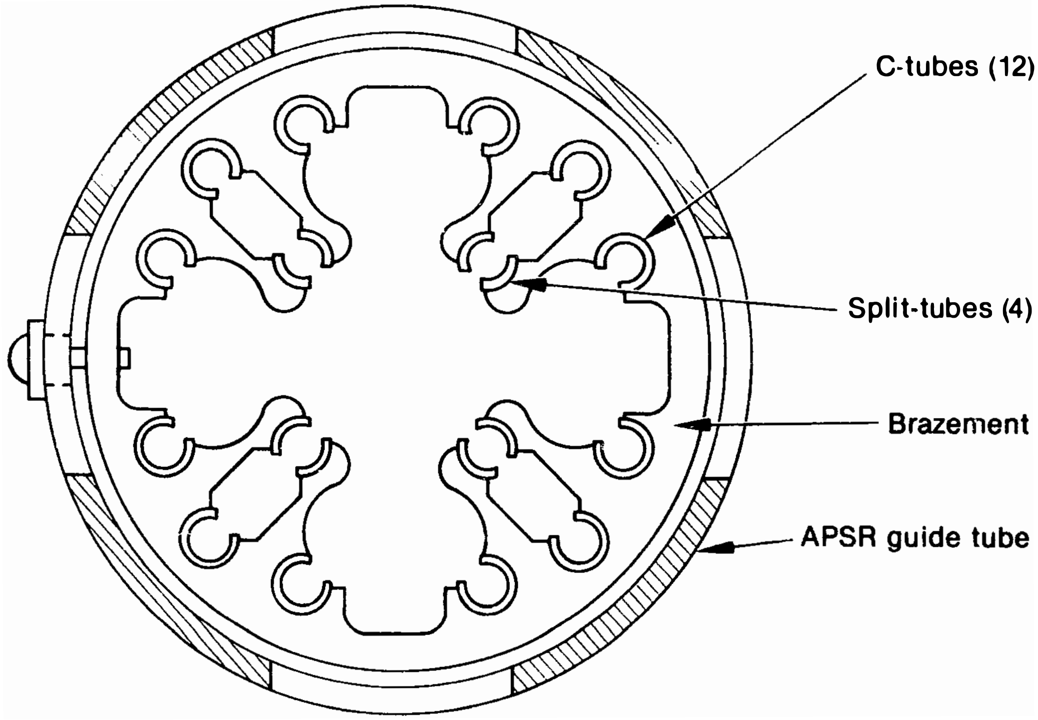
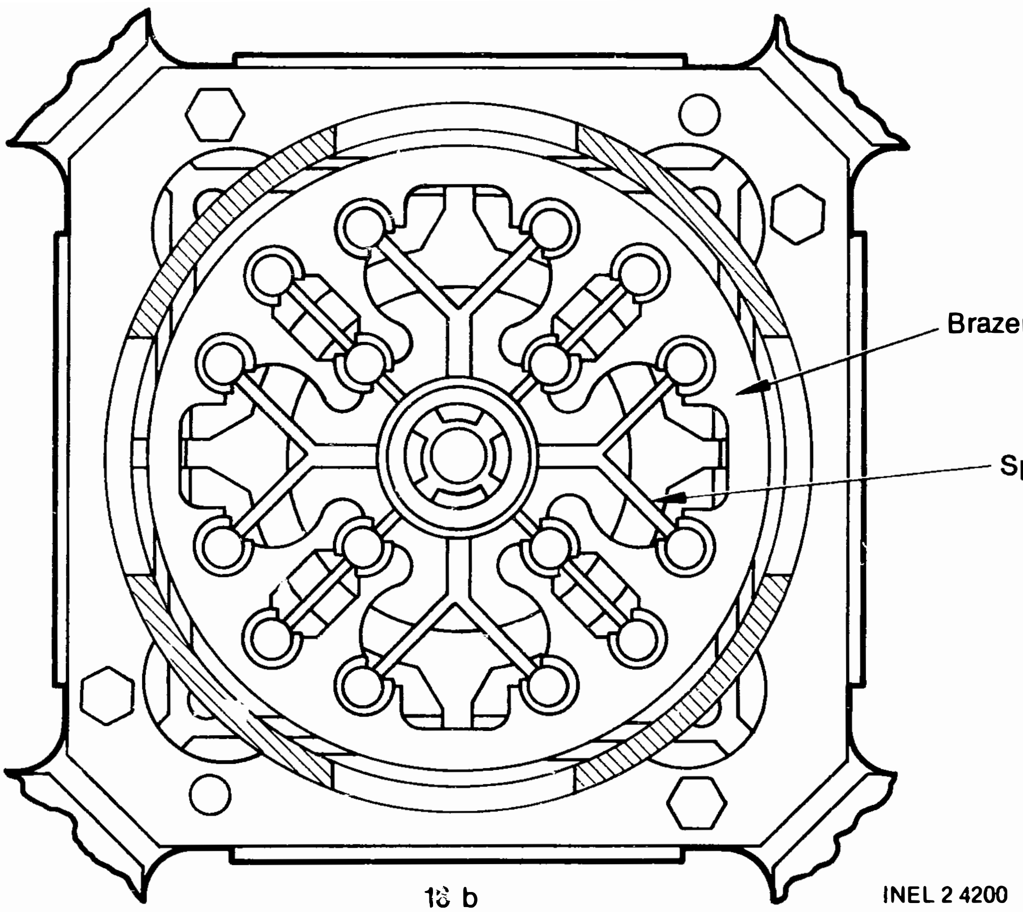


Figure 15. Photograph of grillage on bottom of a stainless steel upper end-fitting, showing partial melting and resolidification.




16 a

Figure 16a. Cross-sectional diagram showing relative orientations and radial location of C- and split-tubes in an APSR guide tube.




16 b

Figure 16b. Cross-sectional diagram showing how APSR spider and rods pass through the C- and split-tubes.

and in good condition. The brazement support plates, which support the C- and split-tubes, appear normal and show no sign of distortion, damage, or braze material melting.

## Conclusions From the "Quick Look" Examinations and Implications for the APSR Insertion Test

The following conclusions can be drawn from the three "Quick Look" camera examinations:

- The reactor upper plenum assembly, including the control rod and APSR guide tubes, brazements, C-tubes, and split-tubes, appears relatively undamaged.
- At the half-radius location there are some fuel assembly upper end-fittings attached to the underside of the plenum that contain some damaged fuel rods and control rods. There is evidence of some melting of parts of the stainless steel end-fittings. Such damage could inhibit APSR motion at the upper plenum support plate.
- The TMI-2 fuel was severely damaged over a significant portion of the core, with the result that a portion of the fuel is in rubble.
- A large void exists in the upper center of the core, due to settling of the damaged core or removal and redistribution of material from the reactor vessel.
- At two points--one at the center and the other midway to the edge--the rubble bed is composed of loose material to a depth of at least 35 cm (14 in.).

## Discussion of APSR Insertion Test Data

When the APSRs are partially withdrawn, part of each rod assembly is within the APSR guide tube assemblies and part is within the core region.

When the APSRs are fully inserted, all of the rod assembly is in the core region. Therefore, when the APSRs are partially withdrawn, resistance to movement may occur due to obstructions either in the guide tube region (also known as the reactor upper plenum region) or in the core region, or both. In the upper plenum region, the APSR rod assembly spider and portions of the APSR rods themselves must pass through guide tubes in the form of so-called C-tubes and split-tubes. Top views of an APSR guide tube assembly at the location of the C- and split-tubes are shown in Figure 16. Figure 16a shows the relative orientations and radial locations of the C- and split-tubes, and Figure 16b shows the C-tubes and split-tubes with an APSR spider and rod assembly passing through the guide tubes. In an APSR guide tube assembly, the C- and split-tubes extend essentially the full length of the APSR guide tube and are held in place by attachment to 10 brazements that are positioned axially as shown in Figure 17.

The relative axial positions of the bottom four APSR guide tube brazements have been superimposed over the APSR rod movement results (Figure 7) in Figure 18. From the data in Figure 18, it is postulated that the resistance to movement of some of the APSRs, as indicated by increased noise levels or, as in the cases of Rods 62, 63, and 66, complete stoppage of movement, may be due to interference caused by distortion or bowing of the C- or split-tubes. It is possible that the severity of the postulated distortions may be greater at the locations of the brazements, thereby resulting in complete stoppage of movement for Rods 62, 63, and 66 at these locations. Severe distortion of the C- and or split-tubes could also account for the fact that Rods 64 and 69 could not be inserted at all, and that Rod 68 could only be inserted a short distance before it reached a hard-stop position. The analysis by B&W of the APSR Insertion Test acoustic data (see Appendix B) concentrated on the role of the C-tubes, split-tubes, and brazement upon APSR insertion. The B&W analysis noted that the interference to rod motion observed for some APSRs coincided with the brazement locations, and concluded that such interference might be explained by core debris on the brazement plates or by local distortion of the C- and split-tubes caused by braze alloy melting.

It is also possible to make a similar comparison between the relative axial positions of the APSR control elements and the locations of possible

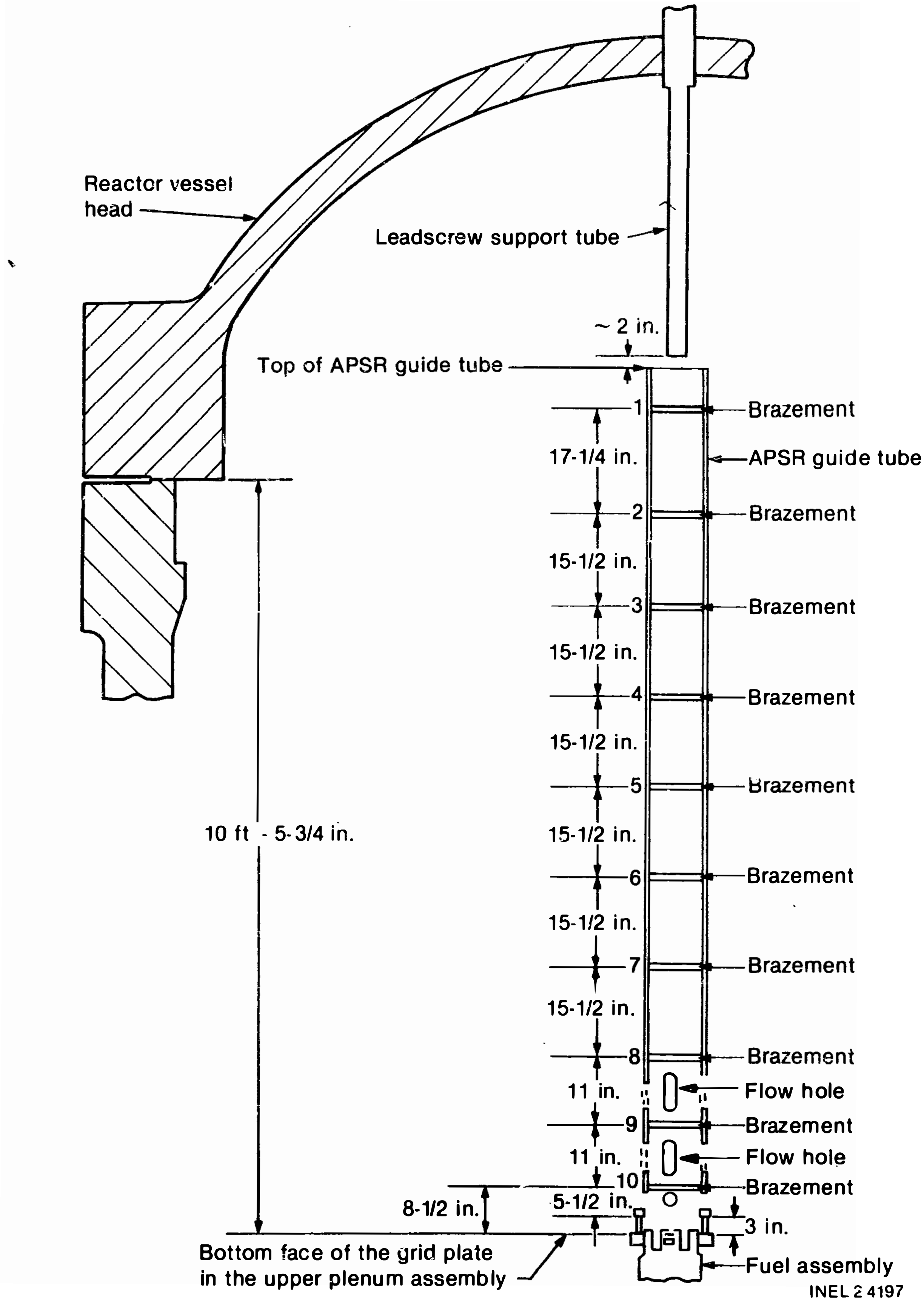



Figure 17. Reactor vessel head and APSR guide tube assembly, showing attachment of C- and split-tubes to 10 axially positioned brazements.

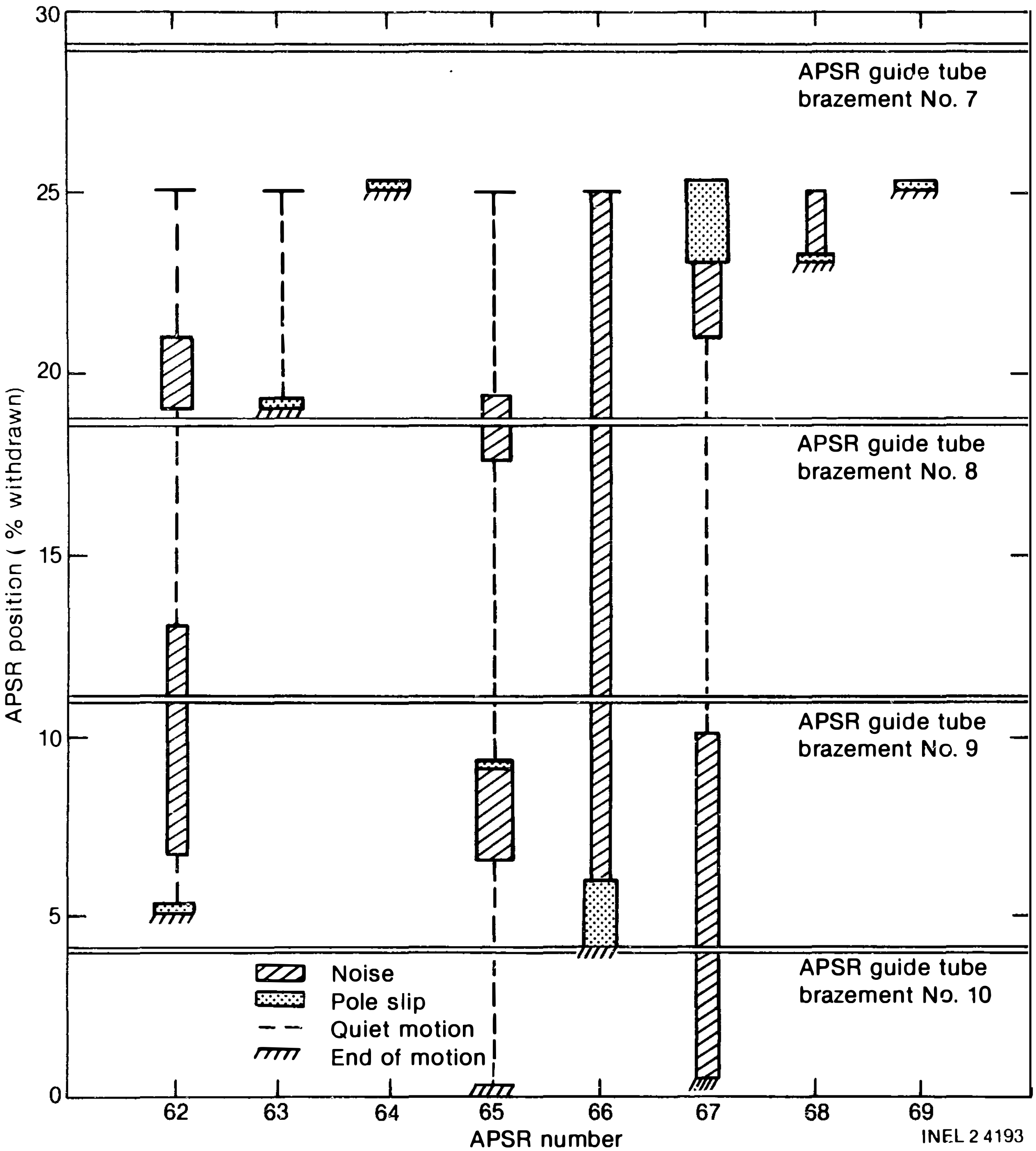



Figure 18. Comparison of guide tube brazement locations and relative APSR rod motion noise levels at different axial positions of the APSR spiders during the TMI-2 APSR Insertion Test.

obstructions in the core region. In the core, each of the APSR control rods must pass through a fuel assembly guide tube that is held in place by spacer grids. The guide tubes span the entire length of the fuel assemblies. Therefore, distortion of the guide tubes in the core region could easily increase resistance to movement of the APSRs, or even prevent movement. If the APSR assemblies are still intact, obstructions to their movement could be due to damage to the guide tubes in the core region. Figure 19 provides a comparison of the relative axial positions of the bottom tips of the APSRs and the axial positions of the lower two spacer grids in the TMI-2 fuel assemblies. From Figure 19, it is seen that of the four APSR control elements that were inserted to positions below the lower spacer grid, two of them exhibited high noise levels in the region of the bottom-most grid, and two of them exhibited reduced noise levels at this location. It is likely that distortion, or possibly extensive damage, to the APSR control rod guide tubes could have occurred over a large portion of the fuel assembly length in the core region, and that this distortion could contribute to APSR movement resistance. This possible explanation for APSR motion interference was noted by Service Application Incorporated (SAI) (Appendix C). However, SAI also concluded that the data obtained during the APSR Insertion Test were insufficient to confirm that the APSR assemblies were intact and connected to the APSR drives. Therefore, it would be highly speculative to attribute APSR movement resistance to specific in-core features such as guide tube distortion or spacer grid locations. It is possible, as shown below, that core damage was extensive enough that some, if not all, of the APSR control elements are themselves missing or severely damaged.

It is likely that the high temperatures that caused severe damage to the fuel assemblies, control rods, and fuel assemably upper end fittings also fused the cladding of the APSRs to the upper end fittings. Such interference might account for the lack of movement of Rods 64 and 69.

The core damage observations support the earlier conclusion that damage to the APSRs in the core region was so severe that the observed interference to APSR rod movement during the APSR Insertion Test could not have resulted from rod interference with fuel assembly guide tubes or spacer grids.

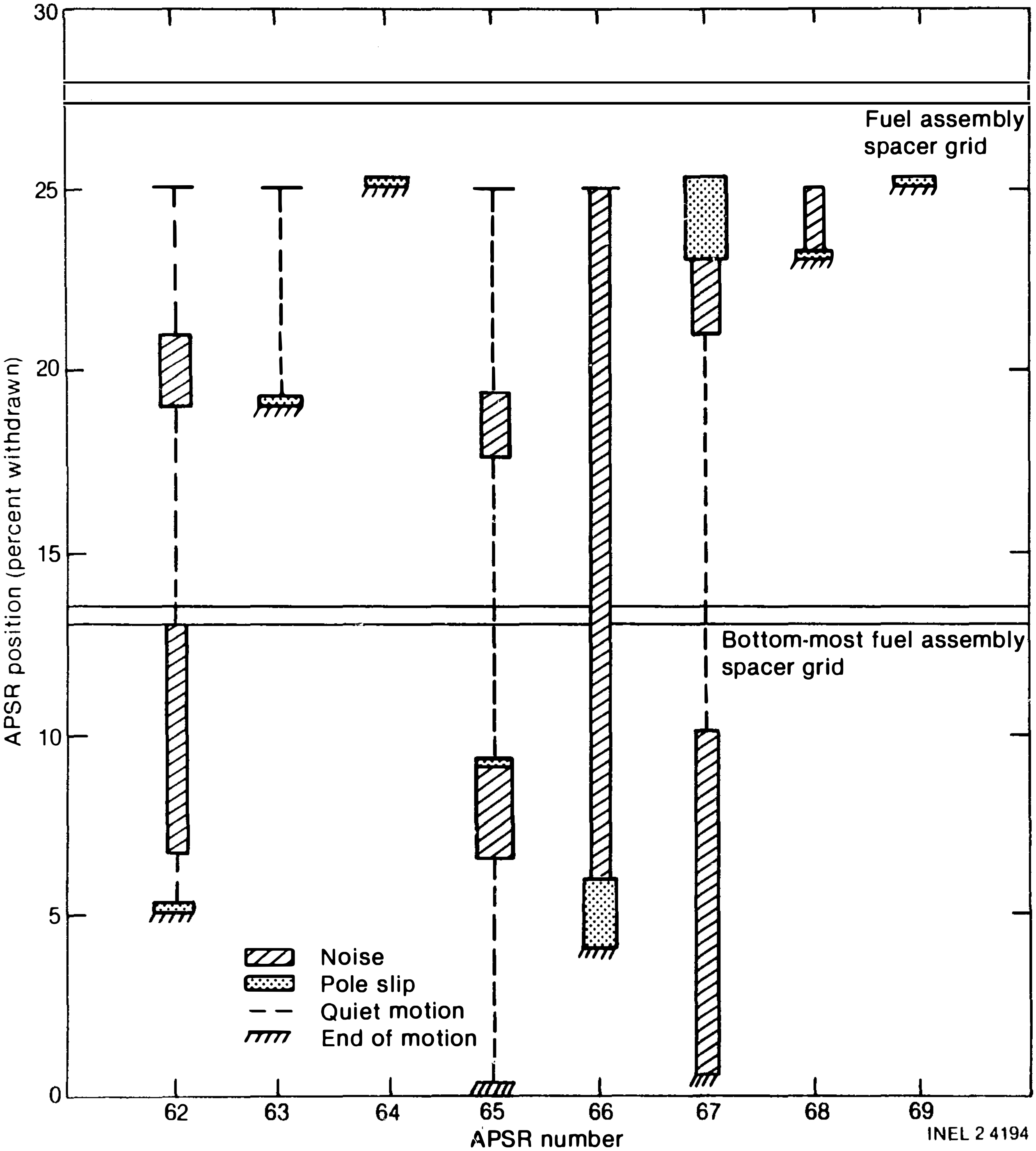



Figure 19. Comparison of fuel assembly lower spacer grid locations and relative APSR rod motion noise levels at different axial positions of the APSR tips during the TMI-2 APSR Insertion Test.

The apparent lack of severe damage to the reactor upper plenum and APSR guide tubes lends credence to the hypothesis that the observed interference could result from local distortion to the APSR C- and split tubes, or in those cases where the APSRs could not be moved at all, to welding of the APSR control rods to the fuel assembly upper end fittings.

# CONCLUSIONS

The TMI-2 APSR Insertion Test was successful because it yielded direct information on the condition of the rod drive motors, and allowed inference of the condition of the leadscrews and the upper plenum guide tubes. All of the APSR drive motors worked properly. The upper plenum guide tubes did not show any evidence of severe damage, based on camera insertion information and on the fact that they did not totally obstruct APSR movement. All of the APSR leadscrews were inserted to a hard-stop position, and subsequently were successfully uncoupled from their rod spiders.

The APSR Insertion Test provided substantial information on the dynamics of APSR motion in the damaged reactor. Key operations, such as latch, unlatch, drive, and pole slip, were readily detected by comparison with acoustic signatures in the undamaged TMI-1 reactor and from out-of-reactor experiments on APSR drive mockups.

The APSR Insertion Test provided little definitive information applicable to determination of the physical condition of the TMI-2 core itself. However, the ability to move APSR Drives 62, 65, 66, and 67 to essentially the fully inserted position correlates well with the information on the physical damage to the core indicated by the in-core instrumentation and with the "Quick Look" camera insertion pictures. The "Quick Look" inspections point to very severe fuel damage extending to the vicinity of the APSRs. Therefore, the movement of APSR Drives 62, 65, 66, and 67 probably results from the nearly total breakup of the fuel assemblies and APSR assemblies at those locations, such that only the APSR leadscrews, the spider, and perhaps the uppermost portion of the APSR clusters were actually moving. Also, the inability to move APSR Drives 64, 68, and 69, and the ability to move Drive 63 only slightly, may indicate that in these locations resistance to APSR rod motion, and acoustic noise, may result from friction and interference in the lower portion of the C- and split-tubes, or from core debris or distortion in the region of the brazements that support these tubes, or from welding of the APSR control rods to fuel assembly upper end fittings that may in turn be distorted or welded to the upper plenum support plate.

## REFERENCE

1. J. A. Gannon, Development of In Situ Test Procedures for TMI-2 Axial Power Shaping Rod Drive Mechanism, GEND-INF-028, December 1982.