PRELIMINARY RESULTS OF THE TMI-2 CORE BORES[a]

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ABSTRACT

This paper presents the core bore acquisition data available to date from the Department of Energy TMI-2 Sample Acquisition and Examination Program. Core bore samples have been recently acquired and video inspection of the lower core and core support regions have been completed via the core bore access holes. The data summarized in the paper include basic observations characterizing the lower region of the core, the core support assembly and lower plenum debris, and details showing how an end-state core configuration was estimated. Implications of the core bore acquisition data on the core damage are discussed in a companion paper[6] also presented in the Conference.

INTRODUCTION

The TMI Accident Evaluation Program[1] of the Department of Energy (DOE) is conducting research to complete our understanding of the TMI-2 accident. THe research findings will aid in resolving severe accident and source term issues and support the TMI-2 recovery effort. The research has determined that damage to the TMI-2 core is extensive, with core melting and relocation of molten core materials into the reactor vessel (RV) lower plenum. A scenario for the accident has been proposed that appears to account for most of the major events and resultant core damage.[2] However, some details of the scenario are not fully understood; these include (a) the physical mechanisms leading to core failure and subsequent relocation of molten materials into the lower plenum, (b) the extent of damage to the core support assembly, instrument structures, and the RV lower head, (c) the long-term cooling of the degraded core and the core debris in the lower plenum, and (d) the retention and distribution of fission products within core materials. An adequate understanding of each of these areas requires extensive physical and chemical evaluation of the core materials and RV components, together with detailed analysis and interpretation of the reactor system thermal-hydraulic measurements recorded during the accident.

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A comprehensive sample acquisition and examination plan[3] was developed to guide the operations that acquire and analyze samples. The sample acquisition and examination work will provide physical samples of the core materials as the core is being defueled and provide video characterization of the state of the core damage.

To provide samples of core materials from known locations of the core and lower plenum regions, a drilling unit was designed to drill through the degraded core material. A drill unit was modified using available mining/geology equipment and technology to provide (a) precise positioning over the reactor vessel, (b) a microprocessor for operational control and safety interlocks, and (c) recorded drilling parameters (torque, load, etc.) The machine drilled "core" samples approximately 2.5 inches in diameter, which were enclosed in slightly larger casing tubes. The encapsulated samples were then removed from the core region. The resulting hole provided access for video inspection. The drill samples will be gamma-scanned, sectioned, and radiologically and metallurgically examined to determine fission product retention, material composition, and peak accident temperatures.

Prior to core boring, it was known that the upper core consisted of an upper void region almost entirely surrounded by standing peripheral assemblies, and a region of loose debris resting on a hard crust, as illustrated in Figure 1. Conditions within the confines of the core boundary but beneath the hard crust were unknown. It was estimated that the RV lower plenum contained 10 to 20 tons of core debris. Based on examination of loose debris from the lower plenum, it was known that the materials were primarily ceramic fuel and cladding, and that UO_2 melting temperatures had been reached.

The primary goal of the core boring operation was to obtain physical samples necessary to spatially characterize the current chemical and physical states and distribution of core materials. Specific operational objectives were as follows:

1. Acquire up to nine core bores spatially distributed such that a representative sampling of core materials is obtained

2. Acquire one core bore from core materials in the lower plenum through the lower plenum inspection port in the core support assembly (CSA) beneath the K9 assembly

3. Acquire a sample of core materials at the location where molten materials relocated into the RV lower plenum

4. Obtain samples for comparison from control rod and burnable poison rod assemblies.

Assemblies were selected for drilling that satisfy the objectives. However, a number of constraints existed that restricted the available drilling locations. These constraints included the following:

1. Drilling was not permitted in instrumented fuel assemblies because of safety considerations related to potential failure of the instrument penetration nozzle weld joints in the lower RV head

2. Drilling in the outer two rows of fuel assemblies was not possible because of hardware interface restrictions

3. Drilling into the lower plenum was restricted to the five lower plenum inspection locations in the core support assembly

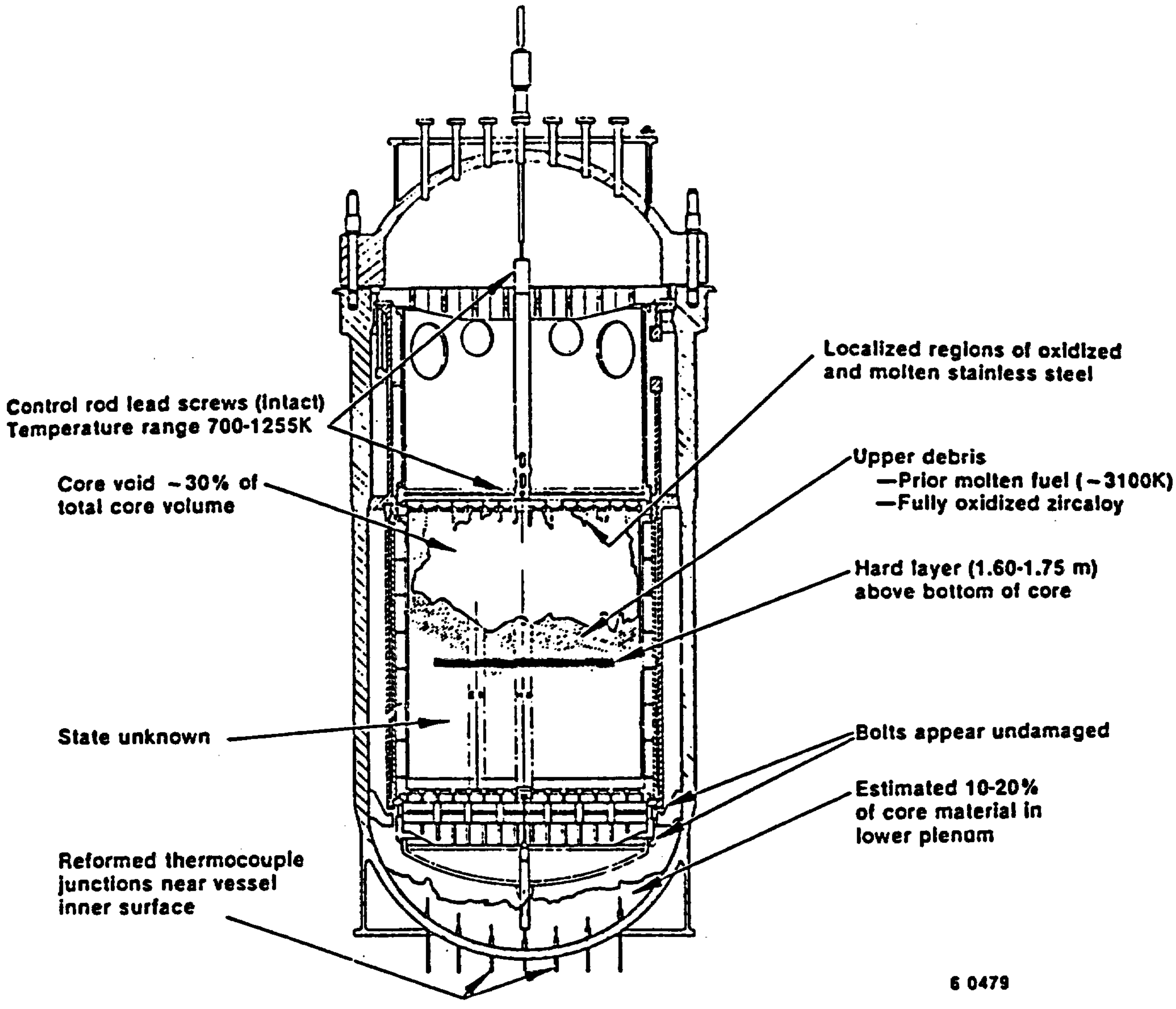

Figure 1. Known core and reactor vessel conditions prior to core bore acquisition.

4. Only twelve locations had been cleared of endfittings, spiders, and fuel debris in preparation for drilling. Drilling at other locations was considered to have a high potential for failure because of the presence of assembly endfittings and spiders.

The assemblies from which the ten core bores were drilled are identified and their locations shown in Figure 2. The pattern provides east-west and southwest-northeast diametral cross-sectional samples, as well as two radial sample cross sections from core center to the north and one to the southeast. A north-south sample line was also established on the eastern side of the core. The ten core bores provide two samples from the center of the core, two samples from near mid-radius, and six samples from around the core periphery. Access into the lower plenum for video inspection was obtained at three inspection locations, N12, D4, and K9, and two samples may have been obtained from the lower plenum at assemblies K9 and D4.

OBSERVATIONS OF THE CORE REGION

Video data[a] viewed from the interior of the core bore holes reveal two distinct regions between the hard crust and the fuel assembly lower endfitting. These are (a) a region containing previously molten core materials directly below and including the hard crust, and (b) a region of intact standing fuel rods extending from the bottom of the previously molten region to the bottom of the core.

The previously molten region was further divided into two types: namely, (a) previously molten ceramic material appearing to have a uniform, homogeneous structure, and (b) previously molten ceramic material surrounding generally degraded but intact fuel pellets and fuel rods. The latter type is hereinafter referred to as "agglomerate" material. In some regions of the agglomerate material, the fuel pellets were axially stacked together as in the original fuel rods; in other regions, the fuel pellets appear to have random orientations. In general, the agglomerate material containing stacked pellets was observed in the peripheral core bore holes and at the bottom of the centrally located core holes (G8, K9, and K6). The agglomerate material containing random fuel pellets was observed at the top of core bore holes G8 and G12.

A summary of the observations from central core bore location K9 is shown in Figure 3. As shown in the figure, homogeneous previously molten core material extends from the top of the core bore hole down to near the top of the second spacer grid, a distance of almost 50 in. (the greatest depth observed in the core bores). The previously molten homogeneous core material is about 40-in. thick at core location G8 and about 30-in. thick at location K6. A 4- to 6-in.-thick region of agglomerate material separates the previously molten homogeneous material from standing fuel rods in the lower regions of the core in core bore location K9. A large metallic-appearing structure that has been partially, or perhaps fully,

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a. Video data were all taken by GPU Nuclear.

molten was observed near the top of the drill hole. A possibly metallic form was observed to be embedded in the homogeneous ceramic material 30 in. above the bottom of the core, and what appeared to be a partially melted spacer grid in the homogeneous ceramic material was observed 26 in. above the bottom of the core.

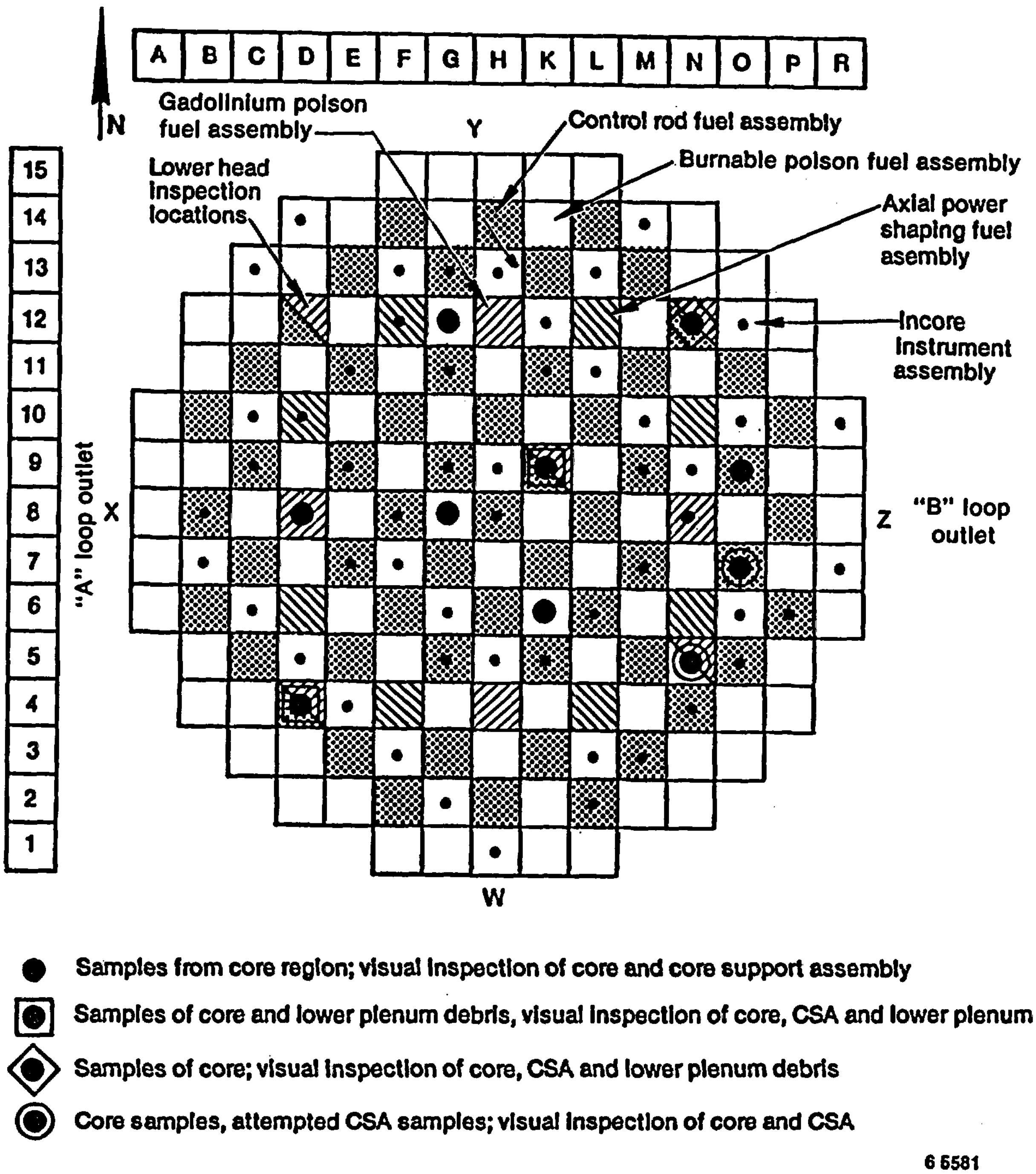

Figure 2. The ten core bore drilling locations.

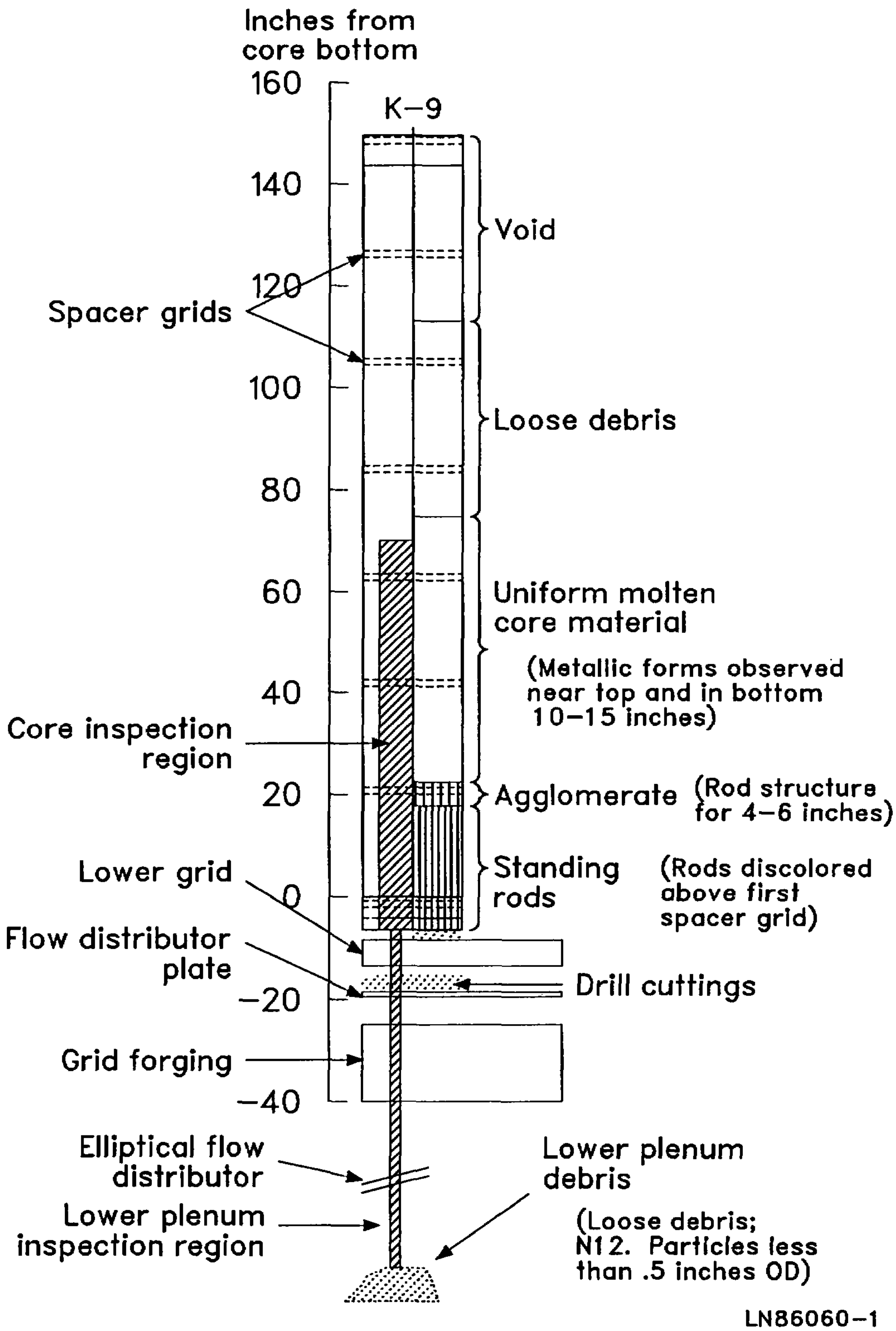

Figure 3. Summary of observations from central core bore location K9.

A summary of observations from peripheral core bore location N12 is shown in Figure 4. Agglomerate material with vertical fuel rod structure extends from the top of the core bore hole to the transition region between agglomerate material and standing fuel rods. The agglomerate material is only about 14-in. thick, and standing fuel rods extend 48 in. above the core bottom. Previously molten homogeneous ceramic material was not observed in any of the peripheral core bore holes (D4, D8, N5, N12, O7, O9).

At location G12, a thin region of previously molten homogeneous core material is bounded by a region of agglomerate material with randomly oriented fuel pellets on the top and a zone of agglomerate material with vertical, intact fuel pellets on the bottom. The standing fuel rods extend about 42 in. above core bottom, as illustrated in Figure 5.

At location D4, there are axial regions of alternating agglomerate and relatively undamaged fuel rods, with solidified melt droplets attached. The axial variability in material structure suggests that molten material may have flowed laterally into this region, rather than axially from above.

The homogeneous, previously molten core region, agglomerate region, standing fuel rod region, and upper core debris bed are spatially defined by contour mapping the interfaces between these regions. The contour map of the transition region between the standing fuel rod stubs and the agglomerate material (as determined from the core bore visual data) is shown in Figure 6, and illustrates that the height of standing fuel rods from the bottom of the core varies from about 30 in. at the core center to between 50 and 60 in. at the core periphery. Data from References 4 (core probe data) and 5 (acoustic topography data) were used to construct contour maps defining the lower supporting surface of the debris bed (upper surface of the molten core region) and the upper surface of the debris bed. These contour data are shown in Figures 7 and 8, respectively. Using these three contour maps, regions defining the lower standing fuel rods, the previously molten core zone, and the upper debris bed can be estimated through any row of core fuel assemblies.

Figure 9 shows these regions as they extend through the G row of fuel assemblies. The standing fuel rod stubs at the core bottom support the agglomerate and molten ceramic regions. The agglomerate region forms a shell surrounding the central zone of previously molten ceramic material. The shell is relatively thin under the previously molten ceramic in the central core region but increases in thickness toward the outer regions and forms all of the degraded core material above the standing fuel rods in the outer fuel assemblies. As noted earlier, the agglomerate in the lower central region of the core appears to be composed of previously molten material surrounding intact vertical rod stubs. The rod pellet boundaries are discernible inside the rods (axial interfaces between pellets) but are not generally well-defined at the outer radial surfaces of the rods, which are in contact with the interstitial, solidified melt material.

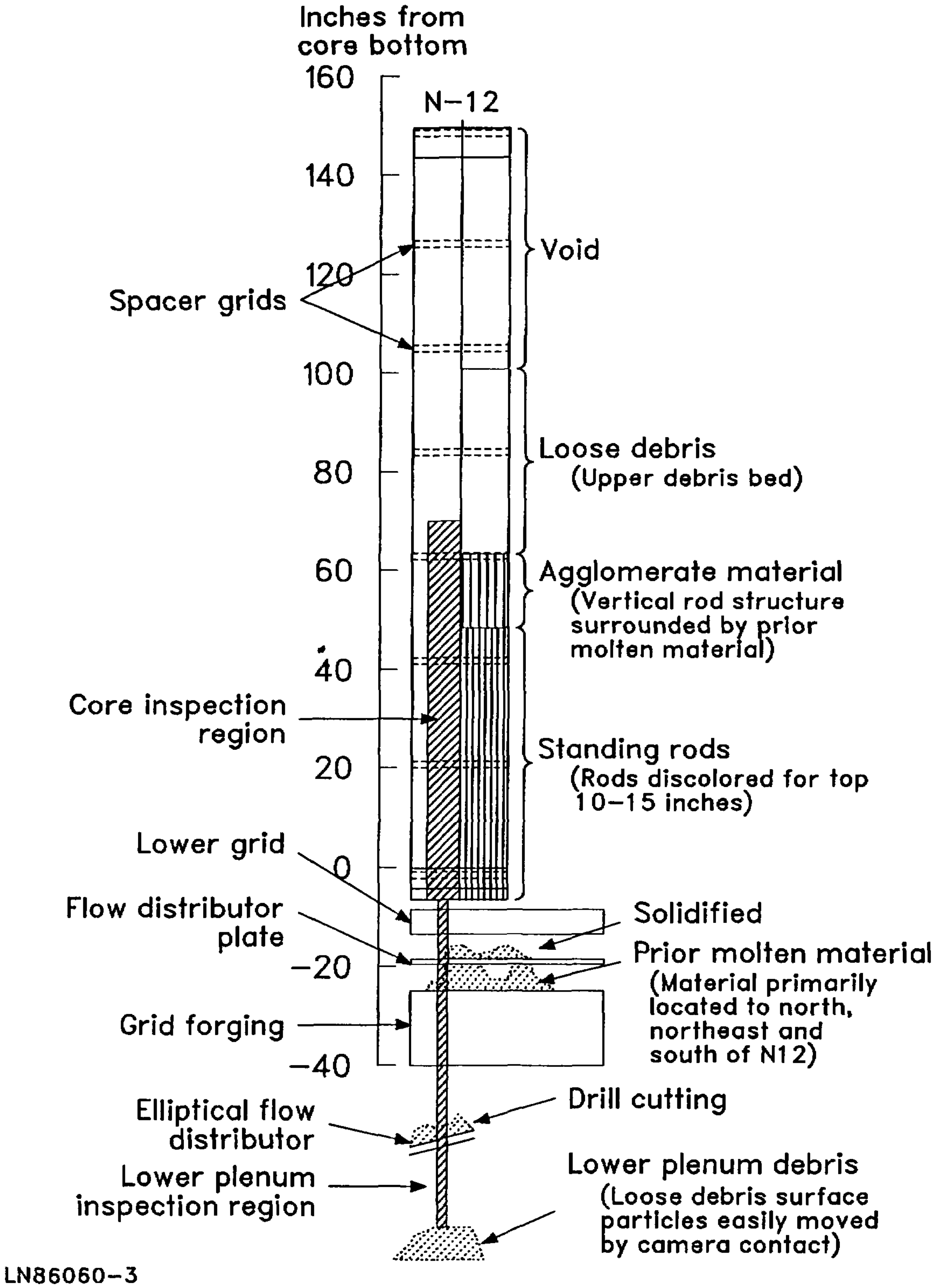

Figure 4. Summary of observations from peripheral core bore location N12.

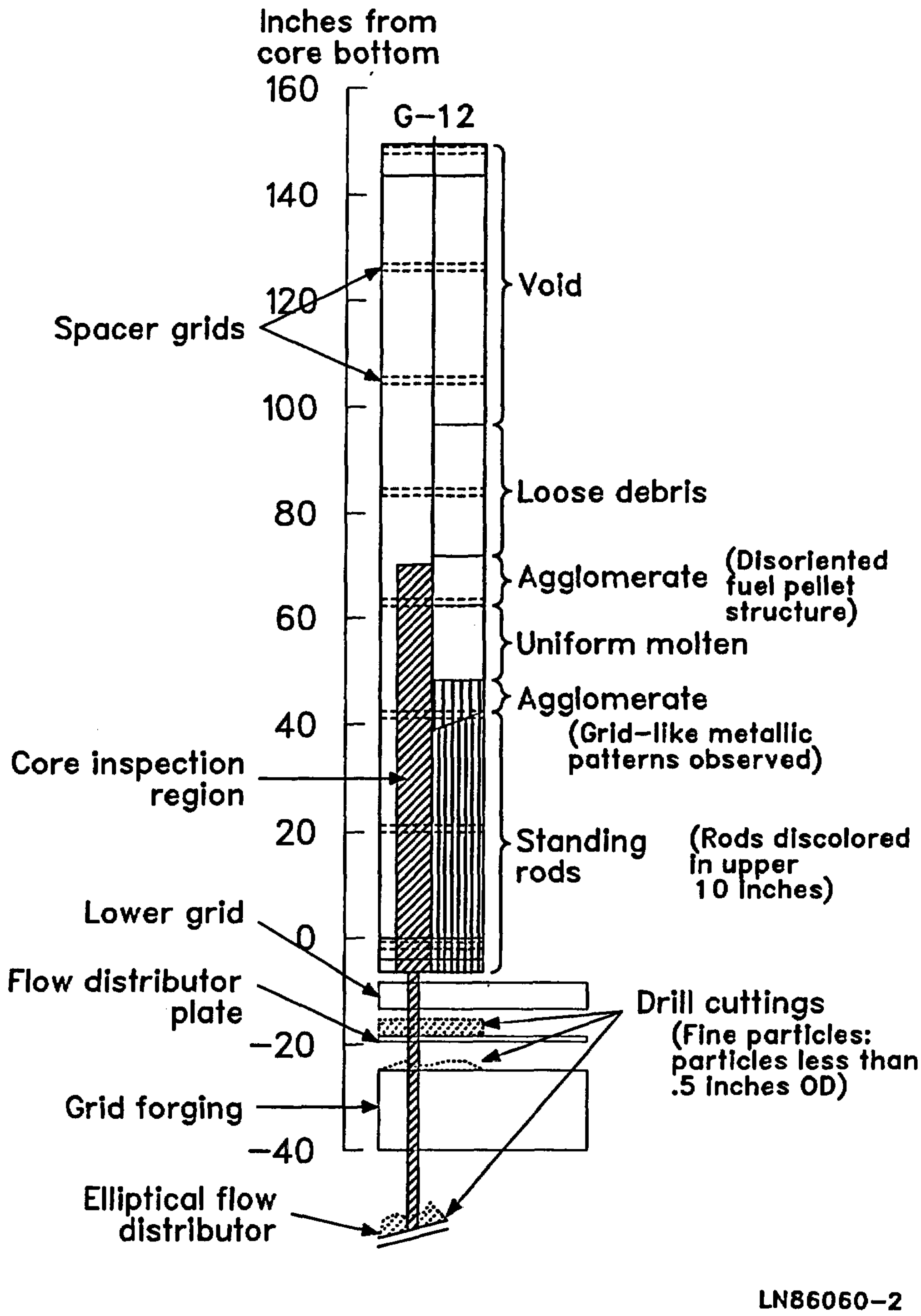

Figure 5. Summary of observations from core bore location G12.

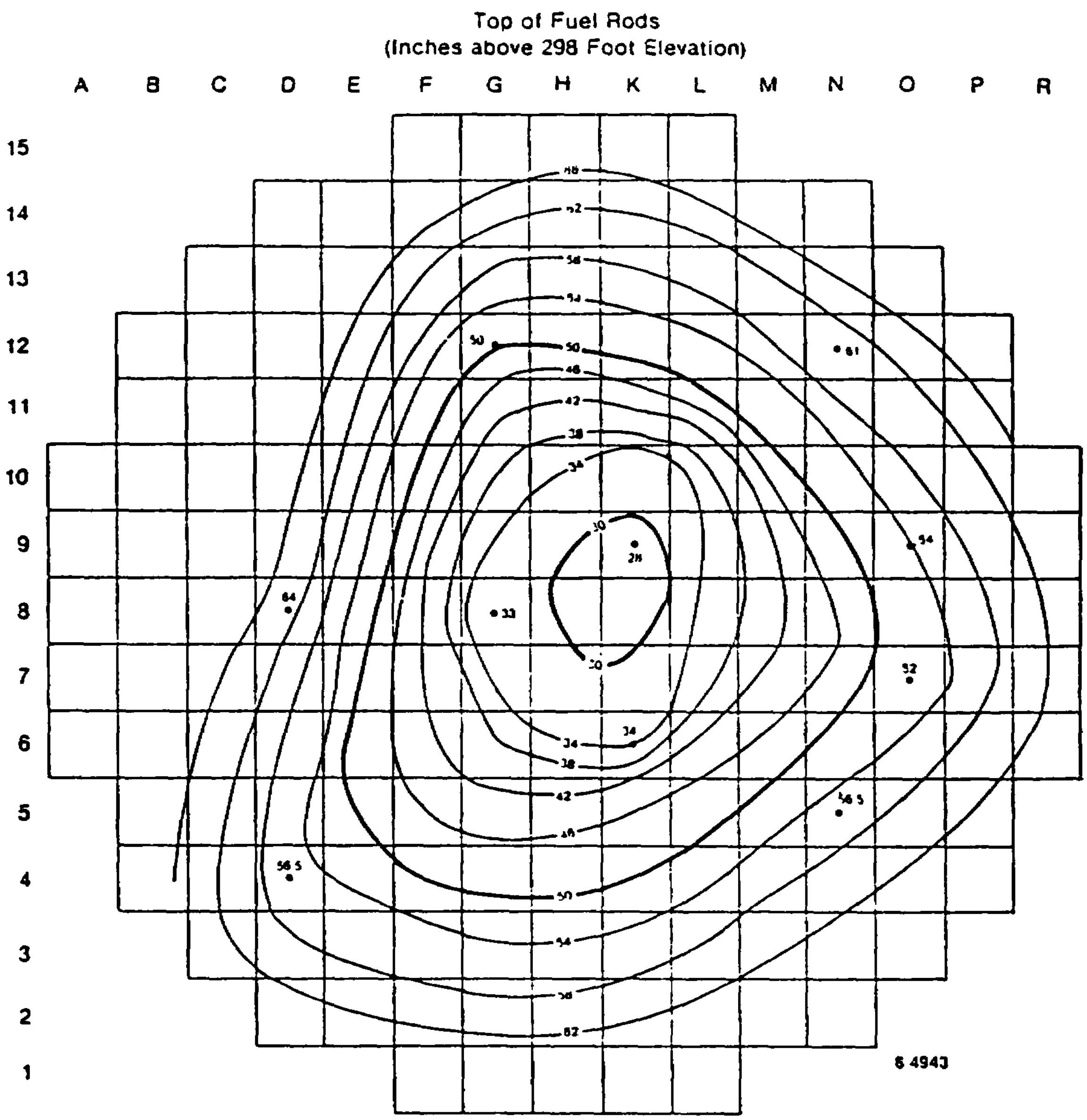

Figure 6. Contour map of the lower, intact fuel rods and molten core interface.

Hardstop Surface from Probe Data
(Inches above 298 Foot Elevation)

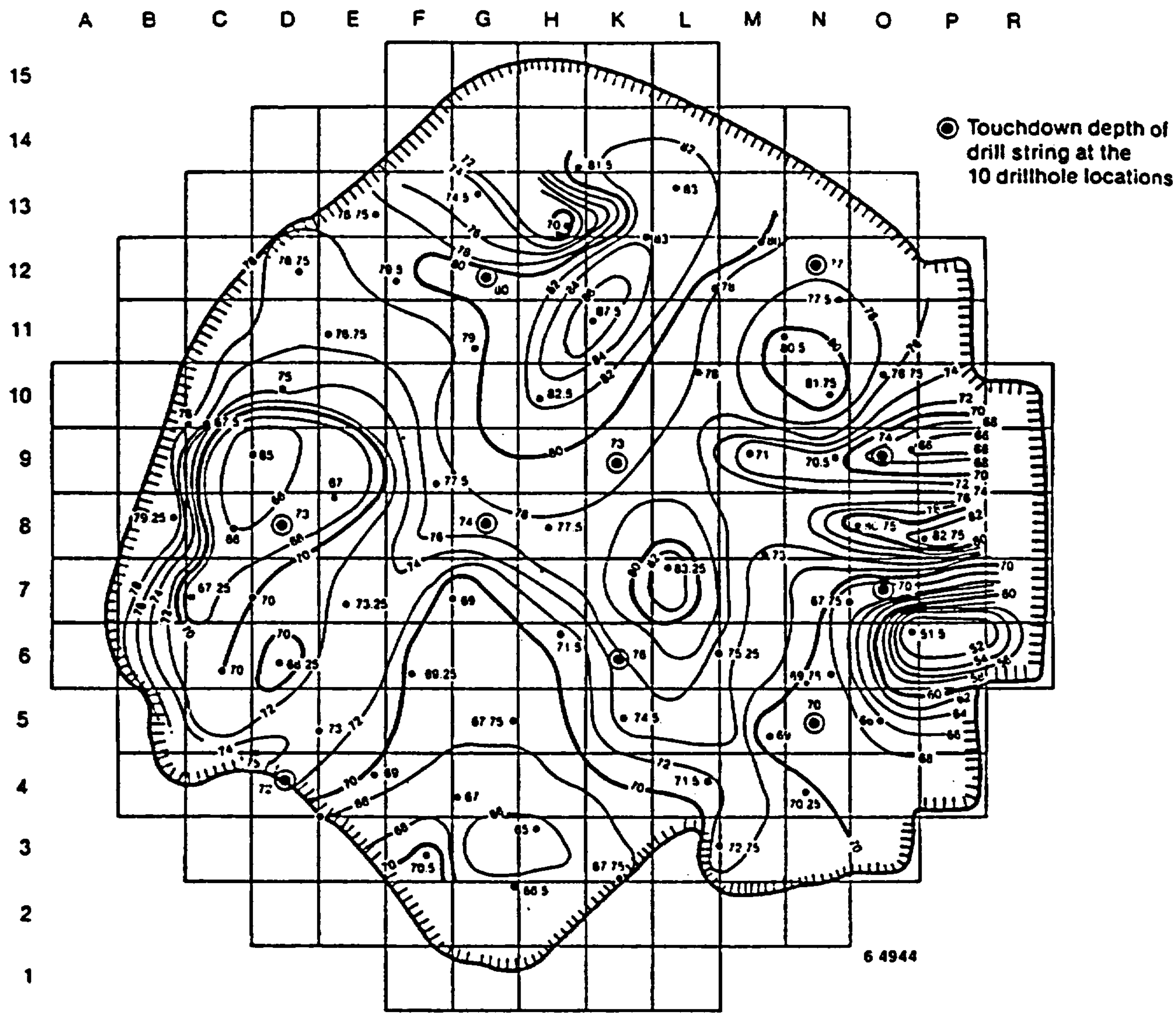

Figure 7. Contour map of the molten core upper surface region developed from hard stop data of rod probe.

Top of Debris Bed
(Inches above 298 Foot Elevation)

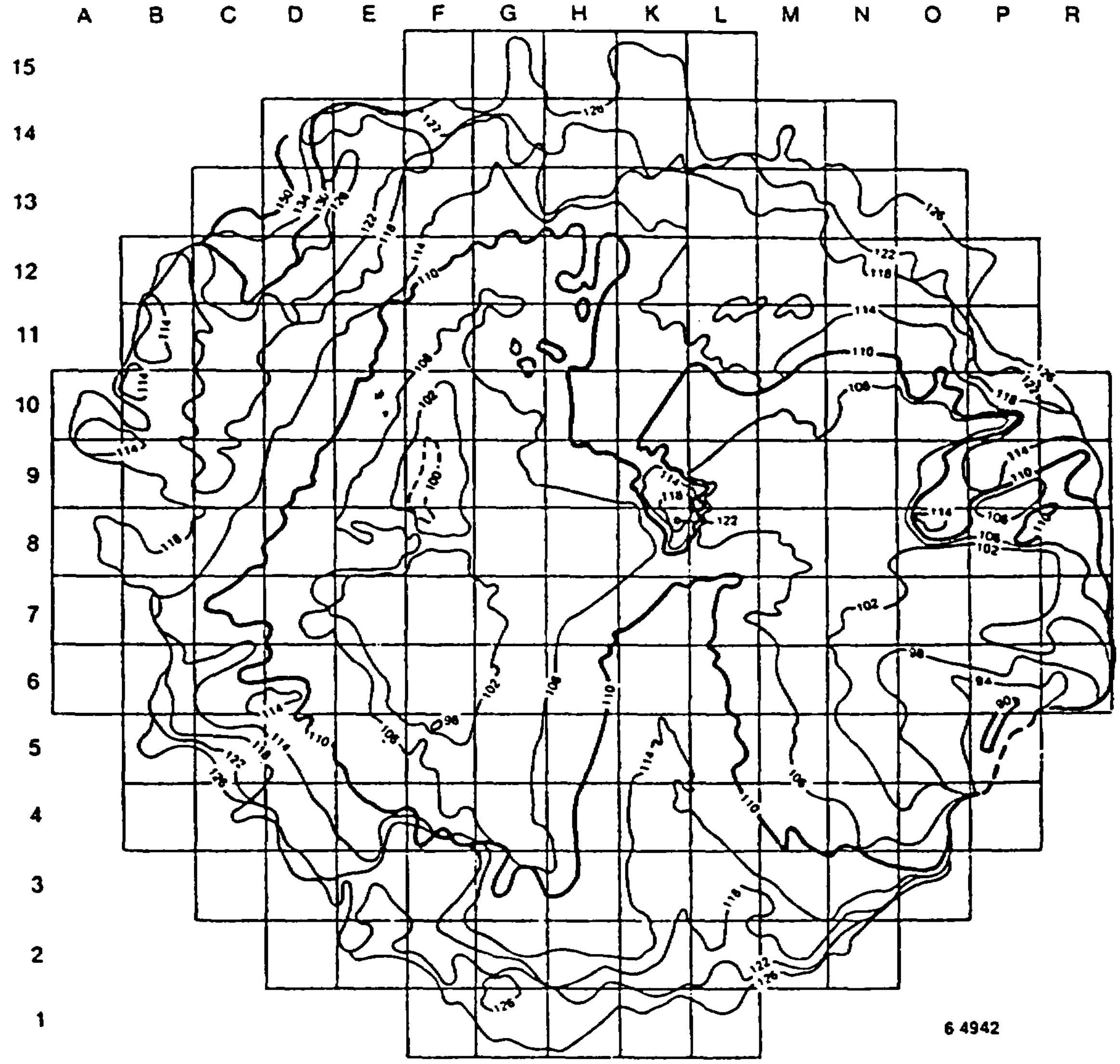

Figure 8. Contour map of core debris upper surface.

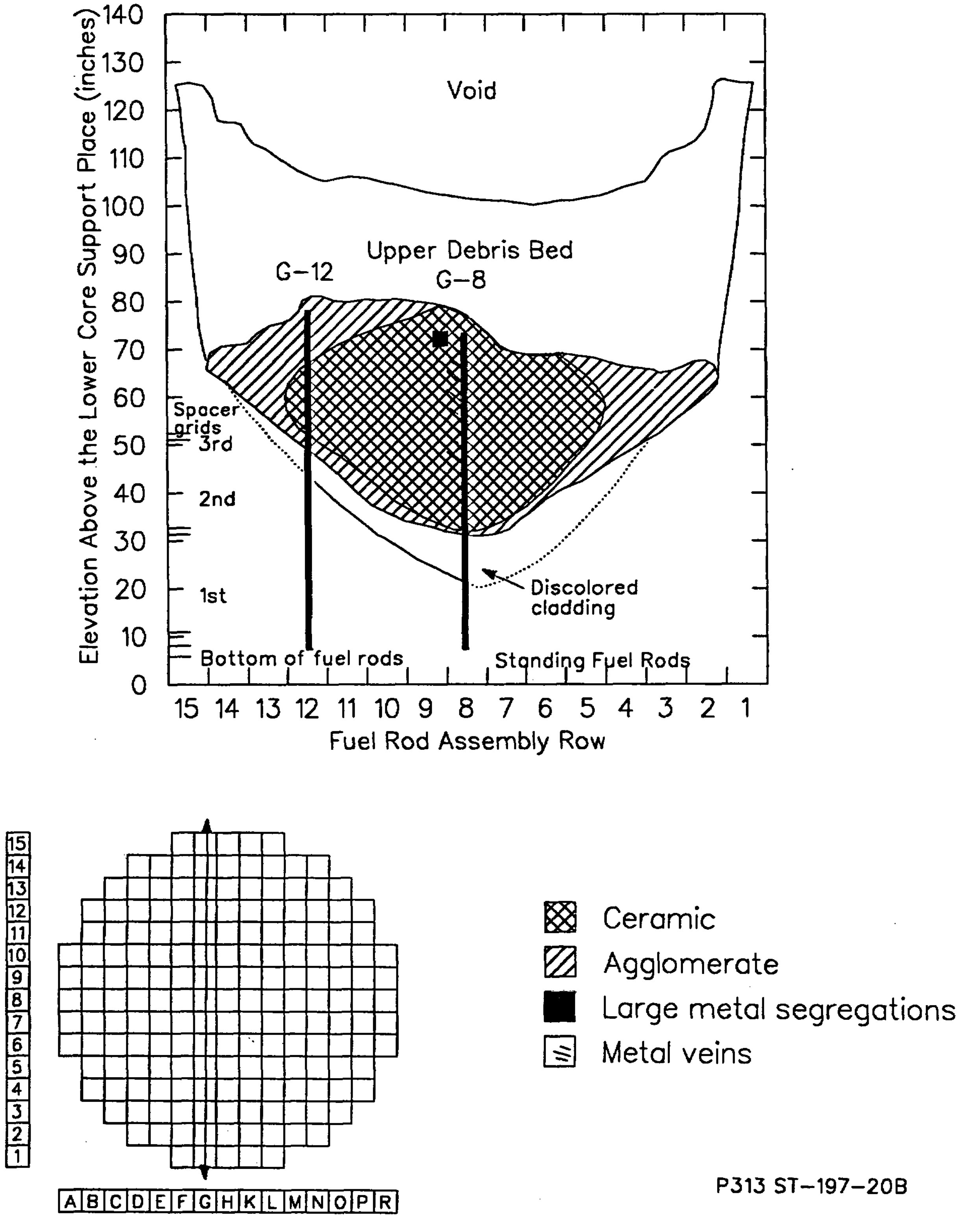

Figure 9. Core cross section across G row of fuel assemblies.

During preparation for the core bore drilling, remnants of agglomerate material similar in appearance to the agglomerate observed in the core bores were observed at the core periphery and above the hard surface supporting the upper debris bed. The exact configuration of this material is not yet well-characterized because of limited video data but is roughly approximated as a ring at the periphery of the core, as shown in Figure 7. This may represent the top of the solid structure prior to relocation of molten material into the lower plenum. The top center of the crust may have collapsed as the molten material relocated, forming what appears now to be a "sinkhole" in the solid, previously molten structure. Fuel pellets within the rim of agglomerate material are generally in the original vertically stacked orientation.

OBSERVATIONS OF THE CORE SUPPORT ASSEMBLY

Video inspection of the core support assembly (CSA) at each core bore location allowed evaluation of CSA damage and identification of the locations where the core material flowed from the core into the lower plenum. Figure 10 summarizes the regions of the CSA that were discernible from the visual inspections and indicates that approximately half of the CSA regions were characterized.

Visual inspection confirms that no damage to the CSA occurred below the central region of the core. Some fine, sandy material, most likely drilling debris, was observed at each of the central drill locations. The only locations that indicated significant core material relocation into the CSA were N5, N12, O7, and O9, all located on the east side of the core near the periphery. The approximate locations in which significant molten, relocated core material was observed in the CSA are shown in Figure 11. The material resembles the molten material observed in the core region and looks like it froze in the CSA regions as it flowed downward, thus resembling a cascade or curtain.

OBSERVATIONS OF THE LOWER PLENUM

The core bore inspection provided the first close-up visual inspection of the debris bed surface in the center of the lower plenum, beneath the K9 assembly. Inspection of the lower plenum was also completed beneath the N12 and D4 assemblies. The surface debris material was similar at all locations and appeared as loose gravel, having particle diameters less than half an inch. However, the debris was finer at K9 than at D4 or N12.

Sampling of the debris material was attempted at locations K9 and D4 by drilling into the debris bed to within approximately 8 in. of the RV lower head. After removal of the sample casing, the debris apparently collapsed into the drill hole. Because the debris was relatively fine, it is doubtful that a significant sample was obtained from either drill location. The estimated heights of the debris bed at each inspection location are illustrated in Figure 12.

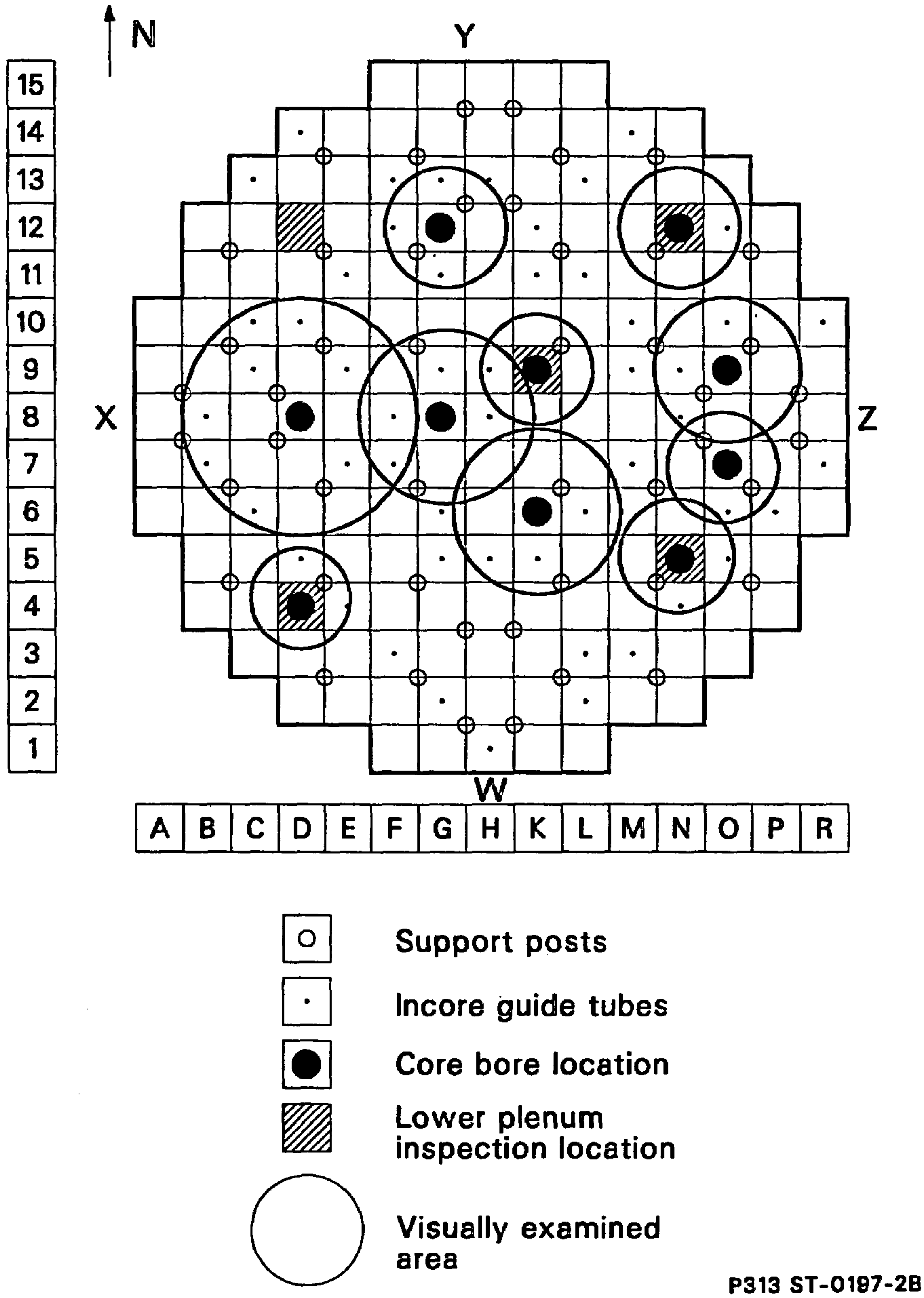

Figure 10. Approximate core support assembly regions discernible in the video data.

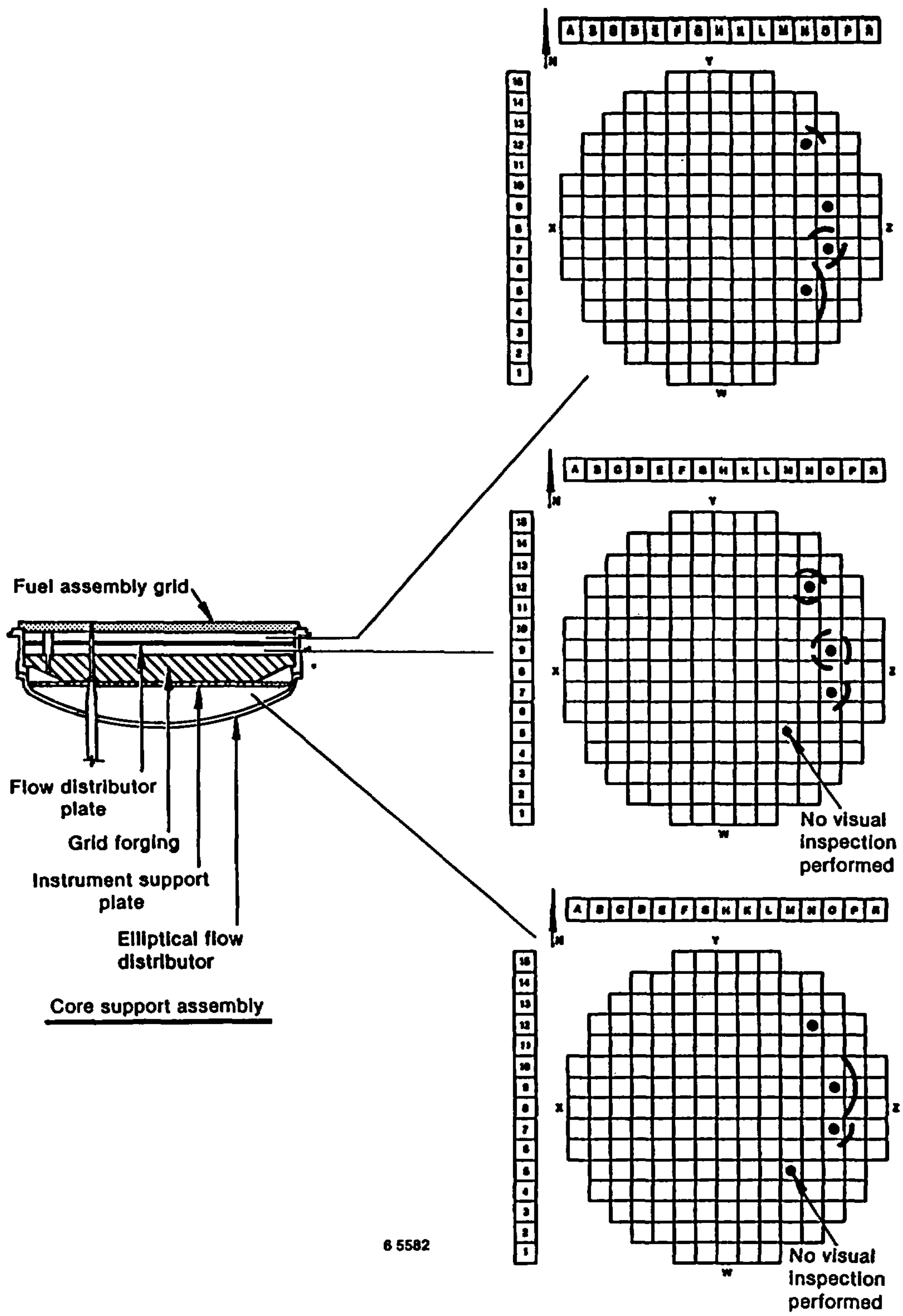

Figure 11. Approximate regions of significant fuel relocation in the core support assembly.

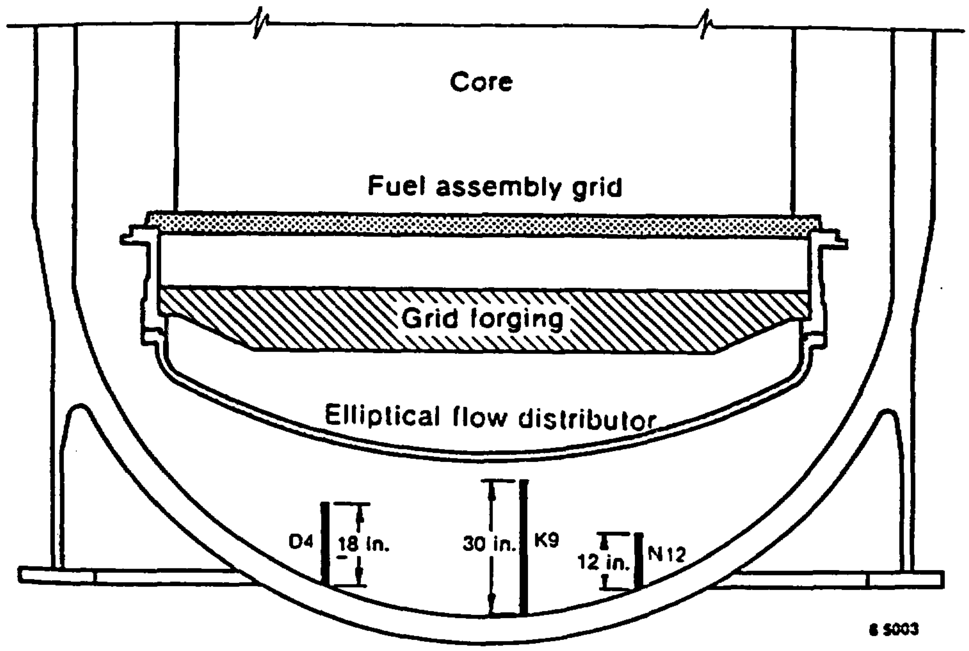

Figure 12. Estimated heights of the debris bed.

Previous inspections of the lower plenum debris have produced a wide range of debris particle sizes and textures, ranging from rather uniform pea-sized gravel to larger, irregular-shaped pieces up to 6 in. in diameter. The core bore inspections indicate that a significant fraction of the debris is likely to consist of relatively fine particles. However, a wall of very large pieces of previously molten material has been determined to exist on the north side of the lower plenum.

ESTIMATED VOLUMES AND MASSES OF THE DEGRADED CORE REGIONS

Estimates have been made for the volumes and masses of the various core regions using (a) the core cross sections (as described earlier), (b) estimated densities of the degraded core material, and (c) known densities of the intact fuel rods. These estimates are summarized in Table 1. The density of the degraded (molten) core material is not known precisely; however, it is assumed to be identical to the TMI-2 lower plenum particles recently examined. Based on the estimated mass remaining in the core region, approximately 17 tons of core material are estimated to be in the lower plenum region.

The core configuration just prior to the breakout was estimated by assuming that the lower plenum debris was part of the upper molten ceramic zone prior to the breakout and relocation. Adding the volume of the lower plenum debris to the volume of the ceramic melt region results in an increased height of from 1 to 2 ft to the upper surface of the degraded core region. This adjusted elevation for the upper surface of the core structure aligns rather well with the axial elevation of the ridge of agglomerate material observed at the core periphery discussed previously.

TABLE 1. ESTIMATED CORE REGION VOLUMES AND MASSES

Region	Estimated Volume (ft^3)	Estimated Mass[a] (lbm)
Upper core debris	236	66,300
Molten zone	122	55,200
Standing rods	499	114,271
Lower plenum debris	74	34,800

a. These total masses do not account for the additional mass caused by oxidation of zircaloy nor for the mass of structural material in the core.

UPDATED END-STATE CORE CONDITION

A revised end-state condition of the TMI-2 core immediately following the accident is shown in Figure 13. This figure was constructed using the cross sections of the upper debris bed region, molten core region (agglomerate and previously molten, homogeneous ceramic), and standing fuel rods for the B through P assembly rows. The different material structures that currently exist within the core are illustrated approximately to scale.

SUMMARY

Video data characterizing each of ten drill locations have provided important data to estimate the end-state damage condition of the lower core and core support structures. Major findings include the following:

1. The central two thirds of the lower part of the core generally consists of two distinct regions:

    - An upper region of previously molten ceramic and structural materials, starting approximately 2 ft above the lower end fittings and forming a convex lens-shaped layer roughly 5-ft-thick near the core center and tapering to 1 ft near the outer edge

    - A region of intact rod stubs below the previously liquified materials

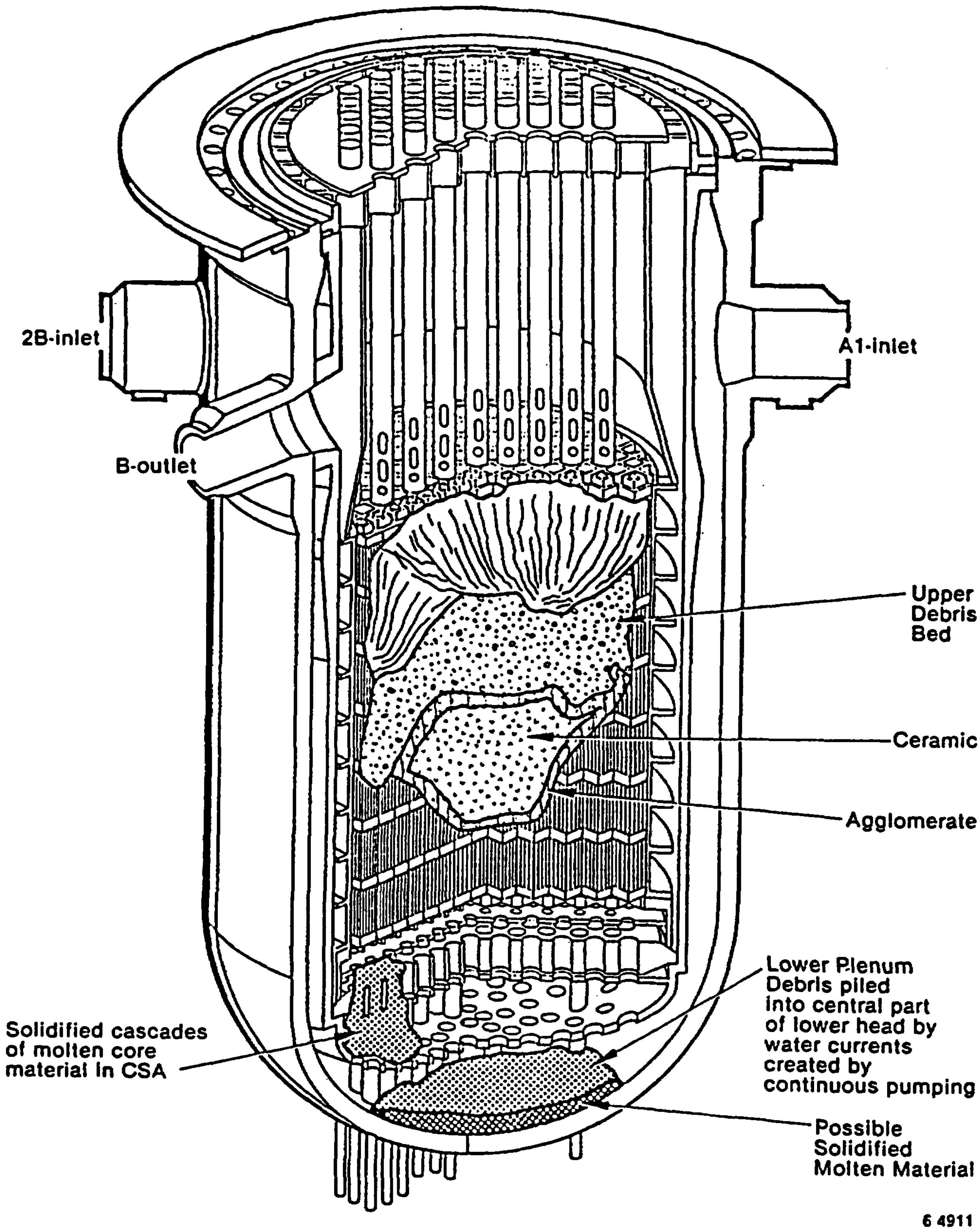

Figure 13. Updated end-state core conditions.

2. The migration path of the previously liquified material to the lower plenum is located near the core periphery

3. There appears to be no major damage to the lower core support assembly, based on the limited video data

4. The fuel debris resting on the bottom vessel head near the center of the reactor vessel appears to be loose and relatively fine, compared with the larger agglomerated debris existing near the edge of the reactor vessel.

Specific implications of the core bore acquisition data relative to our understanding of the core damage progression are discussed in the paper to follow.[6] Examination of the core bore samples will further confirm our understanding of the mechanisms controlling the core damage progression and fission product behavior during the accident.

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