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VERIFICATION OF CRITICALITY CALCULATIONS FOR TMI-2 RECOVERY OPERATIONS THROUGH HEAD REMOVAL

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Executive Summary

Data from recovery operations through the third video viewing inside the TMI-2 reactor vessel has been used to develop a model of fuel damage. This model was compared to the fuel damage models used for the criticality calculations of the reactor shutdown margins in BAW-1738.[1] The results of the comparison verified that the criticality calculations are conservative, since they assume more fuel damage than is evident from the data. Consequently, BAW-1738 is valid for recovery operations through reactor vessel head removal.

1.0 Introduction and Background

The report BAW-1738[1] describes the results of criticality calculations supporting the safety analysis[2] for the recovery operations through reactor vessel head removal. The calculations demonstrated that the reactor was safely shutdown when assuming the worst credible models of fuel damage. The objective of this addendum to BAW-1738 is to verify that these assumed models are conservative based on the data obtained from axial power shaping rod (APSR) insertion, control rod drive mechanism (CRDM) uncoupling and the through head inspection of the damaged fuel.

Section 2.0 describes the assessment of this data to produce what has been termed the Quick Look models of fuel damage. Since the Quick Look operations were intended only to provide an initial observation of damage to the upper internals of the reactor, a complete mapping of the damaged fuel is not available. Therefore, the Quick Look data only provides a localized assessment of damage. Section 3.0 describes how a detailed fuel damage model was constructed by benchmarking analytical models of the core damage to the Quick Look data.

In Section 4.0 the Quick Look model of fuel damage was compared to the damage assumed in the criticality calculations. It is concluded that the calculations for recovery operations through reactor vessel head removal remain valid.

2.0 Quick Look Data Assessment

The Quick Look data includes:

1) The video tapes obtained from inserting a camera into the reactor vessel.
2) The measurements of the depth that the probe penetrated the debris bed.
3) The results of spider assembly movement when uncoupling the CRDM's.
4) The recordings of apparent insertion depth when driving in the APSR's.
5) Detailed descriptions of data evaluations performed by experts associated with the tests.

This data was used to develop two partial models for the damaged fuel. The first model describes the void volume where the fuel was

missing and the second model describes the debris bed resting atop the fuel 5.0 feet below the upper core support plate.
The void volume model was constructed by determining its cylindrical coordinates (r,ϕ,z) at three elevations, (1) the top of the fuel assembly, (2) 30 inches below the top of the assembly, and (3) 60 inches below the top of the assembly.

The upper end fitting on the fuel assembly fits into the upper core support plate. It holds the control rod spider assembly when the control rods are uncoupled from the leadscrew. From the CRDM uncoupling data it can be inferred whether the fuel assembly upper end fitting was in place (the spider assembly did not fall when unlatched) or had been essentially removed (the spider assembly fell). If the upper end fitting has been damaged to the extent that the spider assembly falls, it is most likely that the fuel assembly has been extensively damaged below the end fitting. Figure 1 shows the fuel assembly locations where CRDM uncoupling indicates the upper end fittings may be damaged. Since the control rods are located in a checkerboard pattern in the central part of the core, the CRDM uncoupling can only determine the damage in every other assembly. To construct a complete model of upper end fitting damage, a smooth curve was fit around those assemblies shown in Figure 1. The resulting void model is shown in Figure 2. The APSR insertion data was incorporated in the upper end fitting damage model as shown in Figure 3. It is interesting to note that those APSR's which were apparently inserted are predominantly in the area containing the damaged upper end fittings. This would be expected if there were only a void region below the rods.

The second evaluation for constructing the void model was 30 inches below the top of the upper end fittings. At this elevation the mirror on the camera in assembly E-9 was rotated in a full circle. At a distance of approximately 2 feet towards the core periphery an array of fuel rods was observed. This data, along with data from the debris bed, indicates that the void at this elevation is approximately cylindrical as shown in Figure 4. The radius of the cylinder was estimated directly from the video data by using the known field of view of the camera and the dimensions of the fuel rods.

The third elevation is the bottom of the void, 60 inches below the top of the fuel assembly. At this elevation three sources of data indicated the void was essentially symmetrical. First, the bottom of the void was found to be uniform at both assembly locations H-8 and E-9. Second, the debris bed at both these assembly locations was found to have the same depth. Third, each time the camera was inverted to view the underside of the upper internals, there was no indication of fuel around the camera in any direction in either locations H-8 or E-9.

Figure 5 shows a composite of the void model with the cylindrical void representing the elevation of 30 inches below the top of the fuel assemblies and the skewed blank region representing the void at the top of the fuel assemblies. It is interesting to note how closely the upper void region fits the contour of the cylindrical lower void region since the void models at the two elevations were independently developed.

The Quick Look debris bed model determined the range of UO_2 densities in the bed and the thickness of the bed. (It did not determine the volume of the bed because there is insufficient data). The void depth to the debris at both assembly locations H-8 and E-9 was 60 inches. The probe depth into the debris was 14 inches also at both locations. Consequently, the thickness of the bed seems to be a uniform 14 inches. Figure 6 shows a TMI-2 fuel assembly and the elevations of the void region and debris bed. The debris is resting on the region where the third grid in the active fuel was located. There are apparently no fuel rods protruding from this grid region into the debris. This assessement is based on the fact that the probe was .5 inches in diameter which would cause it to stick between the fuel rods if they were present.

Estimates of the packing faction of the debris ranged from 60 percent rubble to 85 percent with predominantly UO_2 particles in sizes of a few millimeters. The composition of the rubble was assessed to vary from nearly all UO_2 fragments to UO_2 fragments mixed with the stainless steel components of the upper end fittings along with some fuel rod components. (The one pellet observed on the bed was determined by its form to be an Al_2O_3-B_4C burnable poison pellet.)

The combination of packing fractions and UO_2 composition gave a range of UO_2 densities from 8.6 gm/cc to 6.0 gm/cc. This compares to an undamaged UO_2 homogenized fuel assembly density of 3.07 gm/cc. The resistance of the debris bed to the force exerted by the weight of the probe indicates that the packing fraction is nearer 85 percent. Thus, the higher UO_2 density is judged to be the more probable one.

The two Quick Look models of the void volume and debris bed can be assembled to produce a partial Quick Look model of the damaged fuel. This partial model of the damaged fuel can be extended to a complete damaged fuel model by using it to benchmark analytical models that have predicted the degree of fuel damage. The benchmarking of the analytical models with the Quick Look model is discussed in the following section.

3.0 Benchmark of Safety Models

There are several analytical models that predict the extent of fuel damage in the TMI-2 core. However, only two of these models have been used for the criticality safety analysis of the reactor following the accident or during the recovery operations, the NRC model (Reference 3) and the GEND model (Reference 4). Since the objective of this assessment is to verify that the criticality safety analyses remain valid for reactor vessel head removal, the NRC and GEND models have been benchmarked to the Quick Look data to construct a complete Quick Look model of fuel damage.

The NRC and GEND models of fuel damage were derived from thermal-hydraulic information gathered during the accident and other data following the cooldown period. Due to uncertainties in the calculations and timing of events during the accident, the predictions of damage are not a single model, but rather the predictions are maximum and minimum results as reported by the NRC or maximum, reference, and minimum results as shown in the GEND report. The GEND and NRC predictions of damage support each other, and each provides details not provided by the other.

The NRC model gives detailed radial evaluations of damage by fuel assembly at elevation increments of a foot throughout the portion of the core containing fuel. Between 12 and 24 inches into the fuel region, the NRC minimum damage model predicts the outer two rings of fuel assemblies will be essentially in place and the remaining interior fuel region will be gone, oxidized to embrittlement. Figure 4, showing the Quick Look data of damage at this elevation (approximately 30 inches below the top of the fuel assembly), depicts the same degree of damage. The Quick Look data furthermore shows in Figure 6 that the extent of damage to the fuel rods in the core interior (assemblies H-8 and E-9) is complete to the bottom of the debris bed, 74 inches from the top of the fuel assembly. This is equivalent to 59 inches within the fueled region of these assemblies. The NRC's minimum damage model predicts the fueled region for these assemblies to have been oxidized to embrittlement down to a depth of approximately 5.0 feet.

Consequently, the NRC's minimum damage model agrees exceedingly well with the void model of fuel damage derived from the Quick Look data.

By reducing the depth of fuel oxidized to embrittlement by 1 inch, the NRC's minimum damage model can be benchmarked to agree with the Quick Look data. This modified model then forms a complete Quick Look model of the visibly damaged fuel, void and debris. It shows that 35% of the fuel was in these regions. This fuel consists of approximately 19.3 batch 1 fuel assemblies, 23.1 batch 2 fuel assemblies and 18.4 batch 3 fuel assemblies. However, this is not considered to be the total amount of fuel damage. Below the void and debris bed further damage is suspected because the probe into the debris came to rest at the elevation of the third grid without apparently contacting any intact fuel rods. If the ends of the fuel rods that should have been protruding above the grid are missing, then it is highly probable that the inconel grids have melted and formed a collection of fused material. Therefore, it is expected that a region of fuel damage exists below the bottom of the debris bed, not visible with Quick Look data.

The GEND model of the reference damage configuration more closely fits the Quick Look data than either the GEND maximum or minimum configurations. Benchmarking this reference configuration to the Quick Look data by reducing the depth of 100 percent oxidized fuel by 14 inches shows that the region below the bottom of the debris bed probably consists of 14 inches of partially oxidized and fused fuel (see Figure 7). Combining the Quick Look model of the visibly damaged fuel (the modified NRC model of minimum damage) with the benchmarked GEND reference model of fused fuel indicates that the total fuel damage most probably consists of slightly less than 50% of the core. This Quick Look model of fuel damage will be compared to the assumed damage in the criticality calculations in the following section.

4.0 Conclusions

The criticality calculations (BAW-1738)[1] which support the safety analysis[2] for the recovery operations of (1) APSR insertion, (2) CRDM uncoupling, (3) through head inspection of the upper internals and damaged fuel assemblies, and (4) reactor vessel head removal, assumed fuel damage models based on the worst credible scenarios from the NRC[3] and GEND[4] predictions. This addendum to BAW-1738 has used the Quick Look data from the first three of the above recovery operations to verify that the assumptions of fuel damage are conservative.

The Quick Look data provided a partial model of fuel damage. By benchmarking the NRC and GEND calculations to the Quick Look data, a complete model of fuel damage was constructed.
The fuel damage based on the Quick Look model indicates that less than 50% of the fuel is damaged. Within the damaged fuel, 70% is loose debris while the remaining 30% is in a fused layer on the top of the undamaged fuel. If the debris bed has a density of 8.6 gm/cc

of UO_2 (the highest assessed density), then 77% of the damaged UO_2 fuel will be in the core region and 23% in other parts of the reactor and reactor coolant system. If the debris bed has a density of 6.0 gm/cc of UO_2 (the lowest assessed density), then 62% of the damaged UO_2 fuel will be in the core region and 38% in other parts of the reactor and reactor coolant system.

Three damage models were used in BAW-1738 to demonstrate the shutdown margin in the reactor. The first was the damaged core model which assumed 50% of the fuel damaged on top of 50% undamaged. The Quick Look model shows that while 50% of the fuel is undamaged, only 77% of the damaged fuel (39% of the fuel in the core) could be atop the undamaged portion.

The second criticality model assumed that 50% of the core, or 100% of the damaged fuel, collected in the bottom in the reactor vessel. The Quick Look model shows that only 38% of the damaged fuel or 19% of the core could be in the bottom of the reactor vessel.

The last criticality model assumed that greater than 19 batch 3 fuel assemblies could be preferentially distrubed and collect in the bottom of the reactor vessel. The Quick Look model contains less than 19 damaged batch 3 fuel assemblies.

Therefore, the Quick Look model of fuel damage is less severe than the models used for the criticality calculations. Consequently, BAW-1738[1] is valid for the recovery operations through reactor vessel head removal.

References

1) BAW-1738, "Methods and Procedures of Analysis for TMI-2 Criticality Calculations to Support Recovery Activities Through Head Removal," J. R. Worsham III, June, 1982.

2) GPU Letter 4400-82-L-0110 to the NRC, "Safety Evaluation for Insertion of a Camera Into the Reactor Vessel Through a Leadscrew Opening," July 6, 1982.

3) NRC Memorandum, "Bounding Estimates of Damage to Zircaloy Fuel Cladding in the TMI-2 Core at Three Hours After the Start of the Accident, March 28, 1979," M. L. Picklesimer, June 20, 1979.

4) GEND-007, "Three Mile Island Unit-2 Core Status Summary: A Basis for Tool Development for Reactor Disassembly and Defueling," D. W. Croucher, May, 1981.

FIGURE 1 CRDM UNCOUPLING DATA

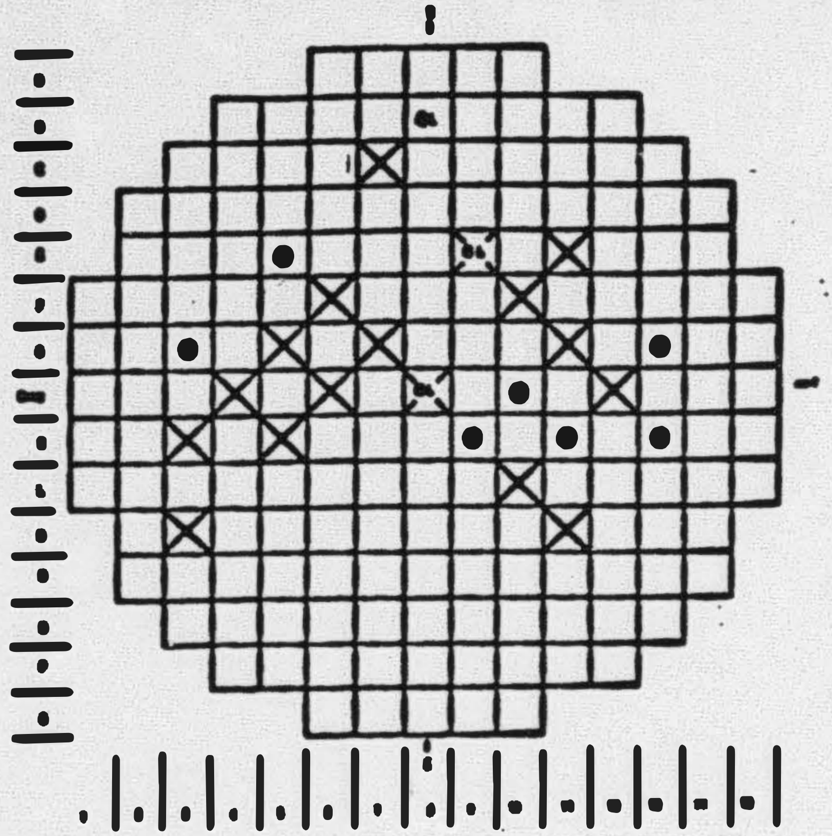
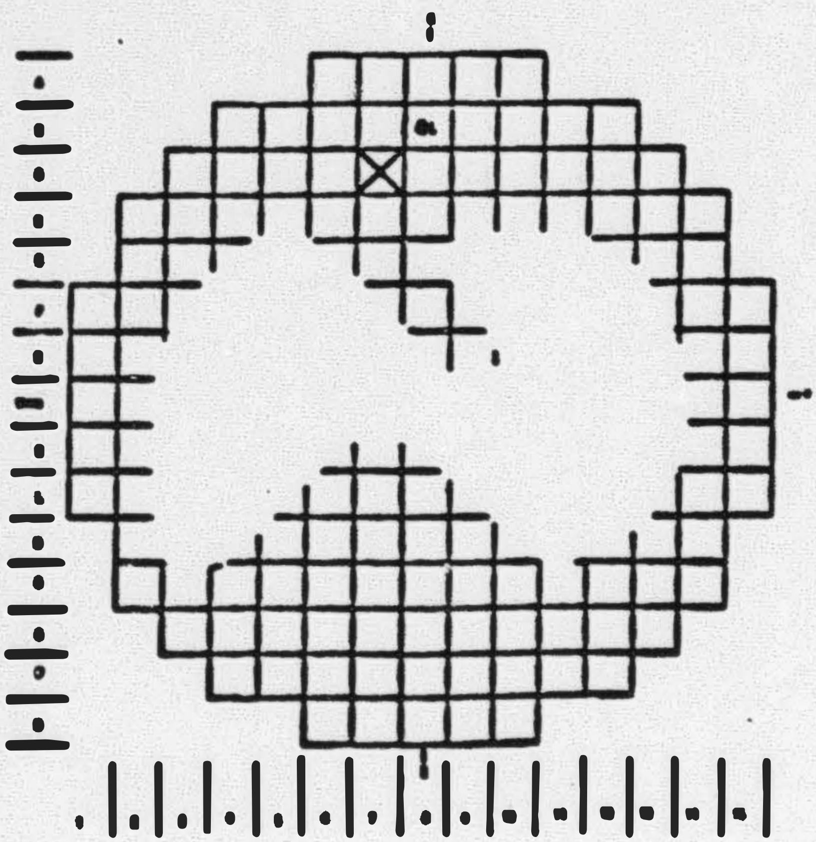


FIGURE 2 VOID MODEL AT TOP OF FUEL ASSEMBLY



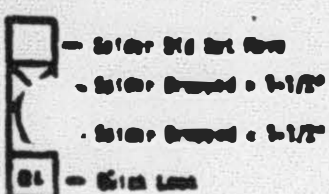


FIGURE 3 APSR INSERTION DATA

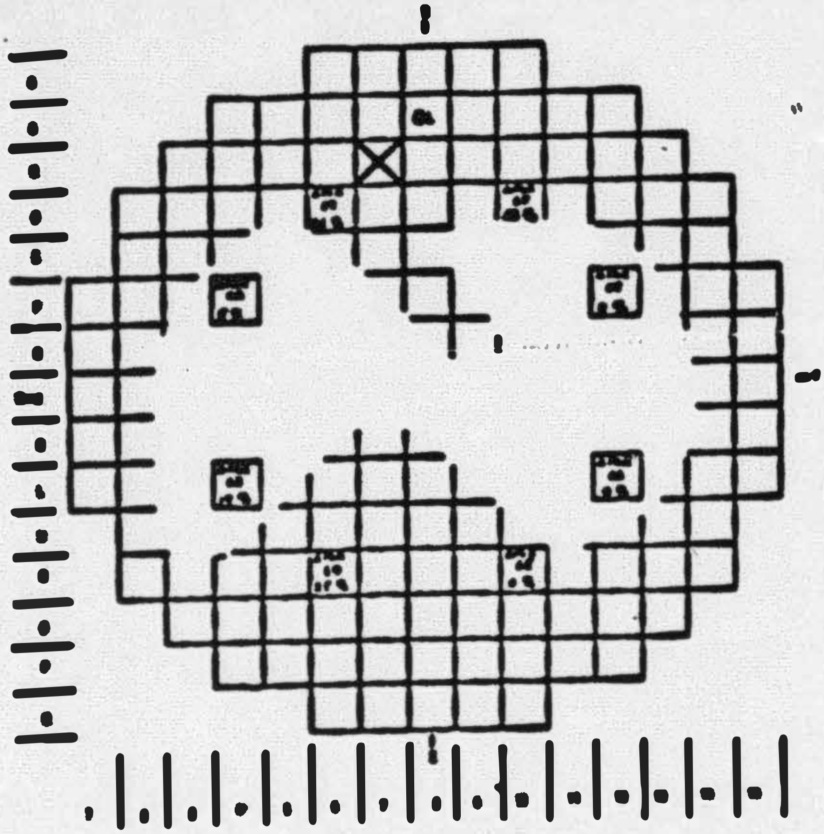
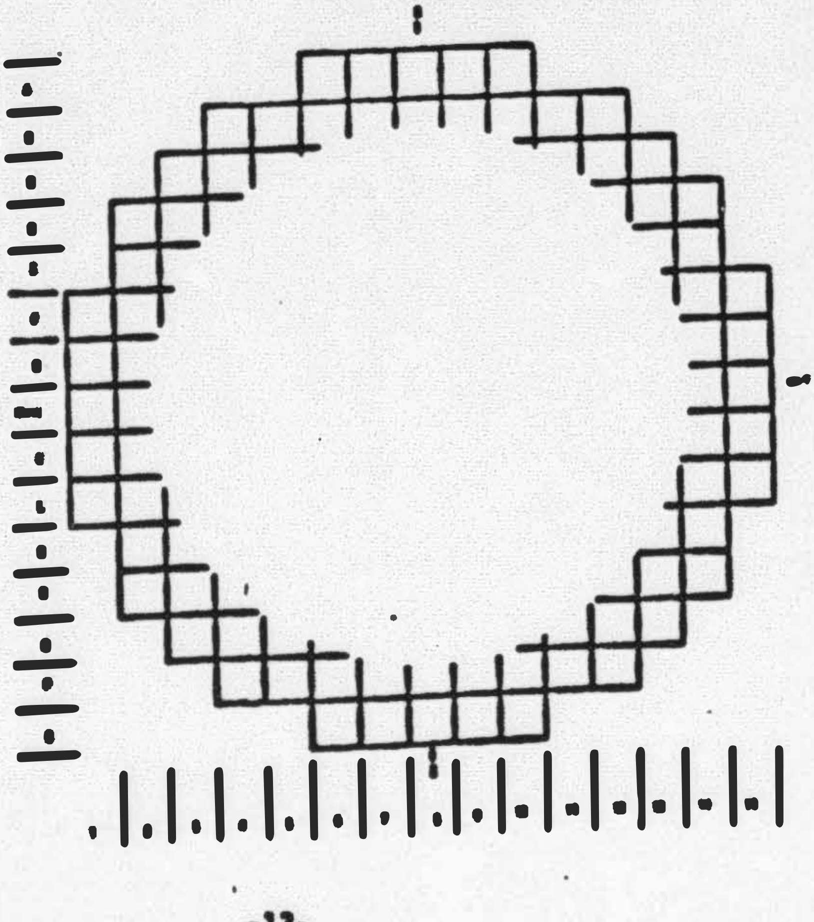


FIGURE 4 VOID MODEL 30 INCHES BELOW TOP OF FUEL ASSEMBLY



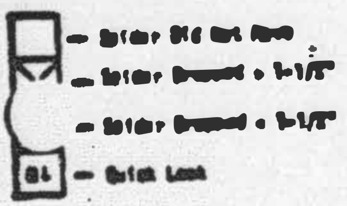


FIGURE 5 COMBINED VOID MODELS

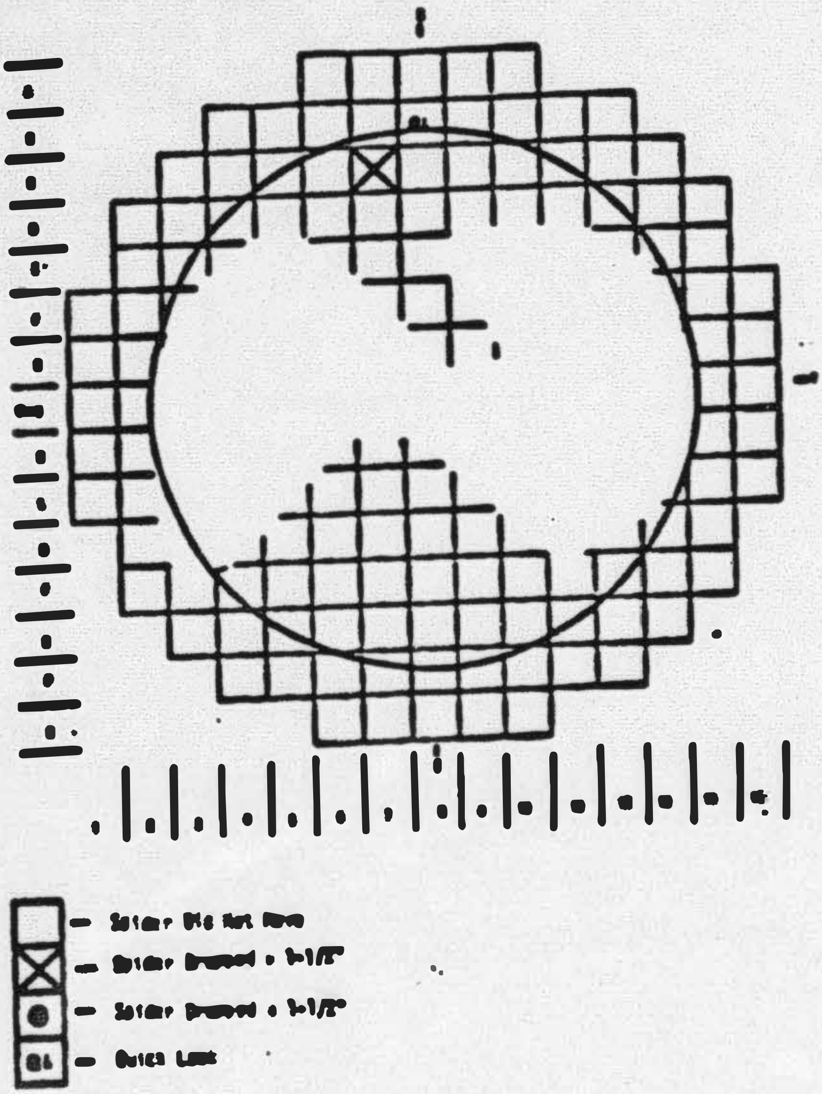


FIGURE 6

DEBRIS BED MODEL

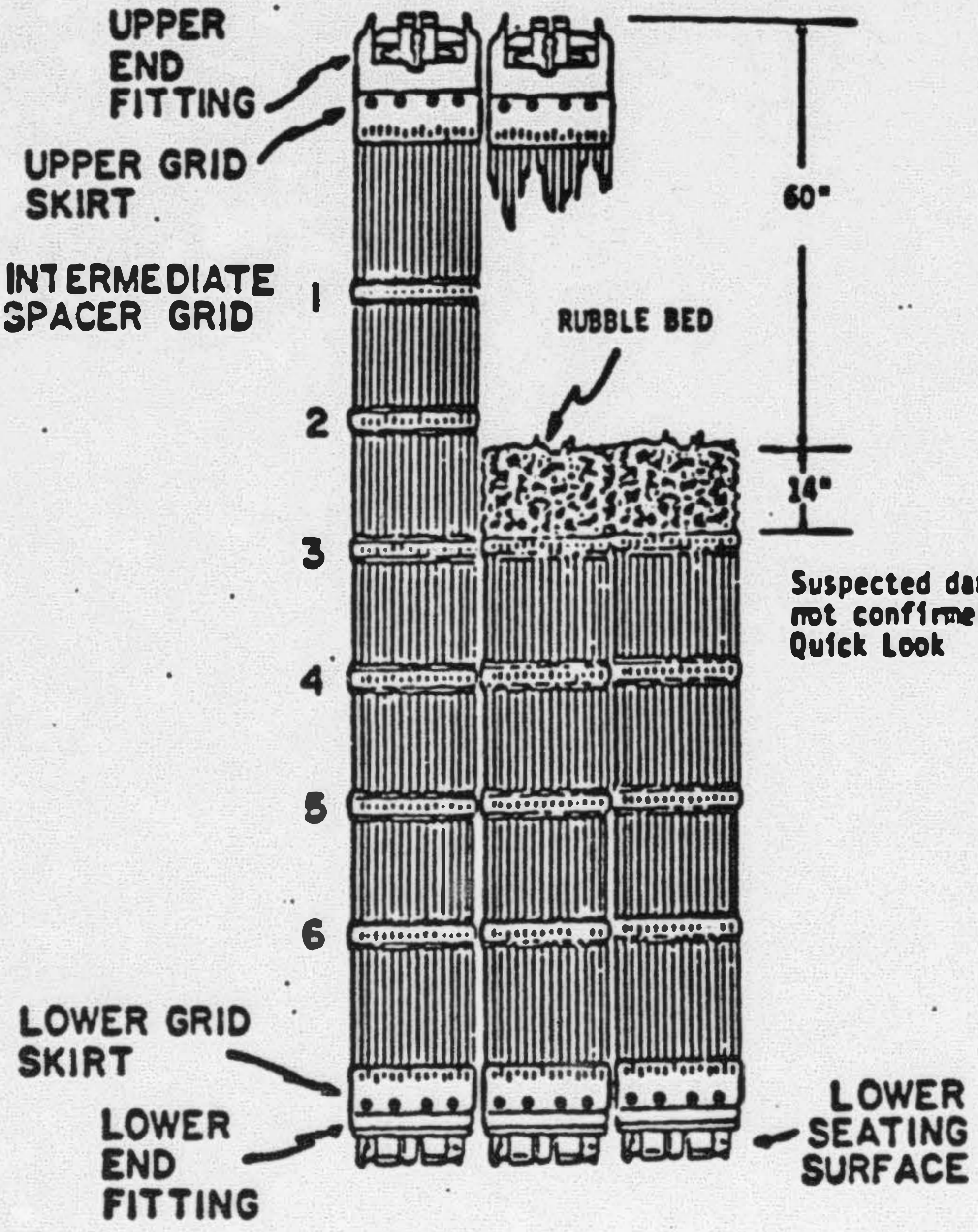
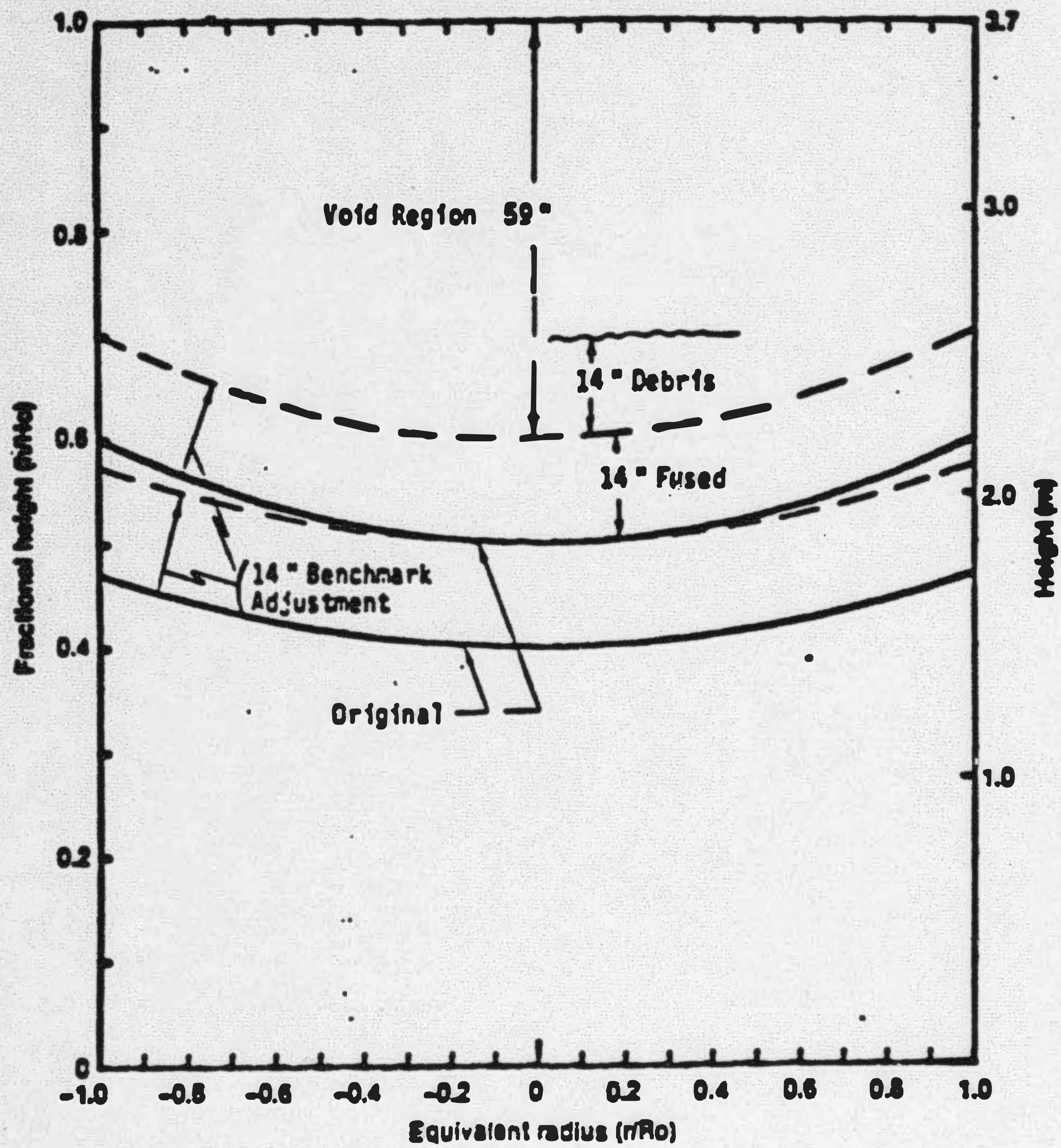


Figure 7*

GEND Reference Configuration With Quick Look Adjustment



*(From Reference 4)