Nuclear

GPU Nuclear Corporation
Post Office Box 480
Route 441 South
Middletown, Pennsylvania 17057-0191
717 944-7621
TELEX 84-2386
Writer's Direct Dial Number:

(717) 948-8400

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Three Mile Island Nuclear Station, Unit 2
Operating License No. DPR-73
Docket No. 50-320
TMI-2 Reactor Vessel Criticality Safety Analysis

REFERENCE:

1. GPU Nuclear letter 4410-90-L-0012, "Defueling Completion Report, Final Submittal," dated February 22, 1990.
2. GPU Nuclear letter 4410-90-L-0026, "Results of Post-Lower Head Sampling Program Cleanup," dated April 12, 1990.

Dear Sir:

A reanalysis of the Three Mile Island Unit 2 (TMI-2) Reactor Vessel (RV) steady state and accident criticality safety evaluations was necessitated by an increase in the estimated quantity of fuel remaining in the TMI-2 RV above that assumed for the previous analyses (References 1 and 2). The reanalysis (attached) was performed by the Oak Ridge National Laboratory (ORNL). A conservative criticality model was used to bound the most credible fuel configurations. The ORNL analyses demonstrated that the TMI-2 RV will remain subcritical by a substantial margin in both the steady state and accident configurations notwithstanding the conservative criticality models and assumptions.

Sincerely,

Robert L. Long

R. L. Long
Director, Corporate Services/TMI-2

2400..

EDS/dlb

cc: T. T. Martin - Regional Administrator, Region I
M. T. Masnik - Project Manager, PDNP Directorate
L. H. Thonus - Project Manager, TMI
F. I. Young - Senior Resident Inspector, TMI

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CRITICALITY SAFETY ANALYSIS REPORT

FOR THE

THREE MILE ISLAND UNIT 2 REACTOR VESSEL

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CRITICALITY SAFETY ANALYSIS REPORT FOR THE TMI-2 REACTOR VESSEL

1.0 INTRODUCTION

The purpose of this report is to provide the results of the Three Mile Island Unit 2 (TMI-2) Reactor Vessel (RV) steady state and accident criticality safety reanalyses performed by the Nuclear Engineering Applications Department (NEAD) of the Oak Ridge National Laboratory (ORNL) (References 2 and 3). The analyses were performed using conservative criticality models which were designed to bound the most credible fuel configuration. The upper bound of the mass of residual fuel in the TMI-2 RV has recently been quantified using a passive neutron measurement technique (Reference 1). The ORNL analyses demonstrated that the TMI-2 RV will remain subcritical by a substantial margin for both the steady state and accident configurations even with the conservative criticality models.

2.0 RESIDUAL FUEL CRITICALITY CHARACTERIZATION

The previous "original" criticality safety analysis (References 4 and 5) was performed based on a visual estimate of the residual fuel in the TMI-2 RV. The upper bound fuel mass quantity for the TMI-2 RV, obtained from the passive neutron measurements program, will be documented in a forthcoming TMI-2 Post-Defueling Survey Report. For the passive neutron analysis, the TMI-2 RV was divided into nine horizontal zones as shown in Figure 1. Neutron measurements were made as the RV water level was dropped from zone to zone. The resulting set of simultaneous equations was solved to determine the quantity of residual fuel (i.e., UO_2) on a per zone basis. The criticality safety analysis presented here conservatively used those results which are viewed as the upper bound of the fuel remaining in the TMI-2 RV. Fuel that is enriched to less than 5 wt% Uranium-235 cannot be critical without an interspersed moderator (Reference 10). The original TMI-2 core contained fuel enriched to 2.96 wt% U-235, i.e., less than the 5 wt% limit. Therefore, for the purposes of this analysis, it is conservatively assumed that the TMI-2 RV is completely filled with unborated water.

2.1 Steady State Criticality Characterization

A comparison of the visual estimate and the upper bound fuel estimate from the passive neutron measurement is provided in Figure 2. The following discussion examines the upper bound residual fuel estimate by zone and characterizes the contribution of each zone to a potential steady state criticality in the TMI-2 RV.

The Zone 1 upper limit is approximately 10 kg of residual fuel. Ten kilograms of UO_2 is much less than the Safe Fuel Mass Limit (SFML) of

140 kg (Reference 5). Furthermore, the zone is neutronically separated from the other zones (i.e., approximately 30 centimeters (12 inches) of water (Reference 10)). Lastly, the conservative criticality model developed by ORNL for Zones 2, 3, and 4 as described below more than adequately accounts for this residual fuel. Therefore, this zone was not considered further in these analyses.

Zones 2 through 4 upper limits are 225 kg, 150 kg, and 99 kg, respectively. Since two of these quantities exceed the SFML and there is no directly applicable analysis, a new bounding steady state criticality analysis was performed by ORNL as described below.

Zones 5 and 6 represent the Upper Core Support Assembly (UCSA). The upper limits are 154 kg and 387 kg of residual fuel in Zones 5 and 6, respectively. Both Zone 5 and Zone 6 extend vertically for approximately 6.9 feet. The residual fuel in Zone 5 is primarily comprised of extensive crusting (approximately 1 mm thick) on the outboard surfaces of the baffle plates. This crusting and the rest of the residual fuel is assumed to be equally distributed at a radius of about 5.5 ft. (167 cm) from the RV centerline (i.e., at the radius of the baffle plates). The residual fuel in Zone 6 is primarily located adjacent to Zone 7. There is approximately 188 kg UO_2 in the one inch annular gap between the core barrel and the thermal shield which extends from the bottom of Zone 6 vertically for less than six inches. An additional 67 kg is located in the orifice holes and on top of the lower grid rib assembly yielding a total of 255 kg for that part of Zone 6. The rest of the fuel in Zone 6 (i.e., approximately 132 kg) is assumed to be equally distributed at a radius of about 5.5 ft (167 cm) from the RV centerline. A negligible neutronic coupling over the nearly 14 vertical feet of Zones 5 and 6 is indicated from the original ORNL steady state analyses (Reference 2) which allows Zone 6 to be considered neutronically decoupled from Zones 7, 8, and 9.

Zones 7 and 8 represent the Lower Core Support Assembly (LCSA); Zone 9 represents the Lower Head. The upper limits for the residual fuel in Zones 7, 8, and 9 are 113 kg, 89 kg, and 95 kg, respectively. As discussed below, the original criticality analysis remains valid for these zones.

2.2 Accident Criticality Characterization

As stated above, the original criticality safety evaluation (References 4 and 5) for both the steady state and accident conditions was performed based on visual estimates and physical examinations of the residual fuel in the TMI-2 RV. As such, these evaluations not only identified the location of residual fuel but also the fuel deposits' physical characteristics. Using the data from these examinations and applying the results of the passive neutron measurements, a conservative amount of loose fuel was estimated to relocate to the bottom head of the RV. This value bounds any credible reconfiguration of the remaining fuel deposits that exist in the TMI-2 RV (Reference 8). Table 3 reports these results by Zone and shows that a grand total of 620 kg of loose fuel is estimated to non-mechanistically relocate to the bottom of the RV.

3.0 CRITICALITY EVALUATIONS

Two criticality evaluations were performed. The first evaluation used two different models to bound the RV fuel configuration for steady state conditions. The second analysis evaluated the reconfiguration of the fuel following a non-mechanistic relocation of the loose residual fuel to the lower head of the RV. The criticality methodology, including computer codes, cross sections, and pertinent modelling assumptions, are described for each of the evaluations below.

3.1 Criticality Methodology

3.1.1 Computer Codes

3.1.1.1 XSDRN-PM

XSDRN-PM is a computer code that was developed as part of the ORNL SCALE package (Reference 6) which, as a system of codes, performs criticality evaluations of complex critical systems. XSDRN-PM is a one dimensional discrete ordinates neutron transport code that solves various eigenvalue problems ranging from determining the k-effective (k_{eff}) of a given system to performing a search for the critical dimension for a given k_{eff}. It is this latter mode that ORNL utilized for this study. An inherent feature of the one dimensional analyses done with XSDRN-PM is that all systems are also treated as infinite in height.

3.1.1.2 KENO V.a

KENO V.a, another module of the ORNL SCALE system, was developed to analyze complex three dimensional geometries. KENO V.a utilizes the Monte Carlo solution technique for the neutron transport. This code was used in previous TMI-2 criticality evaluations, and most recently in the TMI-2 Defueling Completion Report (DCR) (Reference 5).

3.1.2 Cross Sections

Cross section preparation was done with the same modules of the SCALE system as previously reported in Section 5.5.1.2 of

Reference 5. However, for this analysis it was decided to conservatively use the enrichment of 2.67 wt% U-235 associated with burned batch 3 fuel for all the modeled fuel. For the steady state case, the optimized unit cell used to create the cross sections was conservatively based on the standard sized fuel pellet model with the dodecahedral lattice structure described in Reference 5 and an optimized fuel volume fraction of 0.28.

For the design basis accident case the optimized unit cell used an optimized fuel fraction of 0.26 with 0.009 wt% boron in the unit cell's fuel region. For all cases, steady state and accident, unborated water was assumed to exist for the unit cell. For the steady state case, no structural poisons (e.g., boron, zircaloy, or stainless steel) were assumed in the unit cell's fuel region. However, for the accident case a parametric evaluation was performed in which the weight percent of boron and particle size were varied. See Table 1 for a summary of the criticality methodology for the steady state case.

3.1.3 Computer Code Benchmarking

Section 5.5.1.3.4 of Reference 5 describes the basis for the analytical bias of 2.5% Δk, which includes the KENO V.a statistical uncertainty. As noted the bias was used to establish a conservative margin for the highly borated water during the defueling phase of TMI-2. However, for the present analysis, the water regions as noted in Section 3.1.2 contain no boron. Therefore, the use of this benchmarking uncertainty is an additional conservatism for these analyses because the bias for unborated systems has been found to be considerably smaller, i.e., on the order of one percent (Reference 7).

3.1.4 Summary of Conservatisms

As noted above, there were several significant conservatisms built into the criticality evaluations. These are summarized below to emphasize the defense-in-depth concept inherent in these criticality evaluations:

- The unit cells were constructed such that the fuel was in a uniform geometric lattice composed of whole fuel pellets except for those accident analysis cases where the fuel was considered as infinitely dilute.

- No credit was taken for intrinsic poisons, e.g., boron, stainless steel, zircaloy, and control rod debris except for the parametric accident analysis cases.

- The residual fuel was assumed to be of the highest U-235 enrichment, i.e., batch 3 burned to 2.67 wt% U-235.

- For the XSDRN-PM analysis, the geometry was treated as if it were infinite in height.

- A calculational bias of 2.5% Δk was applied based on the highly borated defueling water even though pure, unborated water was used for the moderator regions in the analyses.

- The fuel region of the KENO V.a model was assumed to extend 360° around the periphery of the RV.

3.2 Steady State Criticality Evaluations

3.2.1 XSDRN-PM Steady State Evaluation

An XSDRN-PM model was created by ORNL to determine the required thickness of an infinitely high annular shell of fuel to yield a k_{eff} of 0.945 including the calculational uncertainties referred to above in Section 3.1.3. This k_{eff} value was chosen to be the same as the value that was determined in Reference 5 for the model of the fuel in the lower core support assembly. The outer radius of the shell was also constrained to 67.5 inches which was in agreement with the past ORNL analysis in Reference 5. This particular geometry for an annular shell was initially chosen to depict the geometry of Zones 2 through 4. The thesis was to show that the resultant thickness predicted by the XSDRN-PM exceeded any known or postulated fuel deposits in those zones. Further, the results could be applied to other areas depending on the resultant thickness. For example, the thickest known fuel deposit outside of Zone 8 is the one inch gap between the thermal shield and the core barrel. This gap also represents the largest physical annular region wherein residual fuel is known to exist. As such, it would bound the maximum credible fuel deposit outside of Zone 8.

The XSDRN-PM analysis showed that the fuel thickness required to achieve a k_{eff} of 0.945 was 9.85 cm or 3.88 inches. This is equivalent to an axial lineal density of 29.7 kg/cm or 905 kg/ft of UO_2.

3.2.2 KENO V.a Steady State Evaluation

As stated previously, the original criticality safety evaluation (References 4 and 5) was performed based on a visual estimate of the residual fuel in the TMI-2 RV. The benefit of the video evaluation was not only in identifying where fuel deposits were located but also in identifying where no fuel deposits existed. Therefore, a conservative criticality model was developed that bounded the observed conditions believed to be extant in the TMI-2 RV. As discussed in Section 4.1.4, the computer model and criticality evaluation which yielded the k_{eff} of 0.945 remains valid. However, as an additional check for the steady state condition, ORNL reviewed the previous KENO V.a calculations (Reference 3), i.e., the analyses that yielded the k_{eff} of 0.945 mentioned above. The intent was to determine the amount of fuel that was modelled in the most reactive region of that KENO V.a model. In this instance, the controlling mass for criticality was the trapezoidal shaped region just under the lower grid forging (LGF) of the LCSA (See Figure 3). ORNL calculated (Reference 3) that this region would contain 986 kg of UO_2 assuming the entire trapezoidal region is filled uniformly throughout the entire 360 degree azimuth of the model. This amount exceeds the 838 kg of residual fuel estimated by the passive neutron measurement to exist in Zones 6 through 9.

3.3 Accident Criticality Evaluations

3.3.1 Criticality Criterion for Accidents

A design basis value for k_{eff} of 0.99 was chosen for the present accident analysis. This is consistent with the past TMI-2 licensing bases. For example Reference 5, Section 5.5.2.1.2, utilized this criterion for the evaluation of accident conditions for the assumed relocated fuel in the bottom RV head. Prior to that, Reference 9 used the 0.99 value as the design basis k_{eff} to support recovery activities through RV head removal for postulated accident conditions.

3.3.2 Criticality Model for Accident Conditions

As discussed in Section 2.2, 620 kg of loose fuel is assumed to non-mechanistically relocate to the bottom head of the RV. This value (i.e., 620 kg) was used for the actual KENO V.a computer analysis (Reference 3). In order to form the final fuel/moderator matrix, pure water is assumed to be mixed with the fuel in an optimized fashion. For the design basis accident unit cell, the whole pellet (dodecahedron model) was assumed along with an intrinsic 0.009 wt% B in the fuel itself with an optimized volume fuel fraction of 0.26. The use of 0.009wt% boron is based on TMI-2 debris sample data (Reference 5). All samples collected contained impurities; the minimum quantity of boron found in any sample was 0.01 wt%. For additional conservative representation and to account for measurement uncertainty, this quantity was reduced by 10%. No other impurities were assumed to exist in the residual fuel.

3.3.3 KENO V.a Accident Evaluations

In order to evaluate the subcriticality for the above accident model, several additional parametric sensitivity analyses were performed using KENO V.a. The results of these analyses are summarized in Table 4 along with the design basis case. The parameters varied were particle size and boron content. The effect of size was studied by the use of whole pellets and a homogeneous mixture of fuel and water. The intrinsic poison (boron) concentration was varied over the following values: 0.0 wt%, 0.009 wt%, and 0.072 wt%. Figure 4 displays the actual geometry modelled. This is the same basic model used previously in Section 5.5.2.1.2 of Reference 5 to conservatively account for relocation of fuel debris to the bottom of the RV head. Region 1, height L_1, contains the optimized fuel/unborated water matrix containing the 620 kg of fuel. Region 2, height L_2, contains about 500 gallons of unborated water which represents an essentially infinite water reflector.

4.0 SUMMARY OF RESULTS

4.1 Steady State Criticality Evaluations

Table 2 summarizes the results of the steady state criticality evaluations discussed in Section 3.2. The following sections present additional rationale to justify the steady state subcriticality in the regions of the TMI-2 RV that contain more than the SFML of 140 kg.

4.1.1 Zones 2 through 4

The major quantities of residual fuel in Zones 2 through 4 are at or near the hot and cold leg nozzles (Reference 8). The largest quantity exists as a "pile" of fuel in the "2A" cold leg nozzle that is less than three inches deep; however, its density and UO_2 percentage have been determined to be less than "normal" loose fuel material. In terms of UO_2, a three inch depth of this material is equivalent to a 0.4 inch depth of normal loose material, i.e., less than the one inch thickness of loose fuel in the annular gap between the core barrel and thermal shield (Zone 6). Therefore, the XSDRN-PM analysis resulting in a k_{eff} = 0.945 for a fuel thickness of 3.88 inches bounds the maximum residual fuel quantities that exist in Zones 2 through 4.

4.1.2 Zone 5

As discussed in Section 2.0, the residual fuel in Zone 5 is primarily comprised of a 1 mm thick crust on the baffle plates. Therefore, the XSDRN-PM analysis also bounds the maximum residual fuel quantity that exists in Zone 5.

4.1.3 Zone 6

The one inch annular gap between the core barrel and the thermal shield in Zone 6 contains residual fuel that extends circumferentially for a height of about six inches. Except for a resolidified mass underneath the LGF, the annular gap represents the largest discrete volume of residual fuel in the RV. The visual examinations of the TMI-2 RV verified that there are no other significant masses of residual fuel in Zone 6. Therefore the XSDRN-PM analysis bounds the maximum residual fuel quantities that exist in Zone 6.

4.1.4 Zones 6 through 9

The complex geometry of the LCSA dictated the usage of the KENO V.a computer code. Figure 3 (Figure 1 of Reference 4) depicts the computer model for the steady state case as presented in the original criticality analysis. Table 2 (Table 2 of Reference 4) compares that model to the estimated residual fuel masses as of April 1990. As stated in Section 3.2.2, the controlling mass for criticality in the original steady state criticality analysis was a trapezoidal region located under the LGF. This mass equaled approximately 986 kg (Reference 3). In the passive neutron measurements program, the demarcation line between Zones 7 and 8 was the top of the LGF. Thus, the steady state criticality controlling mass is in Zone 8. The quantity of residual fuel in the visual estimate for Zone 8 was 133 kg. The passive neutron measurement upper bound estimate for that zone is 89 kg. Therefore, the original computer model used in the steady state criticality analysis conservatively bounds the maximum quantity of fuel estimated to be located in Zone 8; thus, the original analysis remains valid for Zones 6 through 9.

4.1.5 Zones 1 through 9

The final steady state subcriticality argument involves the entire TMI-2 RV. Except for the "lump" of residual fuel under the LGF, nowhere does there exist an annular ring of residual fuel approaching 3.88 inches thick. Thus, completion of the TMI-2 Defueling Program (i.e., excision of an eight-foot diameter cylinder from the center of the RV) has precluded the possibility of the existence of an annular ring of fuel 3.88" thick. Therefore, the combination of the XSDRN-PM annular ring of fuel analysis and the KENO V.a analysis (Section 4.1.4) bound the residual fuel quantities extant anywhere in the entire TMI-2 RV.

4.2 Accident Criticality Evaluations

Table 4 reprises the results of the parametric KENO V.a criticality evaluations. As shown, the design basis case meets the design k_{eff} limit of 0.99. The trend of k_{eff} decreasing with particle size for optimized fuel volume fraction is the same as in Table 5-9 of Reference 5.

5.0 CONCLUSIONS

Based on the criticality evaluations and subcriticality arguments, it is concluded that the core debris that remains in the TMI-2 RV is subcritical both for steady state and accident conditions. Furthermore, because of the inherent conservatism in the analyses used in this evaluation, there is a significant defense-in-depth safety margin built into all of the evaluations in this report.

6.0 REFERENCES

1. TMI-2 Reactor Vessel Fuel Assay, C. Distenfeld, M. Haghighi, and B. Brosey, dated September 18, 1992.

2. a. ORNL letter, C. V. Parks to R. E. Rogan, dated July 14, 1992.

   b. ORNL letter, C. V. Parks to R. E. Rogan, dated July 24, 1992.

3. a. ORNL letter, C. V. Parks to R. E. Rogan, dated September 8, 1992.

   b. ORNL letter, C. V. Parks to R. E. Rogan, dated September 24, 1992.

4. GPU Nuclear letter 4410-90-L-0026, "Results of Post-Lower Head Sampling Program Cleanup," dated April 12, 1990.

5. TMI-2 Defueling Completion Report.

6. NUREG/CR-200, L. Petrie, et al., "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations," USNRC, Revision 3, December 1984.

7. GEND/071, R. M. Westfall, et al.,"TMI Criticality Studies: Lower Vessel Rubble and Analytical Benchmarking," DOE, May 1986.

8. GPU Nuclear calculation C312-7370-92-008,"TMI-2 Criticality Safety Analysis Model," Revision 0, April 1992.

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

10. Nuclear Safety Guide, TID-7016, Revision 2, J. T. Thomas, Ed., June 1978.

TABLE 1. SUMMARY OF STEADY STATE CRITICALITY EVALUATION MODEL

	STEADY STATE
WT% U-235	2.67
PARTICLE SIZE	STANDARD PELLET
FUEL VOLUME FRACTION	0.28
COMPUTER CODES	XSDRN-PM & KENO V.a
WT% BORON	0
OTHER POISONS	NONE
MODERATOR	PURE WATER
K-EFFECTIVE	< 0.945

Table 2. Summary of Results of Steady State Criticality Evaluations

Covered Zones	Criticality Model	Fuel Quantity (kg) PNM* Upper Bound Estimate	Fuel Quantity (kg) Model Estimate
2 - 4	XSDRN-PM	476	9413
5	XSDRN-PM	154	6245
6	XSDRN-PM	387	6245
6 - 9	KENO V.a	684	2910
1 - 9	XSDRN-PM	1322	36,655

* PNM is Passive Neutron Measurement

Table 3. Summary of Loose Fuel Estimates for Accident Criticality Evaluation

Zones	Loose Fuel Estimate (kg)
1	10
2	225
3	150
4	99
5	45
6	29
7 & 8	3
9	59
TOTAL	620

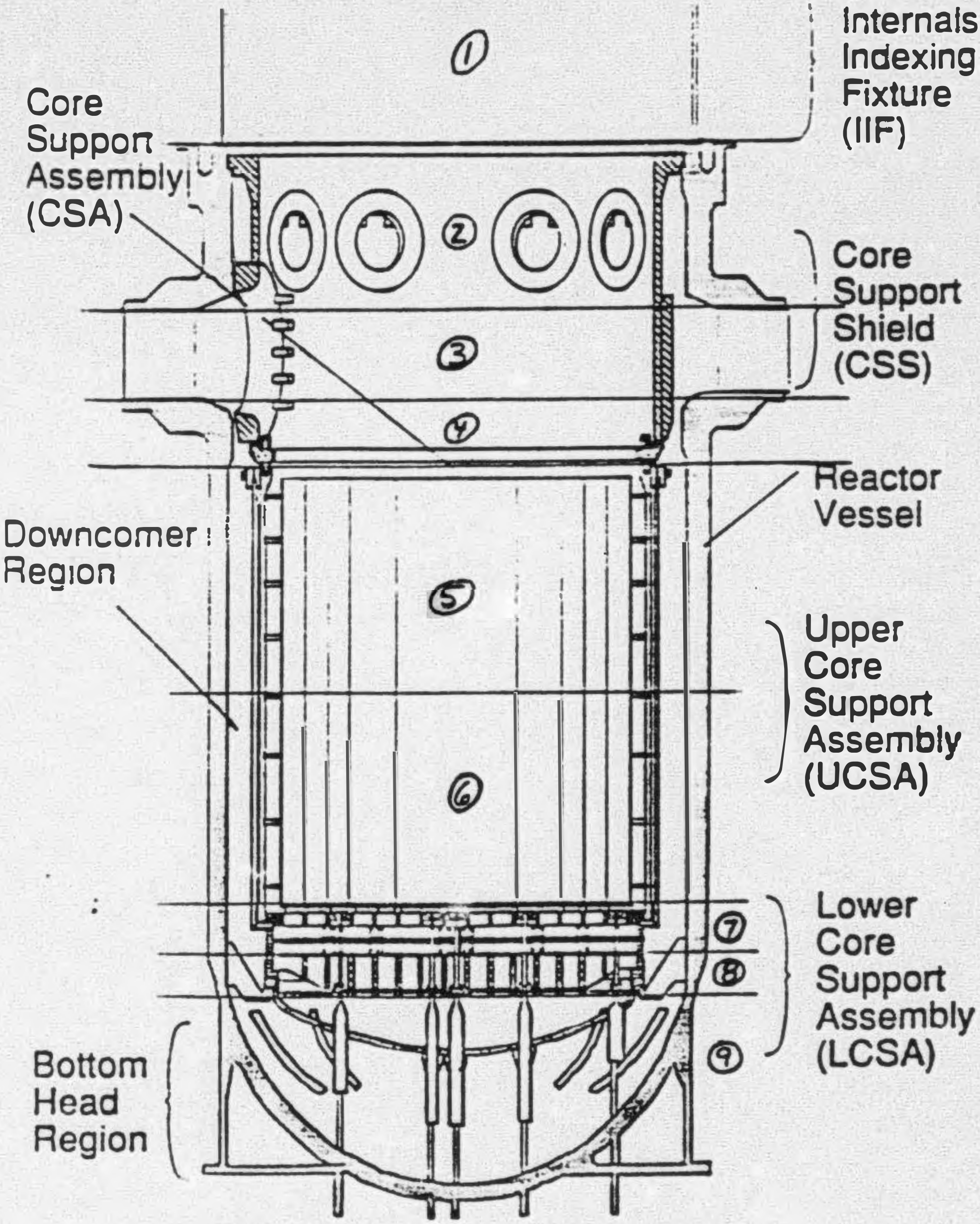
TABLE 4. SUMMARY OF TMI-2 ACCIDENT CRITICALITY EVALUATION TASK MODELS

	ACCIDENT I[1]	ACCIDENT II[1]	ACCIDENT III	ACCIDENT IV[1]	ACCIDENT V[1]	ACCIDENT VI
WT% U-235	2.67	2.67	2.67	2.67	2.67	2.67
PARTICLE SIZE	STANDARD PELLET	STANDARD PELLET	STANDARD PELLET	INFINITELY DILUTE	INFINITELY DILUTE	INFINITELY DILUTE
COMPUTER CODE	KENO	KENO	KENO	KENO	KENO	KENO
WT% BORON[1]	0.009	0.072	0	0.009	0.072	0
OTHER POISONS	NONE	NONE	NONE	NONE	NONE	NONE
MODERATOR	PURE WATER	PURE WATER	PURE WATER	PURE WATER	PURE WATER	PURE WATER
FUEL VOLUME FRACTION	0.26	0.26	0.27	0.24	0.23	0.26
L_1 (cm)	18.67	18.31	18.31	19.44	19.87	18.67
L_2 (cm)	37.22	37.58	37.58	36.45	36.02	37.22
K-EFFECTIVE[2]	0.981	0.735	1.023	0.948	0.719	0.984

[1] The boron is assumed to be integrally mixed in the fuel region of the cell model, not in the external water.

[2] Values for K-effective include the 2.5%ΔK in benchmarking uncertainties.

FIGURE 1.



Reactor Vessel Cutaway View

Visual Estimate (Kg)	Passive Neutron Estimate (Upper Bound) Kg.
10	10
62	225
46	150
27	99
8	154
244	387
93	113
133	89
29	95
652 kg	1322 kg

Totals

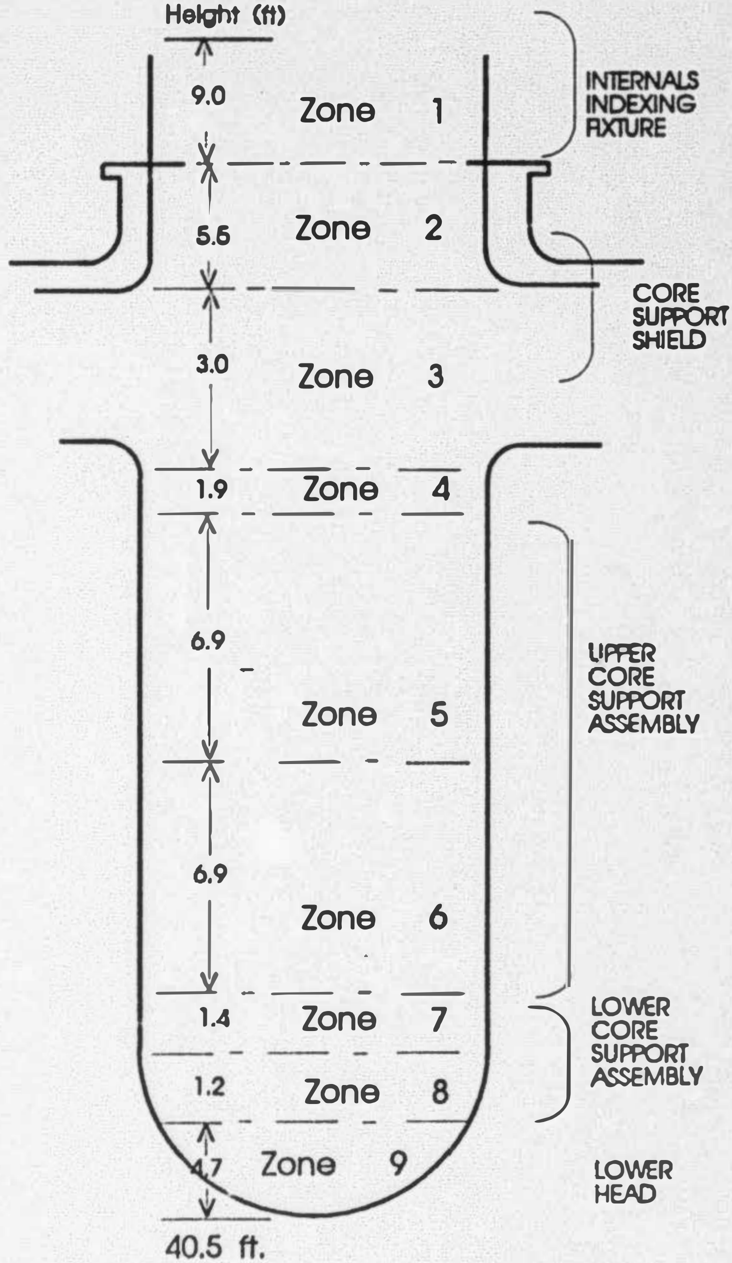


Figure 2. Comparison of RV Fuel Estimates

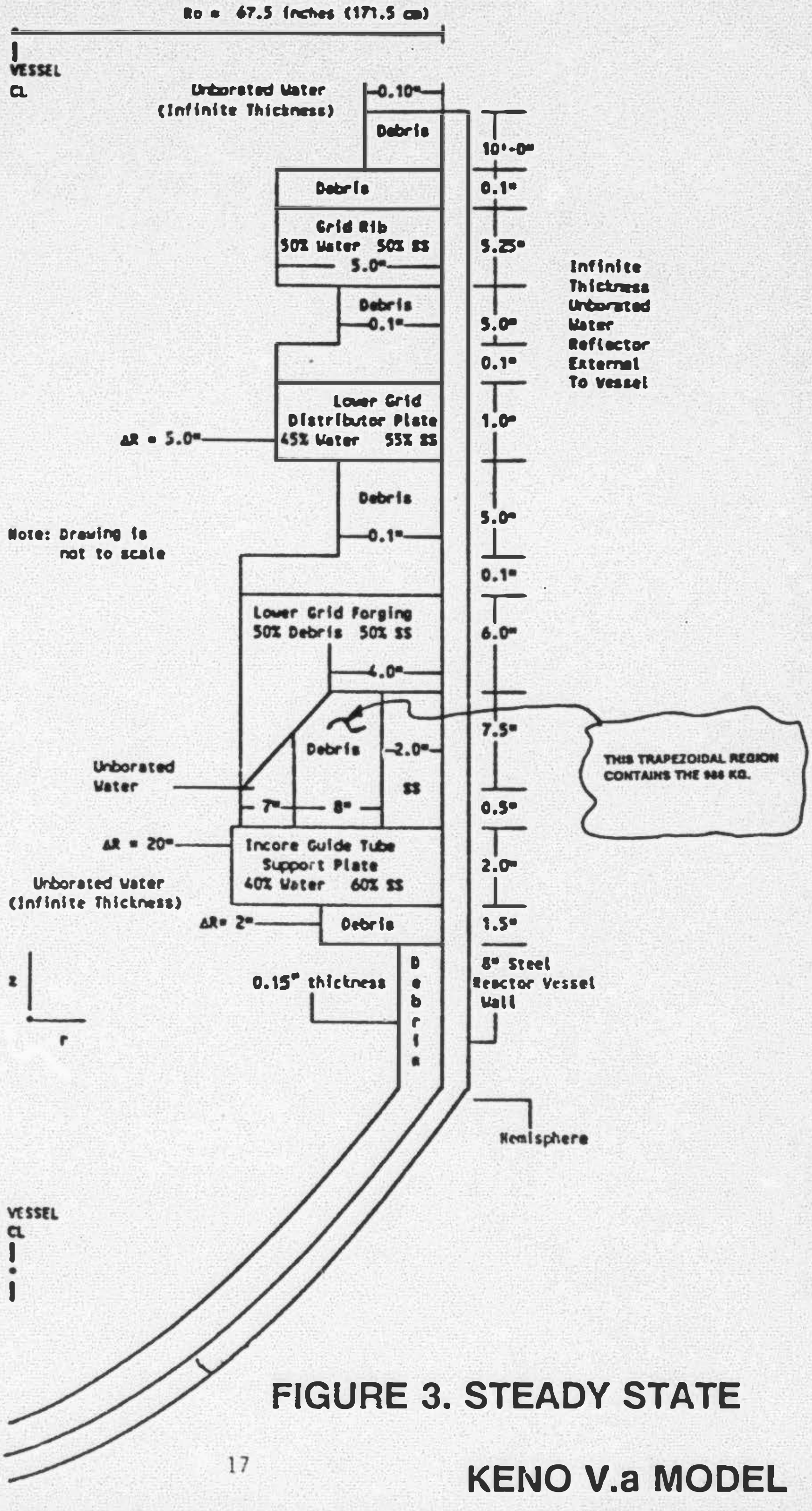
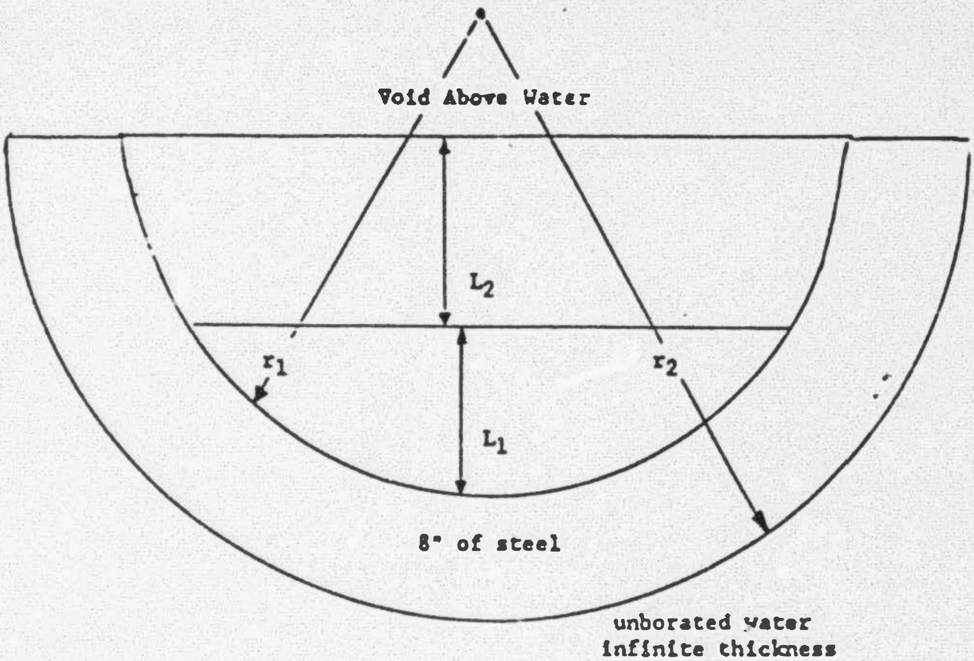


FIGURE 3. STEADY STATE KENO V.a MODEL

FIGURE 4. ACCIDENT RV BOTTOM HEAD MODEL



r_1 - 217.678 cm r_2 - 237.998 cm

L_1 - height of fuel region (620 kg UO_2) mixed with unborated water

L_2 - height of remaining quantities of unborated water (total of 500 gallons unborated water)

See Table 4 for specific values of L_1 and L_2.