Docket File

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

July 6, 1993

Docket No. 50-320

Dr. Robert L. Long
Director, Corporate Services/Director, TMI-2
GPU Nuclear Corporation
P.O. Box 480
Middletown, Pennsylvania 17057-0191

Dear Dr. Long:

SUBJECT: THREE MILE ISLAND UNIT 2 REACTOR VESSEL CRITICALITY SAFETY ANALYSIS (TAC M85664)

We have completed our review of your TMI-2 Reactor Vessel Criticality Safety Analysis dated December 18, 1992, as revised and supplemented by your letter dated April 8, 1993. Your letter of April 8, 1993, provided additional information regarding the assumptions used in your calculations in response to NRC staff questions in our letter of March 22, 1993. In your December 18, 1992 letter, you provided a reanalysis of the TMI-2 Reactor Vessel Criticality Safety Analysis due to a revision in the estimated quantity of fuel in the TMI-2 reactor vessel. The December 18, 1992, GPUN/ORNL analyses of the reactor vessel were based on a maximum remaining fuel estimate of 1322 kilograms (2915 pounds). In your submittal of February 1, 1993, you revised your estimate of fuel remaining in the TMI-2 reactor vessel to 925 kilograms (2040 pounds) with an uncertainty of ± 40 percent. This would result in an estimate of fuel remaining in the reactor vessel with a range of 555 to 1295 kilograms (1224 to 2855 pounds). The upper limit of your February 1, 1993 revised estimate is less than the value used in your December 18, 1992 analyses and therefore conservative. Your reanalysis included both the steady state and accident configurations.

The staff has both reviewed your submittal of December 18, 1992, as revised, and, through Pacific Northwest Laboratories, performed independent criticality analyses of both the steady state and accident scenarios using the revised estimates of residual fuel. A copy of the final criticality report from Pacific Northwest Laboratories is enclosed.

As stated in the enclosed safety evaluation by the NRC staff, we have concluded that the fuel in the TMI-2 reactor vessel will remain subcritical,

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with an adequate margin of safety, during both the steady state and the accident modes. The staff also concluded that your analysis was very conservative based upon the conservatisms in the criticality models and assumptions used in the calculations.

Sincerely,

ORIGINAL SIGNED BY

Seymour H. Weiss, Director
Non-Power Reactors and Decommissioning
Project Directorate
Division of Operating Reactor Support
Office of Nuclear Reactor Regulation

Enclosure:
As stated

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Seymour H. Weiss

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Non-Power Reactors and Decommissioning
Project Directorate
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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

RELATED TO CRITICALITY SAFETY ANALYSIS OF REACTOR VESSEL

GPU NUCLEAR CORPORATION

THREE MILE ISLAND NUCLEAR STATION, UNIT 2

FACILITY OPERATING LICENSE NO. DPR-73

DOCKET NO. 50-320

1.0 INTRODUCTION

GPU Nuclear Corporation (GPUN, the licensee) submitted a revised criticality analysis for the Three Mile Island Unit-2 (TMI-2) reactor vessel for NRC review in a letter dated December 18, 1992 (Reference a). GPUN also submitted additional clarifying information in a letter dated April 8, 1993 (Reference b) in response to NRC staff questions (Reference c). The revised criticality analysis, performed by Oak Ridge National Laboratory (ORNL), demonstrated that the fuel remaining in the TMI-2 reactor vessel would remain subcritical during long term storage. The analysis evaluated both a static and a worst case credible accident scenario.

2.0 BACKGROUND

During the March 28, 1979 accident at TMI-2, the core was severely disrupted and some melting of fuel and cladding occurred. Approximately 99 percent of the core was removed during the defueling process which took place from October of 1985 through April of 1990. The initial core loading consisted of 3 batches of fuel with the most enriched batch having an initial enrichment of 2.96 wt percent of U-235. The burnup during reactor operations of 2535 MWd/MTU reduced this value to 2.67 wt percent. The batch 3 fuel was located at the core periphery and sustained less damage than the batch 1 and 2 fuel located at the core center.

A wide variety of techniques were used during defueling, including scooping, drilling, grinding, plasma cutting, grappling, and vacuuming. The sum of the accident results and the removal techniques resulted in an unquantifiable bias toward preferential removal of the batch 3 fuel. The fuel which remains is largely in the form of either once molten, resolidified masses located in the Lower Core Support Assembly (LCSA) or widely dispersed fines. Although the remaining fuel is biased to enrichment below the core average "burned" enrichment of 2.24 wt percent, localized areas of the resolidified masses may exceed this value. In an inspection report dated June 14, 1990 (reference d), the NRC staff directed GPUN to use a Safe Fuel Mass Limit (SFML) of

93 kilograms (205 pounds) (based on an enrichment of 2.67 wt percent) for fuel in the reactor vessel until an additional safety analysis was approved by the NRC staff. The SFML is the amount of fuel which can be rearranged in any geometry with any reflector and/or moderator and still remain subcritical. The NRC staff contracted with the Battelle Memorial Institute Pacific Northwest Laboratory (PNL) to provide assistance in the review of GPUN criticality analyses for the TMI-2 reactor vessel.

3.0 EVALUATION

The GPUN/ORNL and the NRC/PNL criticality analyses of the reactor vessel were based on a maximum remaining fuel estimate of 1322 kilograms (2915 pounds). The licensee submittal of February 1, 1993, revised the estimate of fuel remaining in the TMI-2 reactor vessel to 925 kilograms (2040 pounds) with an uncertainty of ± 40 percent. This would result in an estimate of fuel remaining in the reactor vessel with a range of 555 to 1295 kilograms (1224 to 2855 pounds). This revised estimate was based on the review and conclusions of a panel of experts headed by Dr. N. Rasmussen, of the Massachusetts Institute of Technology. The revised estimate does not invalidate the GPUN/ORNL or the NRC/PNL earlier criticality analysis since the upper limit of the February 1, 1993 revised estimate is less than the value used in both the GPUN/ORNL and the NRC/PNL analyses.

Two principal cases were evaluated by GPUN/ORNL and NRC/PNL; the first was a steady state condition involving the residual fuel in its current location. The second involved an accident or earthquake scenario. The calculational models were highly conservative. In both cases, demineralized water was assumed to be present as a moderator even though the reactor vessel is dry and steps have been taken to prevent water intrusion. In both cases a fuel enrichment of 2.67 wt percent was assumed, although an enrichment of 2.24 percent could have been justified for all fuel located outside the core barrel. No credit was taken for diluents in either case and only minimal credit taken for poisons in the accident scenario. Both cases assumed optimal credible geometry, reflection, pellet size and fuel to moderator ratio.

The steady state case was modelled as a series of annular rings, which included several times more fuel than is actually present in the reactor vessel. This added an additional degree of conservatism. Both the GPUN/ORNL analysis and the independent NRC/PNL review concluded that K_{eff} was <0.95, indicating a substantial margin of safety to criticality.

The accident criticality analysis assumes that an earthquake, load drop from a crane or some non-mechanistic event relocates the fuel fines to the lower head of the reactor vessel. GPUN/ORNL calculated a maximum K_{eff} of 0.981 using the conservative models described above. NRC/PNL independently evaluated the methodology of the licensee and found it acceptable. The PNL review (Reference e) concluded that "there is no likelihood of an unintentional criticality occurring in the TMI-2 RV." PNL independently verified these conclusions in several parametric studies of minimum slab thicknesses, minimum annular ring thicknesses, and minimum masses in the accident scenario.

4.0 CONCLUSIONS

The GPUN/ORNL analyses indicated that the residual fuel in the TMI-2 reactor vessel would remain subcritical with an adequate margin of safety during steady state and accident conditions. The independent review and analysis performed by the NRC and PNL confirmed the conclusions of the licensee. The assumptions in the analyses were very conservative, indicating that the margin of safety is considerably larger than the calculational results indicate. The NRC staff therefore finds the GPUN criticality analysis to be acceptable.

5.0 REFERENCES

a. GPUN letter, C312-92-2080, R. L. Long to NRC, TMI-2 Reactor Vessel Criticality Safety Analysis, dated December 18, 1992.

b. GPUN letter, C312-93-2021, R. L. Long to NRC, Response to NRC Questions on TMI-2 RV Criticality Analyses and Post-Defueling Survey Report, dated April 8, 1993.

c. NRC letter, M. T. Masnik to R. L. Long, request for additional information re: reactor vessel fuel survey and criticality report, dated March 22, 1993.

d. NRC Inspection Report 50-320/90-03, E. C. Wenzinger to R. L. Long, dated June 14, 1990.

e. PNL letter w/attached analyses, R. I. Scherpelz to M. T. Masnik, re: TMI-2 Criticality Safety Analyses, dated April 30, 1993.

Principal Contributor: L. Thonus

Date: July 6, 1993

ENCLOSURE

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April [illegible], 19[illegible]

Dr. Michael T. Masnik
U.S. Nuclear Regulatory Commission
Nuclear Reactor Regulation
Mail Stop 11, Building 20
Washington, D.C. 20555

Dear Dr. Masnik:

I am enclosing the PNL review of the TMI-2 Licensee's Criticality Safety Study. Please feel free to contact me at the above number if you have any questions or comments on this report.

Sincerely,

Robert I Scherpelz
Senior Research Scientist
Dosimetry Research Section
HEALTH PHYSICS DEPARTMENT

RIS/ag

Enclosure

cc: L Thonus, USNRC
R Harty, PNL

REVIEW OF THE CRITICALITY SAFETY ANALYSIS REPORT FOR THE TMI-2 REACTOR VESSEL

INTRODUCTION

Criticality safety is one of the major safety issues addressed by the TMI-2 Licensee as it prepares the plant for Post Defueling Monitored Storage status. Since measurable amounts of reactor fuel containing fissile isotopes will remain in various locations of the plant, it is important to ensure that an unintentional criticality could not occur.

The licensee's approach to determining the degree of criticality safety was to first establish a Safe Fuel Mass Limit (SFML), which is a conservatively-calculated upper boundary for a mass of fuel that could not experience criticality under any configuration. This limit was documented in the Defueling Completion Report (GPU Nuclear, 1990) as 140 kg UO_2. Masses of fuel in various locations of the plant were compared to the SFML, and in nearly all cases the fuel quantities (including upper error bounds) were substantially below the SFML (GPU Nuclear, 1993). A separate criticality safety study was not necessary for any location with a quantity of fuel below the SFML, since the SFML study itself demonstrated criticality safety for that location.

The Reactor Vessel (RV) is the only location in the TMI-2 plant containing a fuel mass greater than the SFML. (The Nuclear Regulatory Commission's (NRC) Safety Evaluation Review, USNRC, 1992) recommended that a value of 93 kg may be more appropriate than 140 kg for the RV; either value would lead to the same conclu-sion, however.) The entire quantity of fuel, as reported in the final submit-tal of the Post-Defueling Survey Report, in the RV was determined to be 925 kg ± 370 kg (GPU Nuclear, 1993). Earlier, unofficial estimates of the RV inven-tory were 652 kg (based on a video estimate) and 1322 kg (based on passive neutron measurements, before various measurement biases were identified). Since these estimates are all greater than the SFML, a criticality safety study was performed for the RV residual fuel inventory.

The GPU study (GPU Nuclear, 1992) evaluated two fuel conditions: 1) the Steady-State criticality condition; and 2) the Accident condition. In the Steady-State condition, the study looked at the fuel in the configuration that currently exists in the RV. The study concluded that the configuration was not critical, and it evaluated the margin of safety. In the Accident condition, the study determined the maximum quantity of fuel that could credibly relocate into a single location in the bottom RV head, and evaluated this configuration to determine whether it could be critical. The study concluded that the Accident condition could not produce a criticality. The criticality study was performed before the 925 kg estimate-of-record had been established for the RV fuel inventory. Thus the study used the 1322 kg estimate for all RV criticality calculations.

The Pacific Northwest Laboratory (PNL) acted on a request from the NRC to review the GPU criticality safety studies for the RV. This report presents the findings of the PNL review. As part of its review, PNL performed several sets of calculations. These studies are documented in Attachments 1 and 2 to this report.

STEADY STATE CRITICALITY

For the steady state situation, the XSDRN-PM computer code was used to estimate the thickness of an annular cylinder of fuel, with outer diameter matching the inner wall of the RV and infinite in height, that would result in a k_{eff} of 0.945 if it were filled with pure water. The thickness of this annulus is approximately 3.88 inches. The target k_{eff} of 0.945 used for this study is below the NRC's acceptance criterion of 0.95 which is based on the limit in the Standard Technical Specifications for spent fuel storage (USNRC 1991).

In determining the limiting thickness of fuel, the study made certain assumptions about the nature of the fuel. It assumed that the uranium in the fuel contained 2.67 wt% ^{235}U, and it assumed that other nuclides, such as Pu, were present in the fuel as a result of the reactor operation before the TMI-2 accident. For developing the cross sections used by the criticality codes, the fuel was assumed to be in the form of pellets in a dodecahedron lattice structure with a fuel volume fraction of 0.28.

After determining the thickness of a hypothetical annular ring, the study then looked at the fuel quantities estimated to remain in each of the nine zones of the RV to see how close the fuel deposits came to the 3.88-inch thickness. For the individual zones 1-6, the study found that the fuel deposit thicknesses were far less than 3.88-inches, so each individual zone was safely below a k_{eff}=0.945. For zones 6-9, the geometry was more complicated than a simple annular ring, so the KENO-V.a computer code was used to model the fuel deposits in these regions, and it found that the fuel quantities were well below what was required to produce a k_{eff} of 0.945. Finally, an analysis considered the RV as a whole and concluded that the configuration was well below a model of a 3.88-inch thick annular ring. Thus the steady-state configuration had a large margin of safety with respect to a critical condition.

It appears that proper methodology was used to assess the steady state criticality situation. The calculations showed a large margin of safety between the actual fuel deposits and the quantity of deposits required for criticality. It should be noted that "steady state" refers to the configuration of the fuel in the RV, but the actual analysis assumes a dramatically abnormal condition: the presence of water in the RV. Criticality cannot occur with fuel at such low fissile-isotope enrichment without moderator. Thus the study assumes that the RV is filled with water, and the study assumes that the water is pure, containing no boron or other neutron absorbers. Precautions have been taken by the licensee to ensure that no water would inadvertently enter the RV. The steady state calculation therefore assumes that the residual fuel in the RV would be well below critical, even in the presence of unanticipated quantities of moderating water.

ACCIDENT CRITICALITY ANALYSIS

For the Accident situation, the study looked at each zone and determined the quantity of fuel (620 kg) which could possibly, although non-mechanistically, relocate to the RV lower head region. The model assumed full flooding of the bottom head by water, that the fuel contained 0.009% boron, and that the fuel was in the form of pellets rather than powder. A parametric study was performed to test the effectiveness of these two parameters, and they found that the pellet configuration was conservative. They also found that no boron would result in $k_{eff} > 1$. However, by using the stated assumptions, the study calculated a k_{eff} of 0.981 for the relocated fuel. Since the calculated value is below the criterion k_{eff} of 0.99, the study concluded that an accidental fuel relocation would not cause a criticality.

One of the key features of this study is determining the quantity of fuel that could relocate to the lower head. The study looked at each of zones 1-9 to determine the fraction of fuel that could be loose enough to relocate. In the PNL review, a concern was raised about the fraction of fuel in zone 9, the lower head region, that could relocate, since it seems possible that all fuel in the lower head could be available for a relocated configuration. In a more detailed explanation from GPU, we found that 0.6 kg of fuel would be lodged in incore instrument nozzles that are far enough from the location of the relocated mass of fuel to be neutronically decoupled from the mass. The fuel that is assumed to reside in the incore instrument guide tubes left suspended from the flow distributor, is also assumed to be neutronically decoupled from the relocated mass because of the vertical distance from the bottom of the RV. Thus only 58.7 kg of fuel from zone 9 is assumed to be available for the relocated mass.

MODELING ASSUMPTIONS AND CONSERVATISM

The criticality safety study depends on modeling the RV and internal debris, and the modeling necessarily includes some approximation. In good engineering practice, any approximation is made with some degree of conservatism built in. In the various safety studies that have been performed for TMI-2, a number of assumptions must be made in any modeling, since there have been uncertainties associated with measured quantities, and because some aspects of the study are hypothetical. Much of the PNL review of the criticality studies has been concerned with evaluating the assumptions that must be made and the effect of the conservatisms that are built into the modeling. Some of the assumptions and conservatisms that are part of the study include:

1) mass of fuel available for criticality;

2) fuel configuration
   - enrichment in fissile material,
   - inclusion of neutron-absorbing material ("neutron poisons"),

- fuel density,
- lattice or pellet configuration;

3) neutron moderation and reflection;

4) additional neutron poisons;

5) shape and dimensions of fuel configuration; and

6) analytical bias in k_{eff}.

Mass of Fuel Available for Criticality

The mass of fuel available for criticality is bounded by the amount of fuel that could be present in the RV. The GPU criticality study (GPU Nuclear, 1992) assumed that the amount of fuel in the RV is 1322 kg, whereas their estimate of record is 925 kg, with a one-sigma error bound of 370 kg. Thus the plus-one-sigma bound of the estimate of record is 1295 kg. The criticality safety study is using a mass higher than this, which is an appropriate conservatism.

Fuel Configuration

Enrichment of Fuel in Fissile Material

The criticality study needed to make an assumption about the composition of the fuel. Fuel from different regions of the original core contained different enrichments in ^{235}U, so it was important that the study choose an enrichment that is the highest value likely to be encountered in the fuel debris. The enrichment of 2.67 wt% ^{235}U was chosen as the highest enrichment that could be encountered. The inclusion of Pu isotopes in the fuel mixture also ensured that the quantity of fissile material would not be underestimated.

Inclusion of Neutron Poisons in the Fuel

The December 1992 report included the results of a parametric study modeling the effect of boron in the fuel. For the configuration used to model the Accident case, this study found that totally omitting boron from the fuel region would result in a k_{eff}=1.023, including 0.009% boron would give k_{eff}=0.981, and 0.072% boron (representative of the residual fuel in the RV) would give k_{eff}=0.735. The steady state study omitted boron from the calculation for a degree of conservatism. The Accident study included 0.009% boron in the fuel region, which is about 10% lower than the minimum quantity of boron found in the debris samples that have been analyzed.

Fuel Density

The bulk density of the fuel is a major concern in calculating reactivity. The model assumes that the fuel region is a mixture of fuel and water, but the assumed ratio of fuel to water is a crucial factor in determining the k_{eff} of a specific configuration. In a set of calculations performed by PNL, critical configurations were calculated for fuel having a bulk density of 3.78 g UO_2/cm^3 (the density that gave the minimum slab thickness), and these were compared to identical configurations with fuel having a density of 2.06 g UO_2/cm^3 (the density giving the smallest mass). In every case, the lower density produced a critical configuration with a smaller mass than the similar case with the higher density fuel. The higher density case reouired about 67% more mass to produce a critical configuration than did the lower density.

The PNL comparison only used two densities, and it would be incorrect to conclude that decreasing the density always increases the reactivity. The valid conclusion is that the bulk density of the fuel is an important determinant of the reactivity of a configuration, and the study should carefully choose a reasonable value. The GPU Accident study used a fuel volume fraction of 0.26, which is the same as a bulk fuel density of 2.85 g UO_2/cm^3 (assuming that pure UO_2 has a density of 10.97 g/cm^3). The report states that this value is optimized for the assumed lattice structure. This assumption is therefore conservative, because if fuel were to relocate to the bottom of the RV, it is unlikely that it would necessarily fall into a configuration with the optimum bulk density.

Lattice or Pellet Configuration

Criticality calculations must make an assumption about the configuration of the material in the fuel. The December 1992 report included the results of a study that compared a pellet-type configuration to an infinitely dilute solution of UO_2 in water. The dilute solution of UO_2 in water gave lower k_{eff} values than the pellet configuration, so a pellet configuration was used to assure conservatism in the calculation.

PNL performed a series of criticality calculations to understand the effects of various assumptions in the criticality study. In one set of calculations, the fuel was assumed to be in a rod configuration (neutronically similar to a pellet configuration). In one case, the rods were assumed to have a diameter of 0.6 cm, and in another case they had a diameter of 0.254 cm. The results of these calculations are summarized in Figures 1 and 2 and they are explained in Attachment 2. The .254-cm rods always required a larger mass to attain the same value of k_{eff} compared to a similar

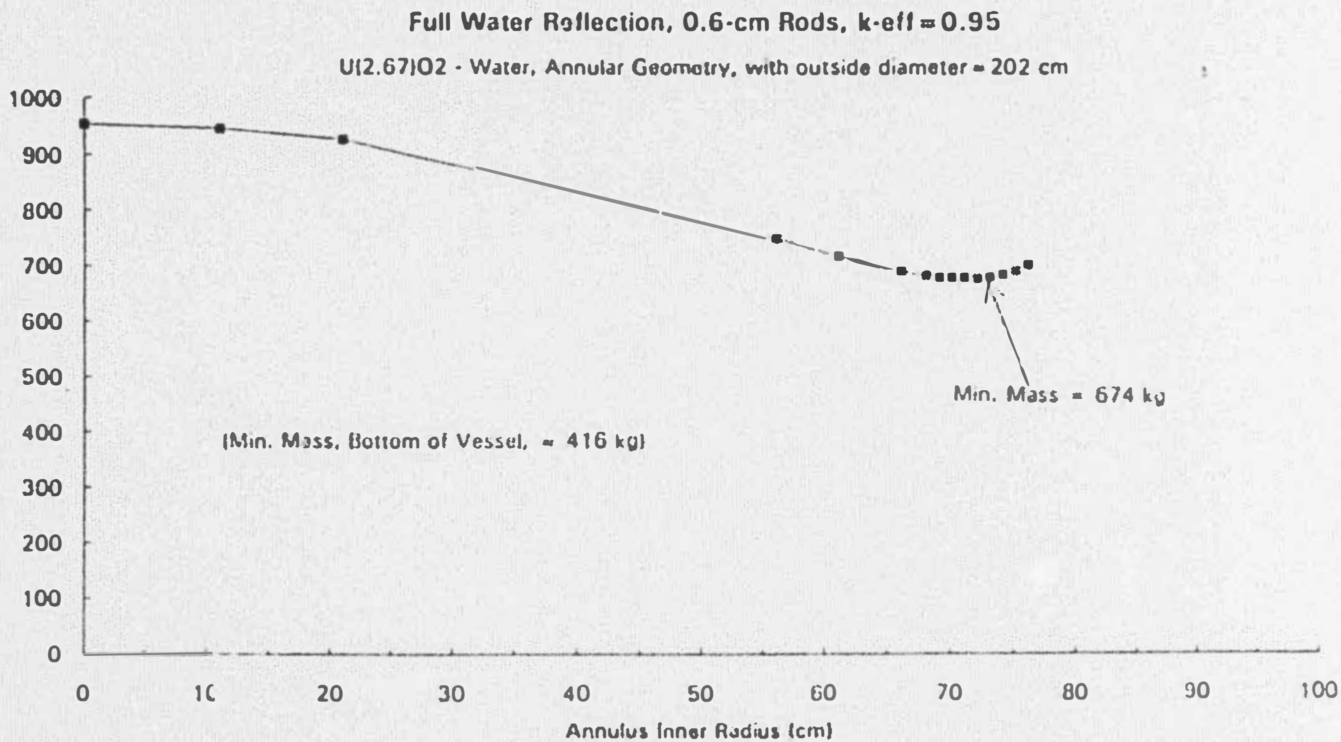
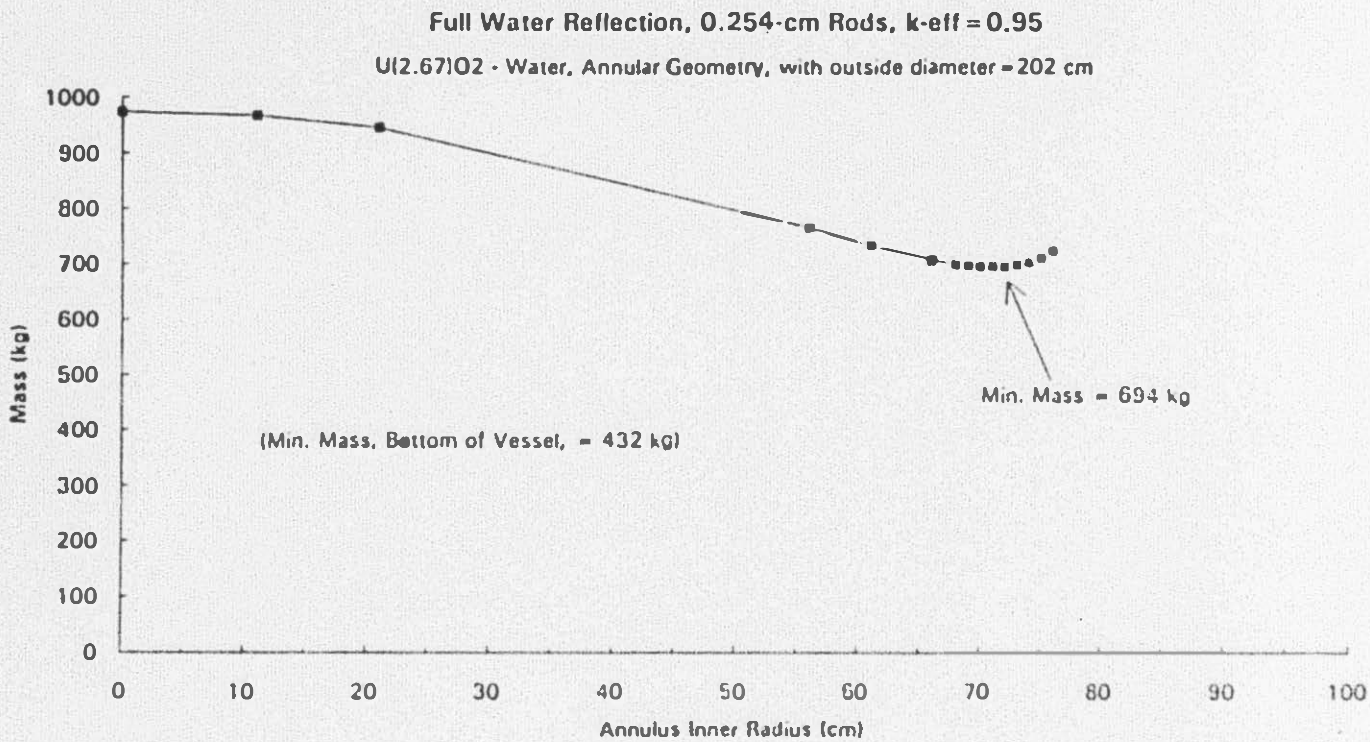

Full Water Reflection, 0.6-cm Rods, k-eff = 0.95
U(2.67)O2 - Water, Annular Geometry, with outside diameter = 202 cm
Mass (kg)
1000
900
800
700
600
500
400
300
200
100
0
Min. Mass = 674 kg
(Min. Mass, Bottom of Vessel, = 416 kg)
0
10
20
30
40
50
60
70
80
90
100
Annulus Inner Radius (cm)

Figure 1

Figure 2



Full Water Reflection, 0.254-cm Rods, k-eff = 0.95
U(2.67)O2 - Water, Annular Geometry, with outside diameter = 202 cm
Mass (kg)
1000
900
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80
90
100
Annulus Inner Radius (cm)
Min. Mass = 694 kg
(Min. Mass, Bottom of Vessel, = 432 kg)

configuration based on 0.6-cm rods. The required masses were larger by 2 to 4% for the .254-cm rods. Thus it is clear that the lattice configuration is an important consideration, and the GPU study chose a conservative configuration.

Neutron Moderation and Reflection

It is certainly possible to have a critical configuration without any neutron moderation, but such a "fast" system requires a high enrichment of fissile isotopes. For the enrichments encountered in the TMI-2 fuel, neutron moderation is required to produce a critical configuration, and the amount of neutron moderation determines the reactivity of the system. The criticality studies are conservative in this respect, because both the Steady State and the Accident case assume that there is sufficient water to provide the necessary moderation to achieve maximum k_{eff}. In reality, the RV does not contain water and efforts have been taken to ensure that water does not accidentally enter the RV.

The study also assumes a degree of neutron reflection, with either water or steel present to reflect neutrons escaping from the fuel region back into the fuel. In the Accident calculation, it was assumed that 500 gallons of unborated water were present above the fuel region to provide neutron reflection. This assumption is a conservatism, since it assumes that water introduced into the RV must be sufficient to not only saturate the fuel region, but also to provide the reflecting layer.

Additional Neutron Poisons

The Accident case assumed that the fuel contained 0.009% boron, but the study assumed no additional poisoning from items such as material from the control rods or internal structural material mixed in with the fuel. It is likely that any fuel debris could contain such neutron poisoning material, which would decrease its reactivity, but no credit was taken for the presence.

As a mitigating measure for criticality safety, the licensee dumped three drums of borated glass shards into the bottom of the RV. For the steady state study, this glass would have almost no effect, but for the Accident case, it could have a small effect that was not considered in the study. Fuel that would relocate into the bottom of the RV would consist, to some degree, of fine particles that could drift down and settle into the spaces between the shards. These fuel particles would be neutronically separated from the larger mass of fuel that settled on the top surface of the layer of shards. It is difficult to quantify, for the hypothetical case, what portion of the 620 kg of relocated fuel would fall into the glass shards, but any amount would have the effect of lowering k_{eff} below the calculated value.

Shape and Dimensions of the Fuel Configuration

The Accident analysis assumes that fuel relocates from the upper regions of the RV into the lower head region, and the shape of this relocated configuration is an important determinant of the reactivity of the configuration. One important feature of the shape of the configuration is the surface-to-volume ratio, since a shape with large surface area would experience high neutron leakage and therefore lowered reactivity (this accounts for the spherical shape of the unmoderated, potentially super-critical assemblies deployed by the military).

The GPU study assumes that the relocated fuel falls into a configuration with a hemispherical bottom surface, matching the curvature of the inside of the RV, and a flat top (like the top of a slab). The hemispherical bottom ignores the presence of the glass shards in the bottom of the RV: the presence of these shards would provide a base to support the relocated fuel, giving more of a nearly flat surface for the bottom. The flat bottom would have a lower reactivity than the curved bottom.

PNL performed a number of criticality calculations for these configurations. The PNL calculations investigated three basic shapes: 1) a slab (actually a short cylinder, with the outside radius matching the inner wall of the RV); 2) an annulus (similar to the slab, but with a large hole in the center); and 3) a flat top with a hemispherical bottom. The annular shape was chosen because of the greater possibility that debris falling from the inner walls of the RV would collect in a ring shape rather than a uniform slab.

In the first set of PNL calculations, the slab was compared to the annulus. This study found that the annulus could achieve a critical configuration with 40% less fuel than a similar slab, assuming that the inner gap dimension was chosen for optimal reactivity. In the second set of PNL calculations, the annular geometry was further investigated, and it was compared to the slab with a hemispherical bottom. Figure 3 illustrates this comparison. The shape with a hemispherical bottom could achieve a critical mass with 34% less fuel than the annular shape.

Of the three shapes investigated by PNL, the flat top with a hemispherical bottom required the smallest mass to achieve a critical configuration. Thus the licensee's choice of this configuration for its Accident analysis is conservative, since the bottom surface would be flattened by the presence of glass shards.

Analytical Bias in k_{eff}

All criticality studies all included an analytical bias in k_{eff} to account for uncertainties in the computer codes used in the modeling. They determined that a conservative margin of safety could be attained

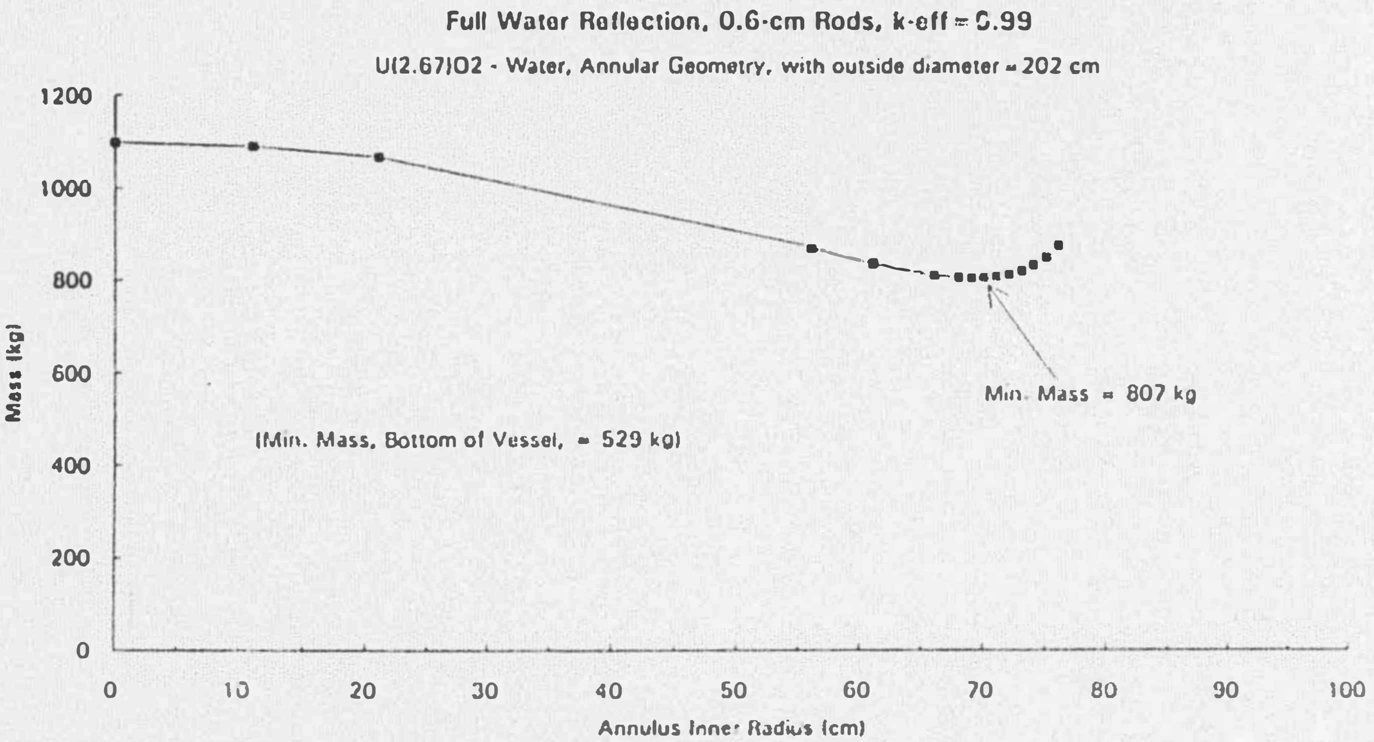

Full Water Reflection, 0.6-cm Rods, k-eff = 0.99
U(2.67)O2 - Water, Annular Geometry, with outside diameter = 202 cm
Mass (kg)
1200
1000
800
600
400
200
0
Min. Mass = 807 kg
(Min. Mass, Bottom of Vessel, = 529 kg)
0
10
20
30
40
50
60
70
80
90
100
Annulus Inner Radius (cm)

Figure 3

by increasing every calculated value of k_{eff} by 2.5%. Thus the k_{eff} reported in the study results is greater by 0.025 than the k_{eff} found in the computer code's output. This practice ensures that there is no chance for the computer code's modeling methodology to introduce a non-conservative uncertainty into the study results.

CONCLUSIONS

The criticality study performed for the TMI-2 RV used appropriate methods for analysis. The computer codes and cross sections are all accepted by the industry as state-of-the-art, so the analysis conforms to indus conventions.

Since the steady state configuration resulted in a large margin of safety from a critical configuration, the analysis was simplified by omitting many criticality-inhibiting mechanisms. In order to perform the study, an assumption was made that the RV was filled with pure, unborated water. This assumption is grossly conservative. Thus the steady state analysis adequately demonstrates that there is no likelihood of criticality without fuel relocation.

The Accident analysis used a quantity of relocated fuel that could be critical under certain ideal conditions. Thus this part of the study needed to include more criticality-suppressing mechanisms, so the presence of boron was acknowledged in the fuel region. Even so, the study still made a number of assumptions that were conservative, as described earlier in this review. With the proper use of analytical procedures and the incorporation of appropriate conservatism, this study demonstrated that there is no likelihood of an unintentional criticality occurring in the TMI-2 RV.

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ATTACHMENT 1

CRITICALITY ASPECTS OF FUEL DEBRIS IN THE TMI-2 REACTOR VESSEL

INTRODUCTION

The TMI-2 licensee has performed a detailed study of the quantity of fuel material that remains in the TMI-2 facility. The results of this study were compiled in the Defueling Completion Report (DCR), submitted to the USNRC on February 22, 1990.

The DCR summarized fuel quantities in different locations of the TMI-2 facility, and compared these quantities to a "Safe Fuel Mass Limit" (SFML). In most locations, the fuel quantities were substantially below the SFML levels, but in the reactor vessel, the estimated fuel quantity was above the SFML. The licensee therefore performed a criticality safety analysis for the fuel in the reactor vessel to ensure that there was no potential for a criticality. The licensee's study gave a k_{eff} of 0.945, which is below the NRC's acceptance criterion of 0.95 for fuel storage facilities.

At the request of the USNRC, PNL performed an independent study of the criticality potential in the reactor vessel.

BORATED GLASS IN THE REACTOR VESSEL

Since the DCR was written, three 55 gallon drums of borated glass shards have been dumped into the reactor vessel. Although the borated shards would have little if any poisoning effect on debris accumulating on their top surface, they do serve to isolate residual material already in the bottom head from any fuel debris that may fall into the vessel in the future. The shards also create a larger surface area in the bottom head over which fallen debris can be distributed. Distributing a fixed amount of a given debris mixture over a larger area increases neutron leakage and thus decreases the reactivity of the system. However, distributing material over a larger area also provides a mechanism whereby an undermoderated system can become optimally moderated and thus have a greater reactivity. Thus it is important to model the possible accumulation of fuel debris that could collect on the top surface of the debris as though it accumulated in optimum configurations.

CRITICALITY IN A SLAB CONFIGURATION

The criticality calculations reported in the DCR (p 5-55, rev. 4/0496P) found that an accumulation in the bottom reactor vessel head of an optimal mixture of 500kg of core debris and water would have a k_{eff} of 0.921 (not including bias) when fully reflected on top by water.

Based on data in DP-1014 (Clark, 1966), the minimum critical thickness of a fully water reflected, optimally moderated slab of $U(2.67)O_2$ pellets in water is 15.2cm.. At optimum moderation the $H/^{235}U$ atom ratio is 199 (for 2.67% enrichment) and the UO_2 bulk density is 3.78 g/cc (which closely approximates the 3.38 g/cc reported in the DCR, p 5-23, for the reactor vessel debris).

The unobstructed region in the reactor vessel above the bottom head has a diameter of about 241 cm (DCR Figures 5-31, 35, 36, & 36). The glass shards, at 165 gallons, create a surface area about 208 cm in diameter across the bottom head as indicated in Figure 1. An accumulation of optimally moderated mixture of $U(2.67)O_2$ and water at least 15.81cm deep on top of these shards is required before criticality would be possible. In other words, criticality can not be achieved unless the thickness of a uniform slab of debris on top of the shards is at least 15.81cm. Under these conditions the critical mass is 2428 kg of UO_2. If only nominal neutron reflection is considered credible (which seems more reasonable than full reflection), the critical thickness will be slightly larger (19.83cm) and the critical mass will increase to 3163 kg of UO_2.

Although the thickness of any such accumulation of debris on top of the shards must exceed either the 15.81cm (if full water reflection is credible) or the 19.83cm (if only nominal reflection is considered credible) for criticality to occur, criticality can occur at smaller masses than those given above - but at lower densities and larger volumes. The above masses of 2428 kg and 3163 kg correspond to the $U(2.67)O_2$ density (3.78 g UO_2/cc) that results in the smallest critical slab thickness. The minimum critical mass, however, occurs at a lower density of about 2.06 g UO_2/cc for 2.67% enriched UO_2. This results in a larger critical slab thickness but a smaller critical mass. At a density of 2.06 g $U(2.67)O_2$/cc, the minimum critical slab thick-

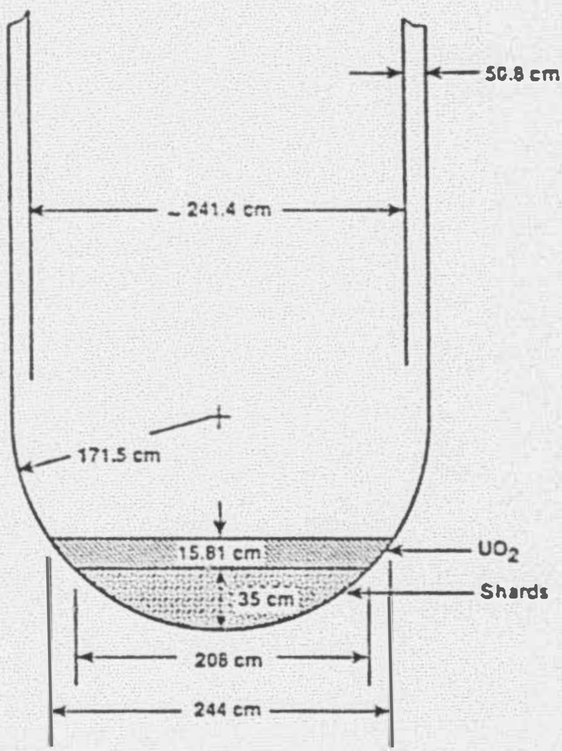

Figure 1 Reactor Vessel Diagram Showing Glass Shards and Accumulated Thickness of Optimum Moderated U (2.67) O_2-Water

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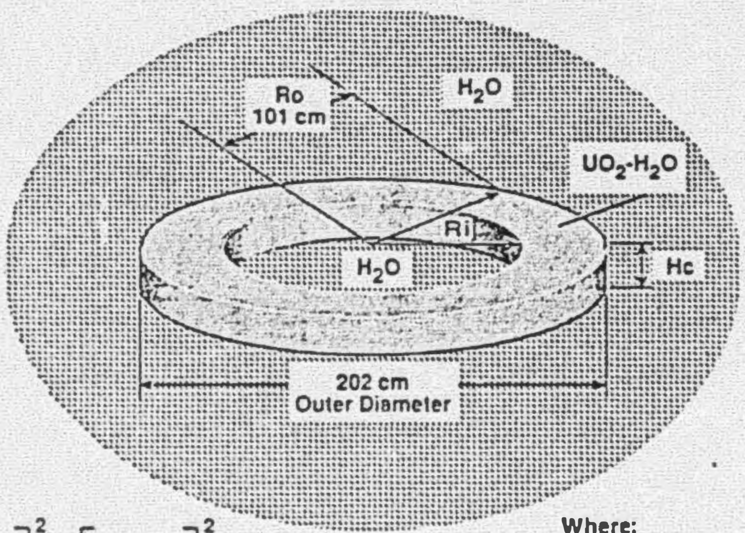
ness of a fully water reflected slab of UO_2 in water is 15.95 cm. The minimum critical thickness of $U(2.67)O_2$-water on top of the glass shards at this density of 2.06 g UO_2/cc is about 16.74 cm and the critical mass is about 1413 kg UO_2. If nominal neutron reflection is considered credible, the minimum critical thickness on top of the shards increases to 21.74 cm and the critical mass increases to about 1922 kg of UO_2.

CRITICALITY IN AN ANNULAR CONFIGURATION

The mass of material needed for criticality could be considerably less than that required for the slab geometry discussed above if the debris were to accumulate on top of the shards in the form of an irregular ring with water in the center region. The height of any such accumulation must, however, always exceed 15.81cm if criticality is to occur. This limit for a fully reflected, optimum moderated slab is valid irrespective of fuel density. If the density is greater than 3.78 g $U(2.67)O_2$/cc the critical slab thickness will be greater than 15.81cm. If the fuel density is less than 3.78 g $U(2.67)O_2$/cc, the critical slab thickness will also be greater than 15.81cm.

"Geometrical buckling" is a parameter used in neutronics calculations to describe the dimensions of a simple critical assembly. An empirical expression for calculating the geometrical buckling of annular rings was developed to investigate the effects that ring geometry has on the critical size of such accumulations of fuel debris on top of the glass shards. The empirical buckling relationship is shown in Figure 2 along with a sketch of the annular ring model used in the calculations (note that the maximum diameter of the annular ring model used in studying these effects is 202 cm, which is slightly smaller than the diameter estimated for the top surface of the shards).

Calculated critical sizes, and corresponding masses, based on this empirical buckling expression are given in Table 1 as a function of the annulus width.



$$B_c^2 = \left[\frac{2.405}{Ro+\lambda-1.11Ri+\lambda}\right]^2 + \left[\frac{\pi}{Hc+2\lambda}\right]^2$$

Where:

Ro = Outer radius
Ri = Inner Radius
Hc = Critical Height
B_c^2 = Critical Buckling
λ = Extrapolation Distance

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Figure 2 Annular Ring Model

TABLE 1

Estimated Critical Sizes of Optimally-Moderated $U(2.67)O_2$-Water in Annular Geometry Having an Outside Diameter of 202 cm (Full Water Reflection and 3.78 g UO_2/cc)

Annulus Width (cm)	Inner Radius (cm)	Critical Height (cm)	Critical Mass (kg UO_2)	KENO-IV k_{eff}
15.25*	0	INFINITE	INFINITE	1.003(0.004)
25	76	28.67	1506	1.005(0.003)
30	71	23.12	1414	
32	69	21.90	1415	
35	66	20.57	1428	
40	61	19.13	1472	
45	56	18.22	1529	1.007(0.003)
80	21	16.05	1860	
90	11	15.91	1904	
101	0	15.84	1919	1.028(0.003)

*Critical radius of a cylinder of $U(2.67)O_2$-water, infinite in length.

The calculated results shown in Table 1 indicate that the most favorable accumulation of fuel in an annular geometry on top of the glass shards in the reactor vessel bottom head would have an annulus width of about 32 cm and contain 1414 kg of UO_2 at 3.78g $U(2.67)O_2$/cc. The height of this fuel would be about 21.9 cm. These results are graphically presented in Figure 3.

Although the results presented in Table 1 yield the smallest critical size for an annual ring of fuel, a smaller mass could achieve criticality as discussed previously for a uniform slab accumulation of fuel. Calculated results are given in Table 2 for annular rings of fuel at the optimum density of 2.06 g UO_2/cc corresponding to the minimum critical mass for a $U(2.67)O_2$-water mixture.

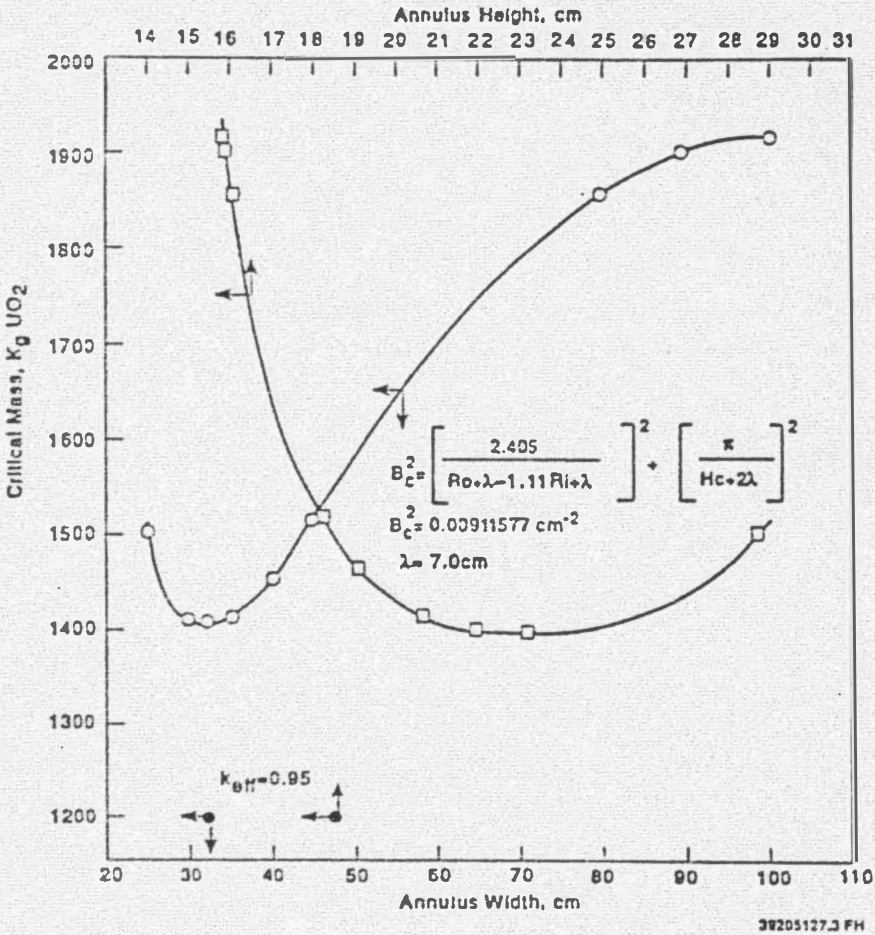

Figure 3 Estimated Critical Size of Optimaly Moderated $U(2.67)O_2$-Water In Annular Geometry Having an Outside Diameter of 202 cm (full water reflection and 3.76g UO_2/CC)

TABLE 2

Estimated Critical Masses of Optimally Moderated $U(2.67)O_2$-Water in Annular Geometry Having an Outside Diameter of 202 cm (Full Water Reflection and 2.06 g UO_2/cc)

Annulus Width (cm)	Inner Radius (cm)	Critical Height (cm)	Critical Mass (kg UO_2)	KENO-IV k_{eff}
INFINITE	0	15.95*	INFINITE	1.005(0.007)
25	76	31.75	909	1.027(0.009)
30	71	25.61	855	
32	69	24.14	850	
33	68	23.54	849	
35	66	22.54	852	
40	61	20.80	872	
45	56	19.70	900	0.989(009)
80	21	17.10	1080	
90	11	16.86	1099	
101	0	16.79	1108	0.991(0.011)

*Critical thickness of a slab of $U(2.67)O_2$-water, infinite in two dimensions.

The calculated results presented in Table 2 indicate that the minimum critical mass of fuel in an annular geometry on top of the glass shards in the bottom of the reactor vessel would be about 849kg $U(2.67)O_2$. The annulus width would be about 33 cm with an height of 23.54 cm. These calculated results are graphically presented in Figure 4.

Since the calculated values shown in Tables 1 and 2 are based on an unverified empirical expression for the geometrical buckling of an annular ring, k_{eff} values were calculated using the KENO-IV computer code for a few of the rings as a means of verifying the validity of the buckling expression. These calculated k_{eff} values are shown in the right-hand columns of Tables I and 2. As can be seen, the critical sizes calculated using the buckling expression agree reasonably well with the calculated k_{eff}.

Also shown in Tables 1 and 2 are calculated k_{eff} values for an infinite cylinder (top entry, Table 1) and an infinite slab (top entry, Table 2) of $U(2.67)O_2$-water. These two entries were included because the expressions for geometrical buckling for these configurations had been used in criticality

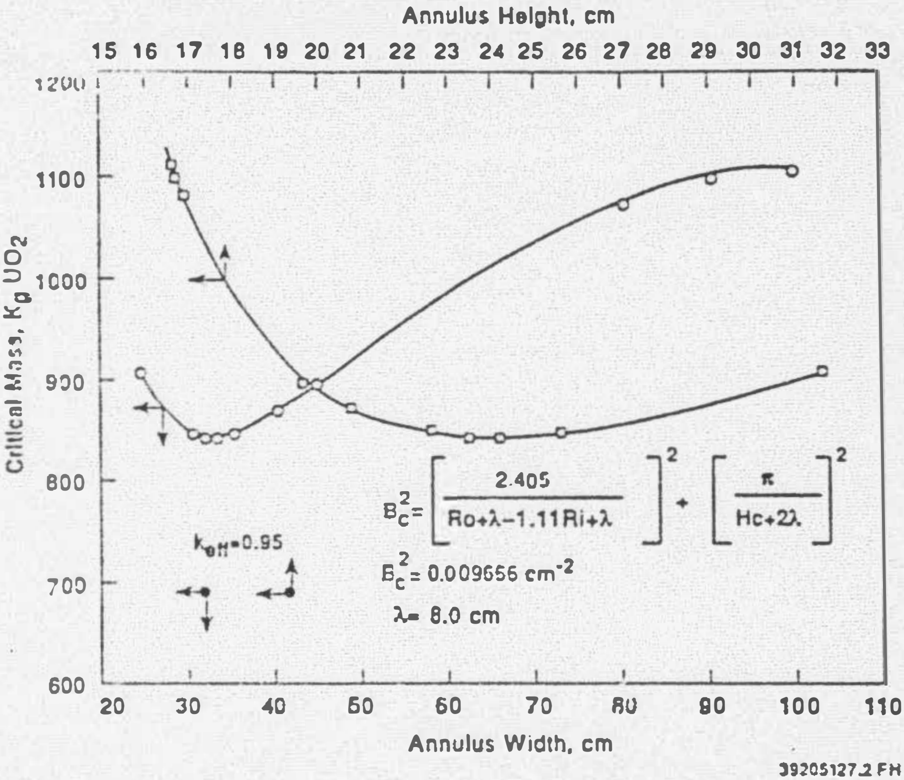

Figure 4 Estimated Critical Mass of Optimaly Moderated $U(2.67)O_2$-Water in Annular Geometry Having an Outside Diameter of 202 cm. (full water reflection and 2.06 UO_2/CC)

calculations long before the empirical expression was developed. Since these values are consistent with the other entries in the table, it increases our confidence in the empirical expression.

To estimate the effect that a 5% reduction of k_{eff} from critical would have on the size of the annular ring, buckling conversions were made to the ring having the smallest volume and to the ring having the smallest mass. For the smallest volume case, the height at a k_{eff} of 0.95 is 18.6 cm (1200 kg $U(2.67)O_2$) as compared to 21.9 cm (1415 kg $U(2.67)O_2$) at the critical condition. For the smallest mass case, the height at a k_{eff} of 0.95 is 19.16 cm (691 kg $U(2.67)O_2$) as compared to 23.54 cm (849 kg $U(2.67)O_2$) at the critical condition.

CONCLUSIONS

Minimum Thickness: The calculations performed in this study indicate that a slab thickness of at least 15.81 cm for a UO_2-water mixture on top of the glass shards in the reactor vessel bottom head is required before criticality is possible. This slab would contain 2428 kg of $U(2.67)O_2$, at a density of 3.78 g UO_2/cc.

Minimum Mass: At a bulk density (2.06 g UO_2/cc) much lower than that postulated for the reactor vessel debris (3.38g UO_2/cc) only about 1413 kg of $U(2.67)O_2$ is required before criticality would be possible. In this configuration, the depth of debris on top of the glass shards would be greater (16.74 cm vs 15.81 cm) than the thickness for a 3.78 g/cc slab. Should the debris accumulate in the form of a well-defined annular ring on top of the shards, the mass of $U(2.67)O_2$ required for criticality to be possible is further reduced to about 849 kg. These values are based on full water reflection and optimum neutron moderation with respect to either volume or mass. Limiting the quantity of water in the reactor vessel significantly increases the amount of material required before criticality would be possible in the above geometries.

Potential for Criticality in TMI-2 Reactor Vessel: The current best estimate for the quantity of fuel in the reactor vessel is 609 kg. Obviously this quantity is below the minimum mass required for a criticality in a geometry that is reasonably attainable, 849 kg. The 609-kg estimate is based on video imaging techniques, however, and a more recent estimate using active and passive neutron measurements indicates that the inventory may be higher, possibly as much as double the 609-kg estimate. 1200 kg of UO_2 is more than the minimum mass required for a criticality, but 849 kg of UO_2 could result in a criticality only if a number of ideal conditions were satisfied. These conditions require that the fuel has a density of 2.06 g/cc and it must fall into the ideal annular configuration with an annulus width of 33 cm and height of 23.54 cm. These ideal conditions also require a fully-reflecting water supply. The calculations show that any deviations from this density, these dimensions and the reflective condition would increase the mass of fuel required for criticality. Most changes in the configuration would increase the minimum required mass by a substantial amount: for example, increasing the fuel density to 3.78 g/cc would increase the minimum required mass to 1414 kg, which is greater than even the upper estimate of UO_2 mass in the reactor vessel. Under the conditions of this study, it is incredible that the fuel re-maining in the reactor vessel could fall into a critical configuration. This fuel exists in various locations, in differing forms (surface films, loose powders, re-solidified fuel) and densities. The mechanism for bringing more than 850 kg into one location is not realistic - some of the fuel is already covered by borated glass shards and are thus neutronically isolated from additional fuel that could collect on top of the shards, and other fuel is located behind baffle plates that would prevent it from falling into the bottom head. The fuel exists in densities different than the optimum 2.06 g/cc, which also argues against the possibility of criticality. Finally, the ability of the fuel to collect in an annular configuration with the precisely correct dimensions is extremely unlikely. Thus the PNL study supports the conclusion that there is no danger from a criticality.

REFERENCES

Clark, H. K., 1966. "Critical And Safe Masses And Dimensions of Lattices of U And UO_2 Rods in Water". DP-1014. Savannah River Laboratory, Aiken, South Carolina.

ATTACHMENT 2

Battelle
Pacific Northwest Laboratories

Project Number

Internal Distribution

SR Bierman
SW Heaberlin
File/LB

Date 14 October 1992

To R.I. Scherpelz

From A.W. Prichard

Subject Additional Criticality Analysis for TMI-2

References:

SR Bierman to R Harty; Residual Debris in TMI-2 Reactor Vessel; 10 June 1992.

SR Bierman to RI Scherpelz; Additional Criticality Analysis - TMI-2; 23 July 1992.

Clark, H.K.; 1966; DP-1014; "Critical and Safe Masses and Dimensions of Lattices of U and UO_2 Rods in Water"; Savannah River Laboratory, Aiken, South Carolina.

Reardon, W.A.; "An Approximate Buckling of Partially Filled Spheres and Application to Critical Experiments; "Physics Research Quarterly Report, October, November, December, 1963; HW-80020; 15 January 1964

In Dr. Bierman's memo to you, he indicated that your sponsor wanted several different conditions analyzed, I am responding to that request. For the additional cases requested, I determined the minimum thickness and minimum annular mass of material to achieve the requested K-effective. The minimum dimensions include a 2.5% bias in K-effective for consistency with previous analysis.

The Case 1 conditions are full water reflection, 2.06 g UO_2/cc, 0.6 cm diameter pellets, and 2.67% U-235. The target k-effective is 0.95. To achieve the target K-effective in the bottom of the vessel, the height is 19.7 cm, the volume is 202 liters, and the mass is 416 Kg UO_2. For annulus of material the maximum diameter is 202 cm. The minimum annulus height required for a K-effective of 0.95 is 14.5 cm, the minimum mass is 674 Kg UO_2. The height, volume, and mass of several different annular regions is shown in Table 1.

The Case 2 conditions are identical to Case 1 except for the target K-effective. The Case 2 conditions are full water reflection, 2.06 g UO_2/cc, 0.6 cm diameter pellets, and 2.67% U-235. The target k-effective is 0.99. To achieve the target K-effective in the bottom of the vessel, the height is 22.3 cm, the volume is 257 l, and the mass is 529 Kg UO_2. For annulus of material the maximum diameter is 202 cm. The minimum annulus height required for a K-effective of 0.99 is 16.6 cm, the minimum mass is 807 Kg UO_2. The height, volume, and mass of several different annular regions is shown in Table 2.

The Case 3 conditions are identical to Case 1 except for the pellet size. The Case 3 conditions are full water reflection, 2.06 g UO_2/cc, 0.254 cm diameter pellets, and 2.67% U-235. The target k-effective is 0.95. To achieve the target K-effective in the bottom of the vessel, the height is 20.1 cm, the volume is 210 l, and the mass is 432 Kg UO_2. For annulus of material the maximum diameter is 202 cm. The minimum annulus height required for a K-effective of 0.95 is 14.8 cm, the minimum mass is 694 Kg UO_2. The height, volume, and mass of several different annular regions is shown in Table 3.

The Case 4 conditions are identical to Case 1 except for being reflected on the bottom by borated glass shards instead of water. The borated glass shards are treated as nominal reflector, which has a reflector saving 2 cm less than full water reflection. The Case 4 conditions are full water reflection on the tops and sides, nominal reflection on the bottom (simulation of the Boron glass shards), 2.06 g UO_2/cc, 0.6 cm diameter pellets, and 2.67% U-235. The target k-effective is 0.95. The maximum annulus is 202 cm in diameter. The minimum height required for a K-effective of 0.95 is 16.5 cm, the minimum mass is 739 Kg UO_2. The height, volume, and mass of several different annular regions is shown in Table 4.

The Case 5 conditions are identical to Case 4 except for being unreflected. The unreflected conditions are treated as a full reflection with 4 cm less reflector savings. The Case 5 conditions are unreflected, 2.06 g UO_2/cc, 0.6 cm diameter pellets, and 2.67% U-235. The target k-effective is 0.95. The maximum annulus is 202 cm in diameter. The minimum height required for a K-effective of 0.95 is 20.5 cm, the minimum mass is 1044 Kg UO_2. The height, volume, and mass of several different annular regions is shown in Table 5.

The Case 6 conditions are identical to Case 4 except for different pellet diameter. The Case 6 conditions are full reflection on the tops and sides, nominal reflection on the bottom, 2.06 g UO_2/cc, 0.254 cm diameter pellets, and 2.67% U-235. The target k-effective is 0.95. The maximum annulus is 202 cm in diameter. The minimum height required for a K-effective of 0.95 is 17.1 cm, the minimum mass is 781 Kg UO_2. The height, volume, and mass of several different annular regions is shown in Table 6.

Table 1. Estimated Dimensions and Masses of $U(2.67)O_2$ - Water in an Annular Geometry having an Outside Diameter of 202 cm. for a K-effective of 0.95 with Full Water Reflection, 2.06 grams UO_2/cc, and 0.6 cm Rods

	Annulus Width (cm)	Inner Radius (cm)	Height (cm)	Volume (liters)	Mass (kg)
Bottom of Vessel	79.9	0	19.7	202	416
	14.1*	0	Infinite		
	25	76	24.4	339	699
	26	75	23.2	334	688
	27	74	22.3	330	681
	28	73	21.4	328	676
	29	72	20.8	327	674
	30	71	20.2	327	674
	31	70	19.7	328	675
	32	69	19.2	329	677
	33	68	18.8	330	680
	35	66	18.2	334	688
	40	61	17.1	347	715
	45	56	16.3	363	747
	80	21	14.7	450	927
	90	11	14.5	460	947
	101	0	14.5	463	955
	Infinite	0	14.0*		

* Radius of an infinite cylinder of $U(2.67)O_2$ - Water at target K-effective
* Height of an infinite slab of $U(2.67)O_2$ - Water at target K-effective

Table 2. Estimated Dimensions and Masses of $U(2.67)O_2$ - Water in an Annular Geometry having an Outside Diameter of 202 cm. for a K-effective of 0.99 with Full Water Reflection, 2.06 grams UO_2/cc, and 0.6 cm Rods

	Annulus Width (cm)	Inner Radius (cm)	Height (cm)	Volume (liters)	Mass (kg)
Bottom of Vessel	84.6	0	22.3	257	529
	15.6*	0	Infinite		
	25	76	30.6	426	877
	26	75	28.8	414	852
	27	74	27.3	405	835
	28	73	26.1	400	823
	29	72	25.1	396	815
	30	71	24.3	393	810
	31	70	23.6	392	808
	32	69	22.9	392	807
	33	68	22.4	392	808
	35	66	21.5	395	813
	40	61	20.0	407	838
	45	56	19.0	423	871
	80	21	16.9	518	1067
	90	11	16.7	529	1090
	101	0	16.6	533	1098
	Infinite	0	16.0*		

* Radius of an infinite cylinder of $U(2.67)O_2$ - Water at target K-effective
* Height of an infinite slab of $U(2.67)O_2$ - Water at target K-effective

R.I. Scherpelz
14 October 1992
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Table 3. Estimated Dimensions and Masses of $U(2.67)O_2$ - Water in an Annular Geometry having an Outside Diameter of 202 cm. for a K-effective of 0.95 with Full Water Reflection, 2.06 grams UO_2/cc, and 0.254 cm Rods

	Annulus Width (cm)	Inner Radius (cm)	Height (cm)	Volume (liters)	Mass (kg)
Bottom of Vessel	80.6	0	20.1	210	432
	14.3*	0	Infinite		
	25	76	25.3	[illegible]	724
	26	75	24.0	[illegible]	711
	27	74	23.0	[illegible]	703
	28	73	22.1	[illegible]	698
	29	72	21.4	337	695
	30	71	20.8	337	694
	31	70	20.2	337	695
	32	69	19.8	338	696
	33	68	19.4	339	699
	35	66	18.7	343	707
	40	61	17.5	356	733
	45	56	16.7	371	765
	80	21	15.0	459	946
	90	11	14.8	469	967
	101	0	14.8	473	974
	Infinite	0	14.2+		

* Radius of an infinite cylinder of $U(2.67)O_2$ - Water at target K-effective
\+ Height of an infinite slab of $U(2.67)O_2$ - Water at target K-effective

Table 4. Estimated Dimensions and Masses of $U(2.67)O_2$ - Water in an Annular Geometry having an Outside Diameter of 202 cm. for a K-effective of 0.95 with Full Water Reflection on Top of Glass Shards, 2.06 grams UO_2/cc, and 0.6 cm Rods

Annulus Width (cm)	Inner Radius (cm)	Height (cm)	Volume (liters)	Mass (kg)
14.1*	0	Infinite		
25	76	26.4	367	757
26	75	25.2	363	747
27	74	24.3	360	742
28	73	23.4	359	739
29	72	22.8	359	739
30	71	22.2	359	741
31	70	21.7	361	743
32	69	21.2	363	747
33	68	20.8	365	752
35	66	20.2	371	764
40	61	19.1	388	799
45	56	18.3	407	838
80	21	16.7	511	1053
90	11	16.5	523	1078
101	0	16.5	527	1087
Infinite	0	16.0*		

* Radius of an infinite cylinder of $U(2.67)O_2$ - Water at target K-effective
* Height of an infinite slab of $U(2.67)O_2$ - Water at target K-effective

Table 5. Estimated Dimensions and Masses of $U(2.67)O_2$ - Water in an Annular Geometry having an Outside Diameter of 202 cm. for a K-effective of 0.95 with Unreflected on Top of Glass Shards, 2.06 grams UO_2/cc, and 0.6 cm Rods

Annulus Width (cm)	Inner Radius (cm)	Height (cm)	Volume (liters)	Mass (kg)
18.1*	0	Infinite		
25	76	84.8	1179	2428
26	75	57.4	825	1699
27	74	46.7	693	1428
28	73	40.8	624	1286
29	72	37.0	582	1200
30	71	34.3	555	1144
31	70	32.3	537	1106
32	69	30.7	525	1081
33	68	29.5	516	1063
35	66	27.6	507	1044
40	61	24.9	507	1045
45	56	23.5	521	1074
80	21	20.8	638	1315
90	11	20.6	653	1345
101	0	20.5	657	1353
Infinite	0	20.0*		

* Radius of an infinite cylinder of $U(2.67)O_2$ - Water at target K-effective
* Height of an infinite slab of $U(2.67)O_2$ - Water at target K-effective

Table 6. Estimated Dimensions and Masses of $U(2.67)O_2$ - Water in an Annular Geometry having an Outside Diameter of 202 cm. for a K-effective of 0.95 with Full Water Reflection on Top of Glass Shards, 2.06 grams UO_2/cc, and 0.254 cm Rods

Annulus Width (cm)	Inner Radius (cm)	Height (cm)	Volume (liters)	Mass (kg)
14.6*	0	Infinite		
25	76	28.2	392	808
26	75	26.8	386	795
27	74	25.7	382	787
28	73	24.8	380	783
29	72	24.1	379	781
30	71	23.4	379	781
31	70	22.8	380	783
32	69	22.3	382	787
33	68	21.9	384	791
35	66	21.2	389	802
40	61	20.0	406	837
45	56	19.2	425	876
80	21	17.4	532	1097
90	11	17.2	545	1122
101	0	17.1	549	1131
Infinite	0	16.6+		

* Radius of an infinite cylinder of $U(2.67)O_2$ - Water at target K-effective
+ Height of an infinite slab of $U(2.67)O_2$ - Water at target K-effective

The methods used for calculating annuluses are described by Dr. Bierman in his memo to R Harty.

$$K_{goal}=\frac{K_{\infty}}{1+M^2 \bullet B_{goal}^2} \tag{1}$$

Equation 1 gives the goal K in terms of M^2, K-infinity, and the goal B^2. M^2, K-infinity, and reflector savings constants (used in equation 4) were interpolated from data given in DP-1014. The goal K is the target K-effective minus the 2.5% bias in K-effective, the only unknown is the goal B^2. Rearranging equation 1 gives equation 2.

$$B_{goal}^2=\frac{K_{\infty}-K_{goal}}{M^2 \bullet K_{goal}} \tag{2}$$

From Bierman (June, 92), B^2 for annular rings of fuel is given in equation 3. This memo indicated that equation 3 had been tested and that the results were less than 2.5% different in estimating K-effective.

$$B^2=\left[\frac{2.405}{R_o+\lambda_o+1.11 \bullet R_i+\lambda_i}\right]^2+\left[\frac{\pi}{H+\lambda_t+\lambda_b}\right]^2 \tag{3}$$

R_o = outside radius of the annulus
R_i = inside radius of the annulus
H = height of the annulus
λ_i = reflector savings for the inside of the annulus
λ_o = reflector savings for the outside of the annulus
λ_t = reflector savings for the top of the annulus
λ_b = reflector savings for the bottom of the annulus

$$H_{goal}=\frac{\pi}{\sqrt{\left[\frac{K_{\infty}-K_{goal}}{M^2 \bullet K_{goal}}\right]-\left[\frac{2.405}{R_o+\lambda_o-1.11 \bullet R_i+\lambda_i}\right]^2}}-\lambda_t-\lambda_b \tag{4}$$

Equation 4 is a result of equating B^2_{geom} (equation 2) with B^2 (equation 3) and solving for H, the height of the annulus. The annulus height is a function of the inner radius and the outer radius (set a 202 cm for this analysis).

The methods used for calculating the critical buckling for partially filled spheres is from W.A. Reardon, which is given in equation 5.

$$B^2=\frac{40.0884 \cdot R \cdot S/V+9.6136}{V} \tag{5}$$

R = radius of the sphere
S = surface area of the partially filled sphere
V = volume of the partially filled sphere

When the dimensions of the sphere and the partially filled sphere have been increased by the reflector savings. The equation orginally developed by W.A. Reardon was for spheres more than half filled. However, the method of development implies that the equation should apply to spheres less than half filled.