TMI-2 CRITICALITY ANALYSIS
FOR A HEAVY LOAD DROP ACCIDENT
IN SUPPORT OF RECOVERY ACTIVITIES THROUGH REACTOR
VESSEL HEAD REMOVAL

B&W Document No. 77-1146499-00

December 1983

Prepared By

J.R. Worsham III

Prepared for

GPU Nuclear Corporation
Under Master Services Contract 665-7100

by

BABCOCK & WILCOX
Power Generation Group
Utility Power Generation Division
P.O. Box 1260
Lynchburg, Virginia 24505

TMI-2 Criticality Analysis

Summary -

The criticality analyses of the TMI-2 reactor to support the recovery activities through head removal have modeled the core assuming 50% cladding failure in all fuel rods. The associated amount of fuel damage is the maximum that could have credibly occurred as a result of the 1979 accident. This report discusses the worst case model of additional fuel disruptions that could occur as a result of a heavy load drop accident, such as dropping the reactor head onto the vessel or plenum. The heavy load drop model is conservative for criticality analyses because it assumes the maximum credible amount of additional cladding failures, with the fuel collapsed to the most reactive configuration. The analyses indicate that with this conservative model the core will remain 1.0%$\Delta\rho$ subcritical (K_{eff} <.99) with a boron concentration of 3500 ppm.

Contents

I. Introduction -

Criticality calculations[1,2] of the core region in the TMI-2 reactor have modeled the fuel as 50% damaged and 50% undamaged. This model was developed by the NRC[3] and was conservatively adapted for criticality safety analyses following the accident. This model has also been used for criticality calculations in support of the safety evaluations for recovery activities through head removal[4]. It continues to be a conservative approach for head removal recovery activities, since there are no plans to disturb the fuel. However, a model with 50% damage could be nonconservative if additional fuel disruptions occurred as a result of a heavy load drop accident. This report describes the worst case model of additional fuel disruptions that could occur in the TMI-2 core resulting from a heavy load drop accident. It shows that the core will remain 1.0% $\Delta\rho$ subcritical for this reconfigured condition with 3500 ppm borated water.

The model of additional fuel failures caused by a heavy load drop accident results in 62% of the core being damaged. Like the 50% damaged model, the 62% damaged model is a conservative adaptation of the NRC model of damage. The development of the 62% damaged model is discussed in more detail in the following section entitled "Damaged Core Model."

The model not only considers 12% additional core damage, but also includes an optimization of all variable parameters affecting the reactivity (ρ) of the core. The optimization analysis determines the physical arrangement and condition of the core parameters such that the highest effective neutron multiplication factor (k_{eff}) is obtained for the worst case. The parameters include fuel particle size, the particle shape, particle spacing, structural debris, temperature coefficients, et cetera. The specifics of the optimization are discussed in a subsequent section entitled "Optimization of Reactivity".

The last two sections of the report discuss the calculational methods and procedures, and summarize the results. The calculational methods and procedures are the same as those used in the previous analyses.[1,4] The methods for optimizing the fuel configurations are based on spectrum and spatial analysis of the various fuel-moderator combinations. The procedures for determining the highest core reactivity are based on determining the reactivity coefficient for all the parameters affecting the multiplication factor. The optimized results of the most reactive worst case model of the heavy load drop accident show the core will be 1.0% subcritical.

II. Damaged Core Model -

The damaged core criticality model for the heavy load drop accident evolved from the existing core criticality models[4,5], the Quick Look data[6], and a hypothetical scenario which produces the maximum amount of additional fuel rod cladding failures. This discussion explains the evolution of the model by (1) reviewing the development of the existing models, (2) indicating how the Quick Look data shows the existing models are conservative, (3) showing how the existing model may be potentially non-conservative if additional cladding failures occur, and (4) developing the scenario of additional fuel disruptions caused by a heavy load drop accident.

The existing core criticality models were developed when the first criticality safety calculations were performed on the TMI-2 reactor following the accident. At that time, there were no predictions as to the degree of damage. Consequently, the criticality calculations assumed a range of damage including a total core collapse. Models of all the fuel collapsed within the vessel indicated the reactor would not be subcritical with 2100 ppm boron in the moderator. Thus, either more boron was required, or assessments of the maximum degree of damage were needed, or both. The NRC used simplifying and bounding calculations to determine the maximum degree of damage. The results indicated that cladding embrittlement would occur to a depth of between 6 and 7 feet in the center assembly locations, and to a depth of 5 to 6 feet in most of the other assemblies[3]. The average amount of cladding failure predicted by the NRC was less than 50%, with much less than 50% of the cladding of the high enriched batch 3 fuel on the periphery predicted to fail. Consequently, a conservative criticality model was developed with 50% of the cladding damaged and 50% undamaged.

The lower 6 feet of the core were assumed to be undamaged. This region was modeled geometrically to be the same as the original core with the fuel pellets in the original fuel cell arrays and the fuel cell arrays comprising the original 177 fuel assemblies. In the damaged upper half of the core, the criticality model further assumed that none of the fuel particles would be confined by the cladding. Without any structural support, the damaged fuel was mixed with the most reactive amount of moderator and placed in a uniform mass on top of the undamaged fuel. Thus, a vertical cross section of the core geometry would show a two region cylinder with the damaged fuel stacked on top of 6 feet of undamaged fuel.[4]

Subsequent to the accident, there were several more predictions of core damage using various calculation methods. These predictions were evaluated and a reference core model was established as well as a maximum damage model[5]. The amount of fuel predicted to be free of the cladding is less than 50%. Thus, these later models further confirmed that the earlier criticality calculations are conservative when treating half of the fuel as completely damaged, without any cladding support.

The Quick Look data has also shown that the 50% damaged core model is conservative[6]. In fact, the Quick Look data indicates that the peripheral fuel (batch 3) may be standing which would indicate much less than 50% of the fuel will be free of the cladding. This would indicate that the criticality analyses used to support recovery activities through head removal (reference 4, BAW-1738) are very conservative because they assume 50% damaged fuel. However, reference 4 does not address criticality accidents. Due to the unknown structural rigidity of any batch 3 fuel that may be standing, there is the possibility of an accident scenario that results in more than 50% damaged fuel. The following discussion explains the scenario for additional fuel damaged as a result of a heavy load drop accident, such as the reactor vessel head drop. The development of the criticality model for the fuel configuration is also explained.

Figure 1 shows a schematic of the damaged core with the peripheral fuel (60 batch 3 assemblies) standing. If the shock of dropping the head has sufficient force to fracture the embrittled cladding of the standing fuel, then the standing fuel will collapse. Rather than attempt to mechanically analyze the embrittled cladding to quantify the amount of fuel failures, if any, the criticality evaluations have assumed that the shock fractures all embrittled cladding.

References 3 and 5 show the predictions of cladding embrittlement as a result of the 1979 accident. The degree of embrittlement follows a slightly parabolic radial distribution with the most embrittled cladding occurring at the center of the core, 7.5 feet from the top of the fuel. Figure 1 schematically shows this embrittlement zone.

To ensure a conservative criticality model, the fracture zone resulting from the heavy load drop accident is specified to occur at the lowest point on the embrittlement zone. This results in the greatest amount of additional fuel damage. Only the bottom 4.5 feet of the original core remain undamaged with this model, while the remaining 62% of the fuel is damaged. Figure 2 schematically represents the potential core configuration following this scenario of a heavy load drop accident. On top of the undamaged fuel rests the fuel damaged in the 1979 accident. On top of this damaged fuel is a layer of the peripheral (batch 3) fuel which collapsed as a result of the postulated heavy load drop accident.

While the amount of additional fuel damage is the maximum that would be credible, the core model is not the most conservative criticality model: (1) There are uncertainties associated with the composition of the existing damaged fuel which could increase reactivity; and, (2) There are uncertainties associated with the configuration of both the damaged fuel and collapsed fuel. The uncertainties associated with the composition of the damaged or collapsed fuel are eliminated by optimizing the parameters affecting reactivity. This optimization is discussed in the following section entitled "Optimization of Reactivity". To ensure the fuel arrangement in the criticality model is conservative, the uncertainties associated with the damaged fuel configuration are enveloped by specifying the criticality model shown in Figure 3.

Figure 3 represents the worst case criticality model. All the damaged batch 3 fuel is sandwiched between the undamaged fuel on the bottom and the remaining (batches 1 and 2) fuel on the top. As discussed in the following section, this separation of all the damaged batch 3 fuel from the other damaged fuel produces a higher reactivity than any homogenized mixture of all the damaged fuel.

III. Optimization of Reactivity -

The previous discussions of the "damaged core model" described a hypothetical scenario of additional fuel damage. While the additional damage is the maximum amount that could be credible, the damaged configuration alone does not produce the worst case criticality model. The criticality model is a worst case when the parameters within and around the fuel regions have been optimized to produce the most reactive conditions. This section outlines the optimization of the core reactivity by indicating how the values of all parameters which affect reactivity are analyzed.

All the materials within the reactor, along with the geometrical arrangement of these materials are parameters affecting the reactivity of fuel configurations. In an undamaged reactor, these parameters are well defined. In the damaged TMI-2 reactor, most of these parameters cannot be defined. Criticality safety procedures require that all parameters which are not specifically known or precisely controlled be treated conservatively to produce the most reactive system possible. This procedure has been followed in both the criticality safety analyses following the accident and the analyses supporting recovery activities through head removal.[4] It will continue to be followed for the analysis of the heavy load drop accident.

Reference 4 contains a detailed description of specific evaluations for obtaining the maximum reactivity in previous worst case criticality models. Reference 4 also explains the optimization techniques for determining the values of all the various parameters affecting the reactivity of the damaged core criticality models. Since the worst case criticality model for the heavy load drop accident contains essentially the same parameters as the previous models, this discussion will be abbreviated. Appendix A gives a detailed description of parameters which have changed from previous analyses while the following discussion gives a synopsis of the optimized fuel conditions.

The two basic parts of the optimized fuel regions are the moderator and the fuel particles. The fuel particles with the highest reactivity are in the form of the original pellets (see Appendices A and C). The pellets are stacked end-on-end like a rod and contain only UO_2 and the isotopics corresponding to the burnup that each rod received during the 94 equivalent full power days of operation. The moderator is the region surrounding the fuel and is limited by Technical Specifications to a minimum of 3500 ppm borated water which establishes its most reactive condition.

The moderator and fuel in the undamaged fuel region are constrained to be in the geometrical form of fuel pins and fuel assemblies. Therefore, optimizing the fuel-moderator combination (hydrogen to uranium ratio) involved an analysis of water logging. The optimal reactivity occurs with the standard cladding in place and the original fuel to clad void space. The optimal fuel-moderator array in the damaged fuel regions is a square (see Appendices A and C). The most reactive combination of fuel and moderator for the damaged batch-3 region is produced when the fuel volume fraction is .58. The corresponding volume fraction for the region with the damaged batch 1 and 2 fuel is .61.

The fuel configurations within the core model (Figure 3) radially extend across the area of the original core. The height of the undamaged fuel, 4.5 feet, is determined by the fracture zone boundary shown in Figure 1. With a fuel volume fraction of .58, the height of the damaged batch 3 region is 1 foot 3.3 inches. Likewise, for the remaining damaged fuel, with a .61 fuel volume fraction, the height is determined to be 2 feet 4.7 inches. The reflectors for this core model are defined by the actual material and components on the top, bottom, and sides of the fuel configuration.

The temperature of the various components of the core (fuel, moderator, and reflector) are all assumed to be uniform. The most reactive temperature is 50°F (the lower technical specification limit) and the core temperature coefficient is negative.

IV. Calculational Methods and Procedures -

The two previous sections (II and III), respectively, described the core model resulting from a heavy load drop accident, and the parameters within the reactor that affect the reactivity of the model. In this section, the methods and procedures for optimizing the parameters to attain the most reactive (worst case) core model will be described, along with methods and procedures used for the core analyses. This description will refer to the computer codes NULIF[7], ANISN[8], and PDQ[9]. These codes have been described in reference 4 which includes other references explicitly detailing the methods used within each code. Therefore, no discussion of the codes per se is included in this section.

The core configuration (Figure 3) was separated into cells of fuel and moderator combinations for the three respective fuel regions, and cells of the non-fuel regions, such as the reflector regions, control rod guide tubes, and instrument tubes. Optimization of the core model to determine the most reactive combination of all parameters began with NULIF analyses of each cell. NULIF calculations determined the sensitivity of the multiplication factor to each parameter. An iterative optimization technique was then employed to determine values for each parameter in combination with all other parameters such that the highest overall multiplication factor was produced for each fuel region.

The three fuel regions and the reflectors were coupled together with the PDQ code to determine the most reactive core configuration. The PDQ calculations in 1-dimension (axial) and 2-groups served as the principal model for predicting the overall core multiplication factor and the associated reactivity changes. While the 1-dimensional calculation only computed the axial flux distribution, the calculation of k_{eff} represented the 3-dimensional core by including radial bucklings for the three respective fuel regions. The accuracy of the 1-dimensional PDQ results was verified by benchmarking them with two 3-dimensional PDQ calculations and with a 13-group 1-dimensional ANISN calculation. The specifics of the benchmark calculations are described in Appendix D.

V. Results -

The worst case criticality model which would occur from the postulated heavy load drop accident is 1.0%$\Delta\rho$ subcritical with the most reactive combination and configuration of the parameters affecting reactivity. The results are summarized in the following table.

Criticality Results

k_{eff} with control rods, 3500 ppm boron	.988
Control rod worth	.2%$\Delta\rho$
Δk_{eff} for an additional 500 ppm boron	-.02
Inverse boron worth	240 ppm/%$\Delta\rho$
Temperature coefficient, 3500 ppm boron	$-.4\times10^{-4}\Delta\rho/°F$
Temperature coefficient, 4000 ppm boron	$-.4\times10^{-4}\Delta\rho/°F$

The k_{eff} (.988) is the maximum possible value including the uncertainties identified as part of the benchmarks for this analysis and uncertainties identified previously[4].

The control rod worth was determined to be .2%$\Delta\rho$. This very low worth reflects the high importance weighting of the damaged fuel regions relative to the undamaged since the control rods are assumed to be only in the undamaged fuel region. In the undamaged region the control rods are worth 6.8%$\Delta\rho$. Thus the implied importance weignting factor is .03 for reactivity changes in the undamaged fuel. Such a low importance weighting factor and low control rod worth means that uncertainties associated with the control rods have essentially no effect on the reactivity of the overall core.

If an additional 500 ppm boron is added to the moderator, k_{eff} will decrease by a value of .02 Δk_{eff}. Thus, the inverse boron worth is 240 ppm/%$\Delta\rho$ when the core parameters are optimized with 3500 ppm borated water. The inverse worth provides an estimate of the boron concentration required to achieve any particular degree of subcriticality.

The temperature coefficient of the criticality model was determined to be $-.4\times10^{-4}\Delta\rho/°F$. This value was obtained by increasing the temperature from 50°F to 73.1°F. It shows that 50°F is the most reactive temperature for the worst case core model (50°F is the lower technical specification limit). The temperature coefficient at 4000 ppm boron was assessed by comparing the calculations of the temperature coefficient for the damaged batch 3 fuel at 3500 and 4000 ppm. It is estimated that the core temperature coefficient at 4000 ppm boron will be essentially the same as at 3500 ppm boron.

Reference 4 shows the worst credible fuel configuration that could exist in the TMI-2 reactor. This configuration[4] meets the shutdown criteria (k_{eff} < .99) with a margin of 1.0%$\Delta\rho$; thus, the calculated k_{eff} is less than or equal to .98. The hypothetical worst case heavy load drop accident results show that a 1.0%$\Delta\rho$ shutdown margin will be maintained (k_{eff} < .99) should such an accident occur. Appendix E describes the reactivity margin associated with this worst case model.

VII. References -

1) NPGD-TM-534, TMI-2 Criticality Evaluation Notebook, J.J. Woods, December 4, 1979.

2) NUREG-0647, Safety Evaluation and Environmental Assessment, Three Mile Island Nuclear Station, Unit No. 2, February 11, 1980.

3) NRC Memorandum, Bounding Estimates of Damage to Zircaloy Fuel Rod 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) 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.

5) 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.

6) BAW-1738, Addendum-1, J.R. Worsham III, October, 1982.

7) BAW-10115, NULIF - A Neutron Spectrum Generator, Few-Group Constant Calculator, and Fuel Depletion Code, W.A. Wittkopf, et al, March, 1976.

8) NPGD-TM-128, User's Manual for B&W Version of ANISN, J.J. Sapyta, et al, December, 1971.

9) BAW-10117, Babcock & Wilcox Version of PDQ07-User's Manual, H.A. Hassan, et al, February, 1977.

10) BAW-297, Vibratory Compaction Process Development, J.M. Kerr and L.D. Barnes, December, 1956.

11) ORNL-TM-3446, Preirradiation Data for ORNL Series II and B&W Oxide Fuel Tests in EBR-II, A.R. Olsen, November, 1971.

12) BAW-1703, TMI-2 Gadolinia Demonstration Assembly Technical Report, L.W. Newman, et al, July, 1983.

Figure 1

Damaged Core Model With Peripheral Fuel Standing

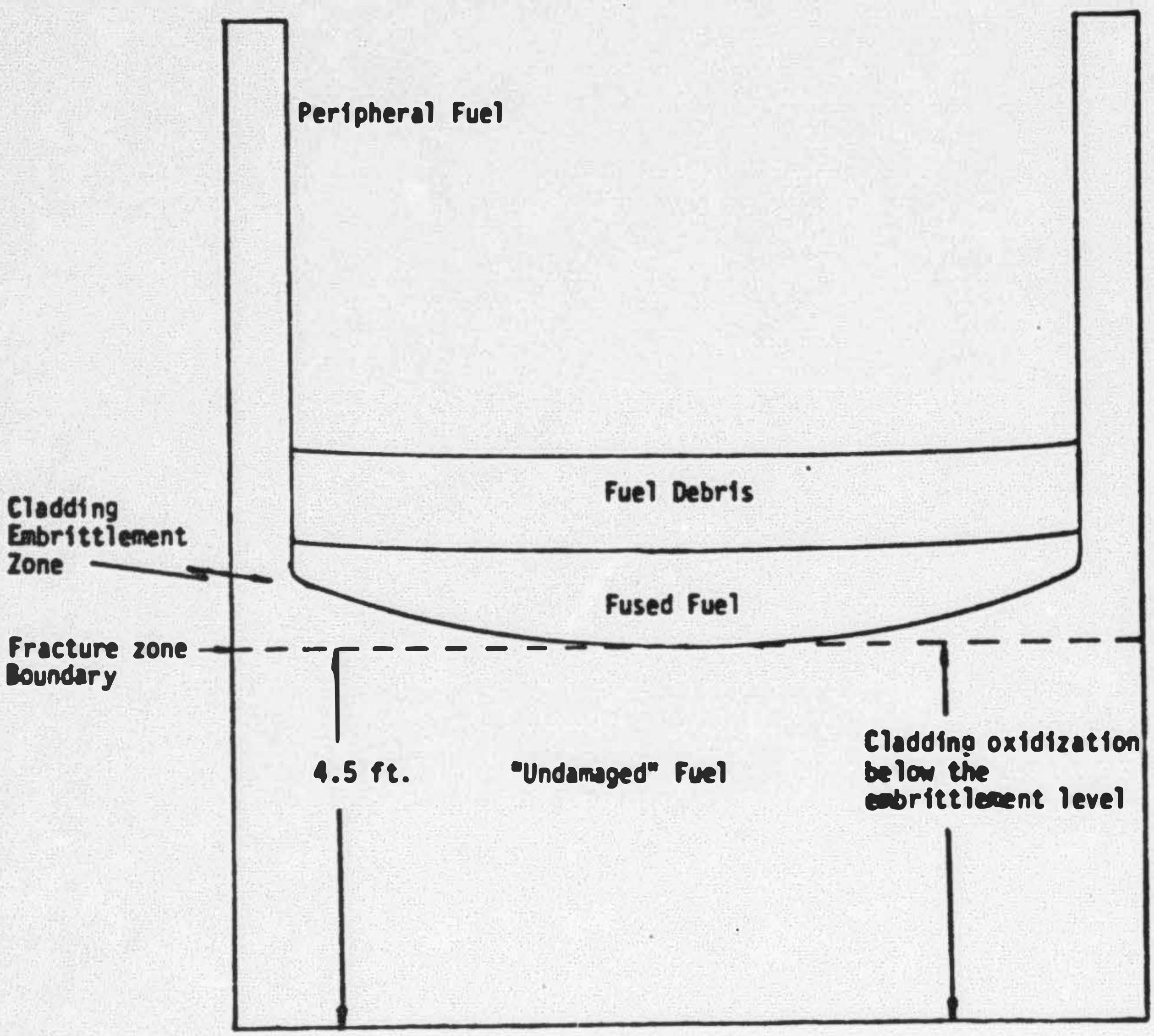


Figure 2

Core Model With Collapsed Peripheral Fuel

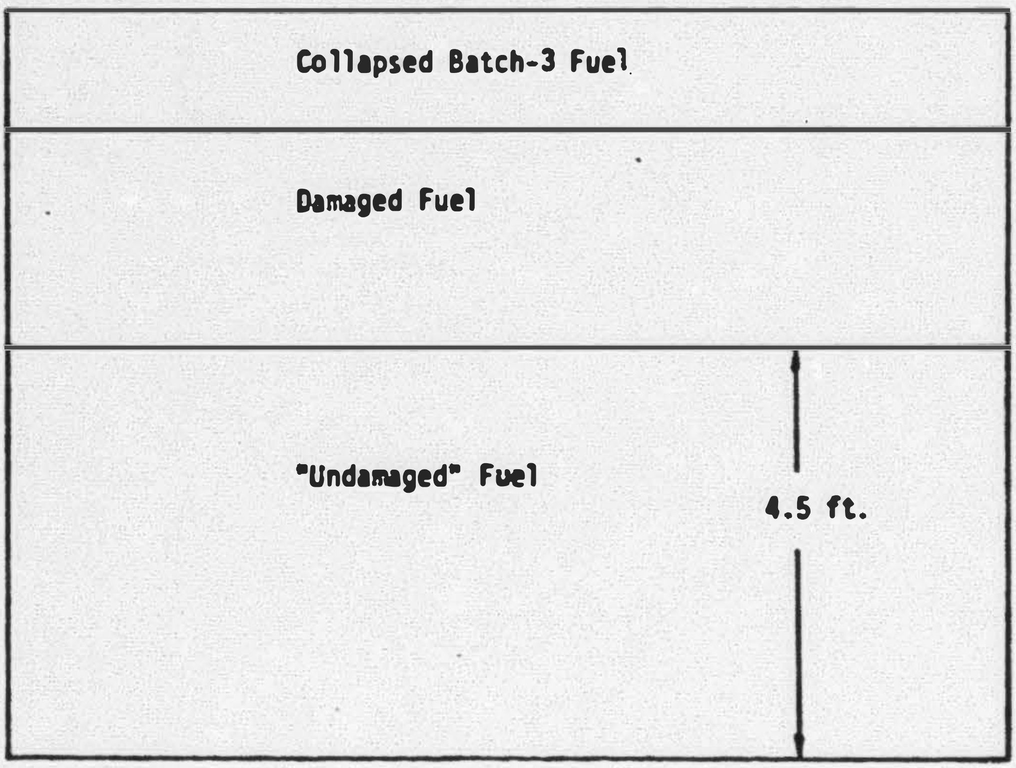
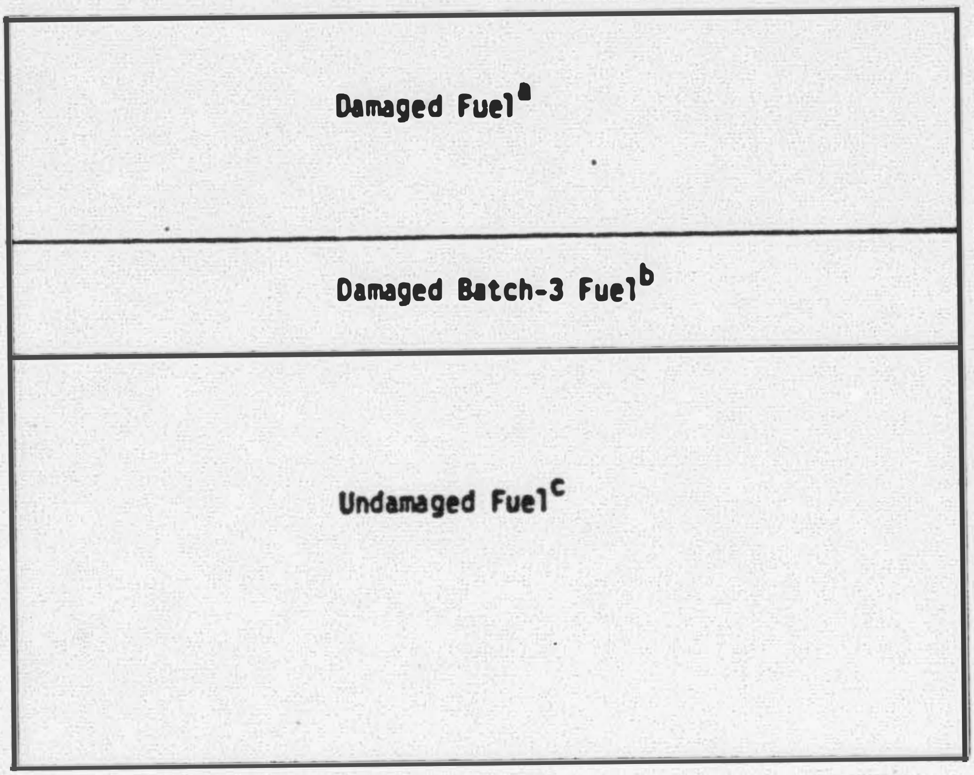


Figure 3

Heavy Load Drop Accident
Criticality Model



a) Core average isotopics based on unburned batch-3 fuel

b) All the batch-3 fuel (60 assemblies) above 4.5 feet

c) Pin by pin burnups in a uniform axial distribution

Appendix A

Parameters Affecting Reactivity -

The discussion of the parameters affecting reactivity is divided into four categories as was done previously.[4] These categories are, (1) fuel composition, (2) moderator composition, (3) fuel-moderator combinations, and (4) fuel-moderator-reflector configurations. By dividing the parameters into categories, the explanation of each parameter's affect on reactivity can be simplified. Knowing each parameter's separate affect on reactivity provides a better understanding of the optimization process, where the most reactive combination of all parameters is determined.

Fuel Composition - The most important parameter change that has occurred in modeling the fuel is the treatment of burnup. Previously, the reactivity effects of burnup were applied to the undamaged and damaged regions by modifying the multiplication factor in these regions. The heavy load drop model has introduced the effects of burnup by implementing the burned isotopics directly into the fuel regions. In the undamaged fuel region, each batch of fuel has the burned isotopics representative of that batch. In the damaged batch 3 fuel region, the fuel is assumed to have no burnup. This ensures that uncertainties associated with the distribution of the burnup within the batch 3 fuel are treated conservatively. In the damaged batch 1 and 2 fuel region, the burned isotopics not only represent those for batches 1 and 2, but also conserve the total uranium and plutonium isotopics for batches 1, 2, and 3. The treatment of the burnup is described further in Appendix B.

The other parameters used in modeling the fuel that were reevaluated for their reactivity effects were, (1) the gadolinium poisoned fuel, (2) the fused fuel composition, and (3) the temperature coefficient of each fuel region as well as the temperature coefficient for the overall core criticality model. The depletion of the gadolinium fuel was explicitly calculated, therefore its burnup effects on the isotopics were explicit. However, the isotopics of gadolinium in the criticality model were conservatively eliminated. The fused fuel will be discussed further when fuel-moderator combinations are discussed and in Appendix C. The temperature of the fuel is not separated from the temperature of the moderator.[4] Therefore, the discussion of temperature coefficients will be deferred to the discussions on fuel-moderator combinations and fuel-moderator-reflector configurations.

Moderator Composition - The moderator has been defined as the region that surrounds the fuel. The changes from previous analyses in the composition of the moderator are, (1) the water logging of the undamaged fuel, (2) the treatment of void and temperature reactivity coefficients, and (3) an analysis with 4000 ppm boron as well as the standard analyses with 3500 ppm boron.[4]

Calculations of reactivity coefficients have indicated the undamaged fuel has a negative moderator density coefficient with 3500 ppm and 4000 ppm boron. Thus, the water logging reactivity affects need to be conservatively treated. Previously, the treatment involved modifying the multiplication factor in the undamaged fuel region. For this analysis, the most reactive condition is when the water in the undamaged fuel was placed outside the cladding. In addition, the cladding was assumed to have its original outside diameter and thickness.

The density of the water in the moderator is principally a function of its temperature and pressure. However, there may be other materials in the moderator which affect the homogenized isotopic concentrations as well as the density of the water. Reference 4 explains the effects of mixtures and solutions of the various reactor materials, showing all will decrease reactivity. The one substance that could possibly increase reactivity is a low density gas in the undamaged fuel region. The existence of such a substance was not considered credible previously. However, further evaluations indicate that voids in the form of fission gases could possibly be present. The gases are contained in the plenum region of the undamaged core. Consequently, should they be released, the voiding would occur in the damaged core region which has a negative void coefficient. Thus, no void coefficient was explicitly evaluated for the heavy load drop criticality model.

The moderator temperature coefficient is normally considered to include both the effects of changes in the scattering properties of the moderator as well as changes in the moderator density. Since the moderator volume is optimized in the damaged fuel regions, the moderator density change with temperature can be ignored in these regions. Therefore, the temperature change in the moderator of the damaged fuel does not reflect a change in moderator density. The moderator temperature and the fuel temperature are the same, thus, there is only a single temperature coefficient. This parameter is discussed in more detail in the subsection on fuel-moderator combinations.

The analysis of the criticality models for recovery activities through head removal are based on a measured boron concentration of 3700 ppm and a minimum value for the safety analyses of 3500 ppm. This concentration continues to be used for the heavy load drop accident. An additional calculation was performed with 4000 ppm to obtain the boron worth for the core criticality model. This worth was based on all other parameters being constant at the values determined from the 3500 ppm optimization analyses.

Fuel-Moderator Combinations - The size and shape of the fuel and surrounding moderator are the parameters that have the predominant effect on reactivity in this category. In the undamaged core region, the sizes and shapes are fixed by the geometrical configuration of the fuel pins and the assembly. In the damaged fuel regions, there are essentially no constraints to the sizes and shapes of the fuel-moderator combinations. The changes in these parameters that have been made for the heavy load drop models include an optimization of fused fuel particles and an analysis of the temperature reactivity coefficients.

Since the previous analysis, additional data on fragmented and crushed UO_2 have been analyzed.[10,11] This data has been used to evaluate the most reactive fused fuel particle that is judged credible. The evaluation includes the UO_2 packing fraction, the materials filling the open porosity, and the composition of a zircaloy-UO_2 eutectic. The details of the fused particle evaluations are presented in Appendix C. The most reactive fused fuel particle with the optimal amount of moderator volume was determined and compared to the reactivity of the originally fabricated UO_2 pellets with the optimal amount of moderator volume. The pellets were found to be the most reactive particle. Thus the damaged fuel was optimized as cylindrical pellet stacks. The most reactive fuel volume fraction for the damaged batch-3 fuel is .58, while the most reactive volume fraction for the combined batch 1 and 2 fuel (2.34 weight percent uranium-235) is .61. The optimal shape of the fuel-moderator combination is a square array as explained in Appendix C.

The temperature coefficients for the damaged and undamaged fuel-moderator combinations were analyzed within Technical Specification limits to determine the most reactive core criticality model. The damaged regions were determined to be most reactive at 50°F (the lower technical specification limit) and had a negative temperature coefficient. The undamaged region was analyzed with 50°F temperatures, but had a positive temperature coefficient. The most reactive temperature for the core model and the temperature coefficient of the core is discussed further in the following subsection on fuel-moderator-reflector configurations.

Fuel-Moderator-Reflector Configurations - The previous discussions of the "damaged core model" described the scenario for additional fuel damage resulting from a heavy load drop accident. The hypothetical worst case shown in Figure 3 has a core model composed of three fuel regions. The reflectors for this core are defined by the actual physical reactor configuration.

Radially, the reflector is composed of the baffle, and the water between the barrel and baffle with the baffle plate directly adjacent to the fuel regions. Axially, there is a top reflector and a bottom reflector. The top reflector is borated water with 3500 ppm boron. The bottom reflector is divided into 2 regions. The first, adjacent to the undamaged fuel region, is the plenum extension of the fuel pins. This reflector is followed by an end fitting reflector region.

The fuel configuration (Figure 3) radially extends across the area of the original core. The height of the undamaged fuel has been defined by the level of cladding embrittlement to be 4.5 feet. The height of the damaged fuel regions is determined by the optimization of the fuel-moderator combinations and the mass of damaged fuel. For the damaged batch 3 region the height was determined to be 1 foot 3.3 inches. The remaining damaged fuel region was determined to have a height of 2 feet 4.7 inches. This fuel-moderator-reflector configuration is the most reactive worst case model of a heavy load drop accident.

The most reactive temperature for the core model is 50°F and the temperature coefficient for the core is negative. The analysis of the temperature coefficient was based on increasing the temperature of all regions, fuel-moderator-reflector to 73.1°F.

Appendix B

Fuel Burnup -

The burnup of the fuel in the criticality model for the heavy load drop accident has been explicitly factored into the fuel isotopics. A two-dimensional PDQ[9] depletion which accurately followed the core operation[12] was used to obtain the fuel pin isotopics. The isotopics were conservatively adjusted to account for the uncertainties associated with power measurements, uranium isotopics and loadings, and isotopic changes during the 4 years following the accident.

In the undamaged fuel region shown in Figure 3, the burned fuel was modeled to be axially uniform. This is a conservative approximation because a non-uniform model would reduce the overall reactivity. This reduction would occur as a result of increased leakage caused by much lower burnups occurring on the ends of the pins than occurs in the central region.

The damaged batch-3 fuel region (Figure 3) was assumed to have completely unburned fuel. By treating batch-3 as unburned, all uncertainties associated with the variation in the batch-3 burnup are eliminated, thus producing the maximum reactivity. This approach is conservative, but not overly so, because the effects of the batch-3 burnup are included in the remainder of the damaged fuel.

The PDQ depletion contains the complete isotopic content of all the damaged fuel. Therefore, if the damaged batch-3 fuel is treated as being unburned, the isotopics of the remaining damaged fuel can be determined by simply conserving the uranium and plutonium isotopic content of all the damaged fuel. The damaged fuel region shown in Figure 3 is consequently a composite of the damaged batch 1 and 2 fuel with burned uranium and plutonium isotopics from all the damaged fuel. The technique for determining the isotopics is as follows:

$$\begin{array}{l}\text{Damaged Fuel} \\ \text{Isotopic Concentrations}\end{array} \times \begin{array}{l}\text{Volume of the} \\ \text{Damaged Fuel}\end{array} =$$

$$\begin{array}{l}\text{Core Isotopic} \\ \text{Concentrations}\end{array} \times \text{Damaged Core Volume}$$

$$- \begin{array}{l}\text{Damaged Batch-3} \\ \text{Isotopic Concentrations}\end{array} \times \begin{array}{l}\text{Volume of the} \\ \text{Damaged Batch-3}\end{array}$$

Since the damaged batch-3 fuel has a higher neutronic importance weighting than the remaining damaged fuel, this technique is conservative.

Appendix C

Fused Fuel -

Previously, fused fuel particles were assumed to have at least 10% zircaloy either bonding the ceramic fuel particles or in solution with the particles as a eutectic[4]. The optimization analysis assessed various particle shapes including spherical as well as cylindrical. The most reactive particles that have settled into a debris bed are the cylindrical ones stacked end-on-end, with a size that is 3.44 times larger than the standard pellet. Various fuel arrays, including triangular, were analyzed. The most reactive array is a square with a moderator volume fraction of .39 and a corresponding fuel volume fraction of .61. Other arrays had the same optimal fuel and moderator volume fractions, but were slightly less reactive due to Dancoff effects. The eutectic density was determined to be less than that of a mixture of ceramic UO_2 and zircaloy. Thus, the conservative procedure of computing the fuel and zircaloy isotopics based on the mixture density was utilized.

While this previous treatment of the fused fuel was assessed to be conservative, there is the uncertainty associated with the fuel containing 10% zircaloy. This much zircaloy decreases the reactivity of the optimized fuel-moderator combination by more than 1.0%$\Delta\rho$. Therefore, this reassessment of the most reactive fused fuel configuration had the objective of defining the highest possible fuel packing fraction with the lowest amount of interstitial or eutectic material.

The fused fuel could be in either of two forms, (1) ceramic fuel particles with structural material on the outside forming an amalgamation, or

(2) eutectic fuel particles stuck together forming an amalgamation. In either case, the maximum packing fraction of the fuel particles is conservatively determined to be less than 91%, as explained below.

The evaluation of the maximum packing fraction was based on material compaction data including that for crushed UO_2[10,11]. The maximum theoretical packing fraction for spherical particles with a uniform size is 75%. If the particle size distribution is varied, and if vibratory or fluid compaction processes have been applied to an agglomeration of particles, then higher packing fractions can be attained. However, the compaction data shows that an 80% packing fraction represents an upper bound.

To be consistent with the fuel particle shapes and arrays considered for the criticality models, the fuel packing fraction was determined assuming the maximum theoretical packing fraction for an array of infinite cylindrical particles. The fuel packing fraction is $(\pi\sqrt{3}/6)$, slightly less than 91%. This provides an interstitial porosity of slightly more than 9%.

Considering the first form of fused fuel, ceramic (UO_2) fuel particles bonded by structural material, the structural material that provides the most reactive fuel is zircaloy. Therefore, UO_2 combined with approximately 9% zircaloy was one limiting type of fused fuel analyzed. It is evident that while the interstitial volume in the fused fuel may contain zircaloy, it could also contain moderator. Thus, a second limiting type of fused fuel was considered with borated water "bonding" the fuel particles. Analyses were performed on these types of fused fuel particles to obtain the most reactive conditions and configurations.

The results showed the zircaloy bonded fused fuel (3.44 times the size of a standard pellet) was 4%$\Delta\rho$ less reactive than standard pellet sized fuel particles with only UO_2.

The water "bonded" fused fuel was .5% $\Delta\rho$ less reactive than the zircaloy bonded case. The following table illustrates the values of K_∞.

	K_∞
Standard Pellet	1.063
Zircaloy Bonded Particles	1.058
Water "Bonded" Particles	1.053

Thus, UO_2 fuel particles (limited to the size of the original pellets) are more reactive than UO_2 fused fuel bonded with structural material. These results also indicate UO_2 fuel particles are more reactive than the second form of fused fuel, zircaloy-UO_2 eutectic particles. The eutectic fuel particles would contain at least 9% interstitial zircaloy or borated water plus zircaloy in the eutectic.

One additional consideration in analyzing the water "bonded" fused fuel was the amount of boron associated with the bonded water. With greater than 9% open porosity in the fused fuel model, it was reasoned that over the years the boron would be in equilibrium throughout the moderator. Thus, the boron concentration was assumed to be 3500 ppm.

Appendix D

Benchmark Calculations -

The 1-dimensional (axial), 2-group PDQ model was the principal model used to compute the multiplication factor of the damaged core configuration (Figure 3). There are two approximations associated with this model that require benchmarking to ensure the results are accurate. The first is the assumption that the three fuel regions and three axial reflector regions can be spectrally separated and then coupled with a 2-group diffusion theory spatial flux. The second approximation is that the spatial flux can be separated into axial and radial (x,y) components such that the axial calculation will represent the overall core multiplication factor when radially averaged leakage and reaction rates are included as input parameters in the solution. The methods and procedures for treating these two approximations in the 1-dimensional PDQ calculation were verified to be accurate by benchmarking them with calculations that did not include these approximations.

The approximation that the spatial flux can be separated into axial and radial (x,y) components was verified to be accurate by performing two 3-dimensional calculations. The 3-dimensional models were of the damaged core shown in Figure 3 with and without control rods in the undamaged region. The comparison of K_{eff} results and the relative axial power profile results for the 3-dimensional and 1-dimensional PDQs are shown below:

Control Rods Withdrawn	1-Dimensional	3-Dimensional
K_{eff}	.987	.987
Undamaged RPD	.174	.171
Batch-3 RPD	3.793	3.808
Damaged RPD	1.065	1.061
Control Rod Inserted		
K_{eff}	.985	.985
Undamaged RPD	.145	.142
Batch-3 RPD	3.814	3.824
Damaged RPD	1.108	1.107

(RPD is the Relative Power Density)

The excellent agreement between the 3-dimensional and 1-dimensional results verifies that the procedures for including the radial bucklings and spatially weighted cross sections are valid. The agreement shows that the multiplication factor is not biased by the approximation of separable axial and radial fluxes.

The 1-dimensional, 2-group PDQ employed cross sections for the damaged fuel regions and the reflector regions that were obtained from MULIF calculations of each respective region. Thus, the multigroup spectrum in each region was not influenced by the spectrum in the adjacent regions. This was also true in the undamaged fuel region. However, in the undamaged fuel region, a 2-dimensional radial (x,y) PDQ calculation was employed to obtain the radial flux weighting for the cross sections.

The procedures for obtaining the radially weighted cross sections and bucklings for each axial region are known to be accurate. The accuracy has been demonstrated with benchmarks of representative critical experiments. However, the axial coupling of each region within the damaged core model with a 2-group diffusion theory method is not benchmarked. Consequently, 13-group diffusion theory (S_2) and transport theory (S_8) calculations were performed on the 1-dimensional core model. These 13-group calculations were performed with the ANISN code and the results compared to the 2-group PDQ results. This comparison is shown below.

	K_{eff}
13-group S_2 ANISN	1.0088
13-group S_8 ANISN	1.0089
2-group PDQ	1.0069

These 1-dimensional models did not have any radial bucklings, nor burnup effects. In all cases, the cross sections for each fuel and reflector region came directly from NULIF.

The results indicate that diffusion theory is completely adequate to solve for the spatial fluxes. This is demonstrated by the nearly identical results of the S_2 (diffusion theory) and S_8 (transport theory) ANISNs. The results further indicate that the assumption of no spectral interaction between regions is very accurate, introducing only a .002 ΔK_{eff} difference between 2 and 13 groups. This small difference has been conservatively applied to the 2-group PDQ model by increasing K_{eff} by .002 ΔK_{eff}.

Appendix E

Reactivity Margin -

The results show the worst case model of the heavy load drop accident will be 1.0%$\Delta\rho$ subcritical. However, the degree of conservatism in the model is an important consideration to be reviewed when assessing the adequacy of this shutdown margin. The worst case model ensures an adequate margin of safety if it is much more reactive than a model with more realistic assumptions. To illustrate the conservatisms in the heavy load drop accident model, five of the credible assumptions having the largest reactivity effects have been reassessed. The following table shows the approximate reduction in K_{eff} as a result of changing the parameters associated in each assumption to more probable values.

Reactivity Effects of More Probable Conditions

	ΔK_{eff} Reduction
1) Model Configuration	.009
2) Random Particle Size[4]	.007
3) Random Particle Arrangement[4]	.015
4) Structural Material Mixed With Fuel Debris[4]	.005
5) 3700 ppm Boron	.008
Total	.044

Worst Case K_{eff} = .988

More Probable K_{eff} = .944

The explanation of the more probable conditions for each of the above parameters is given in the following paragraphs.

1) Model Configuration - The criticality model for the heavy load drop accident (Figure 3) has ensured any uncertainties associated with the composition or location of the batch-3 fuel are conservatively treated by sandwiching batch-3 between the undamaged fuel and the damaged batch 1 and 2 fuel. The more credible scenario is represented by Figure 2 where the batch-3 fuel collapses on top of the existing damaged fuel. The model in Figure 2 is .9% ΔK_{eff} less reactive than the worst case model.

2) Distribution of Particle Sizes - It is not realistic to assume that the fuel particles in the core are solid pellets since during power operation the pellets crack. A more reasonable assumption is that the particles have a random distribution of sizes. This distribution will have an average reactivity affect that can be determined from Reference 4. The reactivity decrease will be more than .7% ΔK_{eff}.

3) Particle Arrangement - The collection of fuel particles cannot possibly be stacked end on end such as cylindrical pellets in fuel rods. A reasonable assumption is that the particles will collect in a random arrangement. Such a random distribution allows the ends of the cylindrical particles to be exposed to the moderator thus decreasing their reactivity by approximately 1.5% ΔK_{eff}.

4) Structural Material - The structural material was not included in the calculations of the most reactive conditions because it always reduces reactivity. Realistically however, the zircaloy cladding, inconel grids, and other structural components will be in the core region in approximately the same proportion to the fuel as before the accident. Including the cladding and grids in with the fuel and moderator decreases reactivity by .5% ΔK_{eff}.

5) Actual Boron Concentration - Measured data indicates that at least 3700 ppm boron is in the reactor coolant system. Therefore, the assumed boron concentration of 3500 ppm used in the most reactive model could be realistically increased by 200 ppm. This additional boron is worth .8% ΔK_{eff} in reactivity.

The total reactivity worth of these five changes to more probable conditions is a .044% ΔK_{eff} decrease in reactivity. Consequently, while the worst case model gives a K_{eff} of .988, the more realistic value of K_{eff} is less than .944. However, the worst case approach is the only basis for ensuring the probability of a criticality event is negligible.