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US Nuclear Regulatory Commission
Attn: Document Control Desk
Washington, DC 20555

Dear Sirs:

Three Mile Island Nuclear Station, Unit 2 (TMI-2)
Operating License No. DPR-73
Docket No. 50-320
Criticality Safety Assessment for Use of the Plasma Arc Torch
To Cut the Lower Core Support Assembly

Attached for your information is a copy of the TMI-2 Criticality Safety Assessment for Use of the Plasma Arc Torch To Cut the Lower Core Support Assembly. The purpose of this assessment is to demonstrate that the plasma arc torch can be used to dismantle the Lower Core Support Assembly without creating a criticality safety concern within the Reactor Vessel.

This report is submitted in support of Revision 1 to the Core Support Assembly and Lower Head Defueling Safety Evaluation Report which has been submitted via GPU Nuclear letter 4410-87-L-0138.

Sincerely,

F R Standerfer

F. R. Standerfer
Director, TMI-2

FRS/CJD/eml

Attachment

cc: Regional Administrator, Region 1 - W. T. Russell
Director, TMI-2 Cleanup Project Directorate - Dr. W. D. Travers

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15737-2-N09-004

Criticality Safety Assessment for Using the Plasma Arc Torch to Cut the Lower Core Support Assembly

Rev. 1

Rev.	SUMMARY OF CHANGE
0	Original Issue
1	Base Case model was revised to reduce the restrictions on defueling operations.

SHEET	LATEST REV	SHEET	LATEST REV.	SHEET	LATEST REV.	SHEET	LATEST REV.	SHEET	LATEST REV	SHEET	LATEST REV	SHEET	LATEST REV
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REVISION STATUS SHEET

DOCUMENT TITLE: Criticality Safety Assessment for Using Plasma Arc torch to Cut the

JOB 15737

SPEC. NO. 2-N09-004

REV. 1

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1.0 Introduction

1.1 Background

As part of the effort to dismantle the lower core support assembly (LCSA), including the flow distributor head, a plasma arc torch may be utilized. Adequate cooling of this torch during cutting operations is provided via a closed, circulating coolant system having an inventory of less than four (4) gallons. Testing of the torch has shown that Reactor Coolant System (RCS) grade or B-10 enriched borated water cannot be used as the coolant due to the high electrical conductivities of these fluids. Further testing has determined that the use of demineralized (i.e., unborated) water results in acceptable torch operation. Consequently, unborated water will be used as the cooling fluid for the torch.

1.2 Purpose

As the unborated water inventory in the torch coolant system exceeds the two (2) gallon limit established in Reference 1, it is the purpose of this report to demonstrate that the plasma arc torch can be used to cut the LCSA without causing a criticality safety concern within the reactor vessel.

1.3 Scope

The evaluation presented in this report addresses the use of the plasma arc torch to cut the LCSA, including the flow distributor head. The use of the plasma arc torch for other purposes should not be considered bounded by this evaluation and will be addressed separately, on an as-required basis.

1.4 Criterion for Justification for Use of Plasma Arc Torch

The criterion used to establish the acceptability of using the plasma arc torch for dismantling the LCSA was that the RCS neutron multiplication (k_{eff}) would not exceed 0.99 for all credible situations during torch usage. This acceptance criterion is consistent with the previous licensing basis for the RCS during defueling (References 1 and 2).

2.0 Plasma Arc Torch

2.1 System Description

A plasma arc torch has been developed for use in the dismantling of the lower core support assembly. The plasma arc torch is a direct current, tungsten electrode, metal burning device. An initial pilot arc will ionize the primary gas, nitrogen, to form a plasma jet which will be focused on the material to be cut. The plasma stream reaches temperatures of approximately 20,000-50,000 degrees F, and thus melts the material at which it is directed. A secondary gas, also nitrogen, is used to aid in flushing away the molten metal from the cut and to provide thermal insulation for the torch head. A low secondary gas purge flow (~5 scfm) will be provided whenever the torch is under water and not performing cutting operations. This flow is maintained to keep the torch tip dry. A simplified schematic of the plasma torch is given in Figure 1.

The Automated Cutting Equipment System (ACES) will be used to position the plasma arc torch. The controls of the ACES consist of two computer electronic systems, one for the plasma process control, the other for position control. The plasma process control selects, adjusts and sequences current, gas and coolant flows. The position controller operates a five axis servo motor driven system that positions the torch, thus controlling the location and speed of the torch. Computer software allows a torch trajectory to be preprogrammed and executed automatically upon command. The torch is limited in its range by the physical restrictions of the tracks on which it rides. This physical restriction prevents the torch from impacting on the reactor pressure boundary. The equipment however has the capability to perform cuts at any fuel assembly location if required to support lower head or LCSA defueling. A torque limitation on the motor devices prevent the torch from being driven into, and embedded within, a significant accumulation of fuel debris.

The plasma arc torch will cut electrically conductive materials, such as stainless steel structures. As the fuel debris is mainly ceramic, which is not electrically conductive, prior to the cutting of any particular piece of stainless steel within the LCSA, any significant quantities of surrounding fuel debris will be removed.

2.2 Coolant System

Because of the high operating temperatures of the torch, the metal components of the torch must be adequately cooled. This cooling is accomplished via a circulating water system (~4.5 gpm system flow rate). The cooling system consists of a standpipe, three water-to-air heat exchangers, a pump and associated hoses and fittings. The standpipe, heat exchangers and pump are provided in a separate unit (HE-200) which will be located on the north end canal platform. The maximum total water inventory of the coolant system is less than 4.0 gallons. A schematic of the coolant system is provided in Figure 2. To ensure acceptable operating characteristics of the plasma arc torch, the conductivity of the cooling fluid must be maintained below ~15 micro mhos. Whenever the conductivity exceeds this value, the process of starting the arc fails. Testing of the torch with water of various boron concentrations (RCS grade down to ~200 ppm) showed that the electrical conductivity of these fluids was too high. Thus, it was concluded that demineralized (unborated) water, starting with a conductivity of about 2 micro mhos, was the most ideal cooling fluid that could be used successfully.

Periodic checking of the fluid conductivity, flushing of the system and recharging the system with new demineralized water will also be required. The flushing tie-in is shown in Figure 2. When a torch tip is damaged, the torch will be removed from the reactor vessel for repairs. The cooling system will also be flushed to return the conductivity of the coolant to acceptable levels. Referring to Figure 2, flushing is initiated by disconnecting the return line from the HE-200, and routing the line to the deep end of the canal. The HE-200 pump is switched on and the remaining coolant is discharged to the deep end of the canal. Occasionally, the three heat exchangers will be flushed in a similar manner. The system is then recharged by initiating a gravity flow from the fifteen gallon demineralized water tank, which is located on elevation 347'-6". The torch coolant system is then fully charged to a maximum capacity not to exceed four gallons. The torch is then reinstalled into the vessel.

Flushing of the coolant system may also occur when the conductivity of the coolant becomes unacceptably high. In this case the torch will either be located in its home position (i.e., two inches above the top of the grid plate) or be removed from the vessel. If the torch is in its home position and a distance greater than one foot exists between the torch tip and the debris bed surface, the torch coolant system may be flushed in a manner similar to that described above except that the torch will remain its home position. If flushing is performed with the torch in the vessel, no load handling activities are allowed in or over the reactor vessel during flushing, thus minimizing the potential for damage to the flush system. Based on the mixing analysis for the torch coolant system, discussed in Section 4.3.1, from which it was concluded that mixing will occur rapidly, any inadvertent leakage of the coolant during system flushing will adequately mix with the borated vessel water so as not to pose a criticality safety concern. If the one foot separation is not available or if load handling activities cannot be suspended, the torch will be removed from the vessel prior to flushing.

3.0 Fuel Configuration and Arrangement

The original loading of the core included 56 assemblies of 1.98% (batch 1), 61 assemblies of 2.64% (batch 2) and 60 assemblies of 2.96% (batch 3) U^{235} enrichment. The loading pattern is shown in Figure 3. Based on this loading, the initial core average enrichment was 2.54%.

3.1 Quantification of Batch 3 Fuel

Early visual inspections and sonar mapping of the core indicated a significant number of the batch 3 fuel assemblies at the core periphery were still standing. Some of them were full length, while a large number of these assemblies were less than full cross-section. Some of these assemblies were knocked down, cut and trimmed and then loaded into canisters during earlier defueling activities. Nonetheless, it has been determined that the total length of batch 3 fuel assemblies that remained standing at the time of the beginning of fuel assembly stub removal corresponded to approximately 50% of the initial batch 3 fuel. It is expected that these assemblies were removed reasonably intact, with little mixing of this batch 3 fuel with other debris within the vessel. Thus it is expected that the majority (~75%) of the initial batch 3 fuel will be removed from the reactor vessel prior to the deployment of the plasma arc torch. Consequently any fuel remaining in the vessel should consist mainly of batches 1 and 2 fuel.

3.2 Fuel Variation Within LCSA/Lower Head

3.2.1 LCSA Region

There are two types of material within the LCSA region. In areas within the 30 inch radius from the reactor centerline the material observed during the Core Stratification and Sampling Program was granular debris and drilling shards. Most of this material is expected to have been generated by the core drilling operations. Referring to Figure 3, this material is expected to be mostly of the lower two batch enrichments as the core drilling operations were limited to the central regions of the reactor vessel. The other type of material observed in the LCSA is columns of material that resolidified as it was flowing downward from the core region during the accident. Based on the information known to date, this material appears to be concentrated at the periphery of the LCSA. It is possible that this material is not from batch 3 and hence would have an enrichment less than 2.96%. It is, however, plausible that portions of this material could have enrichments greater than that of batch 2 (2.64% unburned).

3.2.2 Lower Head Region

The material recently relocated to the lower head due to the core drilling operations is expected to consist mostly of batches 1 and 2 fuel, for reasons similar to those discussed in Section 3.2.1. This applies to the fine vacuumable material that has been observed on the debris surface.

The rock-like material (up to ~2 inch diameter) observed on the surface of the lower head debris during various inspections has been sampled and the results are provided in Tables 1 and 2 (Reference 9). Although credible enrichments as high as 2.6% were observed in the samples, there is significant variation across each sample. The average enrichment of all the samples was 2.3%, with the average enrichment across any sample being no higher than 2.4%, except for sample 11-1-C. This sample had an average enrichment of 2.6%, but only 2 particles were analyzed.

The sub-surface material configuration is not fully understood at this time. It is, however, known that some of this material consists of larger resolidified material, that most likely was relocated in liquid form, and a larger quantity of rock-like material. Having assessed the various possible mechanisms and points of relocation to the lower head, it is concluded that there are possibly large chunks of material in the lower head with an enrichment greater than that of batch 2. However, it is improbable that the entire mass would have an enrichment near this level.

4.0 Criticality Safety Analysis

4.1 Background

4.1.1 Criticality Report for the Reactor Coolant System

The Criticality Report for the Reactor Coolant System (Reference 2) defined a boron concentration (i.e., 4350 ppm) which would ensure that the RCS neutron multiplication (k_{eff}) would not exceed 0.99 for all credible configurations. In the model development for Reference 2, two conservative fuel models were considered. These were the design basis model, also referred to as the lenticular model, and the spherical model. Since the lenticular model was three-dimensional, it was only analyzed with the Monte-Carlo program KENO V.a (Reference 3). The spherical model however, because of radial symmetry, also allowed the use of the one-dimensional, discrete-ordinates transport program XSDRNPM (Reference 3). Comparisons between the lenticular model, with KENO V.a, and the spherical model, with XSDRNPM, showed that the spherical model was slightly more reactive (i.e., ~0.3% Δk). Additionally, comparative studies were made evaluating the spherical model with both KENO V.a and XSDRNPM, which demonstrated that there was excellent agreement between the KENO V.a and XSDRNPM calculated results. For the RCS design basis model, the calculated value of k_{eff} was essentially 0.99, including a 2.5% Δk computer code uncertainty bias, when the RCS boron concentration was set at 4350 ppm (the minimum boron concentration allowed by current technical specifications). To provide an adequate operating margin, an administrative limit on the minimum operational RCS boron concentration was established at 4950 ppm.

4.1.2 Report on Limits of Foreign Materials Allowed in the TMI-2 Reactor Coolant System During Defueling Activities

The 4350 ppm boron concentration established in Reference 2 does not provide total protection against the potential increase in the RCS neutron multiplication (k_{eff}) caused by the introduction of foreign materials into the RCS. In Reference 1, an evaluation was performed to assess the effects on the RCS reactivity which could be caused by such an introduction of foreign materials. In that evaluation, XSDRNPM was used to quantify the increases in k_{eff}. XSDRNPM, rather than KENO V.a, was used since XSDRNPM results do not contain a statistical uncertainty and are therefore more amenable for the determination of small reactivity effects. However, because of the geometrical limitations of XSDRNPM (i.e., one-dimensional), the Reference 2 design basis (lenticular) model could not be used explicitly for the analyses. Instead, the one-dimensional spherical model was used.

The conclusion of the Reference 1 evaluation was the establishment of a two (2) gallon limit on the amount of unborated moderating material (i.e., a material that can become interstitially dispersed within the fuel) that can be introduced into the RCS such that k_{eff} will not exceed 0.99 for all credible situations. This result was based on a RCS boron concentration of 4950 ppm, the lower operational limit permitted by the current administrative procedures.

4.1.3 Conservatisms Inherent in Previous Analyses

The evaluations performed for both References 1 and 2 contained assumptions that were considered overly conservative when applied to the specific activity of using the plasma arc torch to dismantle the LCSA. Consequently, the reduction of some of these conservatisms was considered necessary to allow the plasma arc torch analyses addressed in this evaluation to more realistically model the conditions that will exist during the cutting of the LCSA. Justification for the reduction in these conservatisms is addressed below, while specific assumptions used in the plasma arc torch analyses are addressed in later sections of this report.

First, the evaluations completed for both References 1 and 2 were performed with the intent that the results would be bounding during all credible situations that could be encountered during the entire defueling process. No attempt was made to define assumptions for a particular defueling activity or phase. However the scope of this document limits the use of the plasma arc torch (unless evaluated separately at a later date) to the cutting of the LCSA, including the flow distributor head (see Section 1.3). The assumptions and thus the criticality safety models developed for this evaluation, can be tailored to the specific activities and possible accident configurations associated with the cutting of the LCSA. Second, at the time References 1 and 2 were developed, there was limited knowledge of the spatial distribution of fuel within the reactor vessel. However, current data available from debris samplings, video inspections and defueling records, as well as a better understanding of the accident scenario, allow more realistic modelling of the fuel debris spatial distribution in the current criticality safety analyses. Finally, the previous analyses took credit for fuel burnup in the batch 3 fuel only. The rationale for this assumption was the small reactivity effect that was seen when the batches 1 and 2 fuel were added to the periphery of the batch 3 fuel. Thus any credit for burnup of batches 1 and 2 fuel would essentially have had a negligible effect on k_{eff}. This effect was encountered since the previous analyses placed the entire initial inventory of the highest enriched, batch 3 fuel in the center of the fuel arrangement. However, with the placement of a smaller amount of batch 3 fuel in the central fuel region, as is done with the plasma arc torch analyses, the reactivity worth of the other fuel batches increases. With the higher reactivity worth of the batches 1 and 2 fuel, the burnup worth of these fuel batches also becomes more important. Thus burnup of batches 1 and 2 fuel was included in the plasma arc torch criticality safety analyses.

4.2 Base Case Model

4.2.1 Geometrical Considerations

Prior to the use of the plasma arc torch for cutting the LCSA, all significant fuel masses above the LCSA, with the exception of the fuel behind the core former plates, will be removed. However, the core former plates should prevent any significant quantities of this fuel from falling into a region in which the torch is operating. As the cutting of the various plates of the LCSA proceeds, readily accessible debris will be removed. Also, the safety features inherent in the torch design prevent the torch from becoming embedded within the fuel debris during normal operations (Section 2.1). Furthermore, as unborated water is less dense than the borated water in the reactor vessel water, any coolant leakage would tend to rise rather than sink into the debris (Reference 5). It has therefore been concluded, based on the above considerations, that a bounding mechanism for the unborated water from the torch coolant system to transport to the fuel debris would be for the water to intermix with the debris pile at or near the surface of the debris accumulations. It is highly unlikely that any substantial amount of unborated water would deeply intermix within the debris. It is concluded that the most likely geometry between the unborated coolant and the debris would be where the unborated water forms a layer on, or slightly penetrates into, the debris bed. However, for conservatism, it was assumed that the entire volume of unborated water would be modelled as totally submerged within the fuel. To maximize reactivity effects, the unborated region was placed in the center (i.e., most reactive location) of the fuel model. As it is essentially impossible to make accurate predictions of the shape of any unborated water region, a spherical configuration, which minimizes the surface area to volume ratio, was assumed.

Based on the above discussion, the model shown in Figure 4 was developed for this safety evaluation. This model should be considered the plasma arc torch base case model. The smaller sphere in Figure 4 represents the unborated water mixing with fuel debris. The size of this region was determined based on the volume (i.e., 3.0 gallons, see Section 4.2.3) of unborated water that was assumed to leak into the vessel. The outer and larger spherical fuel volume is determined based on the balance of the initial fuel inventory, optimally moderated with the borated (i.e., 4950 ppm) vessel water. The two spheres are then surrounded by a thickness of borated water representing an infinite reflector layer.

4.2.2 Fuel Model

4.2.2.1 Fuel Enrichment

As was seen in Figure 4, two separate fuel zones were considered in the plasma arc torch model, a smaller sphere comprised of unborated water and fuel, and a larger sphere containing borated water and fuel. Due to the relatively small size of the inner sphere, it was recognized that unborated coolant could interact with a small localized fuel region. Thus an assessment was performed to determine whether it was possible for the coolant to leak into any region of the vessel in which significant quantities of batch 3 fuel (i.e., the highest enriched) could potentially be located. Based on the current damage assessments, the initial core loading pattern and the proposed plasma arc torch usage, it was found that torch usage could potentially occur in the vicinity of batch 3 fuel. Consequently, for conservatism, the enrichment of fuel that was assumed to intermix with the unborated water in the smaller sphere of the base case model was that corresponding to burned batch 3 fuel.

As was noted previously (Section 3.1), prior to dismantling the LCSA most of the batch 3 fuel will have been removed from the reactor vessel. Additionally, most of the fuel in the LCSA is expected to be fuel fines generated from the core drilling operation. As the core drilling operation was limited to the center of the core, whereas the batch 3 fuel is on the periphery, it is not expected that much of the fuel within the LCSA will be batch 3. However, for conservatism, the fuel in the larger sphere was assumed to be a homogeneous mixture (core average) of the three fuel batches. Using the initial enrichment and number of assemblies as shown in Figure 3, the core average unburned mixture enrichment was determined to be 2.54%.

4.2.2.2 Fuel Burnup Worth

In Reference 1 and 2, the additional reduction to k_∞ resulting from including burnup of batches 1 and 2 fuel was conservatively neglected. However as has been discussed in Section 4.1.3, this burnup credit was considered for the plasma arc torch analyses. To determine the burnup effect for batches 1 and 2 fuel, a procedure similar to that previously used for batch 3 fuel was adopted. A detailed discussion of this procedure is given in Reference 6.

Incorporation of burnup effects in the batches 1 and 2 fuel resulted in a net U^{235} enrichment of 2.24% for the average fuel (i.e., the homogeneous mix of the three fuel enrichments). This enrichment is supported as conservative by the enrichment data determined from available fuel debris sample data (presented in Section 3.2.2), based on the following considerations:

- the majority of the batch 3 fuel has been removed from the vessel

- debris in the LCSA is expected to be primarily batches 1 and 2 fuel (in relatively equal amounts) based on the initial loading patterns, earlier defueling activities and the current understanding of the accident scenario

- average initial enrichment (i.e., without burnup) of batches 1 and 2 fuel is 2.31%

- the apparent lack of batch 1 fuel in the sample data (i.e., only one data point has an enrichment lower than the initial batch 1 enrichment of 1.96%)

4.2.2.3 Lattice Structure

As with the previous criticality safety analyses (References 1 and 2), the fuel was represented as a homogeneous medium for which the neutronic data corresponds to a dodecahedral lattice structure of spherically shaped fuel pellets. Whereas the References 1 and 2 analyses limited the maximum size of the fuel particle to the equivalent of a standard fuel pellet, for the plasma arc torch analyses of this report, the presence of melted fuel and thus larger pellets was considered.

Based on the relatively small size of the inner sphere, it was assumed that the entire fuel mass that would mix with the unborated water would consist of batch 3 fuel. According to the most recent damage assessments fuel melting was not initiated in any batch 3 fuel. Rather any dissolution of batch 3 fuel occurred as a result of melted batch 1 and 2 fuel flowing past the batch 3 fuel rods. Consequently, the fuel in any particles that are larger than standard pellets is highly unlikely to be solely batch 3. If batch 3 fuel is present in the large particles, it is likely to be mixed with batches 1 and 2 fuel. Additionally, based on the available sample data it is unlikely that any large fuel particles would be pure UO_2. Some of the impurities present in the sampled debris are quantified in Table 1. The effects of these impurities are evaluated in Section 4.3.3. Nontheless, to maximize the reactivity effects of fuel melting, an optimum (i.e., most reactive) fuel particle size of pure UO_2 was used to represent the fuel within this region. The optimum fuel particle size was determined by performing an extensive series of lattice cell calculations in which the particle size and fuel volume fraction were varied until a most reactive particle size and volume fraction combination was found. The dodecahedral unit cell of the previous criticality analyses, spherical fuel particles surrounded by water, was utilized for these calculations. The 27-group END/B-IV Cross Section Library was applied in the SCALE system (Reference 3) to provide resonance-shielded (NITAWL-S module) and cell-weighted (XSDRNPM-S) cross sections. The optimum particle size was determined to have a diameter of 2.1 cm for the unborated region.

Similarly, a series of lattice cell calculations were performed to determine the optimum fuel volume fraction for core average fuel mixed with borated (4950 ppm) water. However the use of an optimum particle size for the outer fuel zone was considered unnecessarily conservative for the plasma arc torch analyses. This conclusion is based in part on recent core damage assessments. These assessments indicate that a large percentage (~>60%) of the debris in the LCSA/lower head is either fines (less than pellet size) or large fused masses (greater than approximately 20 cm diameter). Additionally, it is unlikely that any melted fuel particles would be pure UO_2 as is assumed in the optimization calculations. Furthermore as discussed in

Section 3.1, as most of batch 3 fuel will be removed from the vessel prior to plasma torch usage, this fuel region will consist mostly of batches 1 and 2 fuel. Finally, the pure UO_2 fuel particle size range in which the k_∞ value exceeds that for standard pellets is somewhat narrow. This is demonstrated by the data presented in Figure 5. Figure 5 provides the relative relationship between k_∞ and fuel particle size for two different fuel enrichments (2.96%, 2.34%) (Reference 6). Although the boron concentration used to develop the data for Figure 5 was 4350 ppm, the general conclusions derived from this curve should not change for the boron concentration of interest in this analysis (i.e., 4950 ppm). Backup for this assumption is provided by the 3.6 cm diameter optimum fuel particle size shown in Table 3 for a 4950 ppm boron concentration.

An optimal fuel volume faction was utilized for each of the different particle size calculations provided in the Figure 5. Pure UO_2 particles were assumed for the analysis. The k_∞ values presented in the figure were normalized to the k_∞ value at the spherical diameter corresponding to standard pellets (1.07 cm). This normalization was performed for the two enrichments analyzed. A review of the figure shows that optimally moderated particles with diameters in the narrow range of greater than the equivalent of standard pellets to less than approximately 10 cm will have a k_∞ value that exceeds the k_∞ value for standard pellets. Consideration for the presence of impurities in the melted fuel along with the use of actual fuel volume fractions would result in decreased values of k_∞ for the melted fuel. (See Section 4.3.3)

Based on the arguments presented in the above paragraphs, it is concluded that the use of fuel particles of a size corresponding to the equivalent of standard pellets would be an appropriately conservative representation of fuel in the outer fuel zone.

4.2.3 Unborated Coolant Volume

The maximum unborated coolant inventory in the plasma arc torch cooling system is, by design, less than four (4) gallons. However, based on the physical characteristics of the coolant system (e.g., system is vented to atmosphere), it is hydraulically impossible for the entire inventory to drain following a line break or torch tip blowout, whenever the torch is operating in the reactor vessel.

To evaluate the maximum amount of unborated coolant leakage that would occur during torch operation, a drain down test was performed. In this test, the system pump was permitted to operate throughout the duration of the test. In reality, a float switch (disabled in test) would shut off the pump on a low inventory level. The measured leakage from the test was approximately 3.45 gallons. As the test was performed with the hoses in air (to assist in measuring leakage quantity), this volume was reduced by the amount of the coolant inventory that would not drain because the torch will actually be immersed in the reactor vessel (~0.47 gallons). Thus, the maximum amount of unborated water that will drain from the torch coolant system during torch operations is limited to less than 3.0 gallons. This volume (i.e., 3.0 gallons) was used as the volume of unborated water in the smaller sphere of the base case model.

4.2.4 Conservatisms

In the development of the plasma arc torch base case criticality safety model, conservative assumptions were utilized. These conservatisms include:

- no credit for presence of steel plates in LCSA
- no credit for large amounts of structural or solid poison materials existing in debris (See Table 1)
- optimized fuel particle size in unborated fuel region
- optimized fuel/moderator ratio in all fuel regions
- no credit for mixing of unborated cooling water with borated vessel water
- minimum allowable boron concentration of 4950 ppm is assumed in borated regions of model
- unborated water region is placed in most reactive configuration (center of fuel model)

Quantification of the reactivity worth of some of these conservatisms is provided in Section 4.3.

It is recognized that isolated regions within the debris bed may have average enrichments that are greater or particle sizes that may be more reactive than those used in the large sphere of the base case model. However, considering the base case model as a whole, including the inherent conservatisms as outlined above, it is concluded that the base case model is a conservative representation of any credible configuration that could be experienced during use of the plasma arc torch to dismantle the LCSA, and thus is appropriate for use in this evaluation.

4.2.5 Base Case Model Results

4.2.5.1 Optimization

An extensive series of calculations were performed to determine the optimum fuel particle size and corresponding optimum fuel volume fraction for the various boron concentrations of interest. The results of these calculations are given in Table 3. During preliminary investigations it was found that the optimum size and volume fraction were mainly a function of boron level and that a change in enrichment had little effect on these parameters. Consequently, optimization was not performed at every combination of enrichment and boron concentration, but rather at one enrichment for each boron level of interest.

4.2.5.2 Base Case

The results of the base case model using both XSDRNPM and KENO V.a were provided by Reference 10. Using XSDRNPM to an analyze the base case model, k_{eff} was determined to be 0.9582. Typically XSDRNPM analyses are performed to provide added confidence to the values predicted using KENO V.a. Generally the results predicted using the two codes for TMI-2 criticality safety analyses have agreed well. However, the first KENO V.a run performed using the base case model predicted k_{eff} to be 0.9663 $\pm$0.0010. The agreement between the results was not as good as that experienced in previous criticality safety analyses for TMI-2. Because of this difference, the analysis was further investigated. As a result of the investigation it was concluded that the difference was most likely due to the statistical nature of KENO V.a (amplified by the presence of an unborated central region in the model geometry). To confirm this conclusion, nine additional KENO V.a runs were made with the result reported in Table 4 (0.9599 ± 0.0011) being the mean value of the 10 runs. The results of all the KENO runs are provided in Table 5. Neither the KENO V.a nor the XSDRNPM results stated above include an analytical uncertainty bias. Applying a 2.5% Δk bias (See Section 4.4) the KENO V.a result becomes 0.9849. This value is considered to be the base case result. This result meets the acceptance criterion as outlined in Section 1.4.

4.3 Quantification of Conservatisms

To quantify the effects on k_{eff} as a result of some of the conservatisms inherent in the base case model, as described in Section 4.2.4, additional analyses were performed. These analyses are provided to demonstrate that there is a large degree of conservatism in the base case model.

4.3.1 Hydraulic Mixing Modelling

An evaluation was performed to determine the extent of a local boron dilution, rather than a local boron displacement as assumed in Reference 1, resulting from a postulated break in the plasma arc torch cooling hoses or from a blown torch tip. The entrainment of the unborated cooling water was calculated using empirical correlations for the mixing of turbulent water jets into large quiescent water systems (Reference 4). No credit was taken for the other mixing mechanisms that would be present (e.g., turbulence created by the torch operation, the gas purge, interaction with debris or the normal vessel convection currents). Based on the correlations from Reference 4, which indicate that mixing is essentially a function of the break area, an analysis was performed to determine the average boron concentration of the fluid entrained in the jet at various distances from the postulated cooling line break, as a function of the assumed break area (See Figure 6). This analysis was performed for two types of breaks: (a) a circular break with both hose ends discharging, and (b) a slot break. The results of this analysis showed that mixing occurred less quickly with larger break areas. Thus, the mixing rates for the maximum break areas were used to incorporate the mixing phenomena into a criticality safety model.

To assess the effect that mixing would have on k_{eff} it was arbitrarily decided that the boron concentration for the analysis would be defined using two mixing regions. The limiting boron concentration between the two regions was also arbitrarily selected to be 2000 ppm. Based on the above, a mixing analysis was completed to determine the distance, and the associated water volume, at which the average boron concentration increased to a level above 2000 ppm for (a) a full area guillotine break of the coolant hose and, (b) a 1.0 square inch slot break. This is the first step in the process to include mixing in the criticality safety model. A 1.0 square inch slot break was considered to be the maximum credible size considering the hose used, the planned operating procedures, and fluid conditions existing within the hose. The full area break bounds all other credible breaks including a torch tip blowout. The arbitrary selection of the 2000 ppm boron level was appropriate since the sole purpose of the analysis was to demonstrate that mixing would occur rapidly and that there is a larger degree of conservatism associated with neglecting mixing in the base case model.

In both scenarios considered, mixing occurred very rapidly with the volume of water, both borated and unborated, entrained in the jet, prior to the 2000 ppm distance (See

Figure 6) being less than 0.25 gallons. For use in the criticality safety model this volume was assumed to be 0.25 gallons of unborated (0 ppm) water. This water was then optimally mixed with optimally sized batch 3 fuel particles in the innermost region of the model (See Figure 7). Next, a region containing 4.61 gallons of 2000 ppm borated water was optimally mixed with the optimal batch 3 fuel particles. The 4.61 gallons was used to simulate the mixing of the additional 2.75 gallons of unborated coolant with 1.86 gallons borated vessel (4950 ppm) water. Outside this region was the balance of the full core fuel inventory, optimally mixed with the burned core average fuel described in Section 4.2.2. Finally, an infinite borated water reflector was placed external to the fuel regions. Conservatisms inherent in this hydraulic mixing model include:

- the effect caused by unborated water being less dense than borated water and thus tending to rise, rather than sink into the fuel, has been neglected

- all water in the jet with boron concentrations $<$ 2000 ppm was assumed to be unborated

- all water in the jet with boron concentrations $\geq$ 2000 ppm was assumed to have a 2000 ppm concentration

- significant mixing mechanisms were neglected (turbulence created by torch operation, gas purge, interaction with debris and normal vessel convection currents)

- unborated water placed in center (highly reactive) location of model

A more elaborate criticality safety model, in which there were more fuel regions, containing a finer boron concentration distribution, could have also been used. This model should result in even a smaller calculated k_{eff} value.

4.3.2 Effects of Stainless Steel

Stainless steel occupies a large portion of the volume within the LCSA region of the reactor vessel. All steel has been conservatively neglected in the development of the base case model. The largest piece of steel within the LCSA, the grid forging, was used as the basis for a model developed to assess the reactivity worth of this stainless steel. The grid forging is a steel plate, approximately 13.5 inches thick, drilled with approximately 6.5 inch diameter holes in a lattice as shown in Figure 8.

A model of the grid forging was developed to perform the stainless steel sensitivity analysis, however each of the holes was assumed to be only (6) inches in diameter. Additionally, the size of the grid forging was assumed to be infinite in the radial direction and fourteen (14) inches high axially. Each hole was assumed filled with an optimum mixture of unborated water and fuel. The fuel used in this case was optimum sized fuel particles, with an enrichment of 2.3%. On the top and bottom of the steel was an infinite thickness of borated water reflector.

It is recognized that the dimensions used in this criticality safety analysis differ slightly from the actual grid forging dimensions. However, based on the extremely low values of k_{eff} seen for this analysis (see Section 4.3.4), the effects of these differences will not affect the overall conclusion that the presence of significant amounts of stainless steel has a negative effect on the neutron multiplication.

4.3.3 Effects of Impurities

To assess the reduction in reactivity due to the presence of impurities in the melted fuel, another series of lattice cell calculations were performed. In these calculations the average impurities identified in Table 1 were assumed to be mixed with optimally sized, burned batch 3 fuel. Unborated water was used as a moderating material. The mixture particle size and fuel volume fraction were varied until a maximum k_{∞} value was determined. The potential depletion of neutron poisons (e.g., B^{10}) was not considered in this analysis.

4.3.4 Results

The results of these additional cases are given in Table 4. The main conclusion to be drawn from this table is that there is a large degree of conservatism associated with the base case model. For example, the results of the simplified mixing model show a nominal k_{eff} of 0.924 $\pm$ 0.001. This corresponds to approximately a 3.6% Δk reduction from the base case analysis. Additionally by virtue of the extremely low calculated value of k_{eff}, the results of the stainless steel model indicate that there is a large negative effect on k_{eff} when credit is taken for the significant quantities of stainless steel that are present in the LCSA. The effects of impurities on the reactivity of the melted fuel can be seen by a comparison of the optimum k_{∞} value for pure UO_2 and the optimum value considering the impurities. The value considering the impurities was less than 0.8, while the pure UO_2 k_{∞} was

1.37. The negative reactivity effect of the impurities would be decreased if the potential depletion of the neutron poisons were considered. Additionally, the relative worth of the impurities would decrease if borated water were assumed to be the moderating material. Nevertheless, the calculated difference in the k_∞ values demonstrates the conservatism associated with neglecting the presence of impurities in the melted fuel.

In conclusion, the results of these additional analyses demonstrate that there is a large degree of conservatism associated with the base case model.

4.4 Benchmarking

In Reference 2, an analytical uncertainty bias of 2.5% Δk, including the KENO V.a statistical uncertainty, was established as an appropriate value for the borated systems being investigated in that report. Uncertainty values reported in the literature for unborated systems have been shown to be somewhat lower than this value. Consequently, the 2.5% Δk value is considered conservative for the plasma arc torch criticality safety analyses provided in this report. This bias is considered applicable for both KENO V.a and XSDRNPM analyses since previous analyses (Reference 2), as well as Table 4 demonstrate the good agreement between the results generated by these codes.

5.0 Conclusions

Based on the evaluation presented in this report, it is concluded that the plasma arc torch, with a maximum coolant system inventory of four (4) gallons of unborated water, can be used to dismantle the LCSA, including the elliptical flow distributor head, without developing a criticality safety concern within the reactor vessel.

5.1 Operational Limitations

The above conclusion is based on the following operational limitations:

- The plasma arc torch will only be used to cut the LCSA.

- All standing fuel assemblies must be removed from the core region prior to the use of plasma arc torch in the reactor vessel.

- A maximum of four (4) gallons of unborated water is permitted in the plasma arc torch coolant system with a system configuration such that a maximum of three (3) gallons can drain following a line rupture or torch tip blowout with the torch operating in the reactor vessel.

- Following the loss of coolant inventory, the torch must be removed and repaired before refilling the torch cooling system.

- If in-vessel flushing of the torch is being performed, no load handling operations (heavy or light) are permitted in or above the reactor vessel.

- Flushing of the plasma arc torch coolant system with the torch within the vessel can only occur if there are no known leaks in the coolant system, the torch is in its home position, there is at least a one-foot separation between the torch tip and significant debris quantities, and the gas purge is operating. Otherwise, the torch must be removed from vessel prior to connection of the flushing tie-in.

- The maximum inventory of unborated water permitted in the flush system storage tank is fifteen (15) gallons.

6.0 References

1. Report on Limits of Foreign Materials Allowed in the TMI-2 Reactor Coolant System During Defueling Activities, Rev. 1, 15737-2-N09-002, September 1985.

2. Criticality Report for the Reactor Coolant System, Rev. 0, 15737-2-N09-001, October 1984.

3. SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations, Vols. 1-3, NUREG/CR-0200, Nuclear Engineering Applications Department (1982, Revised June 1983, December 1984).

4. Perry's Chemical Engineering Handbook, 6th Edition, 1984.

5. Hazards Analysis: Potential for Boron Dilution of the Reactor Coolant System, Rev. 2, September 1985.

6. TMI Criticality Studies: Lower Vessel Rubble and Analytical Benchmarking, GEND-071, May 1986.

7. Letter, R. M. Westfall (ORNL) to D. S. Williams (GPUN), August 11, 1987.

8. Letter, R. M. Westfall (ORNL) to D. S. Williams (GPUN), August 24, 1987.

9. TMI-2 Technical Bulletin 85-21, Rev. 4, "Additional Results of Lower Head Debris Samples"

10. Letter, C. V. Parks (ORNL) to D. S. Williams (GPUN), November 6, 1987.

11. Letter, C. v. Parks (ORNL) to D. S. Williams (GPUN), November 12, 1987.

TABLE 1
AVERAGE ELEMENTAL CONCENTRATION OF THE LOWER HEAD DEBRIS

Core Component/ Element	Particle/Concentration (wt%)								
	7-1-B	11-1-A	11-1-C	11-2-C	11-4-B	11-4-D	11-5-C	11-6-B	11-7-C
Fuel									
U	65.3	66.8	64.2	63.2	65.1	65.6	64.0	69.5	62.3
Zr	12.0	12.8	13.0	12.9	15.0	12.1	12.2	11.7	12.6
Sn	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]
Control Rod									
Ag	0.22[b]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]
Cd	--[a]	--[a]	--[a]	0.025[b]	--[a]	--[a]	--[a]	--[a]	0.065[b]
In	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]
Burnable Poison Rod									
Al	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
B	0.094	0.12	--[a]	0.071	0.066	0.12[b]	0.077	0.36	0.096
Gd	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]
Structural Material									
Fe	2.4	1.88	2.28	2.48	2.90	3.70	2.04	1.83	2.41
Cr	0.95	0.59	0.6	0.79	0.99	0.96	0.65	0.58	0.61
Ni	--[a]	--[a]	0.24[b]	--[a]	0.26[b]	--[a]	0.20[b]	--[a]	0.24[b]
Mn	--[a]	0.097	--[a]	0.068	0.085	0.089	0.065[b]	0.068	0.062[b]
Nb	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]	--[a]
Si	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]	--[c]
Mo	0.14	0.19	0.12	0.093	0.13	0.21	0.11	0.21	0.12
Cu	0.46	--[a]	--[a]	0.21	--[a]	--[a]	-[a]	--[a]	--[a]
Total wt% of sample [d]	81	82	80	80	84	84	81	84	80

a. Below detectable concentrations.
b. Some concentrations for this particle were below the detection limit. They have not been included in the listed value.
c. Results are not included as the samples were contaminated with these elements during dissolution or handling.
d. The remaining percentage is currently attributed to oxygen by the laboratory. Further analyses continues.

TABLE 2
U-235 ENRICHMENT OF THE LOWER HEAD DEBRIS SAMPLES

	Sample Number/U235 Enrichment (wt %) (b)								
Particle(a)	1	2	3	4	5	6	7	8	9
7-1-B	2.2	2.3	2.3	2.4	2.6				
11-1-A	2.0	1.8							
11-1-C	2.3	2.9 (c)							
11-2-C	2.4	2.6	2.2	2.2	2.6	2.5			
11-4-B	2.2	2.4	2.3	2.6					
11-4-D	2.6	2.3	2.2						
11-5-C	2.2	2.1	2.3	2.2	2.2	3.1 (c)	--	2.2	2.2
11-6-B	2.5	2.3	2.4						
11-7-C	2.6	2.5	2.1						

(a) The first number indicates locations the samples were taken from. The second number is a sequential sample number. The letters signify subdivisions of the sample. The samples numbers identify particles taken from each subdivision for analysis. Locations 7 and 11 are on the south and southwest sides of the reactor, respectively.

(b) Typical uncertainty associated with results is about ± 10%.

(c) Large associated uncertainty.

Table 3: Optimization Results

Fuel Particle Diameter (cm)	Optimum Fuel Volume Fraction	Boron Concentration (ppm)	Enrichment (%)	k_∞
3.0	0.67	4950	2.57	0.9675
3.2	0.67	4950	2.57	0.9679
3.4	0.68	4950	2.57	0.9681
3.5	0.68	4950	2.57	0.9682
3.6	0.68	4950	2.57	0.9682(a)
3.7	0.68	4950	2.57	0.9682
3.8	0.68	4950	2.57	0.9681
2.5	0.54	2000	2.67	1.1150
2.7	0.55	2000	2.67	1.1154
2.8	0.55	2000	2.67	1.1155(a)
2.9	0.56	2000	2.67	1.1155
3.0	0.56	2000	2.67	1.1155
2.0	0.33	0	2.57	1.3722
2.1	0.33	0	2.57	1.3724(a)
2.2	0.33	0	2.57	1.3723
2.4	0.34	0	2.57	1.3720

(a) optimum values for noted boron concentrations

Table 4: Results

Case [a]	Computer Code	k_{eff}	k_{max} [b]
Base Case	KENO V.a	0.9599 $\pm$0.0011 [c]	0.9849
	XSDRNPM	0.9582(d)	0.9832
Mixing Case	KENO V.a	0.924 $\pm$ 0.001	0.949
Stainless Steel	KENO V.a	0.794 $\pm$ 0.002	0.819

(a) See Sections 4.2 and 4.3 for descriptions of cases.

(b) $k_{max} = k_{eff} + 2.5\% \Delta k$ uncertainty bias

(c) Value is the mean of 10 KENO V.a runs, each using approximately 200,000 histories.

(d) XSDRNPM convergence is 10^{-4}

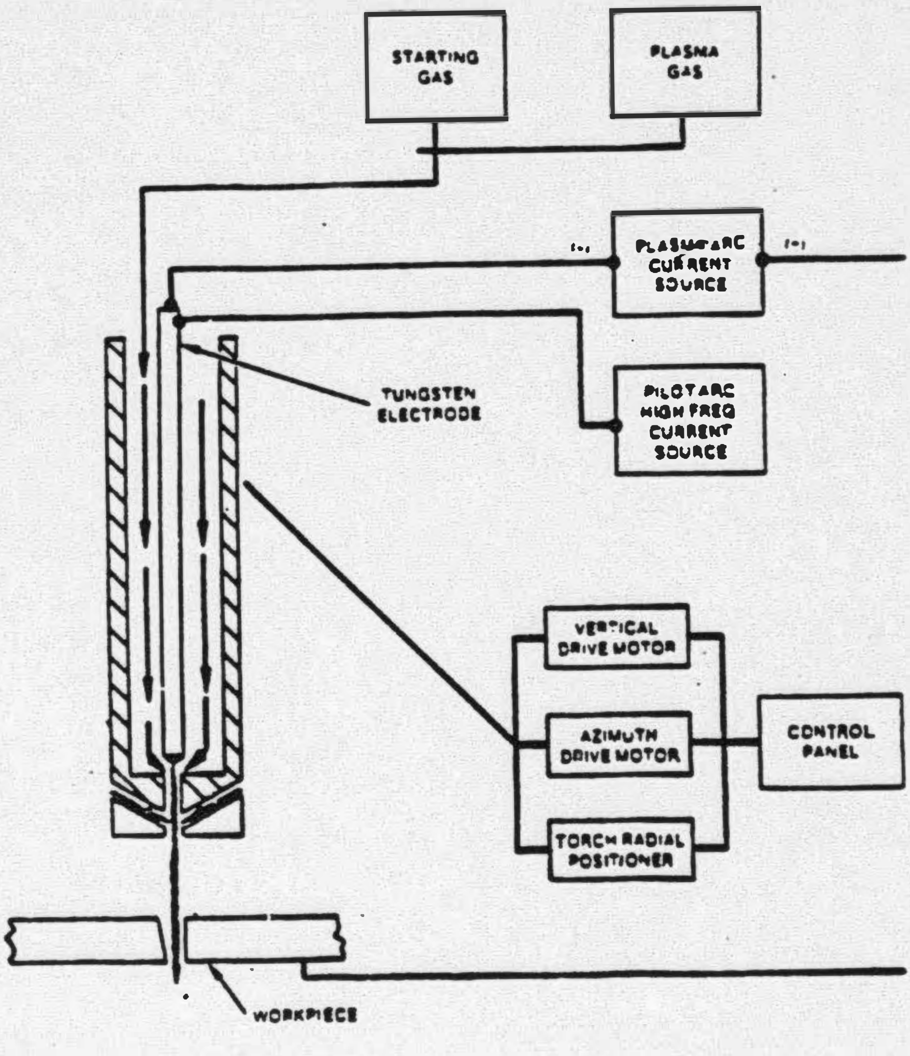
Table 5: Results of KENO V.a Analyses for Base Case Model

Run [a]	k_{eff} [c]
1	0.9663 ± 0.0010
2	0.9550 ± 0.0011
3	0.9612 ± 0.0011
4	0.9648 ± 0.0011
5	0.9608 ± 0.0012
6	0.9574 ± 0.0013
7	0.9584 ± 0.0011
8	0.9576 ± 0.0012
9	0.9566 ± 0.0011
10	0.9610 ± 0.0011
Mean	0.9599 ± 0.0011 [b]

(a) Cases differ only in change in random number. There were 200,000 histories per case.

(b) Mean = $\bar{k} = \frac{k_{eff}}{10} = 0.9599$

(c) Results do not include any uncertainty bias.



PLASMA ARC CUTTING SYSTEM SCHEMATIC

Figure 1

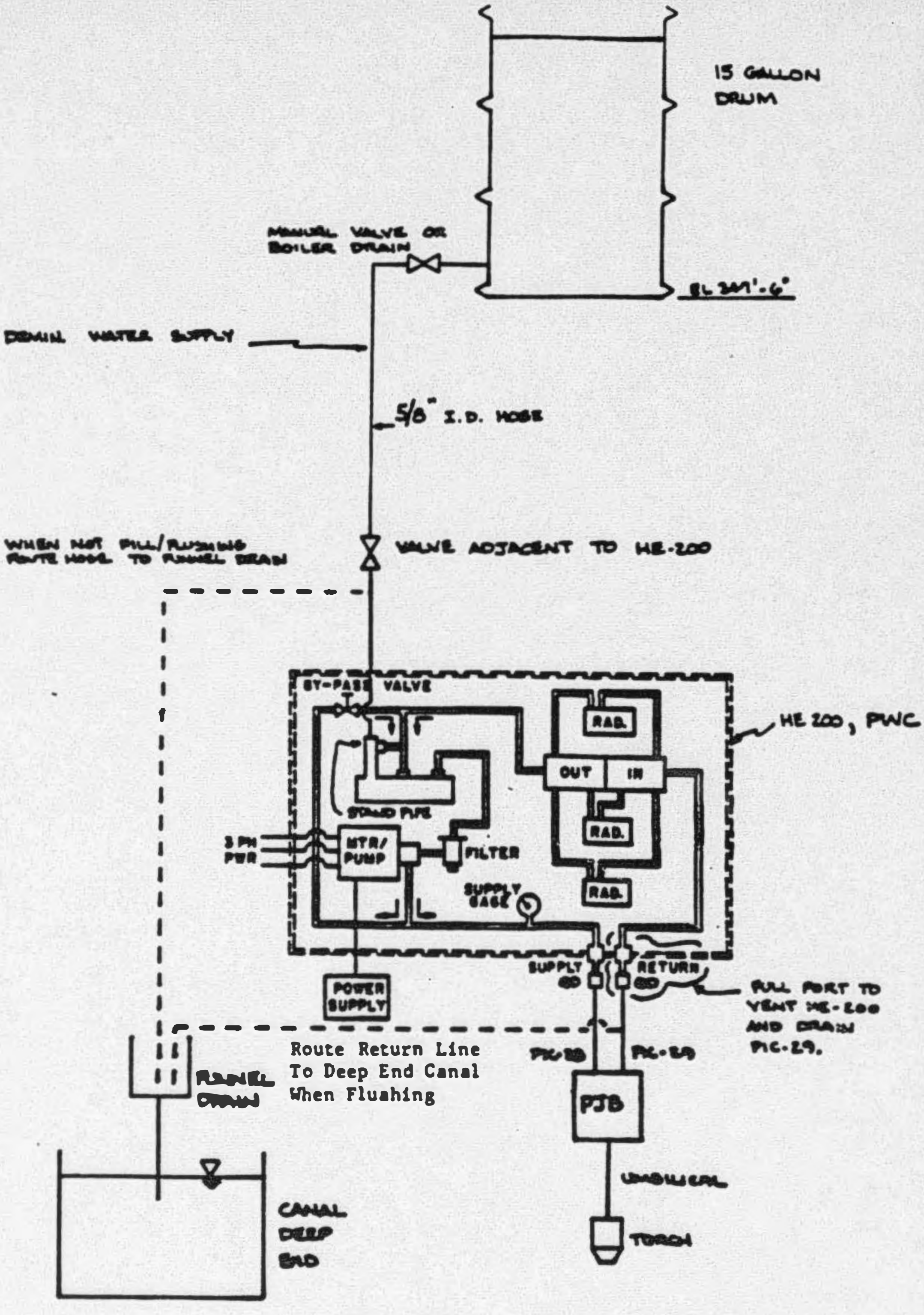
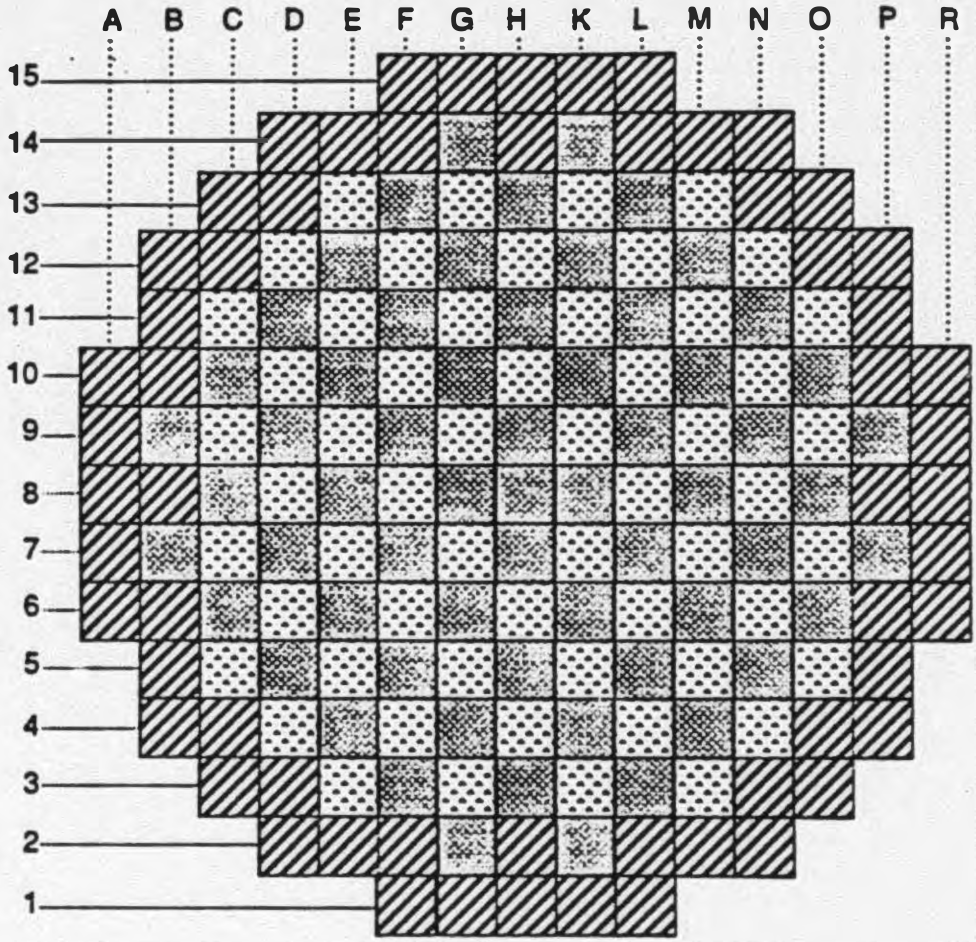


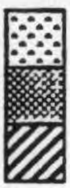
Figure 2

Plasma Arc Torch Coolant System Schematic

Figure 3

TMI-2 CORE ENRICHMENT PATTERN





	ENRICHMENT	No. OF ASSEMBLIES
	1.98%	56
	2.64%	61
	2.96%	60

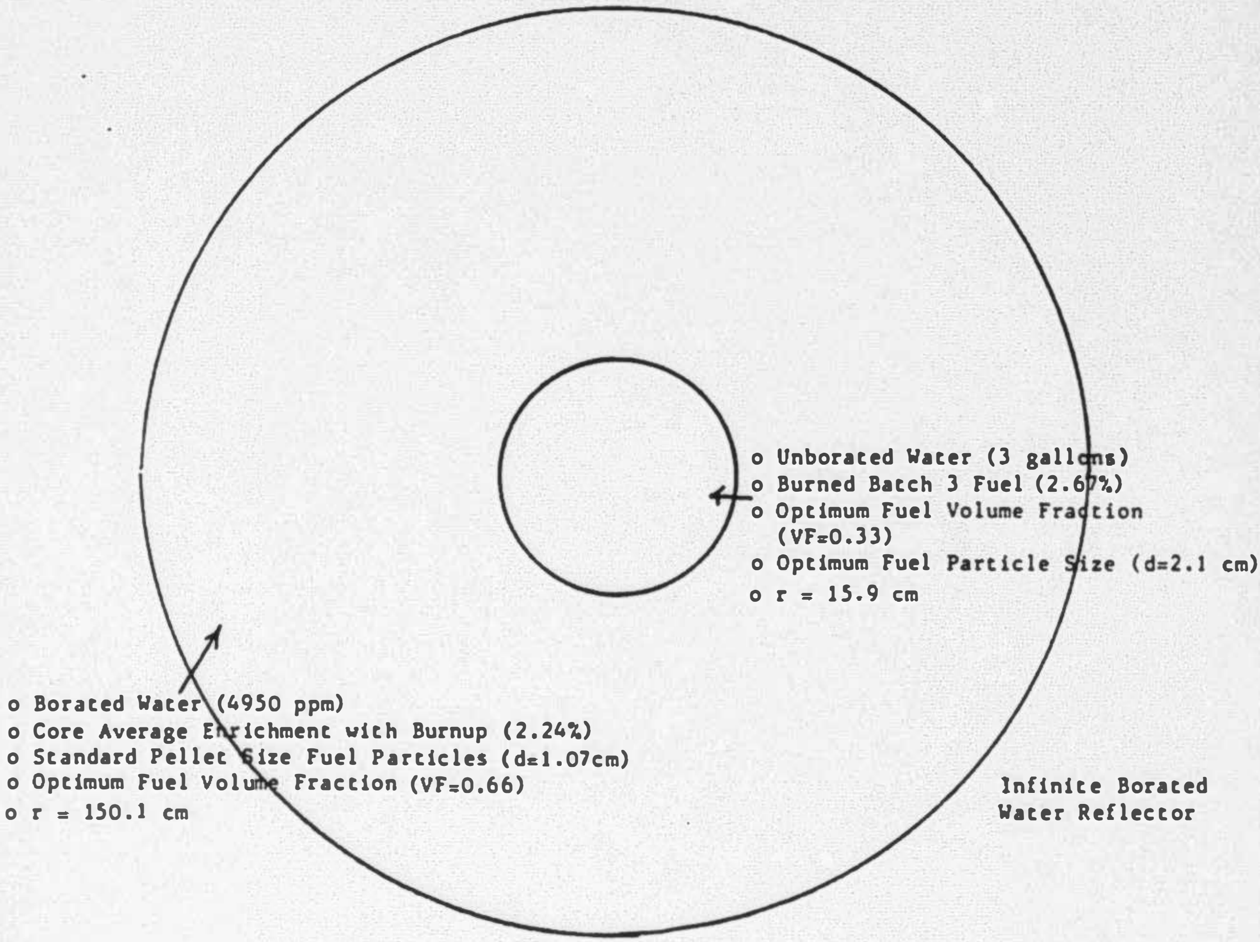


Figure 4: Base Case LCSA Criticality Safety Model

FUEL PARTICLE SIZE EFFECTS

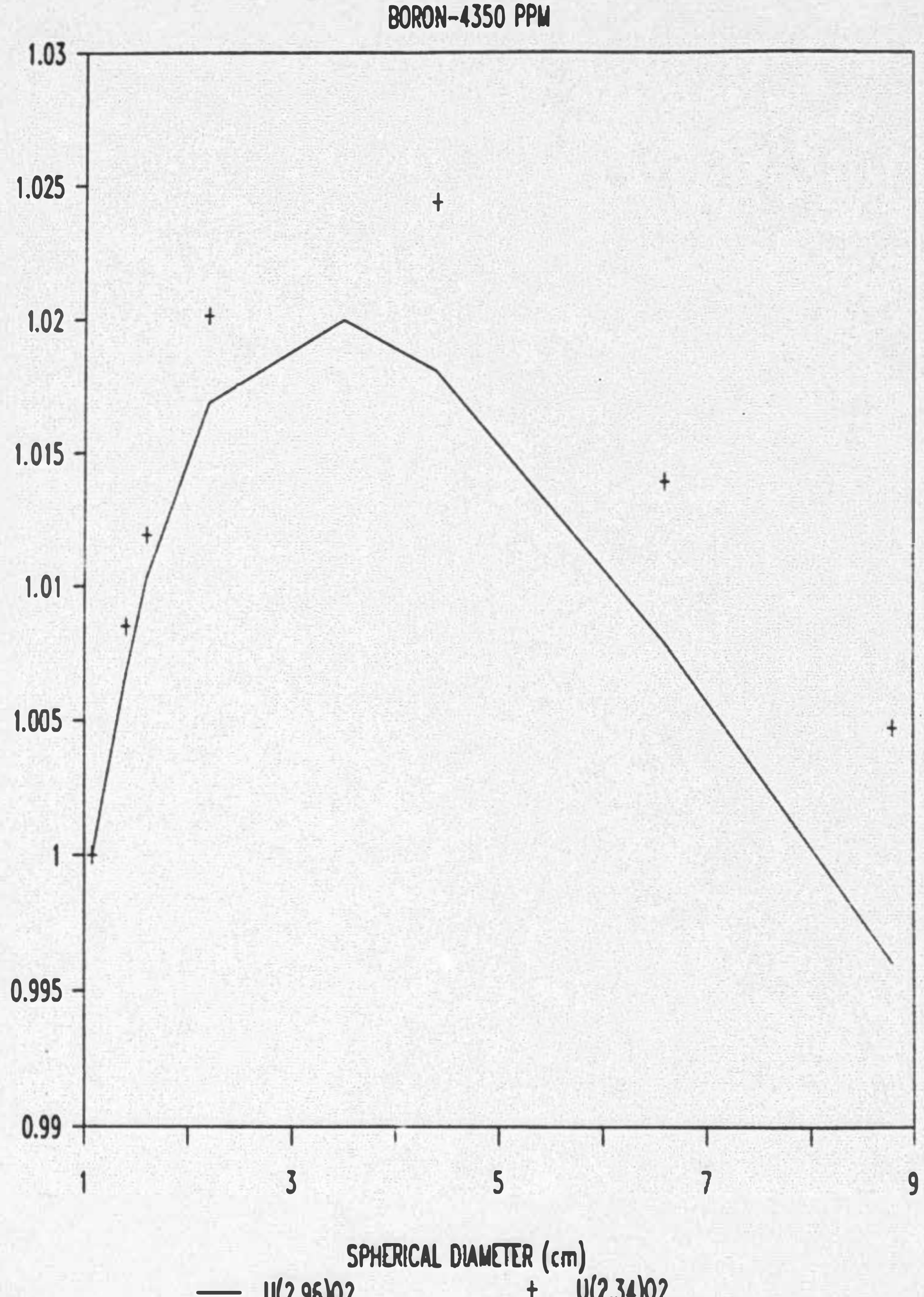


Figure 5

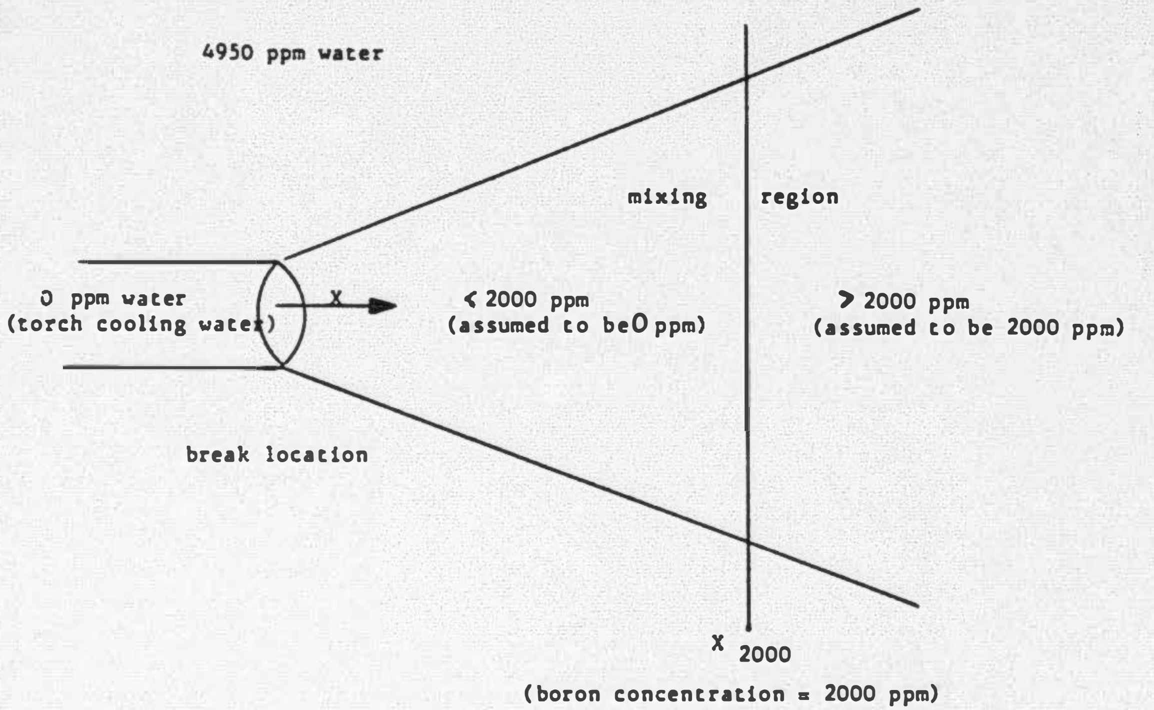


Figure 6: Hydraulic Mixing Modelling

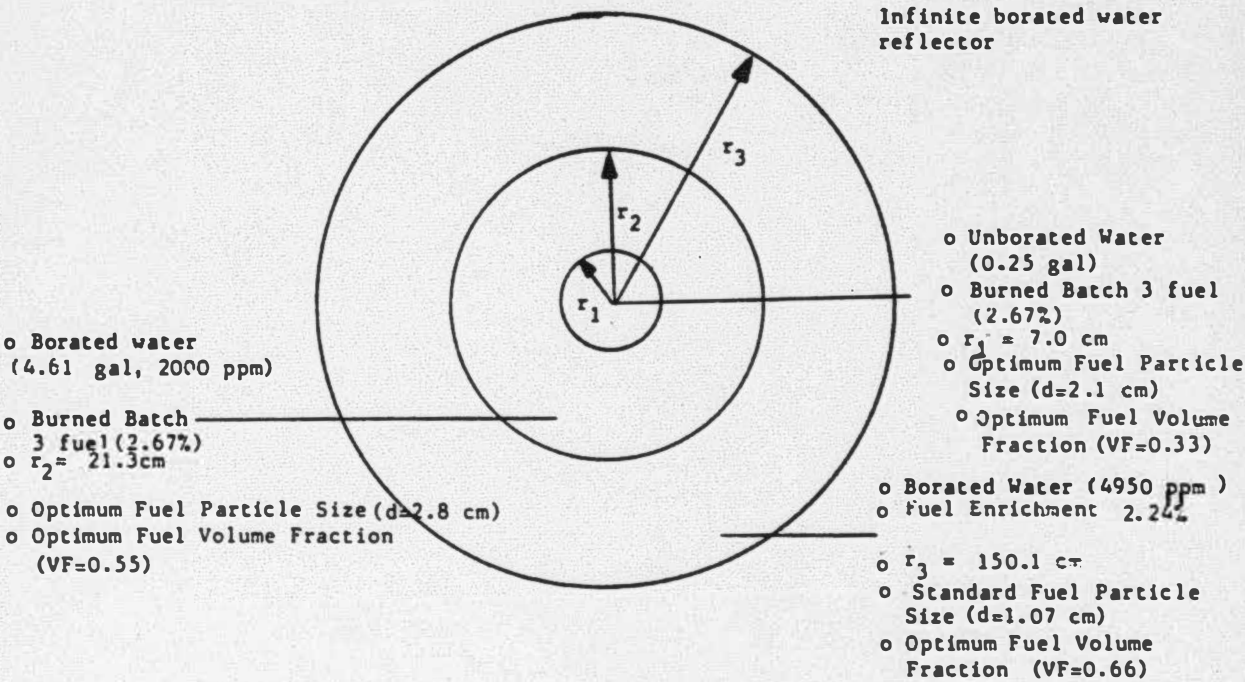
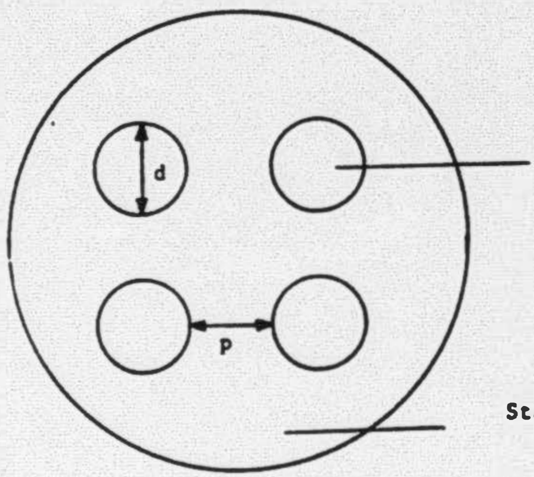


Figure 7: Criticality Safety Model to Assess Effects of Mixing

Actual Dimensions

d = 6.5 inches
p = 2.1 inches



Analysis perfomed using infinite lattice of above arrangement
with d = 6.0 inches, p = 2 inches

Figure 8: Criticality Safety Model Considering Presence of Stainless Steel within LCSA