APPENDIX I

UNITED STATES
NUCLEAR REGULATORY COMMISSION
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THRU: Charles E. MacDonald, Chief
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SUBJECT: CRITICALITY REVIEW OF TECHNICAL EVALUATION REPORT (TER) FOR THE TMI-2 DEFUELING CANISTERS AS DOCUMENTED IN REFERENCE A (BELOW)

REFERENCES:

A. TER (15737-2-G03-114, Rev. 0) dtd 03/22/85 TMI-2 Division Technical Evaluation Report for Defueling Canisters

B. Three (3) IBM Computer Listings (B&W property to be returned to B&W):
   1. KENO-IV, 123 Gps, Gen. Geom: Damaged Fuel Canister
   2. KENO-IV, 123 Gps, Gen. Geom: Damaged Filter Canister
   3. KENO-IV, 123 Gps, Gen. Geom: Damaged Knock-out Canister

   (delivered to NRC on May 23, 1985)

C. Three (3) B&W fiche copies of the above listings giving nuclear data and geometric details (NRC property; delivered to NRC on May 23, 1985)

I. Introduction and Conclusions

As requested in your memorandum to C. E. MacDonald dated April 24, 1985, a detailed review has been performed of the submitted GPU (Refs. A and B, B&W analyses) criticality Safety Analysis for the loading of canisters in the defueling of the TMI-2 core. Based on this review, we find that the criticality calculational method, physical and geometric assumptions, atomic number densities (giving mass loadings of nuclides per region) and description of canisters analyzed to be accurate and represent the cases intended.

In addition to this detailed review and verification, independent KENO-IV Monte Carlo calculations of the knock-out and fuel canisters were performed. The independent calculations agree with the results obtained by B&W as given in Ref. A. A comparison of NRC and B&W's keff's under various conditions is given in Table 1. Since the filter canister contains a similar 2" diameter B_4C central poison rod as in the knock-out canister and in addition contains about ten times the amount of internal steel of that in the knock-out canister, the filter canister was considered less reactive than the knock-out canister and hence not analyzed by NRC.

We, therefore, recommend acceptance of the criticality analysis portion of Ref. A and concur with the subject submittal that there exists at least a 5% shutdown margin for all three canisters under normal and assumed accident modes.

In Table 1, below, and in Ref. A, we note that B&W did not report any keff's for B_4C replaced by water or replaced by a void. NRC calculated a single knock-out canister to have a 4.3% shutdown when the B_4C is replaced by water; a 3.8% shutdown when the B_4C is replaced by water and the remaining steel tubes are deflected off-center by 1.2 inches. We note that these latter two cases are supercritical for the infinite array calculation as given in Table 1. Thus, if the above scenarios can be realized in the postulated accident modes, the 5% margin shutdown is compromised. Further, if a void replaces the B_4C, the shutdown margin is further reduced from 4.3% to 3.4%.

In summary then, we find:

1. The B&W calculational methodology (KENO IV-123 Group GamThermos cross-sections) represents one of the best state-of-the-art approaches which has successfully calculated many appropriate benchmark criticals. In particular, we note that the B&W fuel-water homogenization procedure - fundamental to the B&W approach and results - has been done correctly.

2. The B&W criticality analyses used the most (neutronically) reactive fuel/water mixture in representing the core debris in each canister.

3. Some conservatisms used by B&W were:

   (a) Each canister was loaded up to a height of 14 feet ($\sim$ an extra 3 feet of reactive material).

   (b) The density of B_4C was taken as 1.35 gm/cc; areal density of B-10 for boral was taken as 0.04 gm/cm^2.

(c) The minimum amount of steel has been credited to the knock-out canister ($\sim$ 1-1/2 volume percent) and the filter-canister ($\sim$ 14 volume percent).

4. NRC independent calculations agree very well with the B&W results for the cases considered.

A brief discussion of the criticality methods used to establish the conservative acceptable parameters fundamental to both B&W's and NRC's follows.

II. Basic Assumptions and Methods Used in Criticality Calculations

Both B&W and NRC assumed the TMI-2 debris contents for all three canisters to be $U(3)O_2$ unclad pellets moderated by unborated H_2O with a volume fraction of 0.30 of fuel and 0.70 of water. This has been established via many independent calculations to constitute the most reactive mixture. For a borated water system over the range of 3000 to 5000 ppm boron in water, the most reactive mixture turns out to be a volume fraction of 0.60 of fuel and 0.40 of water. However, for these borated systems, the keff is of the order of 30% less than any corresponding system moderated by unborated water. Thus, the Δ k is of the order of 0.3 and completely controls selection of the most reactive mixture to be fuel moderated by unborated water. All criticality calculations thus use unborated water as moderator.

Both B&W and NRC assume a very conservative density for B_4C viz 1.35 gm/cc versus 2.43 gm/cc given in the handbooks. In addition, an areal density of 0.04 g/cm^2 for B-10 is assumed for boral.

Both B&W and NRC use the KENO-IV Monte Carlo computer program with the 123 group Gam Thermos neutron cross-section set adjusting the resonance nuclide (U-238) with the NITAWL program. B&W then homogenizes the $U(3)O_2$ and the associated water (30/70 mixture) via an XSDRN cell group-spatial weighting into a debris mixture. Using generalized geometry, this homogenized water-fuel mixture occupied all space within the boral plates of the fuel canister, all space inside the knock-out canister not occupied by the 5 B_4C-SS clad rods and all space inside the 17 filter elements of the filter canister.

As a check on the above homogenization procedure, NRC's model required that the $U(3)O_2$ pellet be described as a discrete cylinder surrounded by the cell (30/70) water. This restricted NRC's canister's geometry to a square-cylinder. The pellet-water constituted a box-type in the KENO-IV geometry, and since the fuel canister possesses a square internal region (surrounded by boral) which will contain the debris, it represents the ideal case to check the homogenization process fundamental to B&W's calculated procedure. Results of Table 1, under Fuel Canister show that the homogenization procedure of B&W and the discrete procedure of NRC to be equivalent - they calculate the same keff for the single fuel canister and for an array.

For the knock-out canister, the square cylinder geometry of NRC maintained the exact masses of UO_2, H_2O, steel and B_4C that exist in B&W's cylindrical geometry. Table 1 for the undamaged single knock-out canister, B_4C in place shows excellent agreement; for the infinite array, the NRC value of k_∞ is higher by $\sim$ 4-1/2% since in this geometry the square box ends come much closer to neighboring boxes whereas the cylinders remain effectively further apart from one another.

The damaged cases for NRC were calculated by assuming the B_4C being replaced by water whereas B&W assumed only a displacement of the B_4C-SS rod. Although NRC's condition is more severe, the single damaged knock-out canister is still subcritical, but the infinite array of such damaged canisters is supercritical.

NRC's worth of the B_4C can be estimated from Table 1:

For Single Canister	For the Array
$\frac{\Delta k}{k} = \frac{0.957-0.887}{.922} = 7.6\%$	$\frac{1.033-0.961}{.997} = 7.2\%$

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TABLE 1

COMPARISON OF B&W AND NRC CALCULATED MAXIMUM* Keff's
FOR
KNOCK-OUT AND FUEL CANISTERS
CONTAINING TMI-2 DEBRIS
Using KENO IV with 123 Group GamThermos Neutron Cross-Sections when each canister is loaded with most reactive $U(3)O_2/H_2O$ mixture**

STATUS OF CANISTER CALCULATED	KNOCK-OUT CANISTER						FUEL CANISTER	
	UNDAMAGED				DAMAGED		UNDAMAGED	
	(B_4C in Place)		(B_4C repl by H_2O)		(B_4C repl by H_2O & SS displ 1.2")	(B_4C & SS displ 0.75")	(Boral in Place)	
	NRC	B&W	NRC	B&W	NRC	B&W	NRC	B&W
SINGLE CANISTER (H_2O flooded and reflected)	0.887[a]	0.873	0.957[b] 0.966[d]	---	0.962	0.882	0.866	0.857
INF. ARRAY OF CANISTERS (17.3" c to c spacing in H_2O pool)	0.961[c]	0.915	1.033	---	1.041	---	0.872	0.877

*Maximum value for B&W is keff + 2σ + calc. bias; for NRC, it is keff + 3σ.
**Assumed fuel vol/water vol = 30/70, fuel as pellet in unborated water.

All cases used $\rho(B_4C)$ as 1.35 gms/cc; BORAL assumed 0.04 gm B-10/cm^2

(a) NRC Calc. for this case with 3000 ppm boron in H_2O; keff = 0.582 - no steel in canister.
(b) NRC Calc. for this case with 3000 ppm boron in H_2O; keff = 0.646 - no steel in canister.
(c) NRC calc. for this case with 3000 ppm boron in H_2O; keff = 0.618 - no steel in canister.
(d) B_4C replaced by a void.