CRITICALITY SAFETY MARGINS PROVIDED BY MODERATOR CONTROL IN THE TMI-2 DRY STORAGE CASK

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ABSTRACT

A dry storage cask has been designed to provide storage for TMI-2 defueling canisters at the Idaho National Engineering Laboratory. Criticality safety margins will be provided by moderator controls imposed on the canisters (prior to insertion into the cask) and on the cask (during a 50-yr storage time). Criticality safety calculations demonstrate that an adequate margin of safety exists for the proposed storage of defueling canisters in the TMI-2 dry storage cask.

I. INTRODUCTION

Interim storage of TMI-2 defueling canisters is being provided in the Test Area North (TAN) storage pool at the Idaho National Engineering Laboratory (INEL). The TMI-2 dry storage cask has been designed to provide storage (up to 50 yr) for excess TMI-2 defueling canisters for which storage space in the TAN storage pool is not available. TMI-2 defueling canisters that are presently stored in the TAN pool may also, in the future, be removed from the pool and stored inside dry storage casks.

Prior to being inserted into a dry storage cask, each defueling canister will be dewatered and the contents will be dried. Criticality safety calculations have been performed to determine whether an adequate safety margin exists if dewatered and dried defueling canisters are stored in the TMI-2 dry storage cask. In several past criticality safety analyses for TMI-2 defueling canisters,[1,2,3] core debris was represented as an optimally moderated TMI-2 UO_2 fuel pellet/water composition. For canister storage in the dry storage cask, the reactivity of fully flooded canisters is unacceptably high. Use of neutron poison materials in these casks would be costly because of the large number of casks that could be required (~60) and because periodic verification of poison materials is required at the INEL. Therefore, criticality safety margins for the TMI-2 dry storage cask will be maintained by control of moderator material. A debris composition that corresponds more closely to actual canister payloads was assumed for this analysis. This approach has been submitted to the Idaho Operations Office of the Department of Energy for review and approval.

II. DESCRIPTION OF THE TMI-2 DRY STORAGE CASK AND DEFUELING CANISTERS

A. *TMI-2 Dry Storage Cask Description*

Axial and radial sketches of the TMI-2 dry storage cask are shown in Fig. 1 and 2. The cask consists of a thick [59-cm (23.25-in.) walls, 40-cm (15.75-in.) bottom] concrete shell lined with carbon steel [1.27-cm (0.5-in.) thick on the sides, 1.905-cm (0.75-in.) thick on the bottom]. A cylindrical shielding assembly fits inside the concrete shell. The shielding assembly consists of a 7.62-cm (3-in.) thickness of carbon steel with an inside radius of 64.135 cm (25.25 in.). A thick [30.48-cm (12-in.)] carbon steel shield plug is positioned at the top of the cask cavity and a 1.905-cm-thick (0.75-in.-thick) carbon steel lid is welded to the cask liner about 3.81 cm (1.5 in.) above the shield plug. Two vent and purge ports penetrate the concrete shell about 3 m (10 ft) above the bottom of the cask. Special absolute filters on the vent and purge lines are recessed in the side of the concrete shell at the point of penetration.

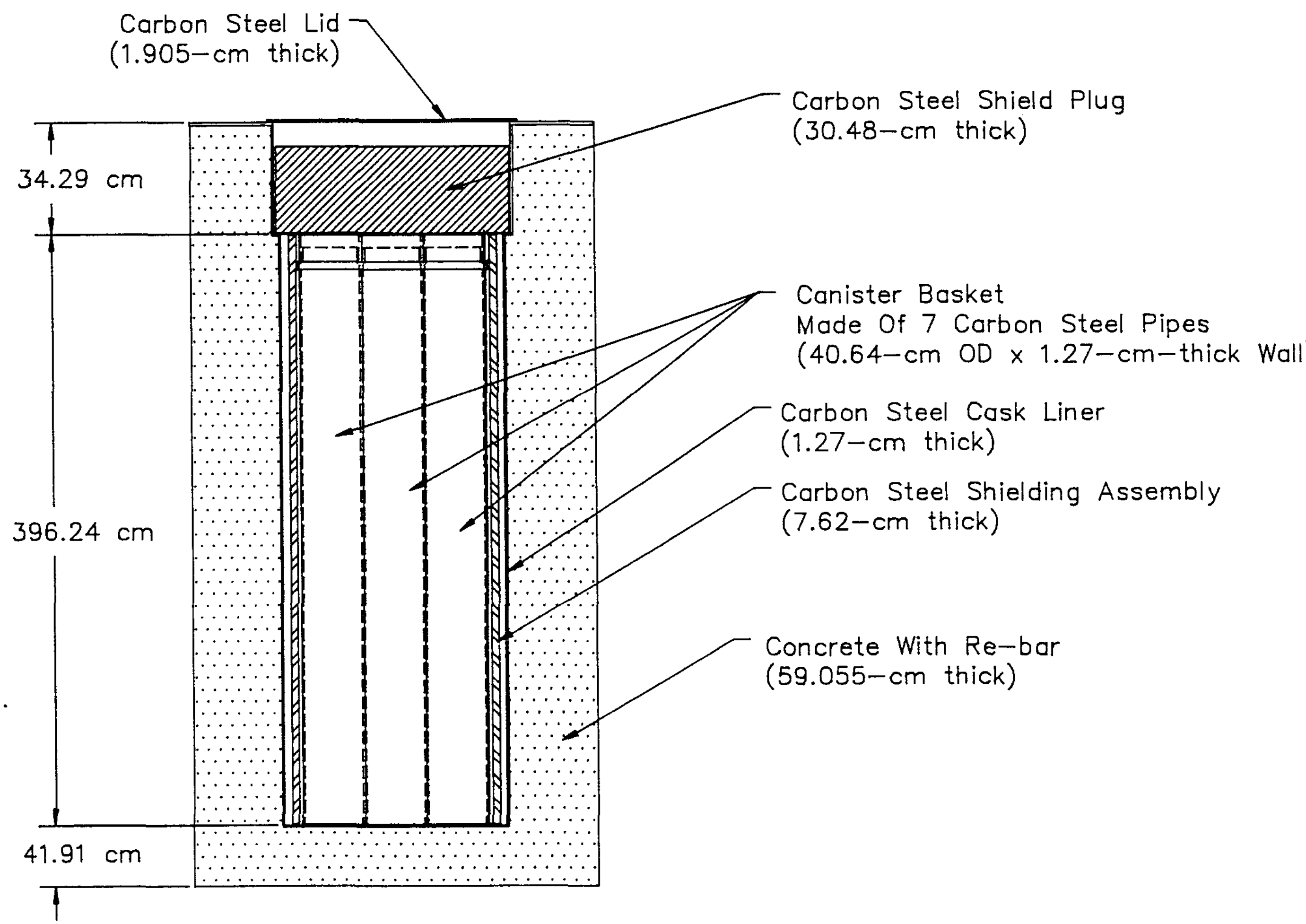

Fig. 1. Elevation view of the TMI-2 dry storage cask.

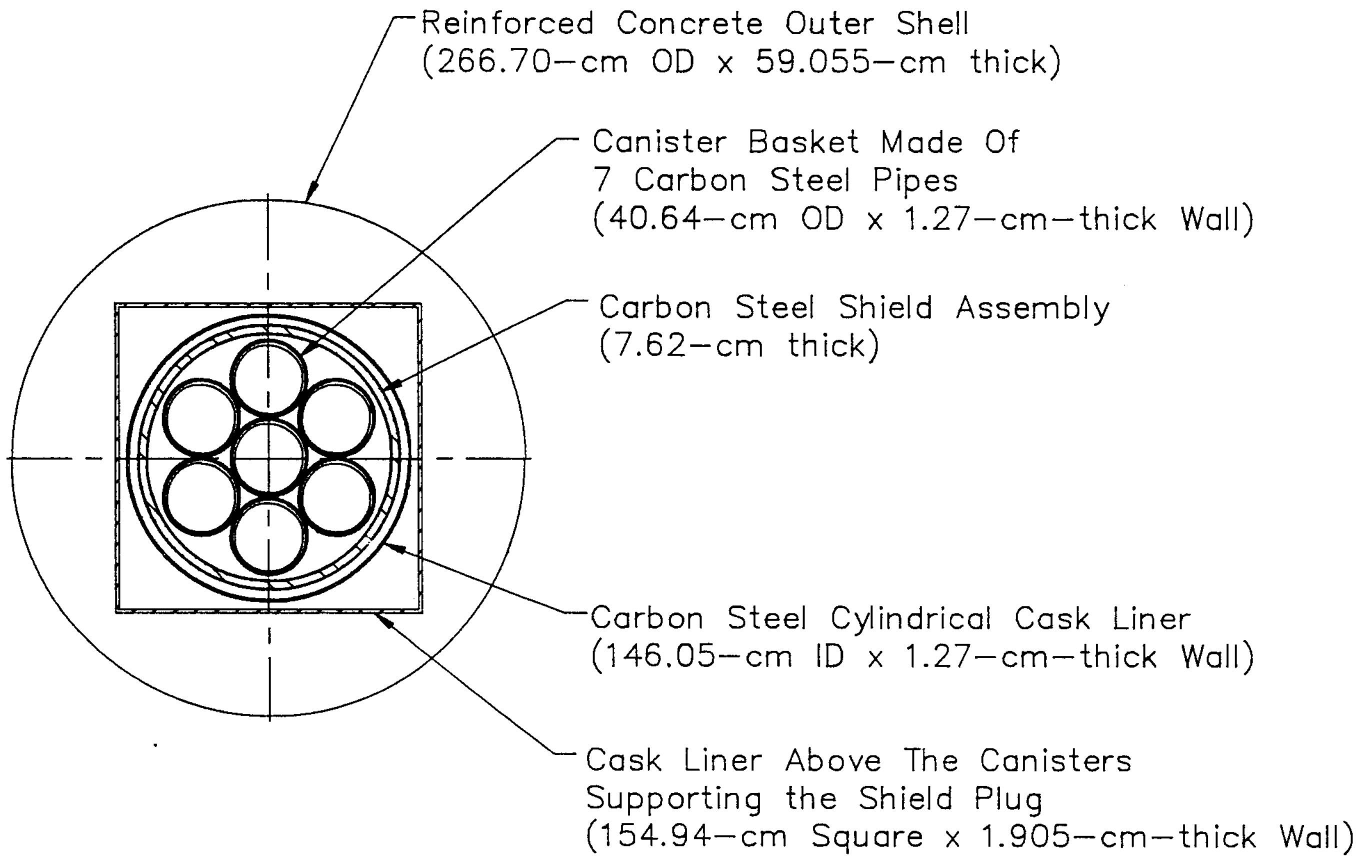

Fig. 2. Plan view of the TMI-2 dry storage cask.

The filters will allow gases to leave the cask, but will prevent moisture from entering the cask. A plate or screen will cover the recess and protect the filters from the environment. A leak test will be performed on each cask to verify that the barrier provided by the cask liner and lid will prevent the introduction of moderator material (water) into the cask and the escape of particulates from the cask. All cask openings (i.e., vent and purge lines and the cask lid) are well above the level of credible flooding.

Canister storage is provided by six carbon steel sleeves arranged in a close-packed hexagonal configuration with a seventh storage sleeve positioned at the center. The storage sleeves have an outer radius of 20.32 cm (8 in.) with a 1.27-cm-thick (0.5-in.-thick) carbon steel wall.

B. TMI-2 Defueling Canister Description

Core debris from TMI-2 is contained in three types of canisters, namely, fuel, knockout and filter. All three types are constructed as cylindrical stainless steel vessels with an outer diameter of 35.56 cm (14 in.) and an overall height of about 381 cm (150 in.). Only internal structures differentiate each type and dictate the function of each. Fuel canisters contain large pieces (e.g., partial fuel assemblies) of core debris; knockout canisters contain fines and debris; and filter canisters contain suspended particulate. Sketches of all three types of canisters are shown in Fig. 3 (taken from Reference 1).

Prior to being inserted into the TMI-2 dry storage cask, each defueling canister will be dewatered and the contents will be dried. Following the drying process, a "worst case" storage canister will contain at most 2.3 kg (5 lb) of free water. Based on test results, the remaining water mass is expected to be less than 0.5 kg (1 lb). A Probabilistic Risk Assessment (PRA) has been independently developed in parallel with equipment design to assure that the dewatering/drying processes are effective and that the worst-case condition is not exceeded.

III. CRITICALITY SAFETY ANALYSIS

A. Codes, Cross Sections, and Validation

The criticality calculations were performed primarily with the three-dimensional Monte Carlo code, KENO-V.a.[4] Cross sections from the 16-energy-group Hansen-Roach[5] data set were used for all materials except core debris. Cross sections representing the core debris were derived from flux-volume-weighted ENDF/B-V data that were generated with the COMBINE[6] code (a combined version of the PHROG[7] and INCITE[8] codes). Calculations were performed for appropriate benchmark critical experiments[9] to validate both the cross- section data and the methods used to process these data. Most calculated k_{eff} values were slightly greater than 1.0, which indicates a slightly conservative bias in the calculations.

B. Model Description

Core debris from TMI-2 includes zircaloy cladding, UO_2 fuel pellets, control rod materials, structural materials, and materials that were introduced as part of the defueling process. In several previous analyses[1,2,3] of the TMI-2 defueling canisters, an optimally moderated fuel/water composition was used to represent the debris. It was assumed at that time that there was no fuel melting, so the largest fuel lump would be that of a TMI-2 fuel pellet. Based on this assumption, an optimally moderated fuel/water composition was determined to be unclad TMI-2 UO_2 fuel rods in the water with a fuel volume fraction of about 0.31.

Since the earlier analyses, the debris payload in a single canister has been more clearly defined. The maximum expected debris payload is about 862 kg (1900 lb). It was also determined that fuel melting occurred. The previously used optimally-moderated core debris composition was found to be overly conservative. Therefore, for this analysis, 862 kg (1900 lb) of core debris was assumed in each canister of which 590 kg (1300 lb) was assumed to be UO_2 and 272 kg (600 lb) was assumed to be zirconium. The UO_2 was assumed to be in the form of unclad TMI-2 fuel rods with a ^{235}U enrichment of 3.0 wt.%. The zirconium was homogenized throughout a moderator region surrounding the UO_2 fuel rod. Since some fuel melting occurred, the effect of larger diameter fuel lumps was determined and the final results were adjusted accordingly.

The water mass values evaluated were relatively small and did not completely submerge the 862 kg (1900 lb) of core debris. Therefore, cross-section data were obtained for both wet and dry core debris. The model of the knockout canister had wet debris represented immediately above the support plate with dry debris in all of the remaining available volume. (Results of preliminary calculations showed this configuration to be more reactive than one in which the limited quantities of wet debris was distributed above and below the support plate.) The model of the fuel canister had wet debris represented in the bottom of the canister with dry debris in all remaining available volume. Provisions were made in the model to allow variations in the height of the

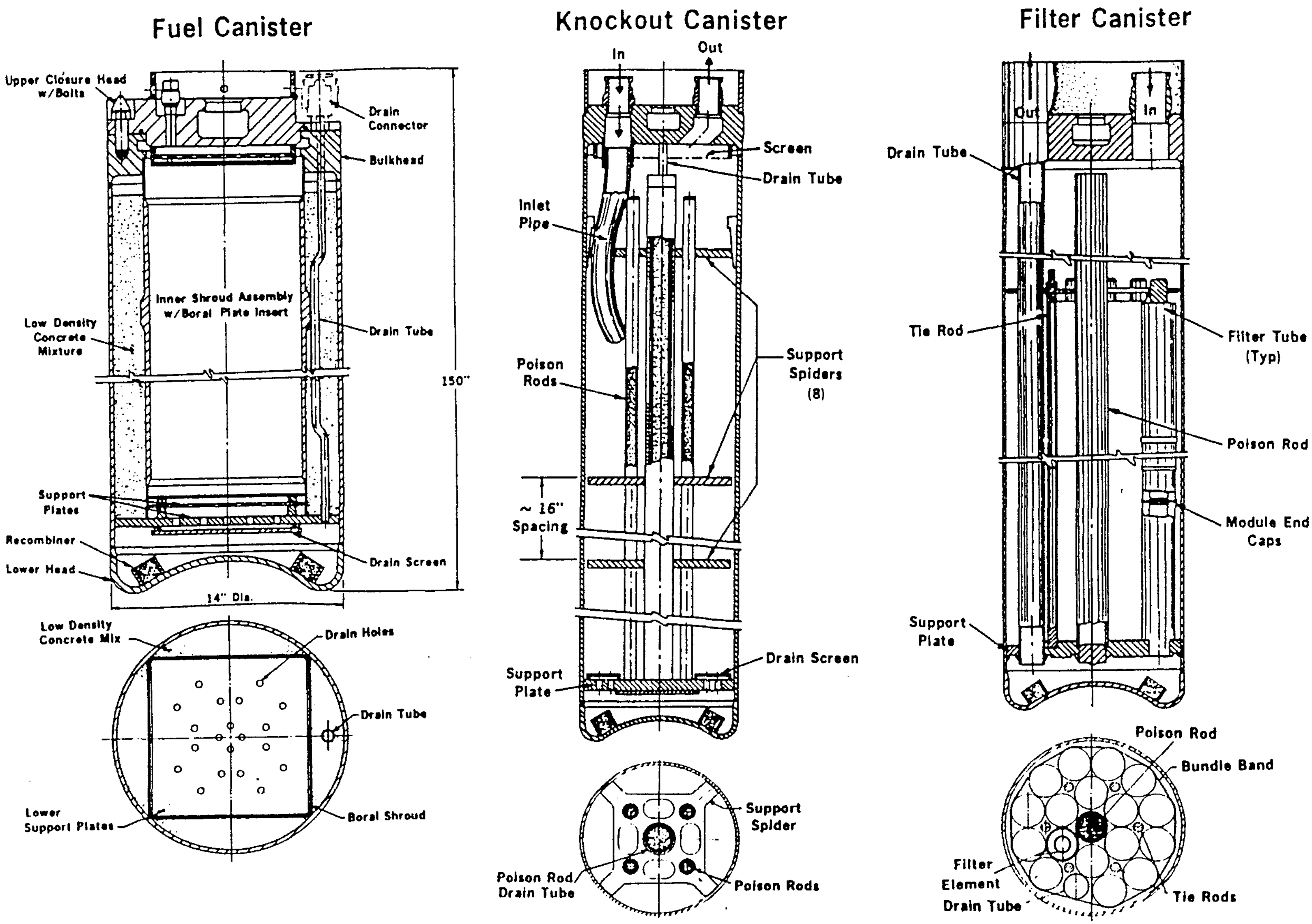

Fig. 3. The TMI-2 defueling canisters; note that the external dimensions of all canisters are the same. (Compliments of Babcock & Wilcox and the American Nuclear Society)

wet debris (i.e., variations in the mass of water) inside the canisters. Variations in the percent of the available debris volume that actually contains the 862 kg (1900 lbs) of debris (degree of compaction) were represented with different cross-section sets. With these representations, cases in which the debris volume was assumed to be less than 100% of the available volume in the canister actually have much more than 862 kg (1900 lb) of core debris inside each canister. However, the additional dry debris has little effect on the calculated results.

It has been demonstrated in previous analyses[1,2,3] that the knockout canister is the most reactive of the three canister types. For this reason, the TMI-2 dry storage cask was assumed to be filled with knockout canisters for the majority of the calculations performed for this analysis. A few calculations were performed with the cask filled with fuel canisters to verify that the knockout canister is the most reactive of the three types of canisters when stored in TMI-2 dry storage casks. The filter canister is generally much less reactive than the knockout and fuel canisters and contains much less fissile material; therefore, calculations were not performed with filter canisters represented.

The canisters and the cask were conservatively represented. All neutronically significant details were represented except the B_4C in the knockout canister and the Boral™ in the fuel canister were replaced with water. Since the calculations were performed, a few changes in the cask design have occurred. The 7.62-cm-thick (3.0-in.-thick) carbon steel shielding assembly originally consisted of a 3.81-cm (1.5-in.) thickness of lead sandwiched between 0.635-cm (0.25-in.) thicknesses of carbon steel. The inside radius of the earlier shielding assembly design was also slightly smaller [63.5 cm (25 in.) compared to 64.135 cm (25.25 in.)]. The original design of the cask shield plug was changed from concrete lined with carbon steel to an all carbon steel design. The effects of these changes are believed to be inconsequential.

C. Calculations and Results

KENO-V.a calculations were performed with a TMI-2 storage cask filled with knockout canisters. The cask storage cavity was assumed to be dry for all calculations reported in this paper. Results of preliminary calculations showed the reactivity of the cask to be much greater when the storage cavity is assumed dry than when the cavity is assumed flooded. The mass of water inside each canister was varied parametrically between 22.7 and 45.4 kg (50 and 100 lb). For each water mass evaluated:

1. The volume of the canister occupied by the 862 kg (1900 lb) of core debris was varied between 50 and 100%.

2. Center-to-center separations between UO_2 fuel rods [0.939-cm (0.370-in.) O.D] that are required for 590 kg (1300 lb) of UO_2 to occupy the volumes considered in Item 1 were determined.

3. Zirconium volume fractions in the moderator region that are required for 272 kg (600 lb) zirconium to occupy the volumes considered in Item 1 were determined.

4. Flux-volume-weighted ENDF/B-V cross section data were obtained for the fuel rod cells determined for Items 1, 2, and 3. Volume in the moderator region of each cell not occupied by zirconium was assumed to contain water for wet debris and to be void for dry debris.

5. The height of the wet debris above the support plate in the lower portion of the knockout canister was determined. The remaining available canister volume was assumed to be occupied by dry debris.

The results of the calculations are summarized in Table 1 and are shown graphically in Figure 4. Shown in Figure 5 are the maximum calculated k_{eff} values (plus the 2σ statistical uncertainties associated with the Monte Carlo calculations) as they vary with the mass of water inside each canister. The lower curve shown in Figure 5 corresponds to results obtained for a fuel lump size equal to that of undamaged TMI-2 fuel pellets.

Parametric calculations were performed in which the fuel rod radius was varied between 1.0 and 2.25 times the radius of an undamaged TMI-2 fuel pellet. For this series of calculations, the debris was represented as an infinite lattice of UO_2 fuel rods moderated with a homogeneous mixture of zirconium and water. The fuel volume fraction was maintained at 0.314. The debris composition corresponded to 590 kg (1300 lb) UO_2 and 272 kg (600 lb) zirconium confined to the lower 60% of the available debris volume in the knockout canister (debris composition used in Cases 2, 7, 12, and 17 of Table 1). This composition was found to be nearly optimum in the knockout canister. The results of the calculations are summarized in Table 2. As indicated by the results, a more optimum pellet size is about 1.75 times the radius of an undamaged TMI-2 fuel pellet; however, only an increase of about 0.7% in the calculated k_∞ values resulted. The lower curve shown in Fig. 5 was adjusted upward by 0.7% as shown by the upper curve in Fig. 5.

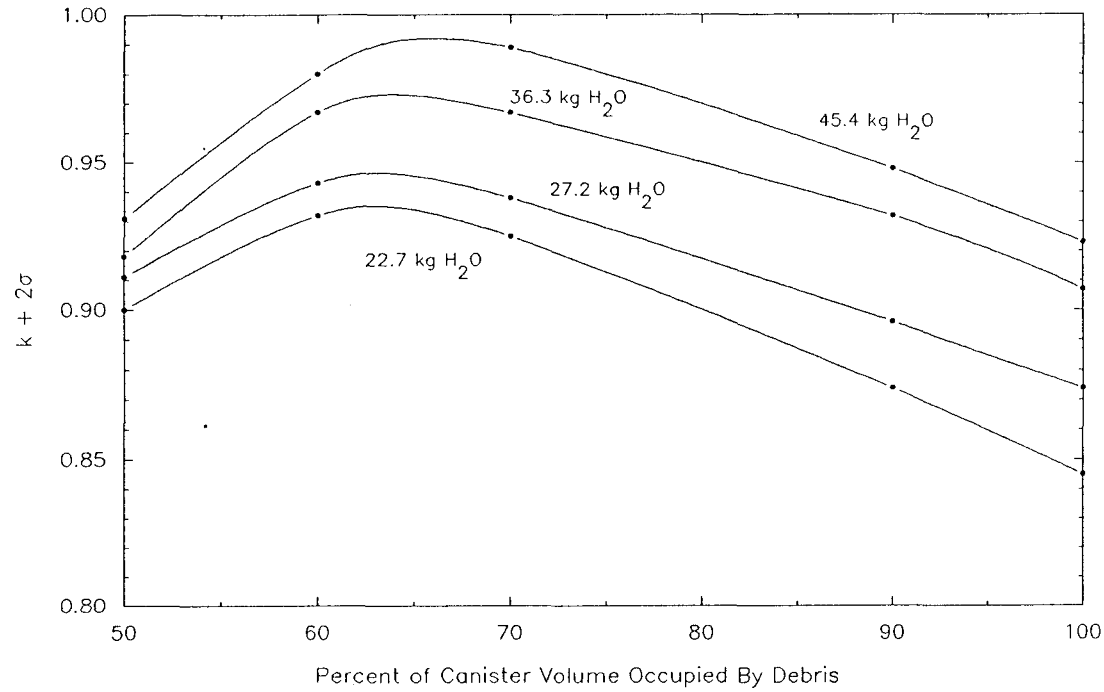

Fig. 4. Calculated k + 2σ versus the percent of the knockout canister volume occupied by core debris for various water mass values.

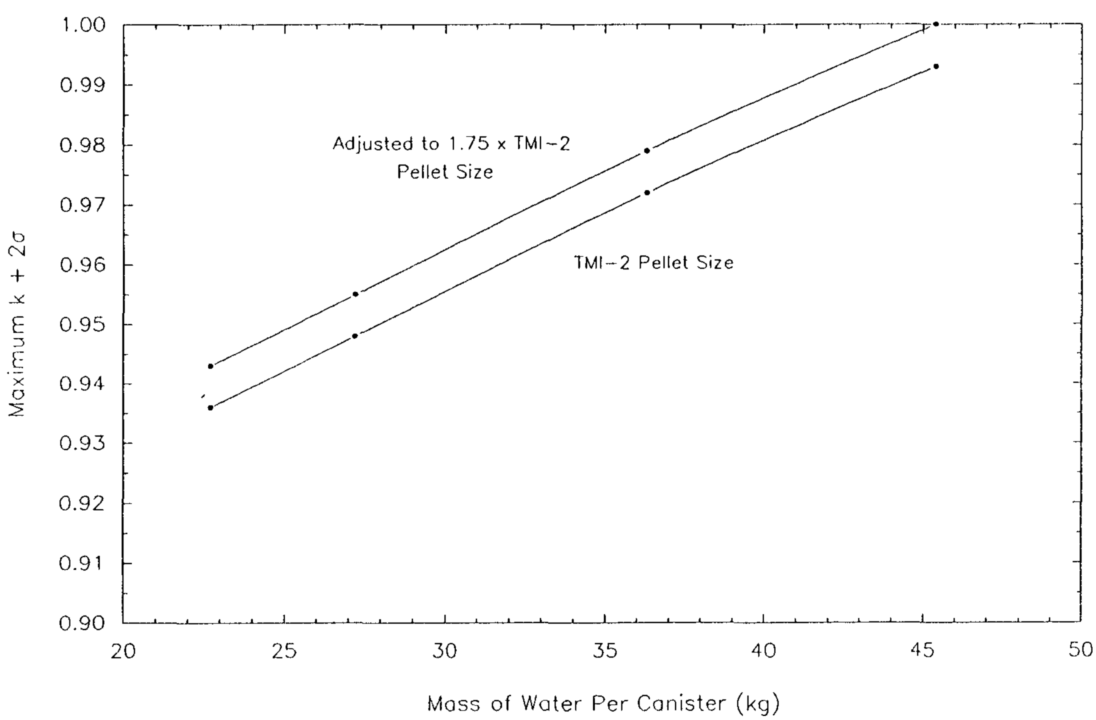

Fig. 5. Maximum calculated k + 2σ versus water mass per knockout canister in a filled TMI-2 dry storage cask.

TABLE 1. SUMMARY OF RESULTS FOR THE TMI-2 STORAGE CASK FILLED WITH KNOCKOUT CANISTERS

Case No.	Debris Volume (%)[a]	Water Volume Fraction[b]	Water Mass (kg/canister)	Water Height (cm)	$k \pm \sigma$	$k + 2\sigma$
1	50	0.345	22.7	76.54	0.892 ± 0.004	0.900
2	60	0.454		58.18	0.922 ± 0.005	0.932
3	70	0.532		49.65	0.917 ± 0.004	0.925
4	90	0.636		41.55	0.866 ± 0.004	0.874
5	100	0.673		39.30	0.837 ± 0.004	0.845
6	50	0.345	27.2	91.85	0.903 ± 0.004	0.911
7	60	0.454		69.80	0.935 ± 0.004	0.943
8	70	0.532		59.58	0.930 ± 0.004	0.938
9	90	0.636		49.85	0.888 ± 0.004	0.896
10	100	0.673		47.16	0.866 ± 0.004	0.874
11	50	0.345	36.3	122.47	0.912 ± 0.003	0.918
12	60	0.454		93.07	0.959 ± 0.004	0.967
13	70	0.532		79.45	0.959 ± 0.004	0.967
14	90	0.636		66.47	0.926 ± 0.003	0.932
15	100	0.673		62.88	0.899 ± 0.004	0.907
16	50	0.345	45.4	153.09	0.932 ± 0.004	0.931
17	60	0.454		116.33	0.972 ± 0.004	0.980
18	70	0.532		99.30	0.981 ± 0.004	0.989
19	90	0.636		83.00	0.940 ± 0.004	0.948
20	100	0.673		78.60	0.915 ± 0.004	0.923

a. Percent of total available debris volume in the canister.
b. Water volume fraction in wet fuel debris.

Criticality safety limits for the the TMI-2 dry storage cask will be established based on data from the upper curve shown in Fig. 5. A calculated failure limit ($k + 2\sigma = 1.0$) is reached with approximately 45 kg (100 lb) of water inside each canister. A safety limit ($k + 2\sigma = 0.95$) is reached with approximately 25 kg (55 lb) of water inside each canister. The safety and failure limits on the the amount of free water allowed inside each canister exceed the "worst case" water mass per canister [2.3 kg (5 lb)] by factors of 11 and 20, respectively.

The series of calculations in which 27.2 kg (60 lb) of water was represented inside each knockout canister was repeated with the TMI-2 dry storage cask filled with fuel canisters. The results of these calculations are summarized in Table 3. The results obtained when the cask was filled with knockout canisters are included in Table 3 for comparison.

As indicated by the results in Table 3, knockout canisters are much more reactive inside the cask than fuel canisters, even though the water height in the debris is much greater (for a given water mass) in the fuel canister. The results also indicate that knockout canisters are most reactive when the 862 kg (1900 lb) of core debris has compacted to about 60% of the available canister volume. However, fuel canisters are most reactive when the debris occupies the entire available canister volume and about 10% of the debris mass is displaced with water. These differences may be attributed to the combined effects of variation in the water volume fraction and water height within the canisters. Calculations were not performed for the filter canisters; however, the filter canister is the least reactive of the three types of canisters.

IV. SUMMARY AND CONCLUSIONS

Defueling canisters containing TMI-2 core debris will be stored for up to 50 yr at the Idaho National Engineering Laboratory in dry storage casks. Criticality safety margins for the TMI-2 dry storage casks will be maintained by moderator control. Prior to being inserted into a dry storage cask, each defueling canister will be dewatered and the contents will be dried. Following the drying process, each canister will contain no more than 2.3 kg (5 lb) of free water (conservative projection from test results). After being loaded into the dry storage casks, exclusion of moderator material will be maintained by engineered safety features incorporated into the cask design (i.e., all openings are sealed to water incursion, leak tested, and positioned well about the level of credible flooding).

TABLE 2. SUMMARY OF CALCULATIONS USED TO DETERMINE THE EFFECTS OF INCREASED FUEL LUMP DIMENSIONS

Case No.	R/R_0	Rod Radius (cm)	Pitch[a] (cm)	k_∞
1	1.00	0.46952[b]	1.48436	1.3557
2	1.25	0.58690	1.85545	1.3595
3	1.50	0.70428	2.22654	1.3629
4	1.75	0.82166	2.59763	1.3648
5	2.00	0.93904	2.96872	1.3641
6	2.25	1.05642	3.33981	1.3599

a. The fuel volume fraction was maintained at 0.314.
b. R_0 = 0.46952 cm is the radius of an undamaged TMI-2 fuel pellet.

TABLE 3. COMPARISON OF RESULTS FOR THE FUEL AND KNOCKOUT CANISTERS[a]

Case No.	Canister Type	Debris Mass (kg/canister)	Water Volume Fraction[b]	Water Height (cm)	$k \pm \sigma$	$k + 2\sigma$
1	Knockout	862	0.345	91.85	0.903 ± 0.004	0.911
2	Knockout	862	0.454	69.80	0.935 ± 0.005	0.943
3	Knockout	862	0.532	59.58	0.930 ± 0.004	0.938
4	Knockout	862	0.636	49.85	0.888 ± 0.004	0.896
5	Knockout	862	0.673	47.16	0.866 ± 0.004	0.874
6	Fuel	862	0.345	146.82	0.833 ± 0.003	0.839
7	Fuel	862	0.454	111.57	0.882 ± 0.004	0.890
8	Fuel	773	0.532	95.21	0.896 ± 0.003	0.902
9	Fuel	601	0.636	79.64	0.878 ± 0.003	0.884
10	Fuel	541	0.673	75.26	0.867 ± 0.003	0.873

a. 27.2 kg (60 lb) water was represented inside each canister in all cases.
b. Water volume fraction in wet fuel debris.

Criticality safety margins were established by analysis (KENO-V.a Monte Carlo calculations). Based on the analysis, approximately 45 kg (100 lb) of water is required inside each canister before a calculated k_{eff} value (plus the 2σ statistical uncertainty associated with the Monte Carlo calculations) of 1.0 can be obtained. Approximately 25 kg (55 lb) of water is required before a calculated k_{eff} value (plus a 2σ statistical uncertainty) of 0.95 can be obtained. The analytical approach used in this evaluation has been submitted to the Idaho Operations Office of the Department of Energy for review and approval.

It is concluded that adequate safety margins are provided by the drying process and the safety features incorporated into the cask design.

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