Orano Federal Services

CALCULATION

Document No.:	CALC-3021788	**Rev. No.** 000	**Page 1 of 37**
Project No.:	02029.00.0000.02	**Project Name:**	License Renewal Support
Title:	TMI-2 Canister Licon Criticality Analysis for TMI-2 ISFSI License Renewal		

Summary:

The Nuclear Regulatory Commission (NRC) has requested additional information to support the technical review of the Three Mile Island Unit 2 (TMI-2) Independent Spent Fuel Storage Installation (ISFSI) license renewal.

- Request for additional information (RAI) 3-7 asks for additional evidence that the TMI-2 Canister will be subcritical following Licon material losses
- RAI 3-8 requests additional justification that changes to the Licon material properties, due to aging, are not important to maintaining TMI-2 Canister subcriticality

This calculation further evaluates the TMI-2 Fuel Canister reactivity following changes to the Licon material to support the responses to the above RAIs.

A comparison of TMI-2 criticality evaluations is presented in Appendix A.

Safety ☒ **Non-Safety** ☐

Contains Unverified Input / Assumptions: **Yes:** ☐ **No:** ☒

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0	Initial Release

Table of Contents

Page

List of Tables

Page

List of Figures

Page

1.0 PURPOSE

The Nuclear Regulatory Commission (NRC) has requested additional information [1] to support the technical review of the Three Mile Island Unit 2 (TMI-2) Independent Spent Fuel Storage Installation (ISFSI) license renewal application (LRA) [2]. Request for additional information (RAI) 3-7 asks for additional analysis that the TMI-2 Canister will be subcritical following Licon material losses. RAI 3-8 requests additional justification that changes to the Licon material properties, due to aging, are not important to maintaining TMI-2 Canister subcriticality.

This calculation further evaluates the TMI-2 Fuel Canister reactivity, using credible limits for water and poison content, following changes to the Licon material. Total loss of Licon is evaluated, including changes due to loss of the structural integrity of the TMI-2 Fuel Canister shell. Water absorption in Licon is also evaluated. After a subsequent reconfiguration of the TMI-2 Fuel Canister into the most reactive configuration, a conservative k_{eff} value is computed by packing the 12 TMI-2 Fuel Canisters together via surface-to-surface contact of their Boral shrouds. The results of this calculation will serve as the technical basis for the responses to RAI 3-7 and RAI 3-8. This calculation is formatted using the guidance for spent fuel dry storage system criticality evaluations in NUREG-1536 [4].

A comparison of TMI-2 criticality evaluations is presented in Appendix A.

2.0 METHODOLOGY

2.1 Criticality Design Criteria and Features

Criticality analysis of the TMI-2 ISFSI is discussed in Section 3.3.4 of the TMI-2 ISFSI Safety Analysis Report (FSAR) [3]. The “original” criticality evaluation discussed in Sections 3.3.4.1 and 3.3.4.2 of the TMI-2 ISFSI FSAR is contained in TN West Calculation 0219.02.0300, “Criticality Evaluation for the 10CFR72 INEL/TMI-2 Fuel ISS (NUHOMS®-12T)” [5], while the “second” criticality evaluation discussed in Sections 3.3.4.3 and 3.3.4.4 of the TMI-2 ISFSI FSAR is contained in Idaho Cleanup Project Report INEEL/INT-99-00126, “Criticality Safety Evaluation of TMI-2 Canister Transportation and Storage” [6]. The second criticality evaluation was performed to model beyond-credible quantities of water content in stored fuel. Due to the significantly higher maximum k_{eff} value calculated in the second criticality evaluation compared to the original criticality evaluation, the analysis contained in this calculation is based on analysis performed in [6]. This is consistent with the logic outlined in RAI 3-7.

The TMI-2 ISFSI storage design is described in Section 2 of [6]. The TMI-2 ISFSI is comprised of concrete horizontal storage modules (HSMs) containing steel dry shielded canisters (DSCs). Within each DSC, a steel basket holds twelve TMI-2 core debris Canisters. There are three types of TMI-2 Canisters: Fuel, Knockout, and Filter. RAI 3-7 and RAI 3-8 are only relevant to the TMI-2 Fuel Canister as that is the only TMI-2 Canister that contains Licon. The TMI-2 Fuel Canister consists of a central cavity containing core debris surrounded by layers of steel, Boral, and Licon. The TMI-2 Fuel Canister may also contain water leftover from wet loading or absorbed during storage. The steel basket and DSC assemblies are detailed in [7], [8], [9], and [10]. The TMI-2 Canisters are detailed in [11], [12], and [13]. The TMI-2 ISFSI DSC and HSM assemblies are shown in Figure 2-1 and Figure 2-2.

To evaluate the importance of Licon with respect to criticality, the design-basis TMI-2 Fuel Canister criticality model in Section 6.4 of [6] (specifically, case LDC-05) is modified and further evaluated following the degradation of Licon due to aging, up to and including complete loss of Licon. Degradation includes non-structural loss of Licon material, structural loss of Licon material, and absorption of water in Licon. Modifications to the criticality model are minimized to ensure outputs are comparable to those originally generated. Cases are not run using the non-credible original assumptions in [6] (10 L of water mixed with the fuel and Boral replaced with water). Instead, cases are run using limits outlined in the FSAR and applicable regulations that are also consistent with the original criticality evaluation in [5] (8 L of water mixed with the fuel per Section 3.3.4.4.1 of [3] and 75% credit for Boral per Section 7.4 of [4]).

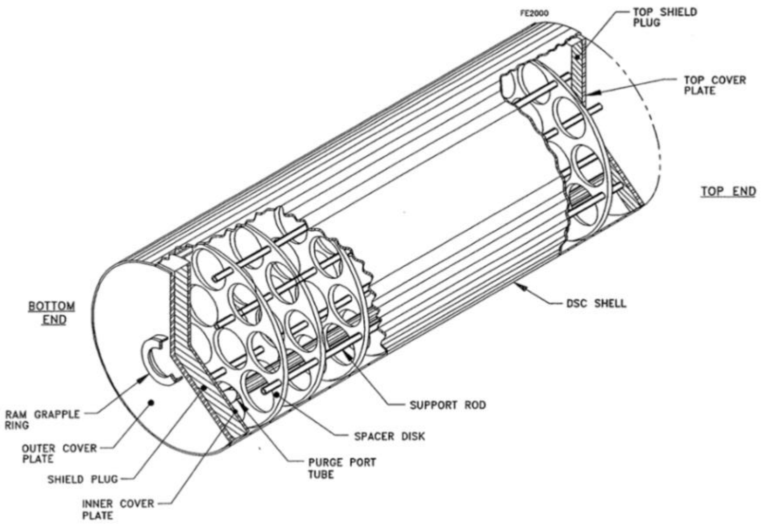

Figure 2-1: NUHOMS®-12T Dry Shielded Canister

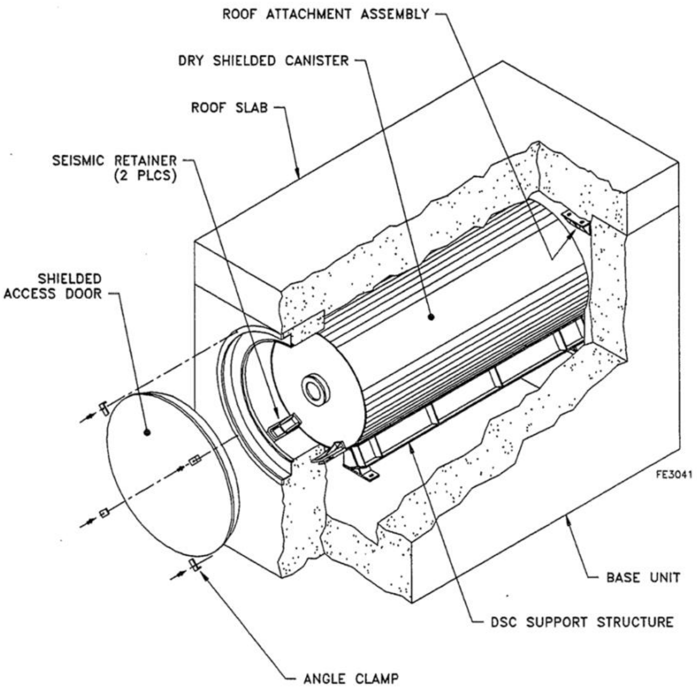

Figure 2-2: NUHOMS®-12T Horizontal Storage Module

3.0 ASSUMPTIONS

3.1 Unverified Assumptions

There are no unverified assumptions.

3.2 Justified Assumptions

The assumptions listed in the FSAR Section 3.3.4.4.A [3] are restated below with applicability addressed as necessary:

1. "Batch 3 fresh fuel only (2.98 wt.% U-235)."
2. "Enrichment: batch 3 average + 2σ."
    - The batch 3 average + 2σ is equal to 2.98 wt.% U-235.
3. "No cladding or core structural material."
4. "No soluble poison or control materials from the core."
5. "Fuel lump is a whole fuel pellet."
    - Fuel pellets are modeled with a 0.939 cm diameter, consistent with [6], rather than the 0.9525 cm (0.375-in.) diameter discussed in FSAR Section 3.3.4.2.B.
6. "*Filter* canisters are enveloped by *knockout* canisters."
    - Though unstated, it was also assumed that the TMI-2 Fuel Canister is enveloped by the TMI-2 Knockout Canister. Only the TMI-2 Fuel Canister is analyzed in this calculation.
7. "Fuel is UO_2 and no credit is taken for degradation to less dense oxides."
8. "Canister fuel regions are filled with 1908 lb of UO_2, which is the maximum reported canister payload."
    - Since only the TMI-2 Fuel Canister is analyzed in this calculation, the maximum TMI-2 Fuel Canister payload used in all fuel regions is 1740 lb UO_2. This is consistent with TMI-2 Fuel Canister modeling performed in [6].
9. "Fuel is smeared to fill all volume available in the fuel regions."
10. "Water and fuel are modeled at the top of the canisters, rather than at the bottom or sides (the nominal canister configuration), since this produces more conservative results."
    - Water and fuel are modeled at the bottom of the TMI-2 Fuel Canister, consistent with the TMI-2 Fuel Canister analysis in [6]. This is more conservative than modeling the fuel region on the side and very similar to modeling the fuel region at top (only steel shell thickness varies between the top and bottom).

Additionally, the second criticality evaluation assumed all poison structures are replaced with water. This is not consistent with the design basis identified in the original criticality evaluation (see FSAR Section 3.3.4.2.A), certain runs in the second criticality evaluation (see FSAR Section 3.3.4.4.B), and applicable regulations where poison structures are modeled with 75% boron credit. All poison structures are modeled in this calculation with 75% boron credit.

Further assumptions, beyond those presented in the FSAR and pertaining specifically to this calculation, are as follows:

1. The TMI-2 Fuel Canister shell could deform following the loss of Licon material. This conservatively bounds the possible structural effects of Licon degradation.
2. The fuel will remain in the TMI-2 Fuel Canister cavity following any Licon degradation. While conservative shell deformation is modeled, the formation of shell holes or openings is not considered credible.
3. No more than 8 L of water will be present in the fuel region of the TMI-2 Fuel Canister.
4. The optimal fuel pitch found in [6] for a TMI-2 Fuel Canister containing 10 L of water will not change for a TMI-2 Fuel Canister containing 8 L of water.

4.0 DESIGN INPUTS

4.1 Fuel Specification

No changes are made to the fuel characteristics specified in [6].

4.1.1 Non-Fuel Hardware

No non-fuel hardware is modeled. Fuel is modeled as either pure UO_2 or UO_2 mixed with water. This is consistent with TMI-2 ISFSI FSAR Sections 3.3.4.2 and 3.3.4.4, which assume “No cladding or core structural material” and “No soluble poison or control material from the core”.

4.1.2 Fuel Condition

Fuel is modeled as 1740 lb of UO_2 (maximum TMI-2 Fuel Canister core debris weight per Section 6.5 of [6]) enriched to 2.98 wt.% U-235 (assumed maximum enrichment per Section 3.3.4.4 of [3]). All fuel is unirradiated. Fuel is modeled as 0.939 cm diameter rods in a 1.45 cm triangular pitch when mixed with water. The 0.939 cm diameter is based on an undamaged, unclad fuel pellet (Section 6.0 of [6]) while the 1.45 cm triangular pitch is the worst-case pitch based on parameter optimization (Section 6.4 of [6]). When not mixed with water, the fuel is modeled 0.939 cm diameter rods in a 0.939 cm triangular pitch.

4.2 Model Specification

4.2.1 Configuration

The geometry used in [6] is maintained. Dimensions are based on those contained in the Listing-12 input file (case LDC-05) in Appendix B of [6]. The TMI-2 Fuel Canister is modeled enclosed in a 14-in. (35.56 cm) outer diameter, 0.19-in. (0.49 cm) thick stainless steel shell. The TMI-2 Fuel Canister internal fuel region is modeled with a 9.13-in. (23.18 cm) square cavity, surrounded by a shroud composed of 0.04-in. (0.1 cm) thick stainless steel, 0.13-in. (0.33 cm) thick Boral, and 0.08-in. (0.2 cm) thick stainless steel. The Licon fills the annulus of the inner shell wall and the outer Boral shroud steel. Compared to [12], the TMI-2 Fuel Canister model geometry has a larger cavity (9-in. square on drawing), thinner Boral (0.135-in. thick on drawing), and a thinner outer wall (0.25-in. thick on drawing). No credit is taken for the DSC basket, resulting in a tight packing of the twelve TMI-2 Fuel Canisters. No water is modeled between TMI-2 Fuel Canisters to maximize reactivity, as proven by the results in Table 17 in [6]. The 0.625-in. (1.5875 cm) thick carbon steel DSC is modeled as “collapsed”, immediately surrounding the twelve TMI-2 Fuel Canisters resulting in a reduced outer diameter of 63.77-in. (161.975 cm) when compared to [8]. Similarly, HSM concrete immediately surrounds the DSC. The HSM concrete is, at minimum, 24-in. (61 cm) thick. All cases analyzed use the “collapsed” geometry.

The TMI-2 Fuel Canister cavity has three regions: fuel-water mixture, unmoderated fuel, and void. The height of each region is based on fuel and water volumes. Region heights are adjusted from the values used in [6] due to the changed water content and confirmed using CSAS5 output file values. The total fuel height for 1740 lb UO_2 is 174.54 cm. The fuel-water mixture height is 24.08 cm for 8 L water (originally 30.04 cm for 10 L water of full-density water). The simplified TMI-2 Fuel Canister model axial dimensions used in [6] are maintained. The cavity is 71.1-in. (180.52 cm) tall, with a 0.375-in. (0.9525 cm) wall on the bottom and a 2-in. (5.08 cm) wall on the top. To assess the effects of non-structural degradation of Licon, the model is configured as shown in Figure 4-1 and Figure 4-2.

To perform a bounding assessment of the effects of structural degradation of Licon, a set of configurations are evaluated without credit for the structural properties of Licon. The TMI-2 Fuel Canisters’ shells are collapsed until in contact with the Boral shroud steel and the TMI-2 Fuel Canister packing configuration is evaluated to find the most reactive orientation. No changes are made to the DSC or HSM dimensions (e.g. the DSC is not further collapsed beyond the non-structural degradation model configuration). The model configuration with no credit taken for the structural properties of Licon resulting in the maximum compression of triangular pitch TMI-2 Fuel Canister packing configuration is shown in Figure 4-3. The model configuration for the maximum possible compression of TMI-2 Fuel Canister packing configuration, a 4 by 3 square array, is shown in Figure 4-4.

4.2.2 Material Properties

No changes are made to the material compositions specified in criticality run LDC-05 in [6]. Boral is defined per Table A-1 in [6] and corresponds to 0.03 g B-10/cm^2 (75% of 0.04 g B-10/cm^2 given in [12]) in natural boron combined with aluminum. Materials defined using CSAS preprogrammed definitions (such as water, carbon steel, and stainless steel 304) change slightly due to changes in the underlying definitions between versions. Densities and volume fractions of water and/or Licon are varied depending on the case. All materials are modeled at room temperature (293 K).

The efficacy of the Boral neutron absorber will not degrade beyond the modeled 75% boron credit. Per page 4 of [14], “the neutron flux produced by the spent nuclear fuel would deplete only a small percentage of neutron absorbing material during several thousand years of exposures.” Similarly, Section 3.4.2 of [15] concludes that any possible degradation of Boral used in dry storage system for spent nuclear fuel is either not credible or will not “reduce the neutron absorbing capability”.

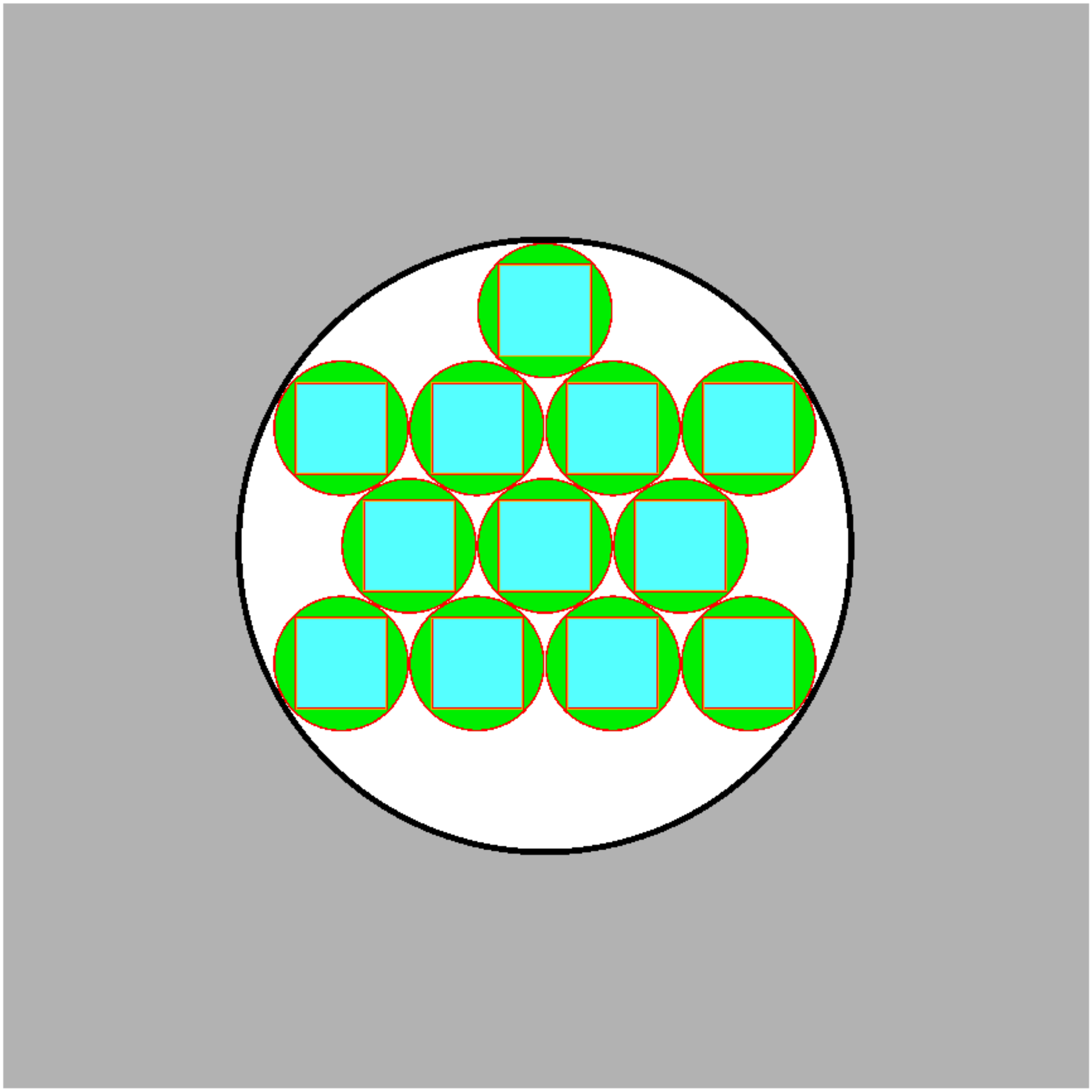

Figure 4-1: Criticality Model with Credit for Licon Structural Properties (Radial View)

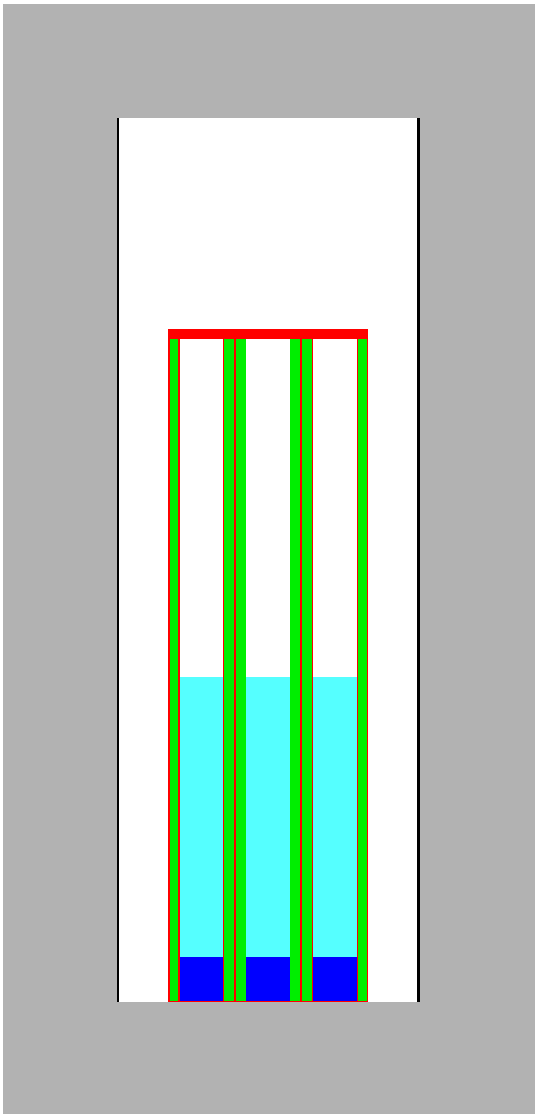

Figure 4-2: Criticality Model with Credit for Licon Structural Properties (Axial View)

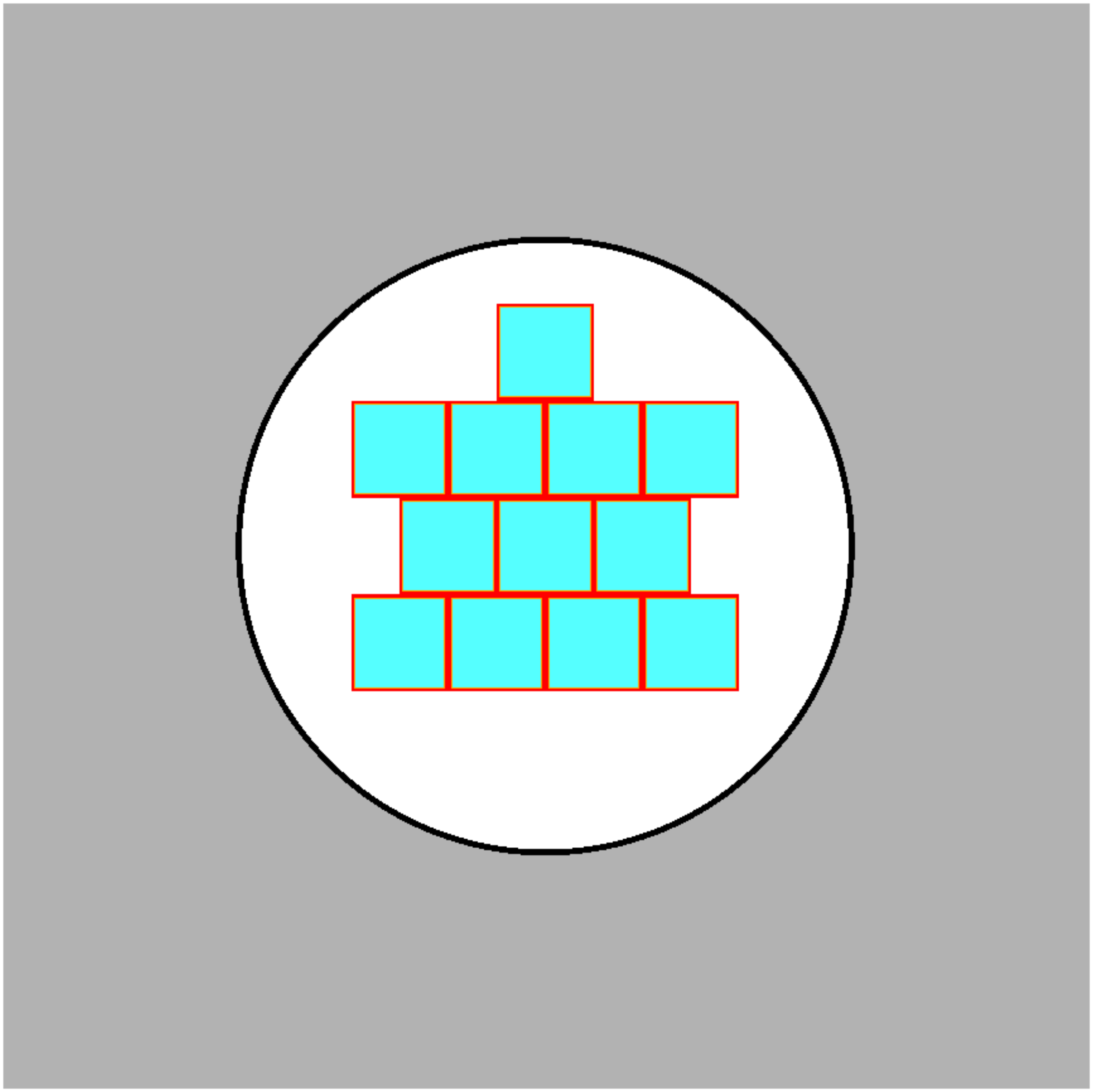

Figure 4-3: Criticality Model with No Credit for Licon Structural Properties (Triangular Array)

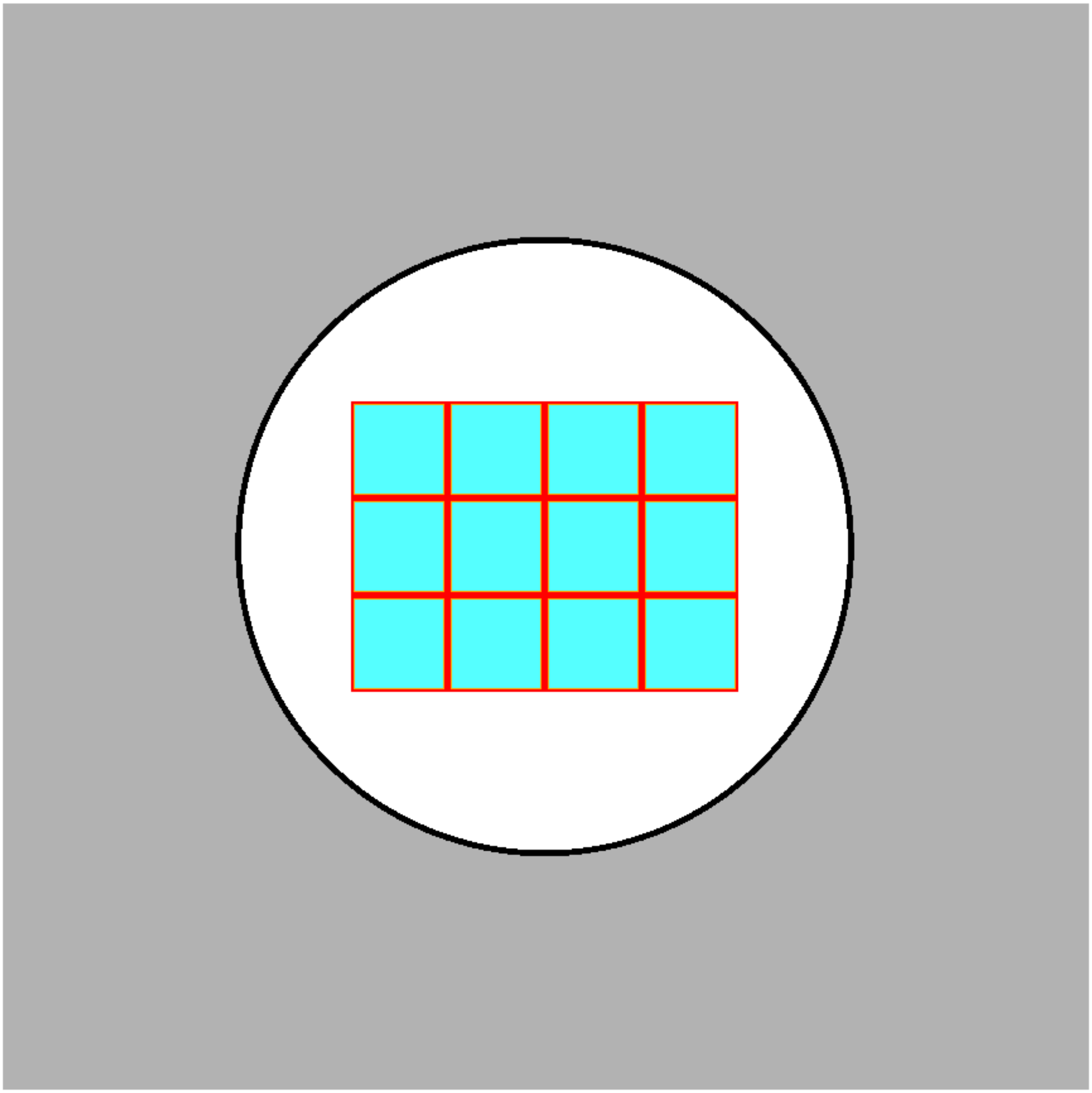

Figure 4-4: Criticality Model with No Credit for Licon Structural Properties (Square Array)

5.0 CALCULATIONS

5.1 Criticality Analysis

5.1.1 Computer Codes

The maximum k_{eff} TMI-2 Fuel Canister case from Section 6.4 of [6] is case LDC-05 (collapsed DSC, 10 L water in fuel region, 0.05 water volume fraction in Licon) and is contained in the file *LDC-05_CSASIX.inp*. All models in [6] were analyzed in SCALE 4, using CSASIX (which is built around the KENO V.a module) and an ENDF/B-IV 27-group library [16]. All new cases are analyzed in SCALE 6.2.1 [17], using CSAS5 (which is also built around the KENO V.a module) and an ENDF/B-VII.0 238-group library. Per Section 10.1.2.1 of [17], the 238-group library is “available mainly for general-purpose criticality analyses”.

To assess the effect of format and library changes between CSASIX and CSAS5, the case LDC-05 input is remade in file *LDC-05_CSAS5.inp* for CSAS5. The CSAS5 input results in a k_{eff} of 0.93028 ± .00058 (k_s of 0.93144, see Section 5.1.3), while the original CSASIX input resulted in a k_{eff} of 0.9260 ± 0.0014 (k_s of 0.9288). Other important parameters, such as fuel mass (1740 lb) and water volume mixed with fuel (10 L), are also confirmed. It is concluded that the conversion to CSAS5 is acceptable as it maintains the original material and geometry definitions and generates similar results (less than 1% difference). All case input files are based on file *LDC-05_CSAS5.inp*.

All cases are run using 250 generations, with 10,000 neutrons per generation and 50 generations skipped. All run errors are less than 0.0008.

5.1.2 Multiplication Factor

Three parameter studies are performed to evaluate the effect of Licon degradation. First, the non-structural loss of Licon is evaluated by reducing the atom density of Licon. Second, the absorption of water in Licon is evaluated by increasing the density of water in Licon. Third, the structural loss of Licon is evaluated by collapsing TMI-2 Fuel Canister outer walls and shifting TMI-2 Fuel Canisters closer together. The third parameter study bounds the structural effects of the loss of Licon. All cases are run using 8 L of water mixed with the fuel and 75% credit taken for the Boral shroud. Unless otherwise stated, all cases use a Licon water volume fraction of 0.00 as this is determined to be the most reactive condition from the results of Table 5-2 (whereas Table 18 of [6] found 0.05 is most reactive). The value k_s, described in Section 5.1.3, is reported alongside k_{eff} and σ for each case.

The results for the non-structural loss of Licon study are shown in Table 5-1 and Figure 5-1. Licon fractional density (the Licon density expressed as a fraction of nominal) is reduced from 1 (full density) to 0 (Licon removed), bounding the non-structural effects of loss of Licon. It can be seen that the decrease in density results in a slight decrease in k_{eff}, showing that the loss of Licon due to aging does not result in an increase in reactivity when structural effects of loss of Licon are not taken into account.

The results for the absorption of water in Licon study are shown in Table 5-2 and Figure 5-2. The water volume fraction in Licon is increased from 0 (no water absorbed) to 1 (full density water absorbed in entire Licon volume), bounding the effects of water absorption in Licon. It can be seen that increase in water volume fraction in Licon results in a decrease in k_{eff}, showing that water absorption in Licon due to aging does not result in an increase in reactivity. This is similar to the results in Table 18 of [6], which showed a small increase in k_{eff} at low water volume fractions before decreasing steadily. Note, the case with a water volume fraction of 0.05 can be directly compared to case LDC-05 in [6] to show the significant effect of reducing the water volume mixed with the fuel and taking credit for Boral.

For the third parameter study, the results for the compression of TMI-2 Fuel Canister packing following the loss of Licon structural properties are shown in Table 5-3 and Figure 5-3. The arbitrary compression factor, describing the compression of TMI-2 Fuel Canister packing through fractional shrinking of x-axis and y-axis separation gaps, is increased from 0 (maximum packing of TMI-2 Fuel Canisters when structural integrity of Licon is credited, same configuration as other parameter studies) to 1 (maximum packing of TMI-2 Fuel Canisters with no credit for Licon structural properties in a semi-triangular array). Additionally, a similar case is analyzed where the twelve TMI-2 Fuel Canisters are arranged in a maximum packing 4 by 3 square array. It can be seen that increasing the compression of TMI-2 Fuel Canister packing results in a significant increase in k_{eff}. The 4 by 3 square array increases k_{eff} further, to a maximum k_s value for all cases of 0.85926.

Table 5-1: Non-Structural Loss of Licon Results

Licon Fractional Density	k_{eff}	σ	k_s
1.0	0.78846	0.00054	0.78954
0.9	0.78520	0.00051	0.78622
0.8	0.78593	0.00048	0.78689
0.7	0.78446	0.00054	0.78554
0.6	0.78573	0.00067	0.78707
0.5	0.78282	0.00061	0.78404
0.4	0.78250	0.00057	0.78364
0.3	0.78157	0.00056	0.78269
0.2	0.78053	0.00051	0.78155
0.1	0.77977	0.00059	0.78095
0.0	0.77832	0.00055	0.77942

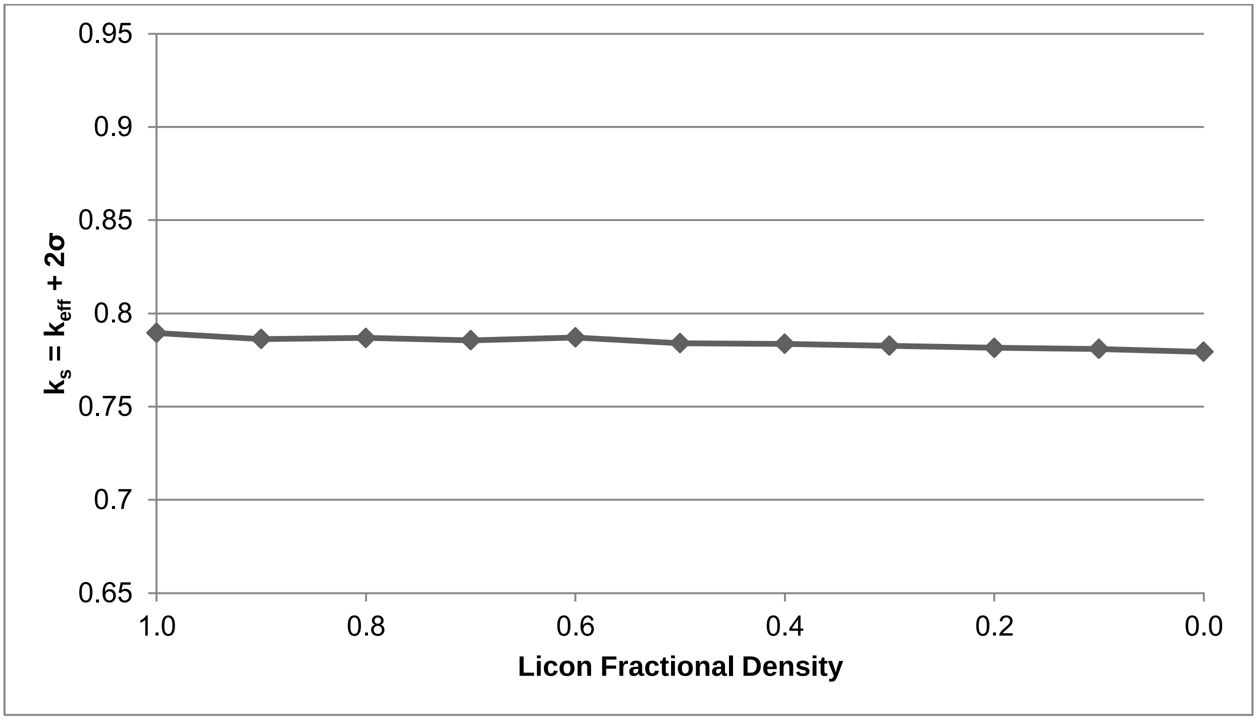

Figure 5-1: Non-Structural Loss of Licon Results

Table 5-2: Water Absorption in Licon Results

Water Volume Fraction in Licon	k_{eff}	σ	k_s
0	0.78846	0.00054	0.78954
0.05	0.77857	0.00061	0.77979
0.1	0.76814	0.00067	0.76948
0.15	0.75867	0.00053	0.75973
0.2	0.75045	0.00069	0.75183
0.25	0.74141	0.00068	0.74277
0.3	0.73299	0.00057	0.73413
0.4	0.71998	0.00067	0.72132
0.5	0.70885	0.00050	0.70985
0.6	0.69949	0.00064	0.70077
0.7	0.69302	0.00063	0.69428
0.8	0.68959	0.00074	0.69107
0.9	0.68171	0.00050	0.68271
1.0	0.67793	0.00062	0.67917

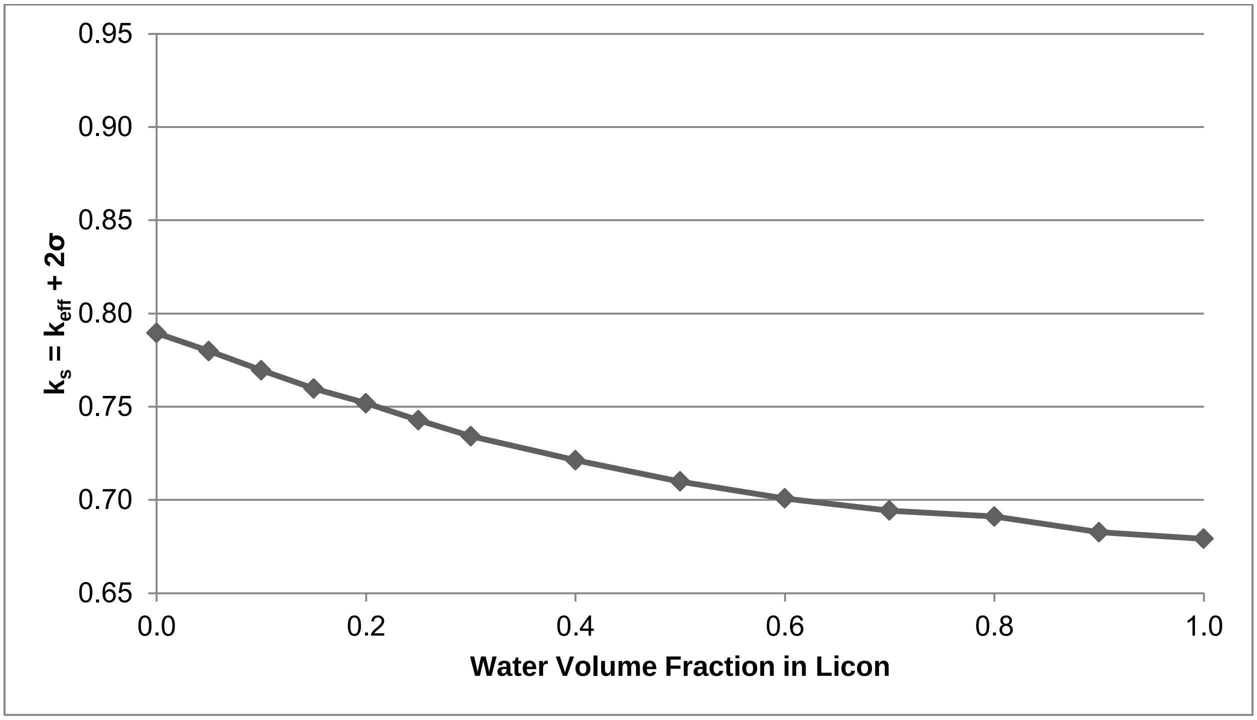

Figure 5-2: Water Absorption in Licon Results

Table 5-3: Compression of Packing due to Structural Loss of Licon Results

Compression Factor	k_{eff}	σ	k_s
0.0	0.77581	0.00059	0.77699
0.1	0.78279	0.00050	0.78379
0.2	0.78860	0.00060	0.78980
0.3	0.79472	0.00058	0.79588
0.4	0.80219	0.00065	0.80349
0.5	0.80886	0.00059	0.81004
0.6	0.81691	0.00059	0.81809
0.7	0.82495	0.00050	0.82595
0.8	0.83392	0.00043	0.83478
0.9	0.84266	0.00062	0.84390
1.0	0.85026	0.00064	0.85154
4x3 Square Array	0.85770	0.00078	0.85926

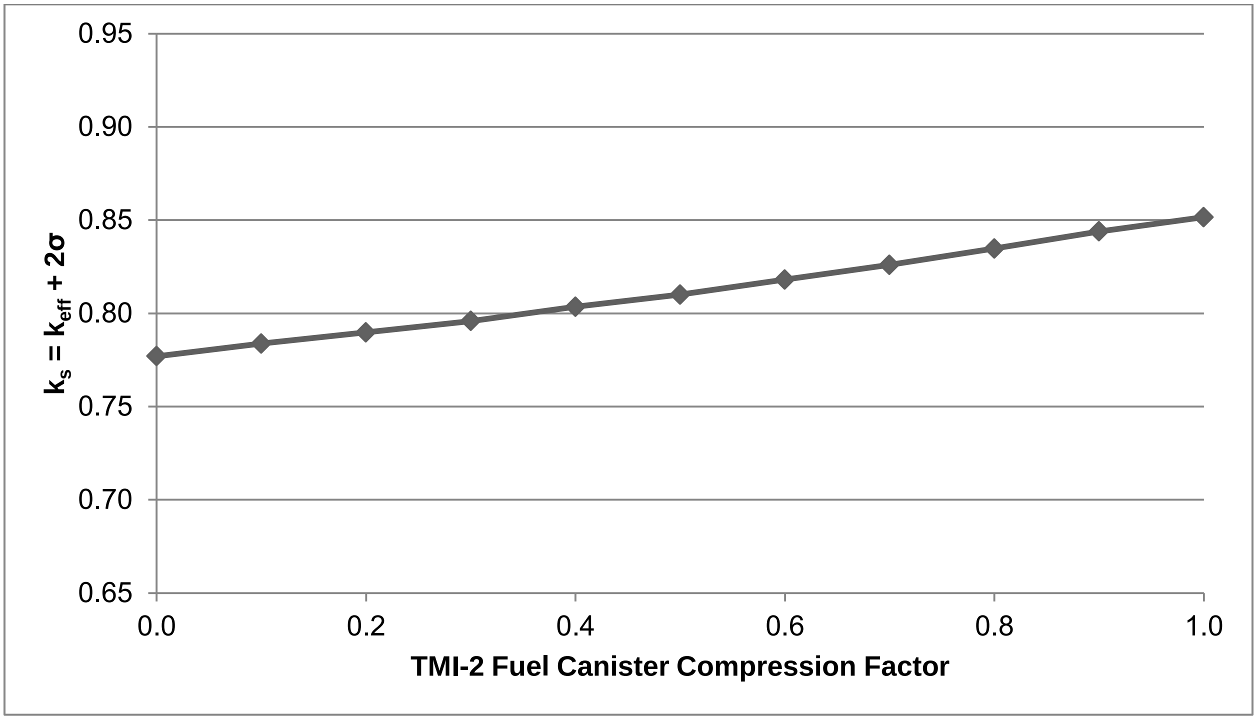

Figure 5-3: Compression of Packing due to Structural Loss of Licon Results

5.1.3 Benchmark Comparisons

The Monte Carlo computer program CSAS5 is utilized for this benchmark analysis [17]. CSAS5, which is built upon the KENO V.a module of the SCALE program, has been used extensively in criticality evaluations and is considered a standard in the industry. ENDF/B-VII 238-group cross section data is utilized for all benchmarks, consistent with the criticality calculations performed in this calculation.

The ORNL USLSTATS code [18] is used to establish an Upper Subcritical Limit (USL) for the analysis. USLSTATS provides a simple means of evaluating and combining the statistical error of the calculation, code biases, and benchmark uncertainties. The USLSTATS calculation uses the combined uncertainties and data to provide a linear trend and overall uncertainty. Computed multiplication factors, k_{eff}, for the package are deemed to be adequately subcritical if the computed value of k_s is less than or equal to the USL as follows:

$$k_s = k_{eff} + 2\sigma \leq \mathrm{USL}$$

The USL includes the combined effects of code bias, uncertainty in the benchmark experiments, uncertainty in the computational evaluation of the benchmark experiments, and an administrative margin. This methodology has accepted precedence in establishing criticality safety limits.

5.1.3.1 Applicability of Benchmark Experiments

The critical experiment benchmarks are selected from the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* [19] based upon their similarity to the TMI-2 Fuel Canister contents and storage configuration. The important selection parameters are low enriched uranium (wt.% U-235 ≤ 10) compounds (UO_2) with a thermal spectrum. Fifty (50) benchmarks are used that meet these criteria. The titles for all utilized experiments are listed in Table 5-4.

Table 5-4: Benchmark Experiments Used

Series	Title
LEU-COMP-THERM-001	Water-Moderated U(2.35)O_2 Fuel Rods in 2.032-cm Square-Pitched Arrays
LEU-COMP-THERM-002	Water-Moderated U(4.31)O_2 Fuel Rods in 2.54-cm Square-Pitched Arrays
LEU-COMP-THERM-010	Water-Moderated U(4.31)O_2 Fuel Rods Reflected by Two Lead, Uranium, or Steel Walls
LEU-COMP-THERM-042	Water-Moderated Rectangular Clusters of U(2.35)O_2 Fuel Rods (1.684-Cm Pitch) Separated by Steel, Boral, Boroflex, Cadmium, or Copper Plates with Steel Reflecting Walls

5.1.3.2 Bias Determination

The USL is calculated by application of the USLSTATS computer program [18]. USLSTATS receives as input the k_{eff} as calculated by CSAS5, the total uncertainty (combined benchmark and CSAS5 uncertainties), and a trending parameter. Two trending parameters have been selected: (1) Energy of Average Lethargy of Fission (EALF) and (2) U-235 number density in the fuel.

The uncertainty value, σ_{total}, assigned to each case is a combination of the benchmark uncertainty for each experiment, σ_{bench}, and the Monte Carlo uncertainty associated with the particular computational evaluation of the case, σ_{CSAS5}, or:

$$\sigma_{\mathrm{total}} = \sqrt{\sigma^2_{\mathrm{bench}} + \sigma^2_{\mathrm{CSAS5}}}$$

These values are input into the USLSTATS program in addition to the following parameters, the values for which are selected in accordance with the USLSTATS User's Manual [18]:

- P, proportion of the population falling above lower tolerance level = 0.995 (note that this parameter is a required input but is not utilized in the calculation of USL Method 1)
- 1-γ, confidence on fit = 0.95
- α, confidence of proportion P = 0.95 (note that this parameter is a required input but is not utilized in the calculation of USL Method 1)
- Δk_m, administrative margin used to ensure subcriticality = 0.05

These values are followed by triplets of trending parameter value, computer k_{eff}, and uncertainty for each case. A confidence band analysis is performed on the data for each trending parameter using USL Method 1. The USL generated for each of the trending parameters utilized is provided in Table 5-5. All benchmark data used as input to USLSTATS are reported in Table 5-6.

Energy of Average Lethargy of Fission

EALF is used as the first trending parameter for the benchmark cases. Over the range of applicability, the minimum USL is 0.9428. The USL is trending upwards for increasing EALF. While case EALF values are slightly outside the range of applicability, "the range of applicability may be extended beyond the range of conditions represented by the benchmark experiments by extrapolating the trends established for the bias" as long the extrapolation is not "large" per Section 4.1 of [20]. No credit is taken for the upwards trend of USL for increasing EALF. The EALF value is 1.19487 eV for the most reactive case.

U-235 Number Density in Fuel

The U-235 number density in the fuel is used as the second trending parameter for the benchmark cases. Over the range of applicability, the minimum USL is 0.9422. The U-235 number density in the fuel is constant for all cases and falls within the range of applicability. The USL is trending upwards for increasing U-235 number density in the fuel. The U-235 number density in the fuel is 6.81347E-04 U-235 atoms/b-cm for the most reactive case.

Recommended USL

For the EALF trending parameter, the minimum USL is 0.9428, while for the EALF trending parameter, the minimum USL is 0.9422. Therefore, a USL of 0.9422 is justified.

Table 5-5: USL Results

Trending Parameter	**Filename**	**Minimum USL over Range of Applicability**	**Range of Applicability**
EALF (eV)	EALF	0.9428	9.36E-2 < X < 6.00E-1
NDEN (U-235 atoms/b-cm)	NDEN	0.9422	4.88E-4 < X < 1.01E-3

Table 5-6: Benchmark Experiment Data

Experiment	Case	K_{eff} (CSAS5)	σ (CSAS5)	σ (Benchmark)	σ (Total)	EALF (eV)	NDEN (U-235 atoms/b-cm)
LEU-COMP-THERM-001	1	0.99805	0.00054	0.00310	0.00315	9.64307E-02	4.87850E-04
	2	0.99864	0.00056	0.00310	0.00315	9.55183E-02	4.87850E-04
	3	0.99766	0.00055	0.00310	0.00315	9.49998E-02	4.87850E-04
	4	0.99772	0.00061	0.00310	0.00316	9.57092E-02	4.87850E-04
	5	0.99642	0.00048	0.00310	0.00314	9.41998E-02	4.87850E-04
	6	0.99738	0.00049	0.00310	0.00314	9.53579E-02	4.87850E-04
	7	0.99710	0.00046	0.00310	0.00313	9.36295E-02	4.87850E-04
	8	0.99668	0.00052	0.00310	0.00314	9.43703E-02	4.87850E-04
LEU-COMP-THERM-002	1	0.99843	0.00061	0.00200	0.00209	1.13063E-01	1.01020E-03
	2	0.99849	0.00072	0.00200	0.00213	1.13313E-01	1.01020E-03
	3	0.99982	0.00057	0.00200	0.00208	1.12867E-01	1.01020E-03
	4	0.99735	0.00050	0.00200	0.00206	1.11899E-01	1.01020E-03
	5	0.99796	0.00066	0.00200	0.00211	1.10367E-01	1.01020E-03
LEU-COMP-THERM-010	1	1.00313	0.00070	0.00210	0.00221	1.18119E-01	1.01020E-03
	2	1.00483	0.00051	0.00210	0.00216	1.14888E-01	1.01020E-03
	3	1.00298	0.00063	0.00210	0.00219	1.13047E-01	1.01020E-03
	4	0.99625	0.00053	0.00210	0.00217	1.10340E-01	1.01020E-03
	5	1.00031	0.00056	0.00210	0.00217	3.55933E-01	1.01020E-03
	6	0.99924	0.00057	0.00210	0.00218	2.65331E-01	1.01020E-03
	7	1.00095	0.00063	0.00210	0.00219	2.11832E-01	1.01020E-03
	8	0.99823	0.00050	0.00210	0.00216	1.86992E-01	1.01020E-03
	9	1.00072	0.00056	0.00210	0.00217	1.22224E-01	1.01020E-03
	10	1.00145	0.00055	0.00210	0.00217	1.18188E-01	1.01020E-03
	11	1.00123	0.00053	0.00210	0.00217	1.15400E-01	1.01020E-03
	12	0.99964	0.00059	0.00210	0.00218	1.12407E-01	1.01020E-03
	13	0.99578	0.00054	0.00210	0.00217	1.10385E-01	1.01020E-03
	14	1.00319	0.00076	0.00280	0.00290	3.06227E-01	1.01020E-03
	15	1.00221	0.00065	0.00280	0.00287	2.93564E-01	1.01020E-03

Table 5-6: Benchmark Experiment Data (continued)

Experiment	Case	K_{eff} (CSAS5)	σ (CSAS5)	σ (Benchmark)	σ (Total)	EALF (eV)	NDEN (U-235 atoms/b-cm)
LEU-COMP-THERM-010	16	1.00275	0.00064	0.00280	0.00287	2.85031E-01	1.01020E-03
	17	1.00194	0.00061	0.00280	0.00287	2.79068E-01	1.01020E-03
	18	1.00232	0.00054	0.00280	0.00285	2.73688E-01	1.01020E-03
	19	1.00134	0.00068	0.00280	0.00288	2.67083E-01	1.01020E-03
	20	1.00287	0.00053	0.00280	0.00285	2.93297E-01	1.01020E-03
	21	1.00400	0.00075	0.00280	0.00290	2.84075E-01	1.01020E-03
	22	1.00295	0.00064	0.00280	0.00287	2.73343E-01	1.01020E-03
	23	1.00140	0.00060	0.00280	0.00286	2.66985E-01	1.01020E-03
	24	0.99951	0.00054	0.00280	0.00285	6.00491E-01	1.01020E-03
	25	1.00316	0.00080	0.00280	0.00291	5.55338E-01	1.01020E-03
	26	1.00237	0.00054	0.00280	0.00285	5.14005E-01	1.01020E-03
	27	1.00274	0.00066	0.00280	0.00288	4.79524E-01	1.01020E-03
	28	1.00194	0.00056	0.00280	0.00286	4.52575E-01	1.01020E-03
	29	1.00263	0.00053	0.00280	0.00285	4.27241E-01	1.01020E-03
	30	1.00029	0.00079	0.00280	0.00291	3.72891E-01	1.01020E-03
LEU-COMP-THERM-042	1	0.99889	0.00057	0.00160	0.00170	1.68544E-01	4.87850E-04
	2	0.99762	0.00053	0.00160	0.00169	1.74907E-01	4.87850E-04
	3	0.99914	0.00056	0.00160	0.00170	1.81329E-01	4.87850E-04
	4	0.99885	0.00052	0.00170	0.00178	1.80811E-01	4.87850E-04
	5	0.99799	0.00054	0.00330	0.00334	1.76997E-01	4.87850E-04
	6	0.99897	0.00050	0.00160	0.00168	1.68774E-01	4.87850E-04
	7	0.99572	0.00069	0.00180	0.00193	1.73449E-01	4.87850E-04

6.0 RESULTS AND CONCLUSIONS

As demonstrated in Section 5.1.1, the use of CSAS5 rather than CSASIX produces similar criticality results. As demonstrated in Section 5.1.2, reducing the water volume mixed with the fuel (in accordance with the TMI-2 ISFSI FSAR) and taking credit for Boral (per applicable regulations) results in a significant decrease in k_s from 0.93144, calculated from the CSAS5 results in Section 5.1.1, to 0.77979, calculated from the 0.05 water volume fraction in Table 5-2. Thus, the margin to criticality for the TMI-2 Fuel Canister under credible conditions is significantly higher than as described in [6]. Furthermore, the three parameter studies in Section 5.1.2 demonstrate that the TMI-2 Fuel Canisters maintain subcriticality following the degradation of Licon due to aging. Non-structural loss of Licon and water absorption in Licon both result in a decrease in reactivity, while structural loss of Licon does not result in a large enough increase in reactivity to exceed the subcriticality limits. It is concluded that the TMI-2 Fuel Canister criticality analysis in [6], which is referred to as the “second” criticality evaluation in the TMI-2 ISFSI FSAR, is sufficiently conservative that it bounds the possible effects of Licon degradation due to aging.

In relation to RAI 3-7 specifically, the effect of material loss of Licon due to aging will not adversely affect the results of the second criticality analysis in Section 3.3.4.3 of the TMI-2 ISFSI FSAR such that the subcritical limit is exceeded. Evaluation of the complete loss of Licon, including collapse of the TMI-2 Fuel Canister outer wall and compressed packing of the TMI-2 Fuel Canisters within the DSC, bounds any credible material losses for Licon as well as the dimensional effects of these material losses. The second criticality analysis in the TMI-2 ISFSI FSAR bounds the criticality results of this evaluation and thus continues to show the TMI-2 ISFSI storage system will be subcritical when these material losses are taken into account.

In relation to RAI 3-8 specifically, the changes to the Licon material properties, as a result of aging, are not significant to maintaining the subcriticality function of the TMI-2 Fuel Canisters. Analysis of both the water content of Licon as well as material loss of Licon shows that the TMI-2 Fuel Canisters stored at the TMI-2 ISFSI will remain subcritical as a result of any possible changes due to Licon aging. Analysis of material loss of Licon includes analysis of complete loss of Licon and the resulting possible structural effects. No other degradation of Licon is considered credible. It is concluded that the Licon is not relied on for maintaining nuclear criticality safety of the TMI-2 ISFSI.

7.0 COMPUTER SOFTWARE USAGE

Computer Name:	EGONSIOROWSKI1
Hardware Profile of Computer:	Intel® Xeon® CPU E5-1650 @ 3.50 GHz, 16.0 GB RAM
Operating System:	64-bit Windows 7 Enterprise, Service Pack 1

7.1 In-Use Testing of SCALE 6.2.1

Input files *p2438al_eg1.inp* and *epru65b_eg1.inp* are taken from the SCALE 6.2.1 software dedication report [21] for in-use testing. Both files are run on 7/16/2018. The resulting output files are identical to those in [21] except for run-unique parameters (such as date and time of run), indicating that SCALE 6.2.1 performs as expected and is acceptable for use.

The input files in this calculation are not affected by SCALE 6.2.1 Error Notice 2018-01.

7.2 File Listing

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-a---          7/18/2018  10:02 AM       3694 H2O_0.10.inp
-a---          7/18/2018  10:10 AM    1087982 H2O_0.10.out
-a---          7/18/2018  10:03 AM       3694 H2O_0.15.inp
```

```
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-a---         7/18/2018  10:03 AM       3694 H2O_0.20.inp
-a---         7/18/2018  10:10 AM    1088203 H2O_0.20.out
-a---         7/18/2018  10:03 AM       3694 H2O_0.25.inp
-a---         7/18/2018  10:09 AM    1088011 H2O_0.25.out
-a---         7/18/2018  10:03 AM       3694 H2O_0.30.inp
-a---         7/18/2018  10:09 AM    1087742 H2O_0.30.out
-a---         7/18/2018  10:03 AM       3694 H2O_0.40.inp
-a---         7/18/2018  10:08 AM    1087823 H2O_0.40.out
-a---         7/18/2018  10:03 AM       3694 H2O_0.50.inp
-a---         7/18/2018  10:08 AM    1087898 H2O_0.50.out
-a---         7/18/2018  10:03 AM       3694 H2O_0.60.inp
-a---         7/18/2018  10:08 AM    1087771 H2O_0.60.out
-a---         7/18/2018  10:03 AM       3694 H2O_0.70.inp
-a---         7/18/2018  10:08 AM    1088033 H2O_0.70.out
-a---         7/18/2018  10:03 AM       3694 H2O_0.80.inp
-a---         7/18/2018  10:08 AM    1087665 H2O_0.80.out
-a---         7/18/2018  10:03 AM       3694 H2O_0.90.inp
-a---         7/18/2018  10:08 AM    1087883 H2O_0.90.out
-a---         7/18/2018  10:50 AM       3694 H2O_1.00.inp
-a---         7/18/2018  10:53 AM    1087783 H2O_1.00.out

    Directory: Runs\In-Use Testing

Mode                LastWriteTime     Length Name
-a---        11/10/2016   3:56 PM       3697 epru65b_eg1.inp
-a---         7/16/2018   7:59 AM     548810 epru65b_eg1.out
-a---          4/6/2015   4:06 PM       1371 p2438al_eg1.inp
-a---         7/16/2018   7:59 AM     547061 p2438al_eg1.out

    Directory: Spreadsheets

Mode                LastWriteTime     Length Name
-a---         7/16/2018  12:59 PM      19200 Benchmarking.xlsx
-a---         8/30/2018   9:36 PM      12014 Evaluation Comparison.xlsx
-a---         7/18/2018   4:37 PM      24201 Tables.xlsx
```

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18. USLSTATS, *USLSTATS: A Utility to Calculate Upper Subcritical Limits for Criticality Safety Applications*, Build Date June 22, 2016. Note: USLSTATS is described in Appendix C, *User's Manual for USLSTATS V1.0*, in NUREG/CR-6361, *Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages*, March 1997. No new user's manual has been developed for later updates to the program.

19. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, Nuclear Energy Agency, NEA/NSC/DOC(95)03, September 2015
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9.0 SAMPLE INPUT FILE

9.1 Collapsed_4x3.inp

```
=csas5 parm=(   )
LDC-05, Remade from Listing-12 of INEEL/INT-99/00126 Rev. 4 (w/ 8L, Boral, and 4x3
Array)
v7-238
read comp
' Wet Fuel, mixed in material 501
U-238 100 0      2.18749-2 293 END
U-235 100 0      6.81347-4 293 END
O     100 0      4.51125-2 293 END
H2O   200 1.0              293 END
' Dry Fuel, mixed into material 502
U-238 1   0      2.18749-2 293 END
U-235 1   0      6.81347-4 293 END
O     1   0      4.51125-2 293 END
' Stainless Steel 304
SS304 4   1.0              293 END
' NOT USED?
H2O   5   8.8-5            293 END
' DSC Carbon Steel
CARBONSTEEL 6 1.0          293 END
' NOT USED?
H2O   7   0.2              293 END
' Boral
B-10  8   0       5.26187-3 293 END
B-11  8   0       2.12228-2 293 END
AL    8   0       5.76341-2 293 END
' HSM Concrete
C     9   0       1.6000-3 293 END
O     9   0       3.9700-2 293 END
NA    9   0       5.5000-4 293 END
AL    9   0       1.6000-3 293 END
SI    9   0       1.5200-2 293 END
S     9   0       5.0000-5 293 END
CA    9   0       3.1000-3 293 END
FE    9   0       3.8000-4 293 END
H2O   9   0.114            293 END
' Licon
'H2O   3   0.00             293 END
'O     3   0       1.1855-2 293 END
'NA    3   0       1.4380-4 293 END
'MG    3   0       3.5859-5 293 END
'AL    3   0       2.8385-3 293 END
'SI    3   0       8.7196-4 293 END
'CA    3   0       1.3101-3 293 END
'FE    3   0       1.3576-5 293 END
end comp
read celldata
LATTICECELL TRIANGPITCH PITCH=1.45    200 FUELD=0.93904 100 cellmix=501 END
LATTICECELL TRIANGPITCH PITCH=0.93904 0   FUELD=0.93904 1   cellmix=502 END
end celldata
```

```
READ PARA
TME=800.0 GEN=250 NPG=10000 RUN=YES FLX=YES FDN=NO
FAR=NO PLT=YES NSK=50 LIB=4 HTM=NO
END PARA
READ GEOM
UNIT 1
COM=* Wet Fuel in Fuel Canister  (1289) 1st layer *
CUBOID 501 1 4P11.59 24.07602 -0.0
CUBOID 4 1 4P11.69 24.07602 -0.0
CUBOID 8 1 4P12.02 24.07602 -0.0
CUBOID 4 1 4P12.22 24.07602 -0.0
CUBOID 4 1 4P12.71 24.07602 -0.9525
UNIT 2
COM=* Dry Fuel in Fuel Canister  (1289) 2nd layer *
CUBOID 502 1 4P11.59 150.46862 -0.0
CUBOID 4 1 4P11.69 150.46862 -0.0
CUBOID 8 1 4P12.02 150.46862 -0.0
CUBOID 4 1 4P12.22 150.46862 -0.0
CUBOID 4 1 4P12.71 150.46862 -0.000
UNIT 3
COM=* Empty Section of Canister  (1289) 3rd layer *
CUBOID 0 1 4P11.59 180.52078 -0.0
CUBOID 4 1 4P11.69 180.52078 -0.0
CUBOID 8 1 4P12.02 180.52078 -0.0
CUBOID 4 1 4P12.22 180.52078 -0.0
CUBOID 4 1 4P12.71 185.60078 -0.000
GLOBAL
UNIT 7
COM=* SILO*
CYLINDER 0 1 79.400001 474.0275 -0.9525
HOLE 1 -38.13   0.00   0.0
HOLE 1  12.71   0.00   0.0
HOLE 1 -12.71   0.00   0.0
HOLE 1  38.13  25.42   0.0
HOLE 1 -38.13  25.42   0.0
HOLE 1  38.13 -25.42   0.0
HOLE 1 -38.13 -25.42   0.0
HOLE 1  12.71  25.42   0.0
HOLE 1 -12.71  25.42   0.0
HOLE 1  12.71 -25.42   0.0
HOLE 1 -12.71 -25.42   0.0
HOLE 1  38.13   0.00   0.0
HOLE 2 -38.13   0.00  24.07602
HOLE 2  12.71   0.00  24.07602
HOLE 2 -12.71   0.00  24.07602
HOLE 2  38.13  25.42  24.07602
HOLE 2 -38.13  25.42  24.07602
HOLE 2  38.13 -25.42  24.07602
HOLE 2 -38.13 -25.42  24.07602
HOLE 2  12.71  25.42  24.07602
HOLE 2 -12.71  25.42  24.07602
HOLE 2  12.71 -25.42  24.07602
HOLE 2 -12.71 -25.42  24.07602
HOLE 2  38.13   0.00  24.07602
```

```
HOLE 3 -38.13   0.00 174.54464
HOLE 3  12.71   0.00 174.54464
HOLE 3 -12.71   0.00 174.54464
HOLE 3  38.13  25.42 174.54464
HOLE 3 -38.13  25.42 174.54464
HOLE 3  38.13 -25.42 174.54464
HOLE 3 -38.13 -25.42 174.54464
HOLE 3  12.71  25.42 174.54464
HOLE 3 -12.71  25.42 174.54464
HOLE 3  12.71 -25.42 174.54464
HOLE 3 -12.71 -25.42 174.54464
HOLE 3  38.13   0.00 174.54464
CYLINDER 6 1 80.9875 474.0275 -0.9525
CUBOID 9 1 4P142.0 534.98 -61.0
END GEOM
end data
end
```

APPENDIX A: COMPARISON OF SELECT TMI-2 ISFSI CRITICALITY CASES

To aid comparisons of the first criticality evaluation in [5], the second criticality evaluation in [6], and this calculation, Table A-1 summarizes the key criticality parameters for select cases in the two evaluations and this calculation. Common parameters across selected cases include:

- Enrichment for all cases is 2.98 wt.% U-235.
- Fuel pellet diameter for all cases is 0.93904 cm except for the analysis of the TMI-2 Filter Canister in [5], which uses a fuel pellet diameter of 850 microns.
- TMI-2 Canisters are modeled in a triangular pitch, close packed configuration within a collapsed DSC for all cases except:
  - Case FUEL002 from [6], which uses a normal DSC configuration
  - Cases from this calculation modeling compression of TMI-2 Canisters following structural loss of Licon.

For cases from [5] and [6], k_s is calculated differently than as described in Section 5.1.3:

$$\mathrm{k_s = k_{eff} + 2\sigma + Bias + Additional\ Margin\ \leq USL}$$

Calculation of bias is discussed within each individual calculation and varies depending on the code version and cross-section library used. For cases from this calculation, bias is included in the USL.

Table A-1: Comparison of Select TMI-2 ISFSI Criticality Cases

	First Criticality Evaluation			
	Individual Fuel Canister	**Individual Knockout Canister**	**Individual Filter Canister**	**12 Knockout Canisters in DSC**
Case Identifier	Single Fuel Canister Model	Single Knockout Canister Model	Single Filter Canister	HSM with 12 Knockout Canisters
Fuel Loading per Can	>1908 lb	>1908 lb	>1908 lb	>1908 lb
Fuel Region Geometry	Homogenous Smear	Homogenous Smear	Homogenous Smear	Homogenous Smear
Water Content in Fuel Region	8.8E-5 g/cc	8.8E-5 g/cc	8.8E-5 g/cc	8.8E-5 g/cc
Fuel Pellet Triangular Pitch	0.93904 cm	0.93904 cm	850 microns	0.93904 cm
Poison Credit	75% Boral	75% Boron Carbide	75% Boron Carbide	75% Boron Carbide
K_{eff}	0.26047	0.26174	0.24641	0.54051
σ	0.00053	0.00055	0.00051	0.00082
USL	0.95	0.95	0.95	0.95
Bias	0.00762	0.00762	0.00762	0.00762
Additional Margin	0.05	0.05	0.05	0.05
K_s	0.31915	0.32046	0.30505	0.59977

Table A-1: Comparison of Select TMI-2 ISFSI Criticality Cases (Continued)

	Second Criticality Evaluation		
	12 Knockout Canisters in DSC	**12 Fuel Canisters in DSC**	**12 Fuel Canisters in DSC**
Case Identifier	DSC420	LDC-05	FUEL002
Fuel Loading per Can	1908 lb	1740 lb	1740 lb
Fuel Region Geometry	Wet/Dry/Air (Inverted)	Wet/Dry/Air	Wet/Dry/Air
Water Content in Fuel Region	8 L	10 L	30 L
Fuel Pellet Triangular Pitch	1.35 cm (Wet), 0.93904 cm (Dry)	1.45 cm (Wet), 0.93904 cm (Dry)	1.45 cm (Wet), 0.93904 cm (Dry)
Poison Credit	Water	Water	75% Boral
K_{eff}	0.9111	0.9260	0.9051
σ	0.0012	0.0014	0.0014
USL	0.95	0.95	0.95
Bias	0.01	0.01	0.01
Additional Margin	-	-	-
K_s	0.9235	0.9388	0.9179

Table A-1: Comparison of Select TMI-2 ISFSI Criticality Cases (Continued)

	CALC-3021788				
	12 Fuel Canisters in DSC	**12 Fuel Canisters in DSC**	**12 Fuel Canisters in DSC**	**12 Fuel Canisters in DSC**	**12 Fuel Canisters in DSC**
Case Identifier	Normal Condition	Licon replaced with Void	Water Volume Fraction in Licon = 1	Compression Factor = 1	4 x 3 Array
Fuel Loading per Can	1740 lb	1740 lb	1740 lb	1740 lb	1740 lb
Fuel Region Geometry	Wet/Dry/Air	Wet/Dry/Air	Wet/Dry/Air	Wet/Dry/Air	Wet/Dry/Air
Water Content in Fuel Region	8 L	8 L	8 L	8 L	8 L
Fuel Pellet Triangular Pitch	1.45 cm (Wet), 0.93904 cm (Dry)	1.45 cm (Wet), 0.93904 cm (Dry)	1.45 cm (Wet), 0.93904 cm (Dry)	1.45 cm (Wet), 0.93904 cm (Dry)	1.45 cm (Wet), 0.93904 cm (Dry)
Poison Credit	75% Boral	75% Boral	75% Boral	75% Boral	75% Boral
K_{eff}	0.78846	0.77832	0.67793	0.85026	0.85770
σ	0.00054	0.00055	0.00062	0.00064	0.00078
USL	0.9422	0.9422	0.9422	0.9422	0.9422
Bias	-	-	-	-	-
Additional Margin	-	-	-	-	-
K_s	0.78954	0.77942	0.67917	0.85154	0.85926