A Criticality Safety Study On Storing Unirradiated Cintichem-type Targets at Sandia National Laboratories

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ABSTRACT

This criticality safety analysis is performed to determine the effective multiplication factor ($k_{\text{eff}}$) for a storage cabinet filled with unirradiated Cintichem-type targets. These targets will be used to produce $^{99}$Mo at Sandia National Laboratories and will be stored on-site prior to irradiation in the Annular Core Research Reactor. The analysis consisted of using the Monte Carlo code MCNP (Version 4A) to model and predict the $k_{\text{eff}}$ for the proposed dry storage configuration under credible loss of geometry and moderator control. Effects of target pitch, non-uniform loading, and target internal/external flooding are evaluated.

Further studies were done with deterministic methods to verify the results obtained from MCNP and to obtain a clearer understanding of the parameters affecting system criticality. The diffusion accelerated neutral particle transport code ONEDANT was used to model the target in a one-dimensional, infinite half-slab geometry and determine the critical slab thickness. Hand calculations were also completed to determine the critical slab thickness with modified one-group, and one-group, two region approximations. Results obtained from ONEDANT and the hand calculations were compared to applicable cases in a commonly used criticality safety analysis handbook. Overall, the critical slab thicknesses obtained in the deterministic analysis were much larger than the dimensions of the cabinet and further support the predictions by MCNP that a critical system cannot be attained for the base case or in conditions where loss of geometry and moderation control occur.

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INTRODUCTION

Sandia National Laboratories has been chosen by the U.S. Department of Energy as the primary domestic source for the production of $^{99}$Mo (molybdenum-99) utilizing the Annular Core Research Reactor (ACRR) in Sandia's Technical Area V. The method to be used to produce $^{99}$Mo is through the fission of $^{235}$U in 93% enriched UO$_2$, based on the process formerly used by Cintichem, Inc. of Tuxedo, New York. The UO$_2$ is electroplated in a thin coating to the inside of a stainless steel tube called a Cintichem-type target. These highly-enriched uranium targets will be manufactured by Los Alamos National Laboratory and transported to the ACRR at Sandia where they will be stored on-site prior to irradiation in the central region of the reactor core. The proposed storage plan for the targets is to store them in a dry, secure compartment similar to a file cabinet. Each cabinet drawer will be filled with targets and emptied as the targets are used for irradiation. For criticality safety purposes, credible process upset conditions which could lead to a criticality event are evaluated and described.

CRITICALITY CONCERNS

Initial considerations address the loss of geometry in the storage cabinet. As such, the effect of target pitch (center-to-center spacing) within the drawer is evaluated under varying degrees of moderation. Storing targets in the proposed dry configuration creates a very subcritical system ($k_{\text{eff}} < 0.01$) due to the lack of moderation. However, the system multiplication increases significantly when the cabinet drawers and the interstitial region between the targets becomes flooded with water. The mass of highly-enriched uranium (HEU) or number of targets within a drawer also impacts system reactivity. The likelihood of approaching an effective multiplication factor of 1.0 is further enhanced when the void region inside the target becomes moderated. In this unlikely extreme flooding scenario, the strong neutron absorption
characteristics of the stainless steel in the targets are insufficient to overcome the high fission production rate. Credible process upset considerations therefore include:

- the effect of target pitch using a storage rack in a drawer;
- non-uniform target loading of storage drawers; or
- loss of interstitial and internal target moderation control.

The concept of a storage rack in each drawer was analyzed merely to determine the optimum point of moderation. Current plans do not include the use of storage racks in the drawers. The probability of a criticality event increases when one or more of the above upset conditions occur.

OBJECTIVES

The first part of this work involved a parametric study using Los Alamos National Laboratory's MCNP (Monte Carlo N-Particle) code, Version 4A. Two major objectives of using MCNP were:

a) to create a three-dimensional model of the storage cabinet filled with targets based on the proposed storage plan; and

b) to determine the effective multiplication factor ($k_{\text{eff}}$) and its associated standard deviation for each identified accident scenario.

Each accident scenario was coupled to a corresponding set of target loading arrangements and pitch configurations to simulate the previously mentioned upset conditions. All of these cases were modeled by creating input files for MCNP to calculate a $k_{\text{eff}}$ and an associated standard deviation.

In the second part of this analysis, the deterministic code ONEDANT was used to model the target as a unit cell in a one-dimensional infinite half-slab geometry and calculate the
critical thickness using a dimensional search. The purpose of using deterministic methods here was to:

a) verify the results obtained from MCNP; and

b) use the results of these calculations to obtain a better understanding of the major parameters affecting the system reactivity.

These results were then compared to hand calculations using modified one-group theory for the cases with no reflection, and one-group theory for two regions (slab and reflector) in the reflected cases. In addition, a commonly used handbook in criticality safety analysis was used as a final basis for comparison.\(^2\)

**CRITICALITY SAFETY CONTROLS**

The following controls are necessary to meet this analysis:

**Control #1 (Geometry)** – Cabinets are limited to storing 3.18 cm (1.25 in.) outer diameter, 45.72 cm (18 in.) long stainless steel annular targets. The inner surface UO\(_2\) coating is limited to a 70 \(\mu\)m thickness and 25.4 cm (16.5 in.) length. Only approved storage locations within each cabinet drawer may be used. Each cabinet is limited to 4 drawers, with no more than 39 targets per drawer.

**Control #2 (Moderation)** – Target storage cabinets shall reside in a moderation controlled area.

The following assumptions are made for the modeled system:

**Worst Credible Contents:**

Form: UO\(_2\) powder electroplated to inner surface of stainless steel tube

Density: 10.96 g/cm\(^3\)

\(^{235}\)U Enrichment: 93.0 %

Moderation: Optimum
Boundary Conditions:

- Top: 30.48 cm (12 in.) H₂O
- Bottom: 30.48 cm (12 in.) H₂O
- Sides: 30.48 cm (12 in.) H₂O
- Interunit Water: N/A - single unit only

MODEL DESCRIPTION

MCNP Model

A Cintichem-type target is a stainless steel, hollow tube 3.18 cm (1.25 in.) in diameter and 45.72 cm (18.0 in.) in length. The thickness of the tube was modeled at the lower limit allowable, 0.0635 cm (25 mils) or 240 grams of stainless steel. Each target was modeled with a UO₂ layer 25.4 cm (16.5 in.) long and 70 μm thick on the inside surface of the tube. The UO₂ layer was assumed to have a mass loading of 36.65 grams of UO₂, which translates to 30 grams of fissile ²³⁵U. Figure 1 illustrates radial and axial views of the target as modeled in MCNP. Figure 2 is an axial cross-sectional view of the target as modeled in MCNP, compared with the nominal Cintichem-type target. A major difference between the two is the omission of the top and bottom end caps from the MCNP model. Consequently, the detail of the model and results for k_eff obtained from MCNP are conservative even with this minor change in the target geometry.

The storage compartment consists of four cabinet drawers, each measuring 25.4 cm (10 in.) high, 30.48 cm (12 in.) wide, and 45.72 cm (18 in.) deep. Each group of targets in the four drawers were arranged in two triangular pitch configurations:

1. a pitch of 3.18 cm (1.25 in.) or the closest packing arrangement possible; and
2. a pitch of 4.50 cm (1.77 in.) to simulate a storage rack.
A parametric study on target pitch was used as a basis to determine the 4.50 cm pitch of the storage rack. For a range of target pitches between 4.0 and 5.0 cm in increments of 0.10 cm, the peak $k_{\text{eff}}$ value occurred at a target pitch of 4.50 cm in arrays of 85 and 163 targets. These calculations simulated the target lattice as flooded and radially reflected with water.

Figure 3 depicts the closest possible arrangement of targets in a single drawer as modeled in MCNP. Figure 4 shows the entire MCNP model for the target storage compartment, with the maximum number of targets possible for a storage rack ($p=4.50$ cm), or 156 targets. The entire storage cabinet is completely surrounded by an infinite reflector of water. MCNP was used to model and evaluate $k_{\text{eff}}$ for the cabinet filled with various numbers of targets in the context of the current storage plan and three postulated, unlikely events. The current storage plan was chosen as the base case which consists of storing the targets in a dry, secure cabinet located in a dry room.

To establish a set of conditions which could upset the system multiplication further, three separate target loading arrangements were evaluated. Though highly unlikely, the following upset conditions are considered credible. For a criticality accident to be possible, at least two of these events would have to occur independently and concurrently.

- **EVENT I**: loss of moderation control, room floods, no water inside storage cabinet.
- **EVENT II**: loss of moderation control, cabinet leaks and the interstitial target region becomes moderated.
- **EVENT III**: loss of moderation control, 10% of target end caps fail per drawer, internal target chamber becomes moderated.
- **EVENT IV**: loss of geometry occurs, more targets stored inside cabinet than permitted.
These upset conditions were calculated to give a measure of which loading combinations yield the most reactive storage arrangements.

**Deterministic Models**

A single target was modeled in ONEDANT as a unit cell in an infinite half-slab geometry consisting of a homogenous mixture of UO₂ and stainless steel cladding. To analyze the effects of flooding the inside void region of the target, water was included as part of the UO₂ and cladding mixture. The region between each target was treated as a reflector and modeled as a separate region of water outside the half-slab. A dimensional search in ONEDANT using the sixteen group Hansen-Roach cross section library was conducted to find the critical thickness of the half-slab in the bare and reflected configurations. Additional critical slab thickness calculations were done using a modified one-group theory approach for the bare cases, and one-group theory applied to two regions for the reflected cases.

Two different cross section sets were used for the cases where the inside void region of the target was modeled as dry or flooded:

- for the dry void, a set of six group Hansen-Roach cross sections (5); and
- for the flooded void, the nominal thermal cross sections (6) at 0.0253 eV for each isotope in the water-UO₂-cladding mixture.

These results obtained from ONEDANT and the analytic calculations were compared with data in LA-10860-MS (Ref. 3) for hydrogenously moderated infinite slabs. This was done only for the flooded void cases, with and without water reflection as comparable data was not available in Ref. 3 for cases where the target void is dry. A subsequent check on the critical half-slab thickness initially calculated with ONEDANT for the base case (dry with no reflection) was done by
calculating a full slab thickness using modified one-group theory with a one group cross section set collapsed from a set of sixteen group macroscopic cross sections output by the code.

RESULTS OF TARGET LOADING ARRANGEMENTS AND ACCIDENT SCENARIOS

MCNP $k_{\text{eff}}$ calculations were performed using a personal, stand-alone computer at Sandia National Laboratories. Consequently, the calculational bias on $k_{\text{eff}}$ for each of the cases were determined with a series of criticality safety benchmarks for HEU systems modeled in MCNP.(7) These covered a range of hydrogen-to-$^{235}\text{U}$ ($H / ^{235}\text{U}$) ratios from 0 to 870. Table I lists the benchmarks evaluated, their $k_{\text{eff}}$ and associated standard deviation results, and the corresponding $H / ^{235}\text{U}$ ratios. For the modeled highly-enriched UO$_2$ system of targets, the MCNP code was determined to have a calculational bias which is represented by the following function of the $H / ^{235}\text{U}$ ratio over the range of $0 \leq H / ^{235}\text{U} \leq 1000$:

$$b = 0.0032 + 3.307 \times 10^{-5} \left( \frac{H}{^{235}\text{U}} \right) - 4.040 \times 10^{-8} \left( \frac{H}{^{235}\text{U}} \right)^2$$

(1)

A plot of Eq. (1) is shown in Fig. 5 which illustrates the bias is conservatively applied over its negative range and assigned a value of zero over its positive range ($110 \leq H / ^{235}\text{U} \leq 705$). Calculations were nominally run with 110 generations and 1000 neutrons each. The first 10 generations were skipped before starting the statistical output processing.

Compared to the $H / ^{235}\text{U}$ ratios of the evaluated benchmarks, the ratios for the cases in Table II where loss of interstitial moderation control occurs with a dry target void ranged from 33 for the 3.18 cm pitch to 382 for the 4.50 cm pitch. The Godiva assembly benchmark was included in the bias evaluation to cover the dry base case where $H / ^{235}\text{U}$ is 0. All of the cases evaluated in Table II are subcritical even with a change in $k_{\text{eff}}$ due to the calculated bias. In contrast, Table III shows a wider variety of $H / ^{235}\text{U}$ ratios apply to the cases where loss of
interstitial moderation control occurs with a flooded target void. This is mainly due to the presence of additional water as a result of internal target void flooding.

The most realistic, postulated case for internal target void flooding with the current pitch arrangement of 3.18 cm shows even with the bias correction, the system is still subcritical. However, when all of the end caps fail on every target in the first drawer, the bias predicts a $k_{\text{eff}}$ for a system very close to criticality. Nonetheless, a second case with 39 flooded targets ($p=4.50$ cm) is still subcritical. Overall, the bias evaluation shows the $k_{\text{eff}}$ results originally obtained are conservative and generally tend to predict a subcritical system even with the bias correction. Only in certain cases the bias corrections predict systems very close to critical or even supercritical where all of the end caps fail in an entire drawer, but even these cases are considered to be highly unlikely events.

Two sets of data tables present the $k_{\text{eff}}$ results and their associated standard deviations for the upset conditions and target loading arrangements modeled in MCNP. Table II presents the $k_{\text{eff}}$ results obtained from MCNP for the cumulative loss of moderation control, Events I and II. In these runs, the inner void region of the targets is modeled as dry. Note the first case represents the close-packed target arrangement where loss of geometry occurs, Event IV. The first three cases were modeled with the closest pitch possible, 3.18 cm, and the second three cases with a pitch of 4.50 cm.

Table III presents the $k_{\text{eff}}$ results for interstitial and end cap failure (internal) loss of moderation control, Event III. These cases were done to establish an upper bound for the analysis on $k_{\text{eff}}$ as worst case, albeit highly unlikely, accident conditions. These cases were evaluated for the maximum target loading patterns of 308 and 156 targets presented in Table II. The results in Table III compare the most likely target void flooding scenario (10% of the targets
in each drawer with a flooded void region) to other more dramatic flooding scenarios. Clearly, flooding the internal target chamber results in a more reactive system.

A parametric study was done with MCNP for a target lattice composed of 85 targets infinite in length. The target lattice was surrounded by an infinite water reflector and the interstitial region between the targets was flooded with water. Figure 6 illustrates the point of optimum moderation for a target with a flooded void occurs at a target pitch of 3.50 cm as compared to 4.50 cm for a target with a dry void. To further bound the maximum reactivity condition, a parametric study on partial water moderator density was done with MCNP. $k_{\text{eff}}$ was evaluated for various water moderator densities at the 4.50 cm target pitch with 156 targets in the cabinet. Results of this study are illustrated in Fig. 7 and show that $k_{\text{eff}}$ steadily rises until the most reactive condition is attained at full water density.

Table IV presents the results obtained from the ONEDANT dimensional search compared to those obtained from the analytic calculations and LA-10860-MS (Ref. 3). All values presented here are critical thicknesses of full width slabs in centimeters. Figures 8-11 are plots of the neutron flux as a function of slab thickness for four neutron energy groups. These were originally calculated as sixteen group flux profiles with ONEDANT and subsequently collapsed to four groups with the code. Table V outlines the ranges of the four groups according to the neutron energy group structure in the sixteen group Hansen-Roach cross section library.

Table VI further illustrates the reasoning for the choice of neutron cross section sets used in the analytic calculations. The average neutron energy group causing fission was calculated using the neutron production spectrum output by ONEDANT for the sixteen energy groups. Note that group 1 is the highest energy ($\sim$5 MeV) and group 16 is the lowest energy ($\sim$0.025 eV). For a fast, bare assembly like Godiva, the average energy group is 3.3 while for a typical well-
thermalized system composed of a homogenous mixture of UO₂ and water, the average energy group is 15.5.

EVALUATION OF RESULTS

MCNP Results

Table II illustrates that a critical condition cannot be achieved for the normal condition and under loss of interstitial moderation control scenarios regardless of target pitch or the number of targets in the storage compartment. All k_eff values presented in Table II are below a k_eff of 0.90, but these results pertain only to scenarios where the inner void region of the target remains dry.

Table III demonstrates the effect of internal target flooding on system reactivity. The increase in the k_eff can be attributed to several factors. First, the water in the void region acts as a moderator while the water outside the target acts as a reflector. This enables the water inside the target to moderate fission neutrons to thermal energies after they have been reflected back into the target. Consequently, the thermalized neutrons are more likely to produce additional fission due to an increase of the ²³⁵U fission cross section at thermal energies. Second, the neutron population is increased or maintained at a level suitable for criticality due to the reduction in neutron leakage by the water reflector outside the cabinet. Although some resonance absorption may occur due to the stainless steel cladding, the additional moderation and reduced leakage are enough to overcome this absorption.

A flooded target lattice was modeled with 85 targets infinite in length (height) and surrounded by a 10 cm radial water reflector. Figure 6 illustrates a shift in the optimum moderation peak for a flooded void which occurs at a target pitch of 3.50 cm, as compared to 4.50 cm when the void is dry. Partial moderator density cases were also evaluated for fully
flooded conditions. As shown in Fig. 7, the system was determined to be the most reactive with the water moderator at theoretical density. A more reasonable flooding scenario for the target void is calculated assuming 10% of the end caps on the targets fail in a fully loaded cabinet for two pitch configurations. Overall, these results are below a $k_{\text{eff}}$ of 0.90 in comparison to more extreme flooding scenarios where the interior of the cabinet and the void regions of every target are flooded with water. This type of flooding scenario is considered to be an extreme case as the targets are held to strict quality assurance standards to ensure they are properly sealed. Thus it is highly unlikely that more than one target might leak at a time.

**Deterministic Results**

Table IV compares the results obtained from two major methods used to calculate a critical slab thickness for a single target analyzed as a unit cell. The first method utilized the ONEDANT code to predict a critical slab thickness for the various target flooding scenarios and associated upset conditions. To verify the ONEDANT results, the same slab was analyzed using modified one-group and one-group, two region approximations. The results obtained from these two methods were subsequently compared to applicable cases documented in LA-10860-MS (Ref. 3). As a result, the differences shown in Table IV clearly illustrate that typical group approximations and reference handbooks should not be used as a primary means in obtaining a reasonable result for a critical slab thickness in this analysis.

There are several major reasons why the results obtained from both methods and LA-10860-MS (Ref. 3) do not match one another:

1. the heterogeneous composition of the actual system;
2. the lack of a set of hand calculation cross sections which handle a variety of neutron energies; and
3. the calculations for the average neutron energy group causing fission which confirm a change in the neutron energy spectrum depending on the modeled case.

First, a large difference between the critical slab thicknesses calculated by ONEDANT and the diffusion theory approximations can be attributed to the effects associated with approximating a heterogeneous system. For a hand calculation analysis, this requires combining the UO₂ and cladding together as a single material. Homogenizing such a complex system can fail to properly account for effects such as self-shielding by the outer layer of fuel nuclei in the UO₂ layer and resonance absorption in the stainless steel cladding. In contrast, a multigroup code such as ONEDANT with a proper set of cross sections can account for small changes in the spectrum.

The third energy group is the average group responsible for fission in the Godiva assembly, compared to the fifth energy group as calculated for the base case in Table VI. These results illustrate that the base case is a fast system with a hard spectrum comparable to that of the Godiva assembly since the average group causing fission occurs in the fast region of the spectrum (see Table V). This is the primary reason for utilizing the fast six group cross sections for this case in the hand calculations. Since the calculated critical slab thicknesses here are much larger than the storage cabinet dimensions, this further confirms the results obtained by MCNP which predict that a critical system cannot be attained in any configuration for the base case or in a flooded condition as there is no additional water in the void region of the target to act as a moderating mechanism to aid in further fission.

Under conditions where the interstitial target region floods and the void region remains dry, neutrons born from fission in the UO₂ layer are either lost through resonance absorption in the stainless steel or through leakage. The addition of a reflector illustrates the possibility of resonance absorption by the stainless steel as the calculated average energy group causing fission...
is the seventh energy group, which is clearly in the resonance regime according to Table V. Consequently, neutrons at these energies are more likely to be absorbed in the cladding. Both ONEDANT and the hand calculations predict an expected reduction in the dimensions of the slab with the addition of a reflector.

In contrast, results presented in Table IV illustrate a thermal system with a softened spectrum when the inside void region of the target is flooded with water. This area of the target effectively acts as a moderating region for neutrons leaking from the UO₂ layer. Neutrons reflected back into the UO₂ layer by the water reflector outside the target are more likely to produce additional fission events as they are thermalized and a higher fission cross section exists at thermal energies. The k_{eff} results obtained with MCNP for these cases further confirms this phenomenon.

Results presented in the second part of Table IV for a target with a flooded void region under dry and externally flooded conditions also have noticeable discrepancies. A very small but noticeable change in the neutron energy spectrum is evident in Table VI when comparing the actual system to a homogenous mixture of UO₂ and water. This is a factor in the difference between the slab thicknesses calculated with ONEDANT and the diffusion theory approximations. The calculated average energy group responsible for fission occurs in the fifteenth group or in the thermal region of the energy spectrum. Therefore, the use of nominal thermal cross sections in a hand calculation is a reasonable approximation; however, this type of calculation does not accurately account for the small change in the energy spectrum. It should be noted in Table IV that LA-10860-MS severely underestimates the critical slab thickness when compared to the ONEDANT results for a hydrogenously moderated, bare slab, and when an infinite reflector of water is added to the slab. This is a result of additional absorption in the stainless steel which
increases the critical thickness in the Cintichem-type target system. Use of a handbook such as LA-10860-MS provides a minimum critical thickness, but relying on this single value would overly constrain the system design.

SAFETY DURING UPSET CONDITIONS

Events I and II are covered by the calculations that demonstrated safety for the proposed target storage cabinet under optimal interstitial moderation, fully reflected conditions. The calculations demonstrated safety for both uniform and non-uniform target loadings. Event III is covered by the calculations for 10% target end cap failure only. If more than 10% of the targets leak and loss of moderation control occurs, safety cannot be demonstrated for this proposed storage configuration. The most plausible scenario for simulating target end cap failure was modeled in Event III where 10% of the targets in each drawer leak. Two other cases were also modeled where the end caps on every target in a drawer fail. These were calculated to serve as boundary cases for the entire analysis and are considered to be extremely unlikely events since the only way for water to enter the void is to have Events I and II to also occur.

Event IV is covered by the above calculations which demonstrates safety for a close-packed triangular pitch maximum target loading in each drawer. In summary, the proposed storage cabinet meets the double contingency principle. Independent parameter controls on geometry and moderation are used for the basis of safety.

SPECIFICATIONS AND REQUIREMENTS FOR SAFETY

The design specification(s) include:

\[^{235}\text{U Enrichment:} \quad 93\% \text{ wt.} \% \]

Uranium Form: Homogeneous UO\textsubscript{2}

Structure: Stainless Steel
The criticality safety requirements for use of this analysis include:

1. The following requirements apply to target storage:
   a) limited to approved Cintichem-type targets only;
   b) limited to four drawer storage (maximum);
   c) maximum number of targets per drawer is 39;
   d) current inventory of cabinet contents (log required);
   e) drawers must remain closed except when attended by operator or operator is moving targets in and out of storage cabinet.

2. All Cintichem-type target end cap seals must be inspected and verified prior to cabinet storage.

CONCLUSIONS

Computer codes, hand calculations, and reference handbooks have proven to be very valuable and reliable tools to the criticality safety analyst. In this analysis, a Monte Carlo approach with MCNP was utilized as the primary modeling and analysis tool; the deterministic ONEDANT code was used to verify and obtain additional information about the behavior of the modeled system; and hand calculations along with a reference handbook were used as additional aids. The complexity of this problem demonstrated that a Monte Carlo code is a powerful tool when used to simulate complicated geometries, however; a major drawback to its use is the large amount of computer time needed to obtain a result for $k_{\text{eff}}$. Likewise, similar tradeoffs can be realized when using deterministic codes since they require a complicated geometry to be
simplified to obtain a comparable result but their execution time is much quicker than a Monte Carlo code.

For the hand calculations, valid cross section sets proved to be a major factor in ensuring that they were applicable to a specific case and that the anomalies encountered in the results are due to the ability of the codes to effectively account for small changes in the neutronics. LA-10860-MS served as an additional point of reference but showed that its must be used with caution since it provided estimates which could overly constrain the system design. Consequently, this analysis clearly illustrates the need to carefully evaluate and pay attention to results obtained from these various approaches to ensure that they are consistent with the theory, and that even small differences encountered can be readily accounted for. In general, the critical slab thicknesses from ONEDANT and the hand calculations were much larger than the dimensions of the cabinet and clearly support the predictions by MCNP that a critical system cannot be attained for the base case or in a flooded condition.

The results obtained from MCNP illustrate that under normal conditions, $k_{\text{eff}}$ does not exceed 0.90 regardless of how many targets are in the cabinet and how they are arranged. Under accident conditions, a maximum 10% end cap seal failure is demonstrated subcritical. This is considered acceptable, since the targets must meet stringent manufacturing specifications, including seal inspection.

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REFERENCES


Fig. 1. Radial and axial views of MCNP target model.
Fig. 2. Comparison of MCNP target model to actual Cintichem-type target.
Fig. 3. MCNP model of a single storage drawer with 77 Cintchem-type targets, p=3.175 cm (1.25 in.).
Fig. 4. MCNP model of Cintchem-type target storage cabinet (156 targets, p=4.50 cm).
Fig. 5. $k_{\text{eff}}$ Bias Correction Fit for HEU Benchmark Cases.
Fig. 6. Comparison of $k_\infty$ for 85 targets with a dry and water filled void.
Fig. 7. $k_{\text{eff}}$ vs. water density for 156 dry void targets with H$_2$O flooding and reflection.
Fig. 8. Four group neutron flux profiles for void target without a H₂O reflector.
Fig. 9. Four group neutron flux profiles for void target with a H\textsubscript{2}O reflector.
Fig. 10. Four group neutron flux profiles for flooded target without a H$_2$O reflector.
Fig. 11. Four group neutron flux profiles for a flooded target with a $\text{H}_2\text{O}$ reflector.


### TABLE I

Results for Criticality Benchmark Models

<table>
<thead>
<tr>
<th>Benchmark File Name</th>
<th>Benchmark Model</th>
<th>H(^{235})U</th>
<th>Calculated Result (k(_{\text{eff}}) ± σ)</th>
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<tr>
<td>HEU-MET-FAST-001</td>
<td>6 Shell Godiva</td>
<td>0</td>
<td>0.9964 ± 0.0019</td>
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<tr>
<td>HEU-MET-FAST-001</td>
<td>Solid Godiva</td>
<td>0</td>
<td>0.9974 ± 0.0018</td>
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<tr>
<td>HEU-MET-FAST-004</td>
<td>Water Reflected HEU Sphere (Actual Model)</td>
<td>350</td>
<td>1.0007 ± 0.0024</td>
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<tr>
<td>HEU-MET-FAST-004</td>
<td>Water Reflected HEU Sphere (3-D Idealization)</td>
<td>378</td>
<td>1.0055 ± 0.0023</td>
</tr>
<tr>
<td>HEU-MET-THERM-003</td>
<td>Oralloy Cube in Water</td>
<td>800</td>
<td>1.0000 ± 0.0023</td>
</tr>
<tr>
<td>HEU-MET-THERM-003</td>
<td>Oralloy Parallelpiped in Water</td>
<td>870</td>
<td>0.9930 ± 0.0022(^a)</td>
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</tbody>
</table>

\(^a\)Subcritical system with k\(_{\text{eff}}\)=0.9840, correlated to k\(_{\text{eff}}\) of an equivalent critical system.
TABLE II

Results for Loss of Interstitial Moderation Control - Dry Target Chamber

<table>
<thead>
<tr>
<th>Total Number of Targets in Cabinet</th>
<th>Room Flooded &amp; Cabinet Leakage ($k_{eff} \pm \sigma$)</th>
<th>MCNP 4A Code Bias (b)</th>
<th>Bias Corrected $k_{eff}$ ($k_{eff} + 2\sigma - b$)</th>
<th>$H^{235\text{U}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>308</td>
<td>0.5583 ± 0.0023*</td>
<td>-0.0022</td>
<td>0.5650</td>
<td>33</td>
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<tr>
<td>152</td>
<td>0.5450 ± 0.0021</td>
<td>-0.0022</td>
<td>0.5513</td>
<td>33</td>
</tr>
<tr>
<td>77</td>
<td>0.3633 ± 0.0018</td>
<td>-0.0022</td>
<td>0.3690</td>
<td>33</td>
</tr>
<tr>
<td>156</td>
<td>0.8310 ± 0.0022</td>
<td>0.0</td>
<td>0.8310</td>
<td>382</td>
</tr>
<tr>
<td>76</td>
<td>0.6615 ± 0.0019</td>
<td>0.0</td>
<td>0.6615</td>
<td>382</td>
</tr>
<tr>
<td>39</td>
<td>0.3748 ± 0.0017</td>
<td>0.0</td>
<td>0.3748</td>
<td>382</td>
</tr>
</tbody>
</table>

*For comparison purposes, the dry normal (base case) condition result $k_{eff} = 0.0171 \pm 0.0001$; the room flooded condition (no water inside cabinet) result $k_{eff} = 0.4022 \pm 0.0023$. 
### TABLE III

Results for Loss of Interstitial Moderation Control - Flooded Target Chamber

<table>
<thead>
<tr>
<th>Total Number of Targets in Cabinet</th>
<th>Total Number of Flooded Targets in Cabinet</th>
<th>Calculated Result (k_{\text{eff}} \pm \sigma)</th>
<th>MCNP 4A Code Bias ((k_{\text{eff}} + 2\sigma - b))</th>
<th>Bias Corrected (k_{\text{eff}})</th>
<th>(H^{235})U</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% of Targets in Each Drawer Flooded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>308</td>
<td>32</td>
<td>0.6644 ± 0.0022</td>
<td>-0.0014</td>
<td>0.6701</td>
<td>60</td>
</tr>
<tr>
<td>156</td>
<td>16</td>
<td>0.8568 ± 0.0025</td>
<td>0.0</td>
<td>0.8568</td>
<td>409</td>
</tr>
<tr>
<td>Drawer #1 Targets Flooded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>308</td>
<td>77</td>
<td>0.9858 ± 0.0025</td>
<td>-0.0003</td>
<td>0.9912</td>
<td>99</td>
</tr>
<tr>
<td>156</td>
<td>39</td>
<td>0.9022 ± 0.0021</td>
<td>0.0</td>
<td>0.9022</td>
<td>448</td>
</tr>
<tr>
<td>All Drawer Targets Flooded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>308</td>
<td>308</td>
<td>1.1397 ± 0.0022</td>
<td>0.0</td>
<td>1.1397</td>
<td>297</td>
</tr>
<tr>
<td>156</td>
<td>156</td>
<td>0.9723 ± 0.0020</td>
<td>0.0</td>
<td>0.9723</td>
<td>645</td>
</tr>
</tbody>
</table>
TABLE IV

Comparison of ONEDANT Dimensional Search Results with Hand Calculations

<table>
<thead>
<tr>
<th>Void Region / Reflector Region</th>
<th>Reflector Thickness (cm)</th>
<th>ONEDANT (16 Group Hansen-Roach Cross Sections)</th>
<th>Two Regions, One Group Theory (Fast 6 Group Cross Sections)</th>
<th>Modified-One Group Theory (Thermal Cross Sections)</th>
<th>LA-10860-MS</th>
<th>Hand Calculation (Modified One-Group Theory with Collapsed Cross Sections)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry / Dry</td>
<td>0.0</td>
<td>736.1</td>
<td>--</td>
<td>1512.1</td>
<td>--</td>
<td>731.5</td>
</tr>
<tr>
<td>Dry / Reflected</td>
<td>0.204</td>
<td>729.2</td>
<td>1752.6</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Dry / Reflected</td>
<td>5.578</td>
<td>557.4</td>
<td>363.3</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Flooded / Dry</td>
<td>0.0</td>
<td>22.6</td>
<td>--</td>
<td>12.2</td>
<td>~12.0</td>
<td>--</td>
</tr>
<tr>
<td>Flooded / Reflected</td>
<td>0.204</td>
<td>22.1</td>
<td>15.2</td>
<td>--</td>
<td>~5.0</td>
<td>--</td>
</tr>
<tr>
<td>Flooded / Reflected</td>
<td>5.578</td>
<td>14.4</td>
<td>2.6</td>
<td>--</td>
<td>~5.0</td>
<td>--</td>
</tr>
</tbody>
</table>
TABLE V

Four Neutron Energy Group Structure

<table>
<thead>
<tr>
<th>Neutron Energy Group</th>
<th>16 Group Structure</th>
<th>Group Name</th>
<th>Group Energy Range (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-5</td>
<td>fast</td>
<td>0.1 - ∞</td>
</tr>
<tr>
<td>2</td>
<td>6-13</td>
<td>resonance</td>
<td>1.0x10^-6 - 0.1</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>epithermal</td>
<td>4.0x10^-7 - 1.0x10^-6</td>
</tr>
<tr>
<td>4</td>
<td>15-16</td>
<td>thermal</td>
<td>0.0 - 4.0x10^-7</td>
</tr>
</tbody>
</table>
TABLE VI

ONEDANT Results of the Neutron Production Spectrum

<table>
<thead>
<tr>
<th>Void Region / Reflect Region</th>
<th>Reflector Thickness (cm)</th>
<th>Average Neutron Energy Group Causing Fission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry / Dry</td>
<td>0.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Dry / Reflected</td>
<td>5.6</td>
<td>7.7</td>
</tr>
<tr>
<td>Flooded / Dry</td>
<td>0.0</td>
<td>15.4</td>
</tr>
<tr>
<td>Flooded / Reflected</td>
<td>5.6</td>
<td>15.5</td>
</tr>
</tbody>
</table>