SANDIA REPORT

SAND2001-1826
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Printed July 2001

Criticality Safety at the Manzano Nuclear Waste Storage Facilities

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ABSTRACT

The objective of this report is to provide technical information regarding the criticality safety of the Manzano Nuclear Waste Storage Facilities (MNWSF) operated by the Radioactive Waste/Nuclear Material Disposition Department (Department 7135). The information provided includes a brief description of the MNWSF, details of the criticality safety issues facing this facility, a detailed discussion of the approach taken to adequately assess these safety issues, and the results of a parametric analysis leading to a set of criticality controls. The contents provide a technical basis for the criticality safety components of the facility operating procedure: "Ensuring Criticality Safety and Inventory Control at the Manzano Nuclear Waste Storage Facilities" Sandia National Laboratories, FOP 96-08. This procedure relies on administrative and geometry controls to ensure criticality safety at MNWSF.

A criticality safety analysis was performed using conservative assumptions that optimize cross-communication between containers of fissile material and eliminate criticality safety controls on U-235 enrichment and moderation (hydrogen-to-uranium atom ratio). The results of this analysis yielded criticality safety driven controls for the safe operation of MNWSF, which are implemented in the facility operating procedure. The double contingency principle is satisfied in that two or more simultaneous changes to the storage conditions must take place to lead to a criticality incident. The analysis shows that when the criticality safety procedure is implemented properly and fissile material stored accordingly, the MNWSF is sufficiently safe to store fissile materials.

ACKNOWLEDGEMENTS

Originally this work was presented in the internal technical memo: "Criticality Safety at the Manzano Waste Storage Facility," from J. Liscum-Powell (9364) to J. Jones (7573), Sandia National Laboratories, Albuquerque, New Mexico, March 7, 1996.

The author wishes to acknowledge Jeff Philbin, SNL Criticality Safety Officer, for suggesting this study and supporting the transition from a technical memo into a SAND report and reviewing the document for technical merit. Ted Schmidt provided the Sandia Nuclear Criticality Safety Committee (SNCSC) review of this document. Gary Harms served as the technical peer reviewer for this work in the original technical memo. Finally, the author wishes to acknowledge the contributions of the Manzano SAR team members who were instrumental in the initial development of this work: LeAnn Adams Miller, Cathy Ottinger, Gary Polansky, Nancy Ries, Gina Rightley and Joe Saloio.

This work is intended to provide the Radioactive Waste/Nuclear Material Disposition Department (Department 7135) which owns and operates the Manzano Nuclear Waste Storage Facilities with supporting documentation for their criticality safety operating procedures.

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1.0 Introduction

The Manzano Nuclear Waste Storage Facilities (MNWSF) are owned and operated by the Radioactive Waste/Nuclear Material Disposition Department (7135). The facility consists of four structures at the Manzano Base: Structures 37057, 37055, 37063, and 37078. These facilities are intended for the storage of mixed wastes, low-level radioactive wastes, and TRU-waste. There are two types of structures in the facility: Type C (37078) and Type D (37055, 37063 and 37057). Table 1 lists the typical dimensions of the main chamber of these structures and their respective maximum storage capacities.

Table 1 Dimensions and Maximum Storage Capacity of MNWSF Structures

Bunker Type	Width (ft)	Length (ft)	Height (ft)	*Maximum Storage Capacity (ft^3)
Type C	29.33	82.92	12.75	9,852
Type D	26.42	60.67	12.50	6,211

*As stated in Chapter 2 of the Manzano Waste Storage Facility SAR[1]

Each MNWSF structure is a Hazard Category 3 Nuclear Facility and is subjected to the radionuclide inventory limits stated in Attachment 1 of DOE Standard 1027-92.[2] Radionuclides that can be stored in this type of facility include the following fissile isotopes: U-235, U-233, Pu-239, Pu-240, Pu-241, Am-241 and Np-237. According to DOE Standard 1027-92, the total U-235 fissile mass equivalent allowed is 1.10×10^5 kg if criticality safety analysis shows it is safe. However, the threshold mass limit at which criticality controls are required for fissile isotopes is 700 g total U-235 fissile mass equivalent. Appendix A provides the U-235 equivalency ratios for the fissile isotopes listed above. The mass limit of 1.10×10^5 kg U-235 fissile mass equivalent is a significant amount of fissile material that could undergo a critical excursion under adequate conditions; and thus, poses a criticality safety concern. The presence of this potential safety issue makes it necessary to evaluate the criticality safety of the MNWSF structures. In assessing the criticality safety at MNWSF, it is important to note that these structures serve only as storage facilities. The material stored at MNWSF does not undergo any process to alter its make-up or geometrical configuration.

Further limitations on the actual fissile mass that can be stored in the MNWSF structures exist due to the maximum storage capacity of each structure, the spacing constraints and the limit of U-235 fissile mass equivalent per storage cell.[3] Table 2 summarizes the maximum amount of U-235 that can be stored in the two types of structures at MNWSF

assuming the maximum storage volume is exhaustively utilized and filled with storage cells containing 2 kg of U-235.[3] Under this assumption the maximum mass of U-235 that can be stored in any given structure at the MNWSF is three orders of magnitude less than the mass potentially allowed at a Hazard Category 3 Nuclear Facility.

Table 2 Summary of Maximum Storage Capacity of the MNWSF Structures in Terms of U-235 Mass.

Bunker Type (Dimensions)	Volume of Bunker (ft^3)	Maximum Storage Volume (ft^3)	Maximum Number of Storage Cells	Maximum U-235 Mass (kg)
Type C (29.33 ft × 82.92 ft ×12.75 ft)	2.43531×10^4	9,852	849	**1,698**
Type D (26.42 ft × 60.67 ft ×12.50 ft)	1.57335×10^4	6,211	535	**1,070**

Although the inherent nature of the structures limits the amount of fissile material that can be stored in MNWSF, the facilities can still accommodate a significant amount of fissile material that could experience a critical excursion under ***sufficient*** conditions. Therefore, it is necessary to demonstrate that adequate criticality safety is present at MNWSF. The primary motivation for this report is to frame the assumptions and limitations supporting a 2 kg U-235 fissile mass equivalent and 2 ft spacing that was being used at storage facilities at Sandia National Laboratories including MNWSF. These limits were based on undocumented analysis before this report.

2.0 Criticality Safety

Criticality safety can be defined as the prevention of an inadvertent critical excursion or and uncontrolled fission chain reaction.[4] An inadvertent critical excursion occurs when an undesired and uncontrolled nuclear fission chain reaction takes place creating a potentially endless source of neutrons and energy resulting from the fission of fissile isotopes. Inadvertent critical excursions may result in extremely severe accidents producing harmful radiation-related effects to personnel as well as release sufficient energy that could harm personnel and equipment.[4] Therefore, ensuring criticality safety is a crucial task at facilities accommodating fissile material.

Criticality safety can be achieved by using a combination of administrative controls, geometry controls, and engineering controls. **Administrative controls** primarily involve keeping a detailed inventory of fissile materials, physical forms and locations. **Geometry controls** include proper spacing of fissile material to ensure a favorable critical geometry is not easily attained and to prevent or substantially limit cross-communication of neutrons between containers holding fissile material. **Engineering controls** usually involve system designs to ensure criticality safety. At the MNWSF facilities administrative and geometry controls are used as a method for ensuring criticality safety.[3] These type of controls are sufficient to provide criticality safety since these facilities are used for storage purposes only and procedures prohibit mechanical or chemical processing.

For a criticality incident to take place at one of the MNWSF structures, the following conditions must occur simultaneously:

Condition (a) A sufficient mass of fissile material must accumulate,
Condition (b) Adequate cross-communication of neutrons between storage cells must exist,
Condition (c) The fissile material must assume a favorable geometry configuration,
Condition (d) Neutrons must undergo sufficient moderation.

The optimum composition of fissile material referred to in ***Condition (a)*** would involve having the ideal amount of moderator mixed intimately with the fissile material; the optimum atom density of fissile isotopes, etc. In ***Condition (d)*** the sufficient moderation referred to is the slowing of neutrons to thermal energies at which fission is a highly probable interaction.

To demonstrate adequate criticality safety the ***double contingency principle*** must be satisfied. This principle demands that two unlikely, independent and concurrent changes in the process conditions occur before a criticality excursion is possible.[4] The analysis presented later in this report will show that the double-contingency principle is satisfied and that administrative and geometry controls at MNWSF are sufficient to reasonably assure that no criticality accident is possible.

As stated earlier, the waste that is to be stored is not subjected to any processes that would alter the geometry of the material, its physical form, or add moderating materials to packaging. ***The MNWSF simply stores the material***. The nature of operation at MNWSF is such to preclude the existence of ***Conditions (a)*** and ***(c)*** above as well as limit neutron cross-communication (***Condition (b)***) between packages containing fissile material through spacing constraints. ***Condition (a)*** can be precluded because fissile material will not be packaged in such a manner as to allow the optimum mass and density to accumulate with an ideal amount of moderator mixed intimately with the fissile material. Typically, material packaged in this configuration would be screened out as a candidate for further processing or subdivided before being accepted for storage. Similarly, fissile material will not be packaged in an optimum geometry for criticality for the same reason (***Condition (c)***). That is fissile material will not be shaped into an optimal critical geometry prior to packaging and storage. For these reasons the main criticality safety concerns at MNWSF are: ***Condition (b)*** cross-communication of neutrons between storage cells; and ***Condition (d)*** addition of moderator to the storage facility (e.g. introduction of water in the event of a fire or flooding of a structure).

The criticality safety operating procedure "Ensuring Criticality Safety and Inventory Control at the Manzano Nuclear Waste Storage Facilities" dictates the use of administrative and geometry controls to ensure the safe storage of fissile material at MNWSF.[3] The fundamental basis of this operating procedure is the specific requirement of a ***minimum two-foot, center-to-center separation of storage cells that contain a fissile mass equivalent of 2 kilograms U-235 or less***. The spacing constraints are imposed to prevent substantial cross-communication between storage cells containing fissile material, and thus, addresses ***Condition (b)*** needed for criticality above. These spacing constraints will be shown to be adequate in the criticality analysis that follows.

The most probable scenario for a critical excursion to occur at MNWSF is following the addition of a sufficient amount of neutron moderator, such as water, to a structure. ***The primary criticality safety issue posed by MNWSF is whether or not any restrictions need to be placed on the use of water as the primary fire-fighting agent or if water entering the structures due to a natural disaster or severe weather conditions is a concern.*** To determine whether or not these are realistic concerns for criticality safety at MNWSF a certain extent of criticality analysis is necessary as described in the following section.

2.1 Approach to Criticality Analysis

The criticality calculations presented herein were performed with MCNP, which is a three-dimensional Monte-Carlo Neutron Photon Transport Code that is used widely throughout the nuclear industry for criticality calculations.[5] MCNP is a general purpose, continuous energy, three-dimensional, coupled neutron-photon transport code capable of calculating eigenvalues or effective multiplication factors (k_{eff}) for fissile systems.[5] For the purposes of criticality safety, $k_{eff}+\in \geq 0.95$, where $\in$ is the uncertainty and bias factor, is considered a potentially critical system allowing for slight deviations in calculations while systems with $k_{eff}+\in \leq 0.95$ are considered sub-critical.[6,7]

A number of criticality safety benchmark calculations using MCNP version 4a and criticality safety benchmark problems presented in "MCNP: Neutron Benchmark Problems" were performed to determine the bias.[8] A number of fissile compositions and configurations were evaluated including configurations that are relevant to the MNWSF including a highly enriched unmoderated system, cylinders containing low-enriched uranium, a water reflected uranium sphere and a system of three interacting uranium cylinders. The results of these benchmarks are as follows:

System	True k_{eff}	MCNP Benchmark Value	SNL MCNP Result
Godiva	1.000	0.9976 ± 0.0011	0.99762 ± 0.00109
Low Enriched Cylinder:			
10.90% U-235	1.000	1.0024 ± 0.0013	1.00124 ± 0.00083
14.11% U-235	1.000	1.0003 ± 0.0014	1.00374 ± 0.00106
H_2O Reflected Sphere	1.000	0.9956 ± 0.0022	0.99508 ± 0.0017
Interacting Units:			
3 Uranium Cylinder	1.000	0.9991 ± 0.0011	1.00133 ± 0.00114

The largest bias observed in the MCNP calculations was 0.00492. The version of MCNP used in the benchmark problems along with the same cross-sections was used in this criticality analysis. As discussed earlier, the configurations of fissile material evaluated are considered sub-critical as long as it is characterized by a $k_{eff}+\in \leq 0.95$, where $\in$ includes the statistical uncertainty and the bias determined by the benchmark calculations.

The primary objective of this analysis is to demonstrate that with proper controls implemented at MNWSF, the facility is sufficiently safe from an inadvertent critical excursion. The controls utilized at MNWSF are geometry, spacing, and fissile mass limits in the storage cells. This analysis will also demonstrate that moderation and enrichment limits are not controls on the waste to be stored at this facility.

The waste to be stored at this facility will be contained in isolated packages; and therefore, from the perspective of a neutron the MNWSF will appear to be a heterogeneous system. Evaluating the criticality safety in these structures requires the development of a realistic model of the stored material. The determination of a worst case scenario from a criticality safety viewpoint, which is the most probable to experience a critical excursion, is also necessary. If a criticality excursion is observed for a given configuration of storage cells, controls are put in place to demonstrate that the facility is safe with the implementation of such controls. The development of such a model brings up a number of difficult questions regarding the modeling of the MNWSF sufficiently.

The problems associated with analyzing the criticality safety at MNWSF are as follows:

- **The problem is very inadequately defined and will remain poorly defined throughout the facility lifetime**. Presently, it is not known what the fissile material will look like, how it is being stored or packaged, what other materials are mixed with it. The outer shape and dimensions of the containers will be known when they are submitted for storage at MNWSF. However, the thickness of container walls and inner container dimensions, and material contents may only be known as a result of process knowledge and records.

- **It is highly improbable that the structures will only accommodate waste containing fissile isotopes**. Thus, modeling the structures as though they retain only fissile materials and moderators is conservative. This assumption could possibly make the structures seem more hazardous in terms of criticality safety than they actually are.

- **While the 2 kg U-235 mass equivalent limit placed on the storage cells is adequate for criticality safety coinciding with proper spacing and geometry of the material, it is a sufficient amount of material that it can be forced into a critical configuration**. It is extremely important to make realistic assumptions regarding the fissile material configuration in MNWSF. For example, Appendix B details the k_{eff} for placing spheres of UO_2 containing 2 kg of U-235 in a 64 cell cubic array showing how easily spheres can reach a critical state.

2.2 Assumptions in the MNWSF Criticality Analysis

To develop an appropriate and valid model of the MNWSF structures MCNP calculations were performed that evaluate waste material in cylindrical containers as both single storage cells and in cubic and linear arrays. A cubic array is considered a worst case configuration because optimum cross-communication may take place. To perform these calculations assumptions must be made to bound the problem. Consequently, all assumptions made in the calculations will determine the requirements of a criticality safety operating procedure.

To bound the calculation realistically the following assumptions were made in this analysis:

(1) Waste is packaged in standard cylindrical containers (R=11.25 in, H=33.5 in). This assumption is based on the fact that waste and other material is often stored in standard 55 gallon steel drums.[9] Representing smaller packages as 55 gallon drums should be conservative for most cases. As long as waste is packaged in a container that fits within the boundaries of the storage cells and meets the criteria outlined in the criticality safety operating procedure, it is acceptable for storage. This means that other shapes such as boxes are allowed as long as they fit within the two-foot by two-foot storage cell and are no taller than 33.5 in.

(2) ***Fissile material and moderator is smeared homogeneously throughout volume of drum***. This configuration maximizes cross-communication between storage cells.

(3) ***The steel material that the standard drum is composed of is not modeled***. This is conservative because steel acts as a neutron poison by absorbing neutrons. Packages made of other materials may be stored in MNWSF.

(4) ***The density of the fissile material will not exceed 70% void ($\rho \geq 0.30\ \rho_{TD}$)***. Increasing the amount of void in the fissile material increases its physical volume, spreading the material over a larger space and making cross-communication more likely. Furthermore, it prevents excessive self-shielding of neutrons in the fissile material. The presence of void also allows for fissile material and moderator to be mixed intimately.

(5) ***The density of water filling the void in storage cells (outside of containers) and acting as a moderator and reflector will be varied from 100% theoretical density (ρ_{TD}) to 0% ρ_{TD}.*** This allows the determination of the worst case for the addition of water into the structures. Flooding the structures may result in over-moderation yielding a sub-critical system while introducing small amounts of water into a system that is under-moderated could be more hazardous yielding a critical excursion. Small quantities of water might be introduced during fire fighting in case of a fire in one of the structures.

(6) ***The fissile material evaluated is uranium dioxide (UO_2) in which all the uranium is U-235 (100% enriched)***. Using highly enriched material will bound lower enrichments, and it is expected that the waste will be UO_2 and could possibly be highly enriched. Other fissile materials are permissible as long as the fissile mass does not exceed 2 kg U-235 fissile mass equivalent. Appendix C presents a few results which demonstrate that the UO_2 calculations bound U metal.

(7) ***The hydrogen-to-uranium atom ratio (H/U) delineated throughout the analysis is a ratio of the total hydrogen atoms to the total uranium atoms in the container analyzed***. It contains only moderator that is intimately mixed with the fissile material but does not contain contiguous materials such as moderator in the storage cell but outside of the containers. This ratio is crucial in understanding whether or not the fissile material is over-moderated or under-moderated. If the material is under-moderated, the addition of moderator will result in an increase in k_{eff}; however, if the material is over-moderated additional moderator will decrease the k_{eff}.

The purpose of the assumptions detailed above are to enable a criticality analysis to be performed that bounds a very poorly defined problem. These assumptions are meant to be conservative, ensuring that MNWSF is safe. Next, the results of this analysis are presented.

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3.0 Results of MNWSF Criticality Analysis

This section presents the results of the criticality analysis performed on MNWSF using the approach detailed in Section 2.0. The determination of the criticality safety controls implemented by the criticality safety operating procedure is detailed.

3.1 Geometry Controls

The first control that is established is the geometry control. This is done by first analyzing a three-dimensional array of storage cells. Each storage cell itself must be a sub-critical unit when fully submerged in water.[6] Each storage cell is 2 ft by 2 ft by 2.79 ft (height of a 55 gallon drum). The three-dimensional array contains 8 storage cells (16 ft) in the x-direction along the width of the bunker, 40 cells (80 ft) in the length of the bunker or y-direction and is 3 cells (≈ 9 ft) high. Thus, this configuration contains 960 storage cells and a total of 1,920 kg of U-235. The three-dimensional array is fully reflected on all six sides with 6 inches of water at full density. The analysis performed with this configuration was done for four different hydrogen-to-uranium atom ratios to evaluate the characteristic k_{eff} as a function of the quantity of moderator mixed with the fissile material. The H/U ratios utilized in this analysis were derived based on filling 5, 2, and 0.9 volume percent of the void in the UO_2 with a polyethylene moderator (CH_2). These values were initially chosen to assess the effect of H/U on k_{eff}. Figure 1 depicts these results.

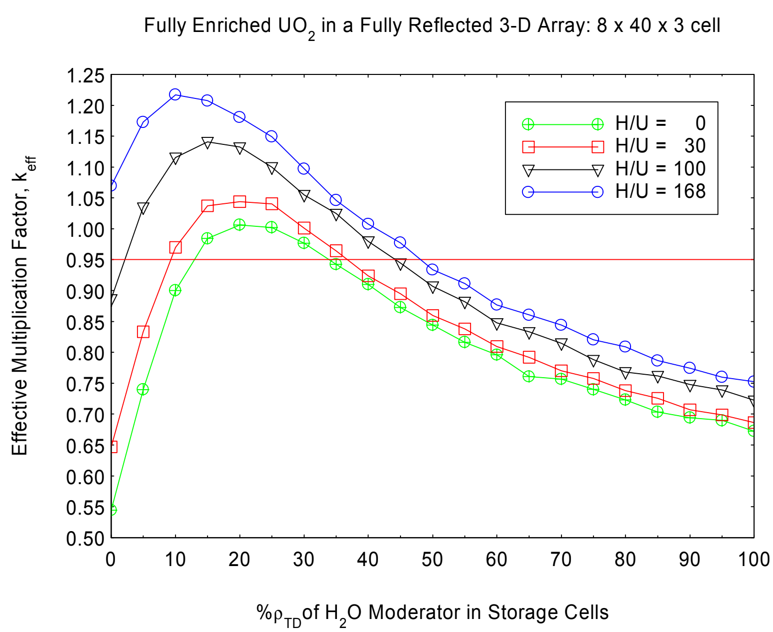

Figure 1 Effective Multiplication Factor Vs. % ρ_{TD} H_2O Moderator in Storage Cells as a Function of H/U for a Cubic Array

Figure 1 clearly depicts that a cubic array of storage cells containing 2 kg of U-235 in the form of fully enriched UO_2 is an unacceptable configuration. In this configuration, the neutrons are undergoing substantial cross-communication between storage cells resulting in a $k_{eff} > 0.95$ at various moderator densities in the storage cells. For all cases evaluated, the configuration is over-moderated when the density of the H_2O moderator is greater than 20% ρ_{TD}. The cases with the higher H/U ratios of 100 and 168 evaluated are under-moderated for moderator densities below 10% ρ_{TD}; while the cases with the lower H/U ratios of 0 and 30 are under-moderated for densities below 20% ρ_{TD}. Spraying an under-moderated configuration with water, such as might occur during fire fighting, could possibly initiate a critical excursion. The results indicate that a complete flooding of the facility would result in a significantly over-moderated system that would remain well below critical for the H/U ratios evaluated here.

Since a cubic-array configuration is unacceptable, more controls are placed on the geometry by eliminating the stacking of storage cells. This reduces the configuration to a two-dimensional array consisting of eight linear arrays with 40 storage cells each that are adjacent to each other with no surface-to-surface separation. The two-dimensional configuration is fully reflected by water at full density on all six sides. This configuration reduces the number of storage cells to 320 containing a total of 640 kg of U-235. The results of this analysis are depicted in Figure 2.

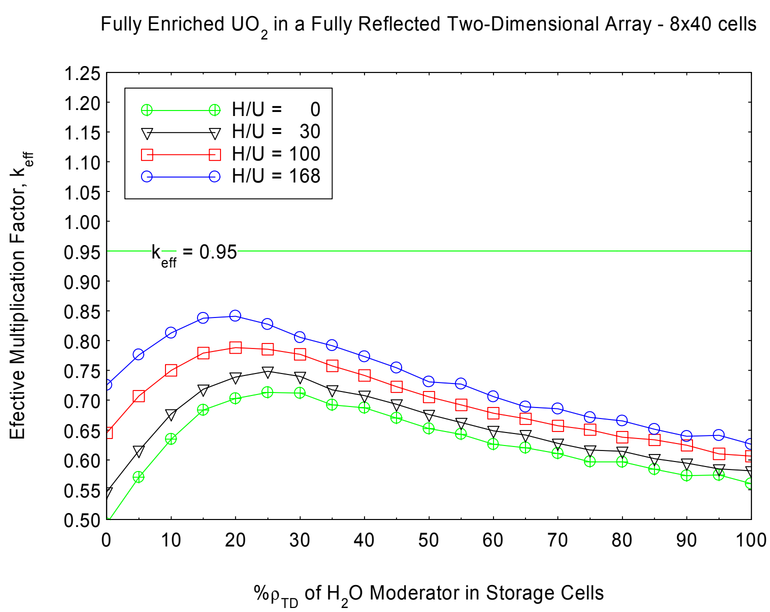

Figure 2 Effective Multiplication Factor Vs. %ρ_{TD} H_2O Moderator in Storage Cells as a Function of H/U for a Two-Dimensional Array

The results presented in Figure 2 demonstrate how eliminating the stacking of storage cells drastically reduces the effective multiplication factor characterizing the system. For all moderator densities evaluated and all four hydrogen-to-uranium atom ratios, the configuration remains sub-critical. The maximum value of k_{eff} is observed at a storage cell moderator density range of 15% to 25% ρ_{TD} for all H/U ratios evaluated.

As the result of this analysis, the following geometry control is placed on MNWSF: ***no stacking of storage cells in the z-direction is permitted at MNWSF***.

3.2 Addressing Moderation Limits

The analysis presented above demonstrates the effectiveness of placing a geometry control on the facility, which prohibits the stacking of storage cells in the z-direction. However, it limits the amount of moderator that can be mixed intimately with the fissile material. The possibility that the containers could be completely or partially flooded with H_2O needs to be addressed to eliminate the need for sealed containers. Such analysis will also identify the worst hydrogen-to-uranium ratio (H/U), or moderator content, which could make a criticality incident a credible scenario. Identifying and using this ratio in further analysis will eliminate moderation limits as a control for criticality safety. A H/U of approximately 30 can be considered a generous ratio for fissile materials; however, higher ratios could be obtained if the containers at the facility are flooded.

Due to the relatively low volume that fully enriched UO_2 containing 2 kg of U-235 occupies, there is a significant amount of void in the standard drums that could possibly be filled with H_2O if the containers leaked when H_2O is introduced into the bunkers (see Appendix D). The UO_2 and H_2O are intimately mixed and smeared homogeneously through the volume of the container to optimize both moderation and cross-communication. The two-dimensional configuration evaluated in Figure 2 is reevaluated in this analysis for various hydrogen-to-uranium atom ratios corresponding to filling different fractions of the void in the drum with H_2O. The moderator in the storage cells outside the container is held constant at 20% ρ_{TD} of the H_2O which represents the vicinity where k_{eff} peaks in Figures 1 and 2. Figure 3 depicts these results.

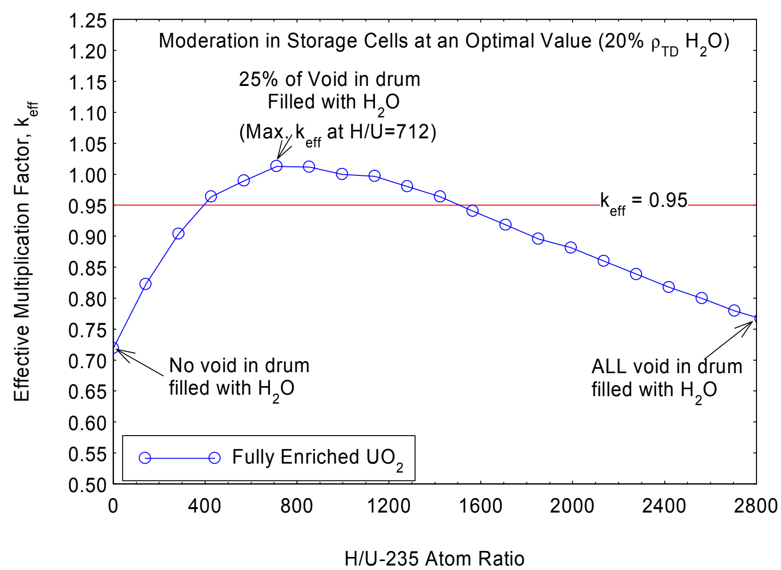

Figure 3 Effective Multiplication Factor of a Two-Dimensional Configuration of Storage Cells Vs. Hydrogen-to-Uranium Atom Ratio in Drum.

Figure 3 demonstrates that the configuration in Figure 2 can be forced into a critical configuration if a sufficient quantity of moderator were added to the fissile material inside the drum. At a hydrogen-to-uranium ratio of 712, a peak k_{eff} is observed of approximately 1.02. This ratio corresponds to 25% of the void in the drums flooded with H_2O. In order to eliminate moderation as a control necessary to maintain criticality safety at MNWSF further evaluations will be made with storage cells containing 2 kg of U-235 mixed intimately with moderator at a H/U ratio of 712.

A requirement of the ANS/ANSI 8.7 standard, "American National Standard for Nuclear Criticality Safety in the Storage of Fissile Material," is that each storage unit remains sub-critical when completely submerged in H_2O.[6] Thus, we must verify that this condition is satisfied at MNWSF. We also need to ensure that a hydrogen-to-uranium ratio of 712 bounds the worst case for a single storage cell. To accomplish this a similar analysis to that given in Figure 3 was performed for a single storage cell that is completely submerged in H_2O. The results of this analysis are delineated in Figure 4.

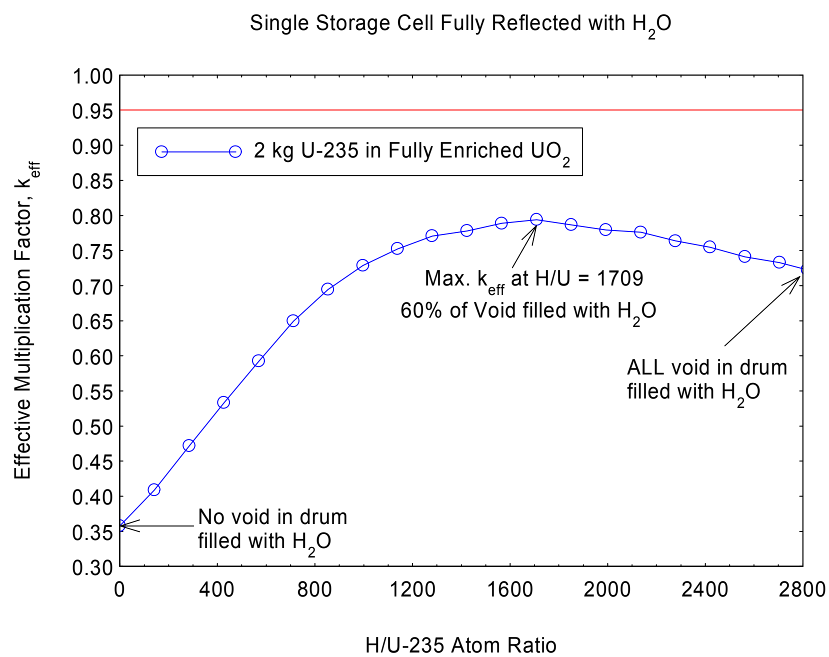

Figure 4 Effective Multiplication Factor of a Single Storage Cell Fully Submerged in H_2O Vs. H/U-235 Ratio

For single storage cells, the worst case H/U ratio is 1709 which corresponds to 60% of the void in the drum flooded with water. To eliminate the degree of moderation in the fissile material as a criticality safety control both H/U ratios (712 and 1709) are evaluated in further analysis. Both of these conditions yield the maximum k_{eff} depending on whether or not a single storage cell or an array of storage cells is evaluated. It is possible that either one of these H/U ratios could result in a critical excursion under sufficient conditions.

Moderation limits at MNWSF are eliminated by performing analysis at the H/U ratios that are identified to be worst case for arrays of storage cells and single storage cells.

The next analysis will evaluate configurations of linear arrays containing storage cells at optimum moderation. The results will indicate how implementing surface-to-surface separation of the linear arrays affects the characteristic k_{eff}.

3.3 Spacing Controls

In this section, the need for separation between the linear arrays is evaluated. In the previous analysis, linear arrays are placed adjacent to each other without any surface-to-surface separation. A similar analysis is performed placing storage cells containing 2 kg U-235 at H/U=712 and H/U=1709 into 2-D arrays, respectively. The storage cells are placed in a 2-D array that is 8×40 cells with no surface-to-surface separation and with a 4 ft surface-to-surface separation. A linear array is 40 cells in length; thus, this configuration is actually made up of 8 side-by-side linear arrays.

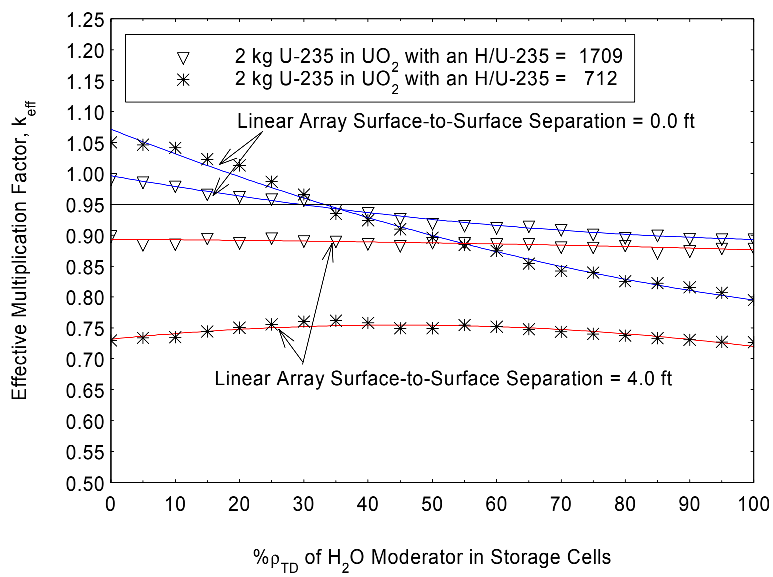

Figure 5 Effective Multiplication Factor Vs. H_2O Moderator Density in Storage Cells as a Function of Surface-to-Surface Separation Between Linear Arrays

Initially, a comparison between the two H/U ratios is made with no surface-to-surface separation between linear arrays as a function of the moderator density in the storage cells. The results are shown in Figure 5. For both H/U ratios, this configuration is unacceptable because $k_{eff} > 0.95$ with no moderator in the storage cells which is the normal operating condition at MNWSF. However, there is a need for spacing between linear arrays to allow for inspectors to survey packages and to permit personnel, forklifts, and other equipment to move around the packages as necessary. Thus, the k_{eff} is evaluated for a configuration of eight linear arrays with 40 storage cells per array with a surface-to-surface separation of 4 feet at various moderator densities in the storage cells and between the linear arrays. As delineated in Figure 5, this configuration remains sufficiently sub-critical for all moderator densities. Appendix E depicts the affect on k_{eff} for this configuration when the thickness of the H_2O reflector is increased to as much as 12 inches.

Thus far, analysis has shown that to undergo a critical excursion, 320 storage cells filled with 2 kg U-235 would have to be arranged side by side with no moderator in the cells. Each drum or storage unit would have to have at least 25% to 60% of its void flooded with H_2O yielding high H/U ratios (> 700). Earlier analysis shown in Figure 2 shows that at low H/U ratios, linear arrays without surface-to-surface separation remain sub-critical under all moderating conditions.

As the result of this analysis, the following spacing control is placed on MNWSF: ***linear arrays of storage cells must be separated by a minimum of 4 ft surface-to-surface***.

3.4 Criticality Alarm Exemption

The ES&H Manual Supplement on Nuclear Criticality Safety, GN470072, in regards to determining the need for a criticality accident alarm system states:

> "In those cases where the mass of fissile material exceeds the above amounts [520 grams U-233, or 700 grams U-235, or 450 grams of Pu-239 or Pu-241, or 450 grams of any combination of U-233, U-235, Pu-239 or Pu-241 in any form but aqueous solutions], but a criticality event is determined to be impossible due to the physical form of the fissionable material, or the probability of occurrence is determined to be less than 10^{-6} per year (as documented in a DOE-approved SAR), an alarm system is not required."[7]

MNWSF is characterized as having a probability of less than $1x10^{-6}$ (one in a million) of experiencing a criticality excursion.[1,10] Thus, due to the nature of the operation of MNWSF, the safety provided by the implementation of the criticality safety controls and the extremely low probability of a criticality excursion MNWSF is not required to have a criticality alarm system.

3.5 Possible Mass Limit Violation

One of the fundamental controls implemented at MNWSF for criticality safety, is a fissile mass limit of 2 kg U-235 or its equivalent per storage cell. Packages containing more than 2 kg of U-235 fissile mass equivalent can only be stored if the material is in a Type B DOT container or the storage cell is enlarged to store this material and it is shown to be safe through analysis. However, there is always the possibility of a package containing more than 2 kg U-235 or its equivalent being inadvertently placed in MNWSF due to a miscalculation by personnel. This type of error would involve a worker violating the written procedure by miscalculating the mass in a given package and the failure of a checker to detect the error.[3] The occurrence of these events is expected to be fairly rare, 1×10^{-4}, and should be multiplied by the average number of times a year that fissile material is brought into the facilities to get a probability per year.[10] It is also important to note that this facility does not store fissile material only and often the addition of packages will not be important to criticality safety issues. Non-fissile packages should not typically be stored in a fissile material storage array unless the fissile material is in trace amounts.

The double-batching of storage cells is often evaluated to observe the effects of a storage cell containing twice the allotted mass of fissile material.[6] Double-batched storage cells must remain sub-critical upon being submerged in water. A single, fully reflected storage cell with 4 kg U-235 and a H/U=712 was characterized by a $k_{eff} \approx 0.9953$; thus, this configuration is completely unacceptable. Double-batching of a cell or cells at this high of a H/U ratio is not allowed in MNWSF. This does not mean packages containing more than 2 kg U-235 or its equivalent cannot be stored at this facility. If a package is identified to have a larger mass but it is sufficiently sub-critical and can be shown to be safe through a separate criticality analysis when placed among other fissile containing storage cells, an exemption may be granted and it may be stored. In addition MNWSF can store such packages as "single" unit which are spaced 6 ft from other arrays.[7] Storing such a package will require performing a criticality analysis and assessing the appropriate spacing between it and other cells as necessary. It should be noted that no processing (chemical or mechanical) takes place at MNWSF as it is a storage facility only which accepts waste at the end of a waste stream. Double-batching is considered incredible once a package is accepted into MNWSF.

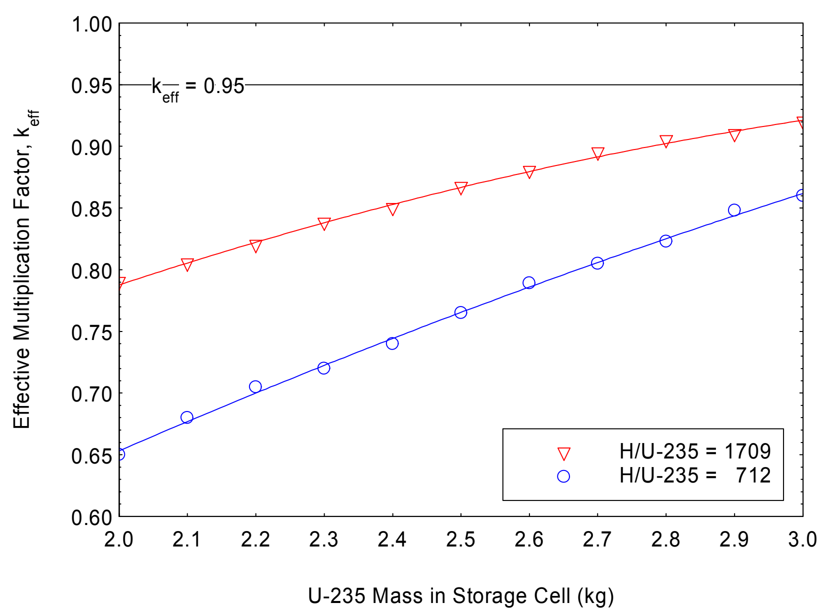

Figure 6 Effective Multiplication Factor of a Single, Fully Reflected Storage Cell Vs. U-235 Mass.

To evaluate what would happen to the k_{eff} of a fully reflected storage cell if it contained more than the equivalent of 2 kg U-235 a simple analysis was performed for H/U ratios of 1709 and 712, respectively. Figure 6 depicts the results of this analysis in which errors in the fissile mass calculation up to 50% higher than the 2 kg limit (up to 3.0 kg U-235) were evaluated. The cells remain sub-critical, but k_{eff} clearly increases monotonically with increasing fissile mass.

In Figure 6 a storage cell containing 3 kg of U-235 at an H/U = 1709 had the highest k_{eff} of ≈ 0.92. Storage cells containing 3 kg U-235 were evaluated in a fully reflected linear array of 40 storage cells with an H_2O moderator in the cells at 20% ρ_{TD}. The results of this analysis are presented in Table 3. These results indicate that placing two storage cells with 3 kg U-235 adjacent to each other in a linear array is a sub-critical with k_{eff} = 0.932. This configuration is fully reflected and contains H_2O moderator in the storage cells at 20%ρ_{TD}. It is highly unlikely that workers will miscalculate the mass on two fissile material packages and place them side-by-side in a linear array if they follow the implemented procedures properly.

Table 3 Values of k_{eff} for a Linear Array as a Function of Storage Cells Containing 3 kg U-235 at an H/U Ratio of 1709.

Number of Cells With 3 kg U-235	Number of Cells With 2 kg U-235	$k_{eff} \pm \in$
1	39	0.920
2	38	0.932
3	37	0.945
4	36	0.945

4.0 Conclusions & Criticality Controls at MNWSF

The criticality analysis summarized in this report is the basis for the criticality safety driven controls implemented at MNWSF by the facility operating procedure[3] which are sufficient to ensure criticality safety. Proper implementation of the criticality controls at MNWSF ensures that the facility will not undergo an inadvertent critical excursion in the event that water is introduced into the structures. These criticality controls are geometry and spacing constraints on the storage cells along with an administrative fissile mass limit in each storage cell of 2 kg U-235 or fissile mass equivalent.

It is important to note that the values of k_{eff} presented herein are conservative, in that they were obtained using the assumption that only fissile material is stored at MNWSF and that the structures are filled to capacity. This scenario is not likely to occur during the operation of MNWSF. It is more realistic that a few packages containing fissile material will be stored in a fissile storage array in a given bunker along with other packages that do not contain fissile material in separate, non-fissile storage arrays. Calculations can be performed to assess the hazard of any storage unit and configuration of storage cells to determine whether they can be stored safely at MNWSF in accordance with the criticality safety operating procedure. These calculations should be documented and serve as a basis for a "posting" that would allow for the documented exemptions. Such units could also be stored as "single" units with a 6 ft separation from all other arrays.

The criticality controls implemented at MNWSF are as follows:

- Storage cells are a ***minimum of 2 ft by 2 ft spaced center-to-center***.
- Only ***one package*** can be placed in a storage cell.
- Storage cells contain ***a maximum of 2 kg U-235 or its equivalent*** unless the material is stored in a Type B DOT approved container or specific analysis has been performed and documented to demonstrate criticality safety.
- A ***linear array*** of storage cells contain a ***maximum of 40 cells*** (40x1x1 - where 40 cells are equivalent to length of bunker).
- Adjacent linear arrays of storage cells must be ***separated by a minimum of 4 ft surface-to-surface***.
- ***No stacking of storage cells*** in the z-direction is allowed.
- ***Any variation from the criticality safety operating procedure must be analyzed with the proper calculation techniques*** and proven to be sufficiently safe prior to being implemented at MNWSF. Temporary storage arrays are allowed for the transition of material into MNWSF as documented in the

memo from J. Liscum-Powell to D. Beets "Transition from 10268 Criticality Safety OP to 7577 FOP 96-08," dated October 1, 1997.[11]

5.0 References

1 Final Safety Analysis Report for the Manzano Waste Storage Facilities, Sandia National Laboratories, Albuquerque, NM, August 2000.

2 DOE-STD-1027-92, "Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports," U.S. Department of Energy, Washington, D.C., December 1992.

3 "Ensuring Criticality Safety at the Manzano Waste Storage Facilities (DRAFT,)" Sandia National Laboratories Department 7577 Radioactive and Mixed Waste Management Operating Procedure FOP-9608, January 1996.

4 Knief, R. A. "Nuclear Criticality Safety: Theory and Practice," American Nuclear Society, La Grange Park, IL, 1993.

5 Breismeister, J. F. MCNP-A General Monte Carlo Code for Neutron and Photon Transport, Los Alamos National Laboratory, Los Alamos, NM, LA-7396-M, Rev. 2, September 1986.

6 ANS/ANSI 8.7: "American National Standard Guide for Criticality Safety in the Storage of Fissile Materials," American Nuclear Society Standards Committee Working Group 8.7, December 1998

7 ES&H Manual Supplement GN470072, "Nuclear Criticality Safety," J. S. Philbin, January 1998.

8 Whalen, D. J., D. A. Cardon, J. L. Uhle, and J. S. Hendricks, "MCNP: Neutron Benchmark Problems," LA-12212, Los Alamos National Laboratory, Los Alamos, NM, November 1991.

9 Personal communications with Joe Jones, Sandia National Laboratories Department 7573, February 6, 1996.

10 Internal Memo to J. Liscum-Powell from J. Saloio, "Probability Estimate for Violating Criticality Safety Limits at Manzano Waste Storage Facilities," March 4, 1996.

11 Internal Memo to D. Beets from J. Liscum-Powell, "Transition from 10268 Criticality Safety OP to 7577 FOP 96-08," October 1, 1997.

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Appendix A Hazard Category 3 U-235 Fissile Mass Equivalents

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Table A-1 U-235 Equivalency Ratio Table[A-1]

Material Name	U-235 Equivalency Ratio	Unit Mass Limit
Uranium-235	1	2 kg
Uranium-233	3	0.66 kg
Americium-241	1	2 kg
Plutonium (all isotopes)	5	0.4 kg
Neptunium-237	1	2 kg

Appendix A. References

A-1 Clayton, E. D. "The Nature of Fission and the Criticality Process (From Protactinium to Californium and Beyond)," Battelle Report, Pacific Northwest Laboratories; Richland, Washington, May 1973.

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Appendix B Effective Multiplication Factor for Spheres of UO_2 as a Function of Hydrogen-to-Uranium Atom Ratio

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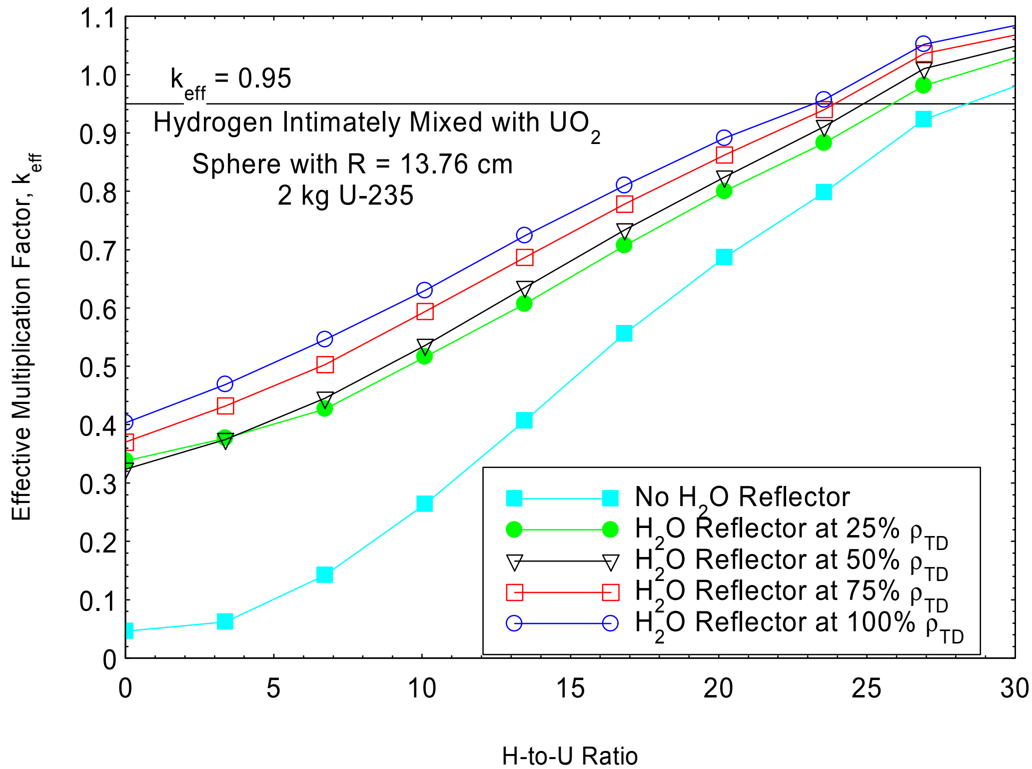

Figure B-1 Effective Multiplication Factor Vs. H/U Ratio for Spheres of UO_2 at 10% ρ_{TD}

A parametric study of the k_{eff} characterizing UO_2 spheres at 10% of its theoretical density (10.5 g/cm^3) as a function of the H/U atom ratio was performed for various reflector configurations. The amount of external reflector in the form of H_2O was varied from no reflector to a fully reflected sphere. A sphere of fissile material is an optimal geometry to yield criticality. As the H/U ratio increases, the k_{eff} characterizing the spheres of UO_2 monotonically increases eventually going critical with a k_{eff} of 0.95 for all the reflector scenarios. For example, a sphere of UO_2 (20 weight percent enriched U-235) at 10% theoretical density (R = 13.76 cm with 90 volume percent CH_2 moderator and H_2O reflector) placed in a 64 cell cubic array is characterized with a k_{eff} = 1.074. This system has a H/U ratio of 30.3 and its geometrical configuration is such that self-shielding is limited and the neutrons can undergo sufficient interactions resulting in a large critical excursion. However, if the volume percent of moderator is reduced to 50 volume percent the k_{eff} drops significantly to approximately 0.810.

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Appendix C Effective Multiplication Factor for U Metal Versus UO_2

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The results in this appendix are meant to demonstrate that performing this analysis with the fissile material in the form of UO_2 does not mean that U metal is not an acceptable form.

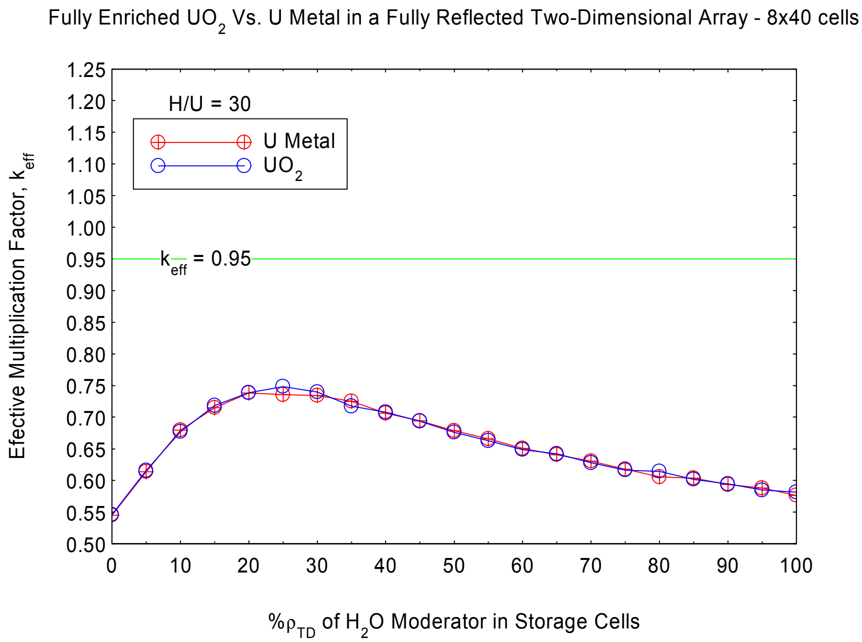

Figure C-1 Effective Multiplication Factor of U Metal Vs UO_2 in a Two-Dimensional Array with an H/U = 30

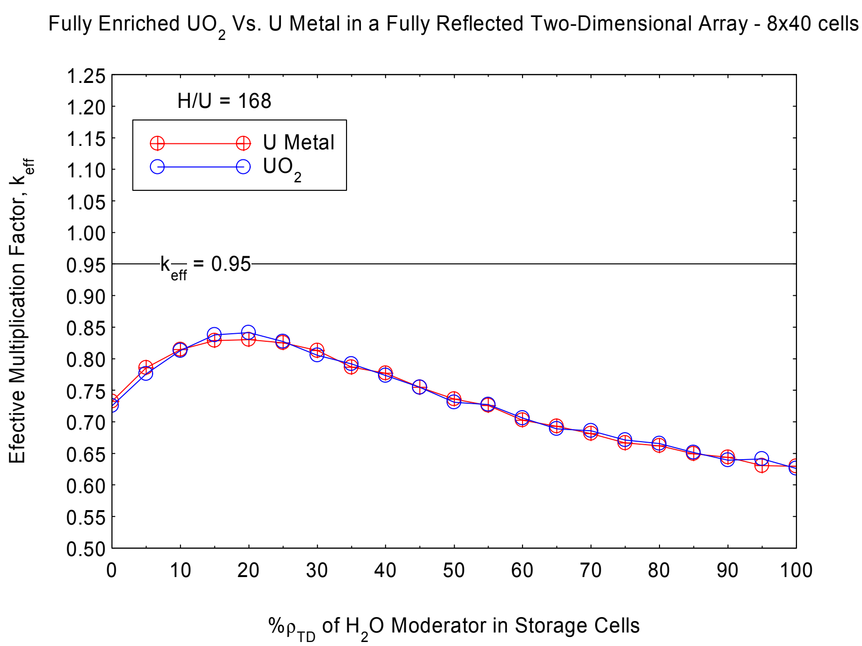

Figure C-2 Effective Multiplication Factor of U Metal Vs UO_2 in a Two-Dimensional Array with an H/U=168

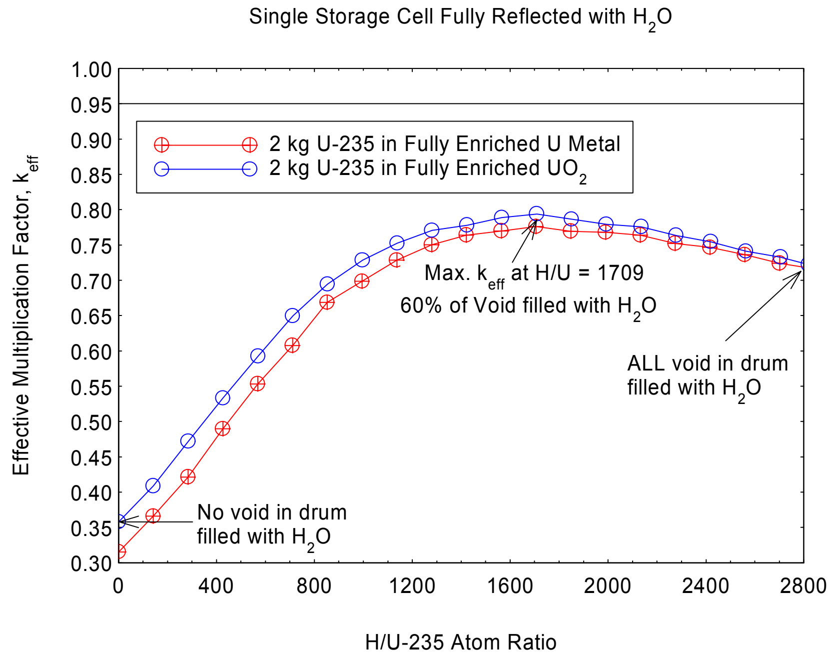

Figure C-3 Effective Multiplication of a Fully Reflected Single Storage Cell of U Metal Vs. UO_2 as a Function of the H/U Atom Ratio

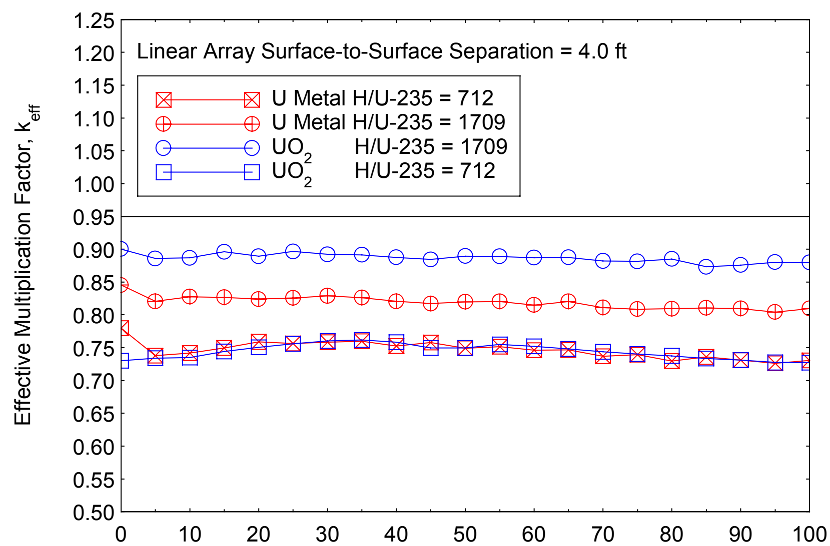

Figure C-4 Effective Multiplication Factor for Linear Arrays of U Metal Vs. UO_2 as a Function of Moderator Density in the Storage Cells

At the lower H/U-235 ratio of 712 in Figure C-4, the array configuration of U Metal is characterized with a higher k_{eff} than the configuration of UO_2 when there is no moderator (H_2O) present in the storage cells, although it remains well below critical. When water is added to the storage cells at this H/U-235 ratio the U Metal and the UO_2 curves are virtually indistinguishable from each other with both configurations remaining well below critical.

Appendix D Hand Calculations for Cylindrical Containers of UO_2 Volumes, Atom Densities, Hydrogen-to-Uranium Atom Ratio

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To calculate the atom density of nuclides for MCNP input:

$$N_i = \frac{\rho_i \cdot N_{Av}}{MW_i}\left(1\times10^{-24}\ \frac{\text{cm}^2}{\text{b}}\right)$$

N_i = Atom density of isotope i (atoms/b·cm)
ρ_i = Mass density of isotope i (g/cm^3)
N_{Av} = Avogadro's number
= 6.022×10^{23} atoms/mole
= 6.022×10^{23} molecules/mole
MW_i = Molecular or atomic weight of isotope i (g/mole)

To generate the MCNP model of a material you multiply the atom density of the material by the volume fraction it takes up in a cell (i.e. a cylindrical container). This effectively smears the material throughout the cell volume and ensures the MCNP cell contains desired amount of material.

To determine the volume fraction of a material in a cell:

$$VF_i = \frac{V_i}{V_{cell}}$$

VF_i = Volume Fraction of material i
V_i = Volume of material i (cm^3)
V_{cell} = Volume of cell (cm^3)

Volume of a cylindrical cell: $V_{cell} = \pi R^2 H$

Volume of a spherical cell: $V_{cell} = \frac{4}{3}\pi R^3$

Volume of a cubic cell: $V_{cell} = x^3$

Examples of calculating the atom densities for materials used in the criticality safety analysis:

Fully Enriched UO_2

ρ_{TD} = 10.5 g/cm^3 — *UO_2 theoretical density*

$A_{UO_2} = MW_{U-235} + 2 \cdot MW_{O-16}$ — *atomic weight UO_2*

$= 235.0439 + 2(15.9949)$

= 267.03 g/mole

$$N_{UO_2} = \frac{\rho_{TD} \cdot N_{Av}}{A_{UO_2}} \cdot \left(1 \times 10^{-24} \frac{cm^2}{b}\right)$$ *UO_2 molecular density*

= 2.36794×10^{-2} molecules/b·cm

$N_{O-16} = 2 \cdot N_{UO_2}$ — *O-16 atom density in UO_2*

= 4.73587×10^{-2} atom/ b·cm

$N_{U-235} = N_{UO_2}$ — *U-235 atom density in UO_2*

= 2.36794×10^{-2} atom/ b·cm

UO_2 with Uranium Enriched to 20 Weight Percent (w/o) U-235

ρ_{TD} = 10.5 g/cm^3 — *UO_2 theoretical density*

$A_{UO_2} = 0.20 \cdot MW_{U-235} + 0.80 \cdot MW_{U-238} + 2 \cdot MW_{O-16}$ — *atomic weight UO_2*

$= 0.20(235.0439) + 0.80(238.0508) + 2(15.9949)$

= 269.439 g/mole

N_{UO_2} = 2.34676×10^{-2} molecules/b·cm — *UO_2 molecular density*

$N_{O-16} = 2 \cdot N_{UO_2}$ — *O-16 atom density in UO_2*

= 4.69353×10^{-2} atom/b·cm

$N_U = N_{UO_2}$ — *U atom density in UO_2*

= 2.34676×10^{-2} atom/b·cm

$N_{U-235} = af_{U-235} \cdot N_U$

$N_{U-238} = af_{U-238} \cdot N_U$

Atom fractions of U-235 and U-238 are determined as follows:

$$af_i = wf_i \frac{\overline{A}}{A_i}$$

wf_i = weight fraction of isotope i

$\overline{A}$ = molecular weight of element in with this composition

A_i = molecular weight of isotope i

$\overline{A} = A_U$

$= 0.20 \cdot MW_{U-235} + 0.80 \cdot MW_{U-238}$

= 237.449 g/mole

$af_{U-235} = 0.2020$ and $af_{U-238} = 0.7980$

$N_{U-235} \;=\; af_{U-235} \cdot N_U = 4.74046\times10^{-3}$ atoms/ b·cm

$N_{U-238} \;=\; af_{U-238} \cdot N_U = 1.87271\times10^{-2}$ atoms/ b·cm

Water, H_2O

ρ_{TD}	=	1.0 g/cm^3	*theoretical density*
A_{H_2O}	=	$2 \cdot MW_H + MW_O$	*atomic weight H_2O*
	=	$2(1.0078) + 15.9949$	
	=	18.015 g/mole	
N_{H_2O}	=	$\dfrac{\rho_{TD} \cdot N_{Av}}{A_{H_2O}} \cdot \left(1\times10^{-24}\,\dfrac{cm^2}{b}\right)$	*H_2O molecular density*
	=	3.34277×10^{-2} molecules/b·cm	
N_H	=	$2 \cdot N_{H_2O}$	*H atom density in H_2O*
	=	6.68554×10^{-2} atoms/b·cm	
N_O	=	N_{H_2O}	*O atom density in H_2O*
	=	3.34277×10^{-2} atoms/b·cm	

Polyethylene, CH_2

ρ_{TD}	=	0.92 g/cm^3	*theoretical density*
A_{CH_2}	=	$MW_C + 2 \cdot MW_H$	*atomic weight CH_2*
	=	14.0269 g/mole	
N_{CH_2}	=	$\dfrac{\rho_{TD} \cdot N_{Av}}{A_{CH_2}} \cdot \left(1\times10^{-24}\,\dfrac{cm^2}{b}\right)$	*CH_2 molecular density*
	=	3.94973×10^{-2} molecules/b·cm	
N_C	=	N_{CH_2}	*O atom density in CH_2*
	=	3.94973×10^{-2} atoms/b·cm	
N_H	=	$2 \cdot N_{CH_2}$	*H atom density in CH_2*
	=	7.89946×10^{-2} atoms/b·cm	

If the actual density of a material is less than its theoretical density, multiply its component atom densities by the ratio of $\dfrac{\rho}{\rho_{TD}}$ as follows:

for UO_2 at 30% ρ_{TD}

$$\frac{\rho}{\rho_{TD}} = 0.30$$

$N_{UO_2} \;=\; 0.30(2.36794\times10^{-2}$ molecules/b·cm)

$\;=\; 7.10382\times10^{-2}$ molecules/b·cm at 30% ρ_{TD}

55 Gallon Drum Volume

$$V_{drum} = \pi R^2 H$$

$$R = 28.575 \text{ cm}$$

$$H = 85.09 \text{ cm}$$

$$V_{drum} = 2.18273\times10^5 \text{ cm}^3$$

Volume of UO_2 at 30% ρ_{TD} in a 55 Gallon Drum Volume

- Fully Enriched UO_2

Weight fraction of U-235 in UO_2:

$$wf_{U-235} = \frac{235.0439}{267.03} = 0.8802$$

Mass of UO_2 containing 2 kg U-235:

$$M_{UO_2} = \frac{M_{U-235}}{wf_{U-235}}$$

$$= \frac{2 \text{ kg}}{0.8802} = 2.27221 \text{ kg } UO_2$$

Volume of UO_2 at 30% ρ_{TD}:

$$V_{UO_2} = \frac{M_{UO_2}}{\rho_{UO_2}}$$

$$= \frac{2.27221\times10^3 \text{ g } UO_2}{(0.30)\left(10.5 \text{ g/cm}^3\right)} = 7.21337\times10^2 \text{ cm}^3$$

Volume fraction of fully enriched UO_2 at 30% ρ_{TD} in a 55 gallon drum:

$$VF_{UO_2} = \frac{V_{UO_2}}{V_{drum}}$$

$$= 3.305\times10^{-3}$$

Volume of drum that is VOID or can be filled with moderator:

$$VF_{void} = 1 - VF_{UO_2}$$

$$= 0.996695$$

- UO_2, 20 w/o Enriched U

Weight fraction of U-235 in UO_2:

$$wf_{U-235} = \frac{47.0088}{267.439} = 0.1745$$

Mass of UO_2 containing 2 kg U-235:

$$M_{UO_2} = \frac{M_{U-235}}{wf_{U-235}}$$

$$= \frac{2\ \text{kg}}{0.1745} = 11.4613\ \text{kg}\ UO_2$$

Volume of UO_2 at 30% ρ_{TD}:

$$V_{UO_2} = \frac{M_{UO_2}}{\rho_{UO_2}}$$

$$= \frac{1.14613\times10^4\ \text{g}\ UO_2}{(0.30)\left(10.5\ \text{g}/\text{cm}^3\right)} = 3.63851\times10^3\ \text{cm}^3$$

Volume fraction of 20 w/o enriched UO_2 at 30% ρ_{TD} in a 55 gallon drum:

$$VF_{UO_2} = \frac{V_{UO_2}}{V_{drum}}$$

$$= 1.667\times10^{-2}$$

Volume of drum that is VOID or can be filled with moderator:

$$VF_{void} = 1 - VF_{UO_2}$$

$$= 0.98333$$

Calculating Hydrogen-to-Uranium Atom Ratio

The Hydrogen-to-Uranium (H/U) ratio is the ratio of the number of atoms of hydrogen mixed intimately with the fissile material to the total number of Uranium atoms (U-235 and U-238). It does not include contiguous hydrogen which is the hydrogen in any reflecting regions.

$$H/U = \frac{N_H}{N_{U-235} + N_{U-238}}$$

or

$$H/U-235 = \frac{N_H}{N_{U-235}}$$

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Appendix E Effect of Increasing Reflector Thickness on the k_{eff} Characterizing the Final Linear Array Configuration

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The effects of increasing the water reflector thickness from 6.0 inches to up to 12.0 inches is depicted in the figure below for the final configuration of linear arrays with a surface-to-surface separation of 4 feet. This figure shows that the 6.0 inches of water is essentially an infinite reflector at all data points on this figure except for when there is no moderator in the storage cell. In the event that there is no moderator in the storage cell, the k_{eff} remains well below 0.95 at a value of 0.78015.

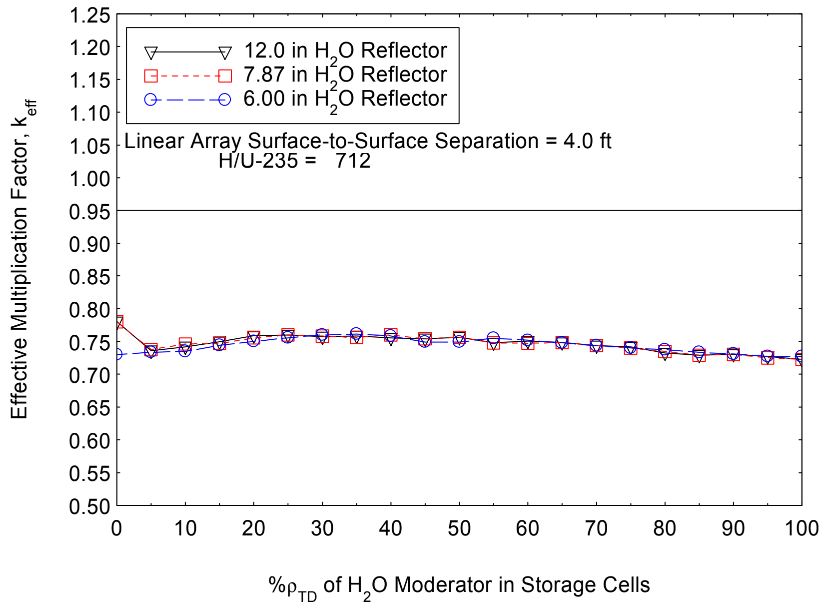

Figure E-1 Effective Multiplication Factor of UO_2 Linear Array Configuration as H_2O Reflector Thickness is Increased as a Function of Moderator Density in Storage Cells

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	MS		ORG
10	1179	J. Liscum-Powell	15341
1	1179	L. Lorence	15341
1	0346	D. Bild	12870
1	1142	W. Mickey	7213
1	1142	T. Culp	7123
1	1114	A. West	7100
1	1143	D. Berry	6433
1	1141	R. Knief	6433
1	1143	J. Mahn	6433
1	1136	M. Morris	6433
6	1141	J. Philbin	6433
1	1136	D. Vehar	6433
1	1136	S. Walker	6433
1	1143	N. Schwers	6432
1	1142	K. Boldt	6431
1	1142	J. Bryson	6431
1	1142	J. Ford	6431
1	1142	M. McCrory	6431
3	1145	T. Schmidt	6430
3	1139	K. Reil	6423
1	1146	P. Griffin	6422
1	1146	G. Harms	6422
1	1146	S. Wright	6422
1	0748	W. Cheng	6413
1	0748	C. Ottinger	6413
1	0727	G. Polansky	6406
1	0736	T. Blejwas	6400
1	1202	L. Miller	5902
1	1203	J. Saloio	5327
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