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Title: Parametric Criticality Safety Calculations for Arrays of TRU Waste Containers

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Criticality Safety Technical Document
Nuclear Criticality Safety Division

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Date: 2016-04-26

Parametric Criticality Safety Calculations for Arrays of TRU Waste Containers

1.0 Summary

The Nuclear Criticality Safety Division (NCSD) has performed criticality safety calculations for finite and infinite arrays of transuranic (TRU) waste containers. The results of these analyses may be applied in any technical area onsite (e.g., TA-54, TA-55, etc.), as long as the assumptions herein are met. These calculations are designed to update the existing reference calculations for waste arrays documented in Reference 1, in order to meet current guidance on calculational methodology.

2.0 Process Description

TRU waste staging & handling operations include various non-invasive processes, such as waste receipt, movement, lifting, labeling, overpacking, double-packing, filter replacement, etc. Waste containers may be staged outside or inside, and arrays of different containers may be commingled in a staging area. Waste containers are generally staged on pallets to facilitate movement by forklift, and aisles are typically maintained between pallets in order to allow access to each waste container and to satisfy Resource Conservation and Recovery Act (RCRA) requirements, although these aisles are not credited herein.

TRU waste is typically contained in 55-gallon and larger drums (including pipe overpacks (POCs) or smaller drums overpacked in 85- and 110-gallon drums) or Standard Waste Boxes (SWBs) and larger volume containers. Drums and SWBs used onsite are fabricated from carbon steel, and some containers may be wrapped in plastic and tape for contamination control. Containers may also include liners and/or fillers using such materials as plastics, cardboard, Celotex, bubble wrap, Styrofoam, etc. Drums of suspect integrity may be overpacked into larger drums (e.g., 85-gallon or 110-gallon) or SWBs. Containers with known or suspected free liquid may be staged on pallets that can collect leaked solution. Some individual containers may include radiological shielding (e.g., nylon-covered lead wool blankets, lead liners).

Fissionable material in TRU waste is typically in the form of small, heterogeneously distributed quantities of uranium or plutonium present as low density surface contamination on gloves (or other personal protective equipment), wipes, bags, filters, tools, dismantled process equipment (e.g., sieves, filters), and laboratory vessels. Small quantities of salt cakes, cemented solids, or other residues may also be present, and these materials may contain low concentrations of plutonium or other nuclides if it was not feasible to recover them. As opposed to the more distributed form of waste, these residues might be present in small volume inner containers, e.g., 5-gallons or less.

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The current Waste Isolation Pilot Plant (WIPP) Waste Acceptance Criteria (WAC) limits 55-gallon drums to 200 FGE and SWBs to 325 FGE. However, prior to the establishment of the WIPP WAC, waste drums and other containers could be loaded with greater masses, resulting in a number of legacy containers that do not meet the WIPP WAC (e.g., drums with up to 300 FGE each). Database information from 2002 shows an average of ~30 FGE per waste drum with respect to PF-4 generated waste, with approximately 7% of the containers having greater than 150 FGE, less than 0.6% of the containers having greater than 200 FGE, and less than 0.2% of the containers having greater than 300 FGE (Reference 1). For 2012 and 2013, based on current packaging targets (~160 FGE per drum), the average waste container content was 63.3 FGE, with only 0.8% of waste containers having greater than 150 FGE and a maximum waste content of only 181.5 FGE (Reference 5).

3.0 Methodology

The methodology used in this evaluation consists primarily of MCNP6 calculations performed on the "Moonlight" High Performance Cluster (HPC) using MCNP6 with ENDF/B-VII.1 continuous energy cross-section sets. MCNP6 Version 1.0 and the ENDF/B-VII.1 cross section data on the Moonlight HPC were approved-for-use by Reference 2 and validated in Reference 3, satisfying the requirements defined in ANSI/ANS-8.24.

The Reference 3 validation derives the following Upper Subcritical Limit (USL):

$$\text{USL} = 0.990 - \text{MoS} - \text{AoA}$$

where MoS is the margin of subcriticality and AoA is a margin used to account for any interpolation or extrapolation with respect to the validation area of applicability.

Based on the simplicity of the calculations documented herein and their similarity to the benchmarks that define the validation area of applicability (see Table 5 of Reference 3), no AoA margin is judged to be required and the minimum MoS of 0.02 defined in Reference 4 is judged to be sufficient. Therefore, all computational results contained herein may be considered subcritical if the following condition is met:

$$\text{adjusted } k_{eff} = k_{eff} + 2\sigma \leq 0.97$$

4.0 MCNP Models

4.1 Materials

The calculations herein are limited to a few simple materials: plutonium metal/water solutions (waste), carbon steel (container walls), water (reflection and interstitial moderation), and concrete (reflection). Plutonium is modeled as 100% ^{239}Pu at its theoretical density of 19.84 g/cc, while water is modeled at 1.0 g/cc. Carbon steel and concrete (Los Alamos Mix) are modeled using the compositions given in Reference 7, at densities of 7.82 and 2.25 g/cc, respectively. In a limited number of cases, the Los Alamos Mix concrete is replaced with PF-4 concrete with 40% water, using the composition given in Reference 14. The individual nuclides and the modeled cross-section libraries are given in Table 1. The lwtr.20t *S(α, β)* table is used to model thermal scattering in hydrogen in water for waste solutions, water, and concrete.

Table 1: Materials

Material	Library
Waste	1001.80c
	8016.80c
	94239.80c
Water	1001.80c
	8016.80c
Carbon Steel	26054.80c
	26056.80c
	26057.80c
	26058.80c
	6000.80c
Los Alamos Concrete	1001.80c
	8016.80c
	14028.80c
	14029.80c
	14030.80c
	13027.80c
	11023.80c
	20040.80c
	20042.80c
	20043.80c
	20044.80c
	20046.80c
	20048.80c
	26054.80c
	26056.80c
	26057.80c
	26058.80c

Material	Library
PF-4 Concrete (40% water)	1001.80c
	8016.80c
	11023.80c
	12024.80c
	12025.80c
	12026.80c
	13027.80c
	14028.80c
	14029.80c
	14030.80c
	16032.80c
	16033.80c
	16034.80c
	16036.80c
	19039.80c
	19040.80c
	19041.80c
	20040.80c
	20042.80c
	20043.80c
	20044.80c
	20046.80c
	20048.80c
	22046.80c
	22047.80c
	22048.80c
	22049.80c
	22050.80c
	26054.80c
	26056.80c
	26057.80c
	26058.80c

4.2 Dimensions

Per References 8 and 9, a 55-gallon drum has nominal outer dimensions of 24” diameter by 35” high, with a nominal internal volume of 208 liters. The drums used on site are typically constructed of 18 gauge (0.0478”) steel.[a] To conservatively account for construction tolerances and minor structural damage, 55-gallon drums are modeled herein with reduced outer dimensions of 22.6” diameter by 34.75” high. Note that due to stability concerns, drums are not typically stacked directly on top of each other. Instead, drums are generally staged on pallets which may be stacked on top of other pallets of drums. This would increase the effective height of a single layer of drums by 4 to 6” in reality.

Per References 8 and 9, a SWB has nominal outer dimensions of 71” long by 54.5” wide by 36.875” tall, and the short sides are curved with an overall diameter of 71”. The nominal internal volume is 1880 liters.[b] SWBs are constructed of 10 gauge (0.1345”) steel. To conservatively

[a] Drum lids may be thicker, e.g., 16 gauge (0.0598”).

[b] An SWB therefore has a volume and footprint that are both ~9 times greater than a 55-gallon drum.

account for construction tolerances and minor structural damage, SWBs are modeled herein with outer dimensions of 68.75” long by 52” wide by 36.5625” tall, with the curved sides modeled explicitly.[c]

With respect to wall thickness, 55-gallon drum walls are modeled at half the thickness of 18 gauge steel (0.0239”). This modeling convention is judged to conservatively bound any degradation of the steel, any manufacturing tolerances, or the use of thinner gauge steel drums.[d] Although SWB walls are typically thicker (10 gauge versus 18 gauge), SWB walls are conservatively modeled at the same thickness (0.0239”).

4.3 Modeling Conventions

TRU waste is modeled as spherical ^{239}Pu-water solutions in the center of each waste container, with the fissile concentration varied to determine optimum moderation. Given that waste is generally low-density and randomly distributed in each drum, it is not judged to be credible that multiple drums could achieve optimum moderation in close proximity to each other. Further, the analyses herein do not model any other waste matrix materials (e.g., iron or chlorine) or ^{240}Pu (typically present as 4 to 7 at%), while these materials would actually be present in the waste and act as neutron absorbers and diluents. Therefore, modeling the waste as a pure ^{239}Pu-water solution over the full range of fissile concentration is judged to represent significant safety margin.

This modeling convention also clearly bounds any moderation effects due to water from precipitation or fire-fighting mixing with the waste. In addition, References 11 through 13 demonstrate that typical uses of Met-L-X, carbon spheroids/powder, silicon dioxide (i.e., sand), magnesium oxide, or Foray (i.e., Type ABC) fire extinguishing agents are also bound by the full-density water moderation/reflection modeled herein.

In reality, waste matrix material will primarily contain hydrogenous materials other than water, such as plastics, oils, Celotex, etc. This material may be present as bags/wrapping, residues, drum liners, or larger pieces. Some of these hydrogenous materials may have higher hydrogen densities than water and could thus be more effective moderators than water. However, the majority of these materials are present as solid material in small volumes with very low packing densities and large void spaces, without the ability to flow and mix readily with fissile material in the waste. Even in the presence of a fire inside a waste container, these materials would flow slowly with no motivation to form an optimally moderated mixture with fissile material. Therefore, given the random heterogeneous distribution of fissile material in typical waste, it is judged that such hydrogenous materials cannot credibly form intimately concentrated mixtures with fissile material that could challenge the optimum full-density water moderation modeled herein.

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[c] These are the nominal inner dimensions per Reference 9.

[d] 55-gallon drums for general industrial use may be manufactured with 16 to 20 gauge steel (0.0359” to 0.0598”). The modeled drum wall thickness of 0.0239” bounds even the thinnest gauge typically available by 33% and the expected 18 gauge by 50%.

Although some types of oils or similar residues may have significant flowability, such materials are limited in solid TRU waste. It is not judged to be credible that any such materials could be present in a TRU waste container in sufficient volume, density, and distribution to challenge the optimum full-density water moderation modeled herein.

Finally, note that waste material nominally contains only minimal amounts of graphite or beryllium. In large enough quantities, these materials can challenge the moderation or reflection assumptions herein. However, per Reference 6, very large quantities of beryllium or graphite are required before these materials transition from diluents to moderators (~10s to 100s of kilograms). Similarly, large volumes and optimal geometry would be required to assemble sufficiently close-fitting and contiguous reflection to invalidate the full-density water or concrete reflection modeled herein. Therefore, while small amounts of beryllium or graphite are considered to be an anticipated condition, credible amounts of these materials in the waste material are judged to have no impact on criticality safety.

5.0 Evaluation

5.1 Infinite Three-High Arrays of 55-gallon Drums with 200 FGE Each

55-gallon drums are initially modeled in infinite planar, three-high, square-pitch arrays, with the drums in contact. Each drum is modeled with the dimensions given in Section 4.2, with half-thick 18 gauge steel walls. TRU waste is modeled as a spherical ^{239}Pu-water solution in the center of each drum. The fissile concentration of the solution is varied from 10 g/L ^{239}Pu to 19,840 g/L ^{239}Pu (i.e., theoretical metal density), with each drum modeled to contain 200 Fissile Gram Equivalent (FGE) ^{239}Pu (modeled herein as 100% ^{239}Pu).[e]

Full concrete (60 cm) reflection is modeled below the array, and 1” of full-density water reflection is modeled above the array. An infinite 1” thick slab of water over the top of the array is judged to bound reflection from precipitation, sprinkler activation, active firefighting, or incidental reflection from structures, vehicle barriers, radiological shielding, heating blankets, etc.[f]

The results are presented in Figure 1 for the entire range of modeled concentrations, while Figure 2 depicts the concentration range yielding the maximum adjusted k_{eff} values.

[e] 200 FGE is the WIPP WAC limit for 55-gallon drums (Reference 10). Such drums are also known as Low FGE drums.

[f] Note that neither firefighting nor sprinkler activation is considered a normal condition.

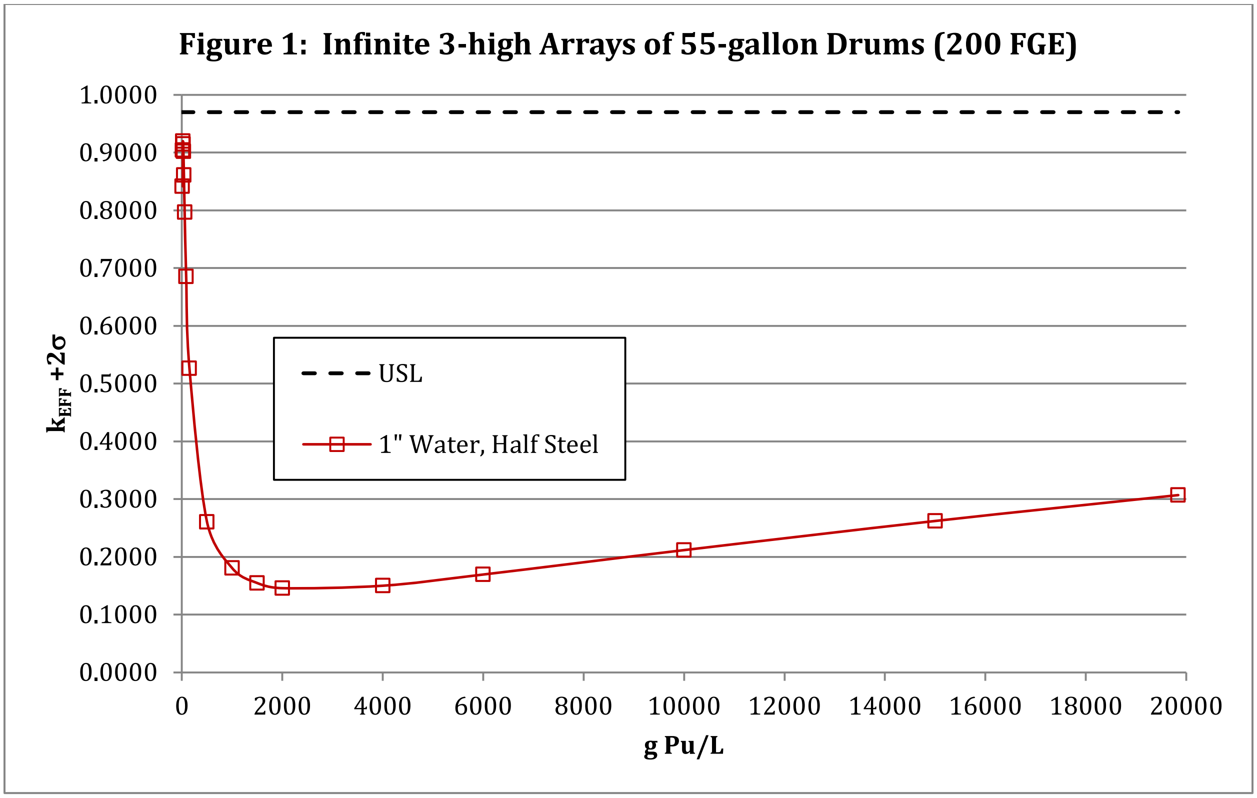


Figure 1: Infinite 3-high Arrays of 55-gallon Drums (200 FGE)
1.0000
0.9000
0.8000
0.7000
0.6000
0.5000
0.4000
0.3000
0.2000
0.1000
0.0000
k_EFF +2σ
USL
1" Water, Half Steel
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
g Pu/L

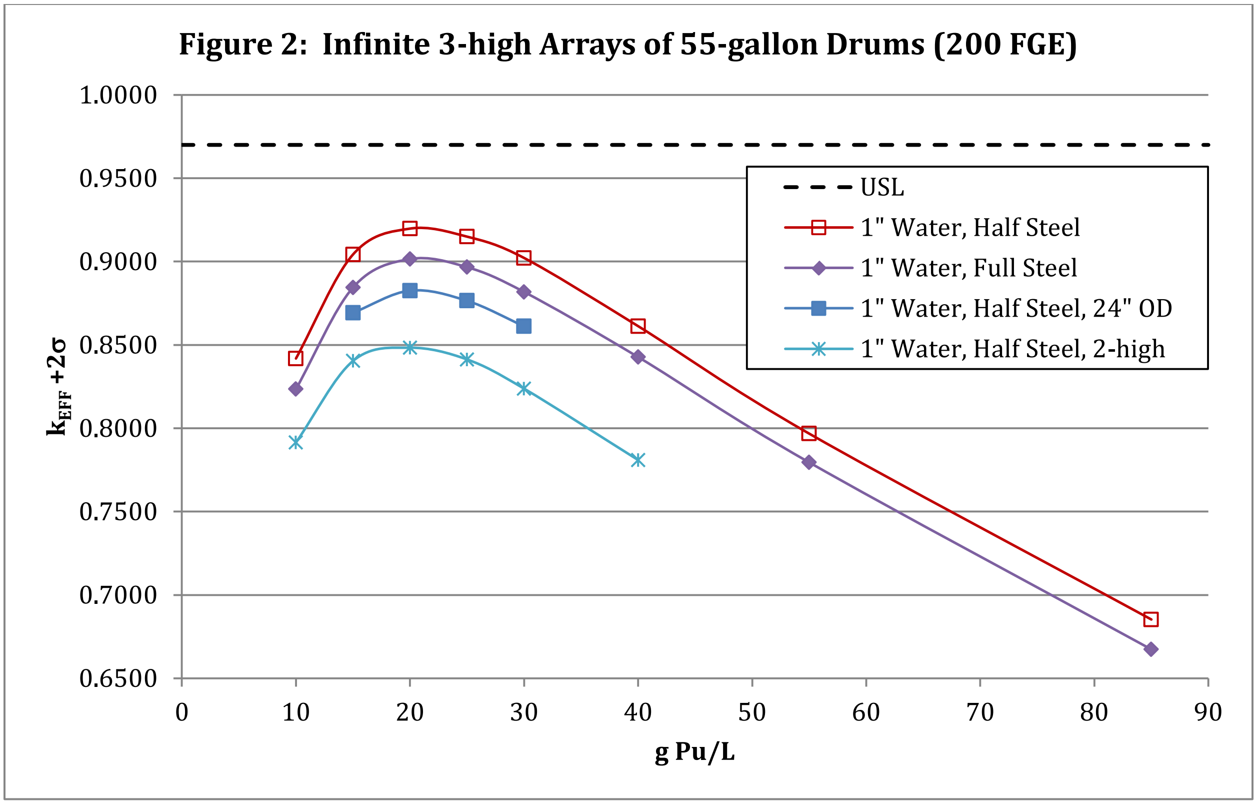


Figure 2: Infinite 3-high Arrays of 55-gallon Drums (200 FGE)
1.0000
0.9500
0.9000
0.8500
0.8000
0.7500
0.7000
0.6500
k_EFF +2σ
USL
1" Water, Half Steel
1" Water, Full Steel
1" Water, Half Steel, 24" OD
1" Water, Half Steel, 2-high
0
10
20
30
40
50
60
70
80
90
g Pu/L

The results demonstrate that reactivity increases with increasing fissile concentration until optimum moderation is achieved. As concentration increases further, reactivity decreases until approximately 2,000 g/L. After this point, reactivity increases monotonically until full metal densities are achieved. The maximum adjusted k_{eff} is 0.92 at an optimum moderation of 20 g/L ^{239}Pu, while the adjusted k_{eff} at theoretical metal density is only 0.31. Since these values are well below the USL, these configurations will remain subcritical.

Further, Figure 2 demonstrates that the adjusted k_{eff} drops significantly even at fissile concentrations close to the optimum (e.g., $\Delta k = -0.02$ at concentrations < 15 g/L or > 30 g/L). As described in Section 4.3, it is not judged to be credible that multiple drums could achieve optimum moderation in close proximity to each other. Therefore, modeling the waste as an optimally moderated solution is judged to represent significant safety margin.

These results also bound drums larger than 55-gallons with ≤ 200 FGE each (direct-loaded drums or 55-gallon drums overpacked into larger drums) since larger drums would increase spacing and thus neutron leakage. In addition, the use of 6" or 12" POCs (i.e., steel, cylindrical inserts used to confine waste inside a drum) are also bounded by the results above since POCs would constrain the geometry of the waste and introduce a parasitic neutron absorber (steel) into the system.

Figure 2 also presents the results of three sensitivity studies for this configuration. First, the drums in the array are modeled to have full 18 gauge steel walls, which decreases reactivity by $\Delta k = -0.02$. This is considered additional safety margin in the calculations since actual drums will have wall thicknesses closer to this nominal value.

Second, the drums in the array are modeled at their nominal outer diameter of 24", rather than the conservative 22.6" diameter otherwise modeled. The nominal diameter yields a large decrease in reactivity ($\Delta k = -0.04$), demonstrating that this modeling convention also provides significant safety margin.

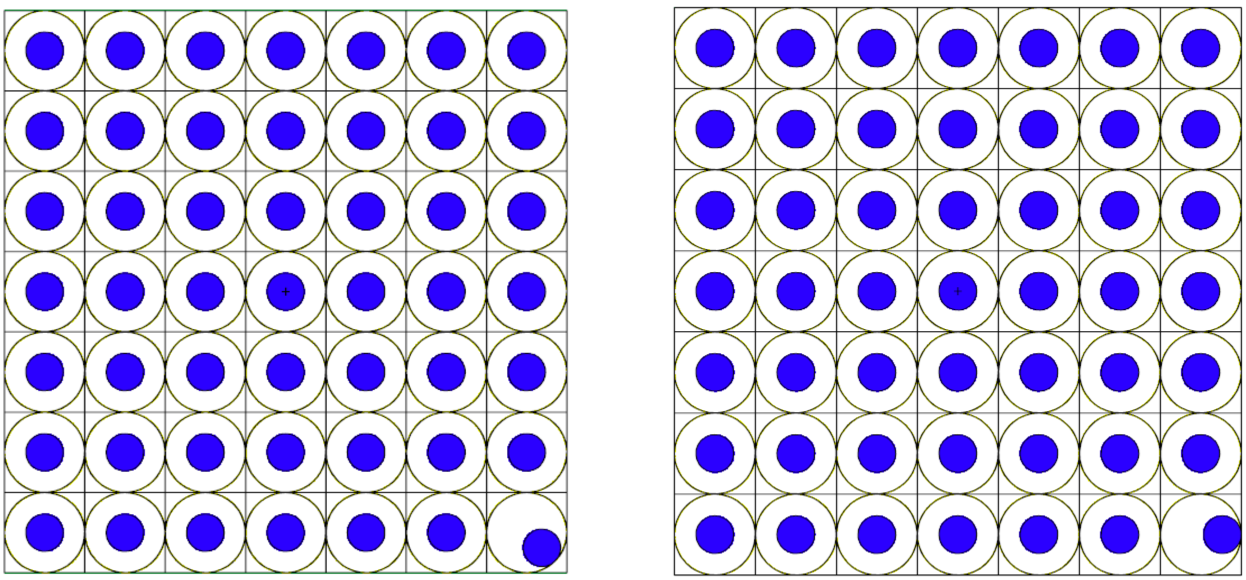
Third, the drums are modeled in an infinite planar, two-high array instead of three-high. In some waste staging areas, practical considerations or safety basis rules prevent stacking greater than two-high, and it is informative to understand the safety margin. These cases result in a maximum adjusted k_{eff} that is significantly lower than the corresponding three-high array ($\Delta k = -0.07$).

A single case is also executed that modifies the base case with the maximum adjusted k_{eff} (20 g/L) to replace the Los Alamos Mix concrete with PF-4 concrete with 40% water. The change in concrete mixture results in a negligible increase in k_{eff} ($\Delta k = 0.003$).

The models described above all assume that each spherical waste unit is centered in its drum, both vertically and radially. Modeling waste as an optimally moderated, centered sphere is a very conservative modeling constraint rather than any reflection of credible waste geometry since actual waste is expected to be distributed randomly and heterogeneously throughout most of the drum volume and at low densities. Therefore, any significant clustering of spherical waste units in a significant number of proximate drums (i.e., to bring waste in adjacent drums closer together) is judged to be not credible.

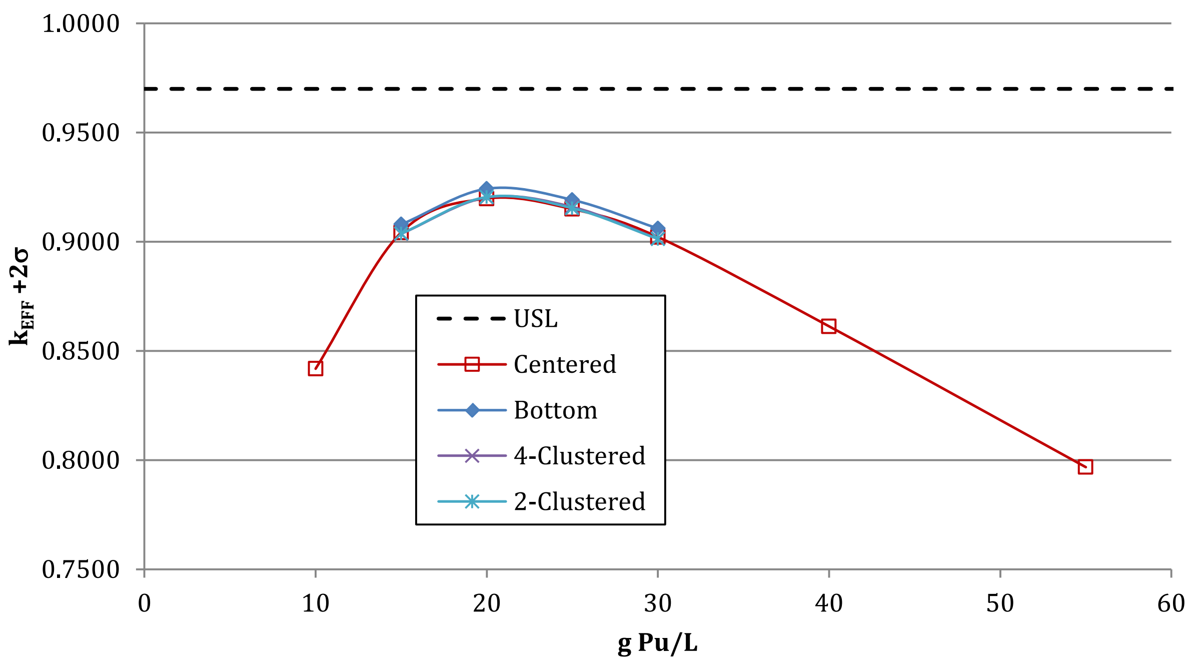
Nonetheless, three series of cases are executed to evaluate the effects of varying the distribution of waste in the drums. First, the spherical waste units are modeled at the bottom of each drum, in closer proximity to the concrete floor. Second, reflected 7 by 7 by 3-high arrays are used to simulate the radial clustering of groups of four fissile units in a 2 by 2 by 3-high configuration, as depicted in the first image in Figure 3. Third, reflected 7 by 7 by 3-high arrays are used to simulate the radial clustering of pairs of fissile units in a 2 by 2 by 3-high configuration, as depicted in the second image in Figure 3. Both clustering models approximate 12 clustered drums repeated infinitely in each block of 14 by 14 by 3 drums (i.e., 12 drums in each group of 588 drums).

Figure 3: Clustering Models



The results are depicted in Figure 4. Modeling the fissile units at the bottom of the drums increases k_{eff} by a negligible amount ($\Delta k = 0.004$), while both clustering configurations result in even smaller k_{eff} increases ($\Delta k = \sim 0.001$ to 0.002). Therefore, centered fissile units are modeled hereafter in this section, unless otherwise noted.

Figure 4: Infinite 3-high Arrays of 55-gallon Drums (200 FGE) (Clustering Units)



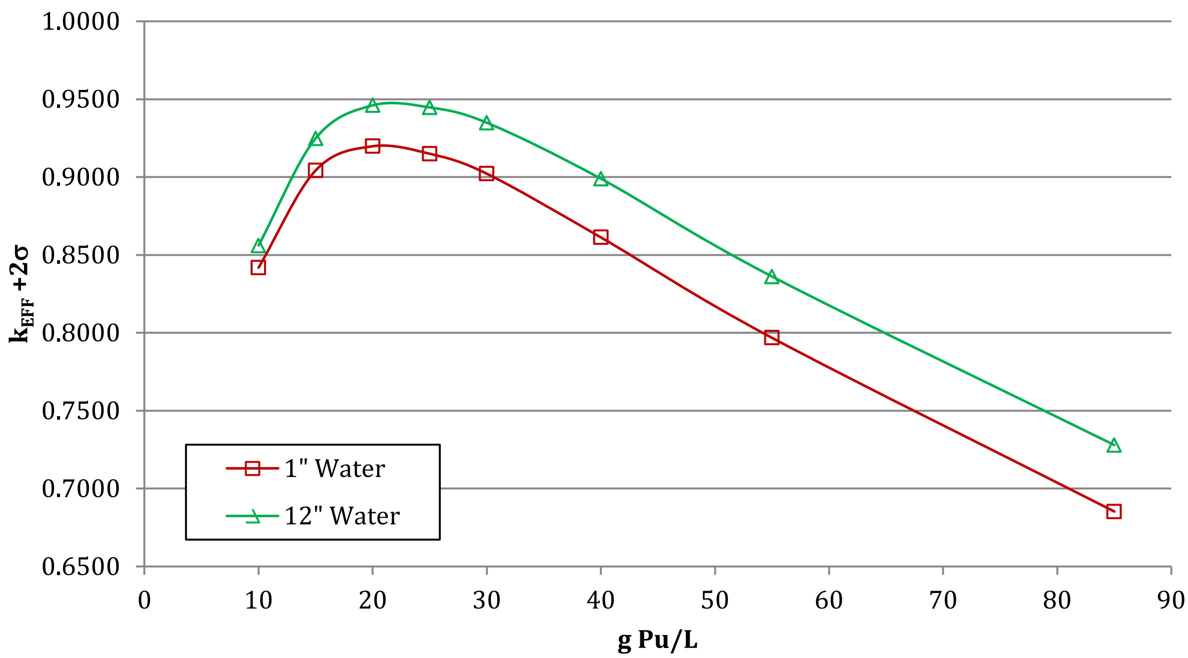
Finally, note that the calculated k_{eff} results presented here are driven by modeling constraints rather than reality. The majority of actual TRU waste will be low density, heterogeneously and randomly distributed, poorly reflected/moderated, and mixed with neutron poisons and diluents. However, these intangible qualities cannot readily be quantified and thus cannot be explicitly credited in the models. Under realistic conditions, the k_{eff} for such arrays is expected to be much smaller than shown above. Therefore, these results are judged to greatly bound normal conditions, while various upsets are evaluated in the following sub-sections.

5.1.1 Reflection Upsets

As described previously, an infinite 1” thick slab of full-density water modeled on top of the drum array is judged to reflection due to precipitation, sprinkler activation, active firefighting, or other incidental reflection. Further, as described in Section 2.0, only small amounts of graphite or beryllium are credibly present in TRU waste, and these materials are judged to be bounded by the full-density water or concrete reflection modeled herein.

Nonetheless, one series of cases is executed that replaces the 1” water reflection above the array with 12” water reflection, The results, depicted in Figure 5, demonstrate that maximum reactivity increases by $\Delta k = 0.03$, while the maximum adjusted k_{eff} of 0.95 remains below the USL. Therefore, this configuration will remain subcritical.

Figure 5: Infinite 3-high Arrays of 55-gallon Drums (200 FGE)
(Full Water Reflection Effects)

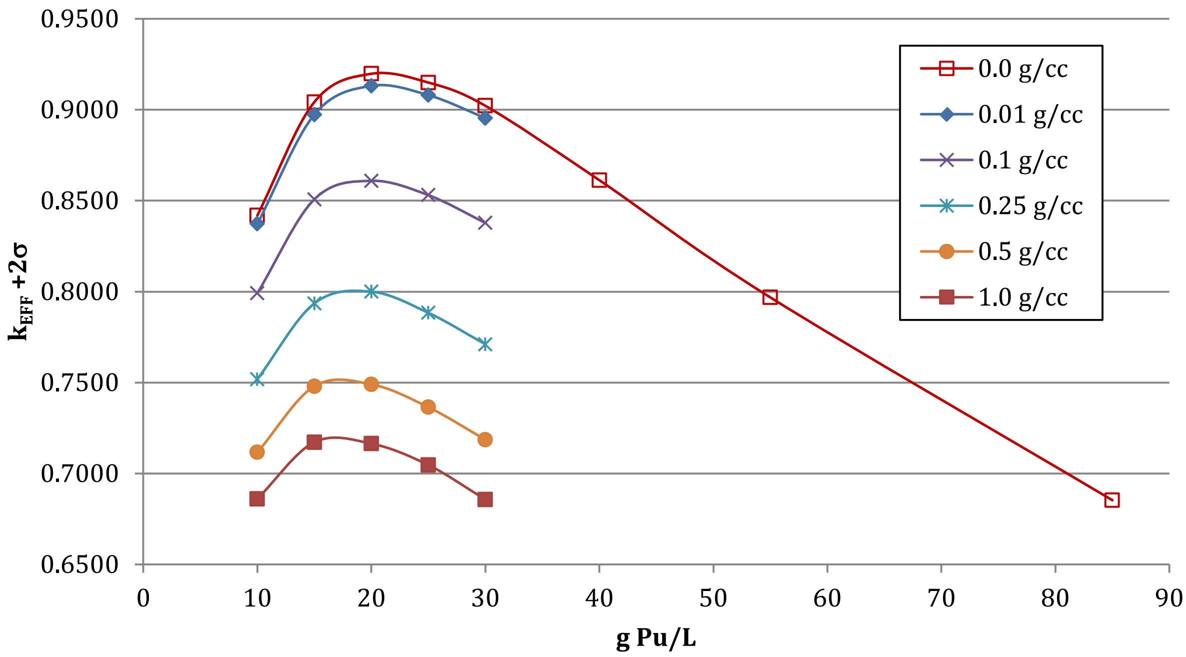


Note that it is recognized that these results do not bound infinite planar, three-high arrays staged in close proximity to concrete reflection (e.g., thick concrete walls or ceiling). In fact, modeling an infinite planar, three-high array with 12" or greater concrete reflection above the array results in adjusted k_{eff} values above the USL. However, concrete reflection in conjunction with more realistic finite arrays is evaluated in Section 5.2.

5.1.2 Moderation Upsets

TRU waste is modeled herein as an optimally moderated solution of ^{239}Pu metal and water. As stated in Section 4.3, this modeling convention is judged to bound any internal moderation due to precipitation, fire-fighting, or waste matrix material. Nonetheless, several series of cases are executed to investigate the effects of interstitial moderation in the array. For these cases, the spaces between drums in the array are modeled to be filled with water at varying mass densities (0.01 g/cc to 1.0 g/cc). The results, depicted in Figure 6, demonstrate that interstitial water reduces reactivity for all modeled densities.

Figure 6: Infinite 3-high Arrays of 55-gallon Drums (200 FGE) (Interstitial Water Effects)



5.1.3 Mass Upsets

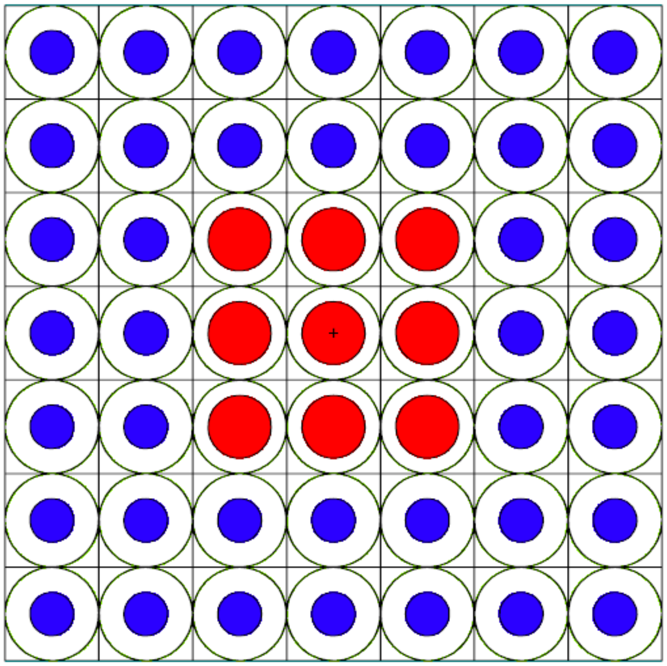
As described in Section 2.0, the average fissile loading of waste drums is expected to be significantly lower than the 200 FGE per drum modeled herein. Therefore, modeling every drum in an infinite planar, three-high array to simultaneously contain 200 FGE is judged to be a very conservative modeling convention with respect to actual fissile mass.

It is qualitatively judged in Reference 1 that even if a few higher mass containers (each with a 50% overmass) were accidentally introduced into an array of 200 FGE drums, the criticality safety of the system would not be challenged, based on the very conservative modeling conventions employed therein (e.g., infinite arrays with optimal moderation and maximum fissile mass modeled in every container). Similar modeling conventions are employed herein, and this conclusion is judged to remain valid.

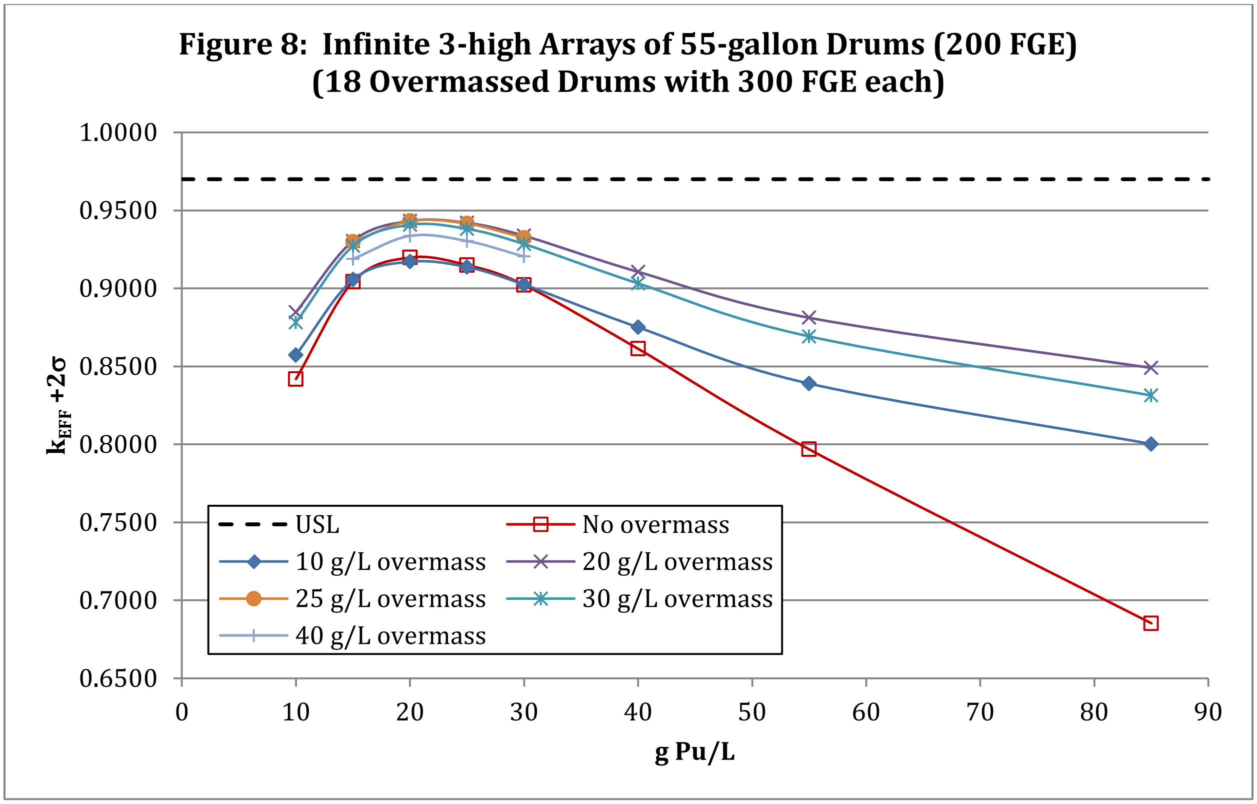
Nonetheless, an overmass upset is explicitly evaluated herein that postulates that 18 drums at 300 FGE each (50% overmass) are inadvertently present in an array. To bound this configuration, the infinite planar, three-high array modeled for normal conditions is modified to instead explicitly model a finite array of 7 by 7 by 3-high drums. A subset of 18 drums with 300 FGE each is modeled as a 3 by 3 by 2-high sub-array in the center of the bottom two tiers of the 7 by 7 by 3 array, while all other drums are modeled to contain 200 FGE. The finite 7 by 7 by 3 array is then reflected on four sides to approximate an infinite planar, three-high array with groups of 18 overmassed drums in each larger collection of 147 drums (i.e., 7 by 7 by 3).

Since each group of 3 by 3 by 2 overmassed drums are modeled in a near ideal configuration with respect to leakage (L/H = 0.98) and are repeated infinitely throughout the array (representing over 12% of the total modeled drums), this configuration is judged to be very conservative. A top view of the bottom tier of the array is depicted in Figure 7, where red represents overmassed drums.

Figure 7: 300 FGE Overmassed Drum Model



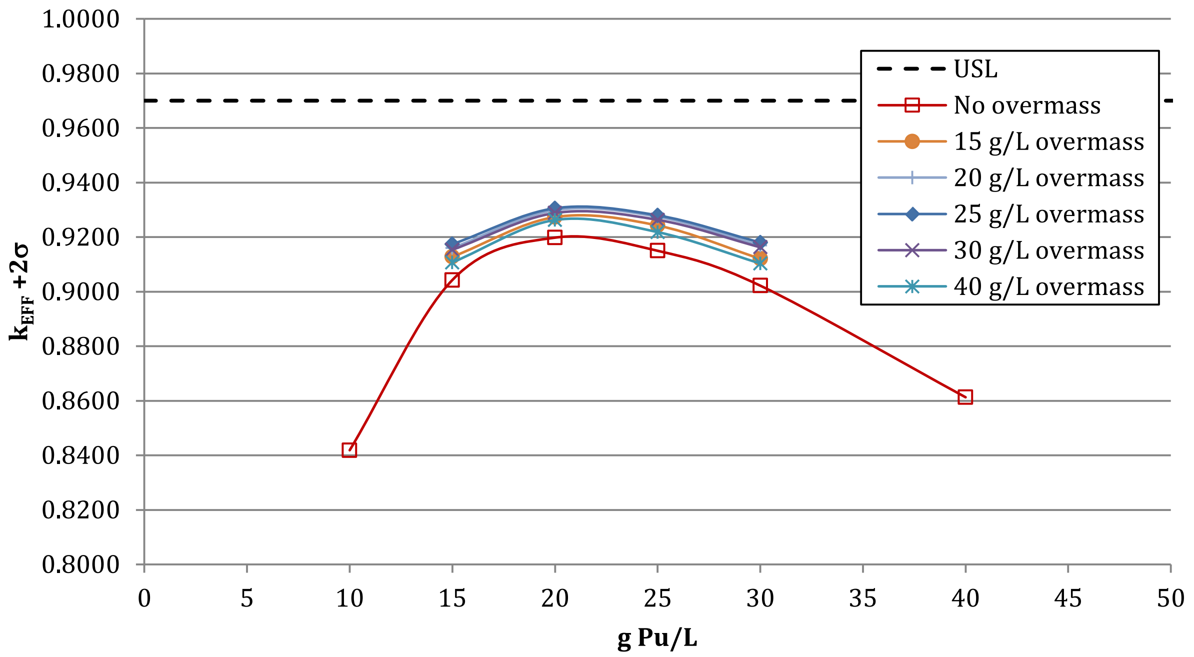
The results are presented in Figure 8. Each distinct curve depicts adjusted k_{eff} as a function of the fissile concentration of the normal drums while the fissile concentration of the overmassed drums is held at a constant value. The results demonstrate that reactivity is maximized when both the normal and overmassed drums are modeled at 20 g/L. At this point, the maximum adjusted k_{eff} is ~0.94. Although this represents a significant increase in reactivity ($\Delta k = 0.02$), the adjusted k_{eff} remains below the USL. Therefore, a mass upset involving up to 18 drums with ≤ 300 FGE each will remain subcritical.



One additional overmass upset is modeled using the same finite 7 by 7 by 3-high array of drums. In these series of cases, a single overmassed drum in the bottom tier is modeled to contain 520 FGE, with the finite array reflected on four sides to approximate an infinite planar, three-high array with one overmassed drum in each larger collection of 147 drums.

The results, presented in Figure 9, demonstrate that reactivity is maximized when the normal drums are modeled at 20 g/L and the overmassed drum is modeled at 25 g/L. At this point, the maximum adjusted k_{eff} is ~0.93. This represents a small increase in reactivity ($\Delta k = 0.01$) with the adjusted k_{eff} remaining below the USL. Therefore, a mass upset involving one drum with ≤ 520 FGE will remain subcritical.

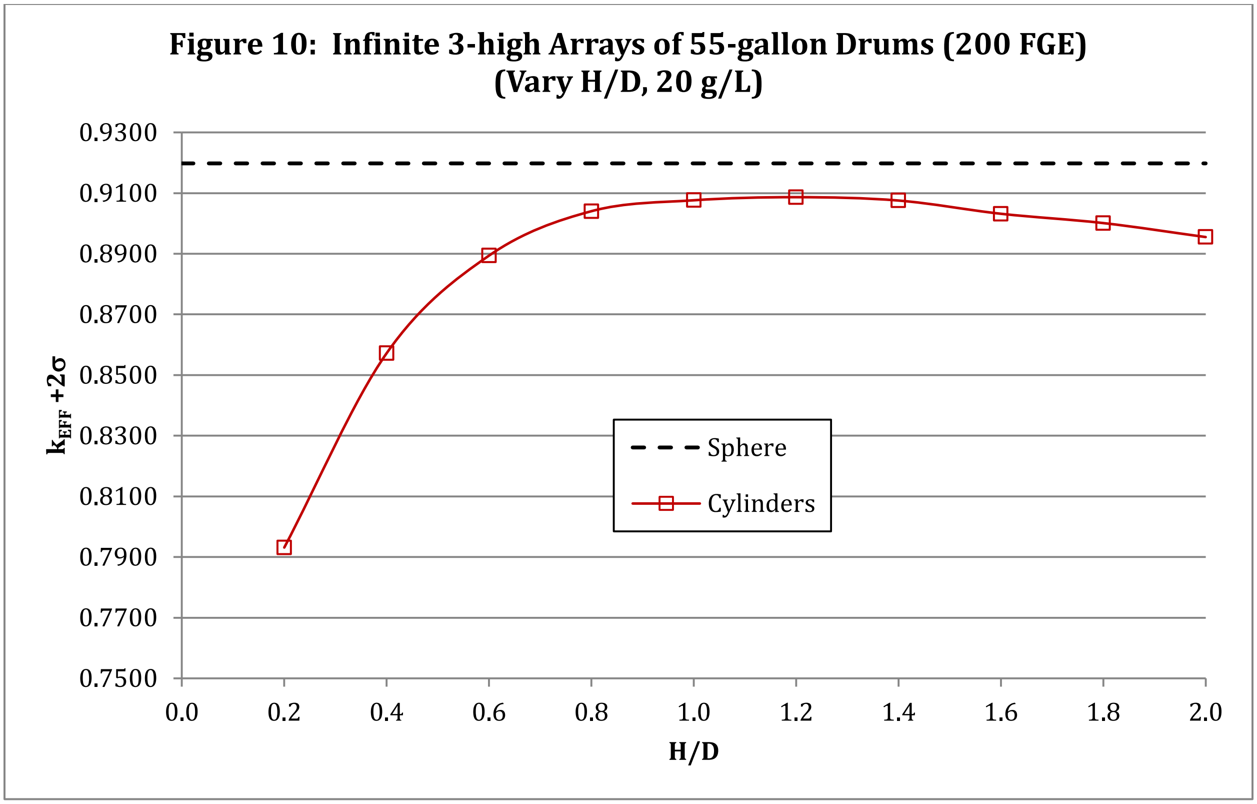
Figure 9: Infinite 3-high Arrays of 55-gallon Drums (200 FGE)
(1 Overmassed Drum with 520 FGE)



5.1.4 Geometry Upsets

As described previously, the decreased dimensions modeled for 55-gallon drums are very conservative, with the radial reduction alone worth approximately Δk = -0.04. These modeled dimensions are judged to bound any minor structural deformation to a limited number of drums due to a low-energy impact (e.g., forklift impact, dropped drum). Further, any credible rearrangement of drums from such an impact would only reduce reactivity from the uniform, infinite planar, three-high array of drums in contact modeled for normal conditions. Although a rearrangement of a large enough collection of drums in four or more tiers could possibly increase reactivity, no credible event is postulated herein that could create a large enough array to challenge the normal conditions modeled herein. Similarly, given practical considerations and industrial safety practices, it is judged to be not credible that drums would be inadvertently stacked four-high in an array.

Furthermore, TRU waste is conservatively modeled as ideal spherical solutions in each drum. Reference 1 concludes that modeling the waste as spherical units bounds any other geometry, i.e., cylinders at varying H/D ratios. This conclusion is confirmed by the results presented in Figure 10 which model the most reactive normal condition case (20 g/L, see Figure 2) but with the fissile units modeled as cylinders with varying H/D ratios rather than spheres. The results demonstrate that the maximum adjusted k_{eff} occurs at an H/D ratio of 1.2 (k_{eff} = 0.91) and that all cases result in lower adjusted k_{eff} values than the base spherical case (k_{eff} = 0.92). Thus, no change to the fissionable material geometry *inside* a drum (e.g., an individual container spill or distribution of waste within a container) could impact criticality safety.

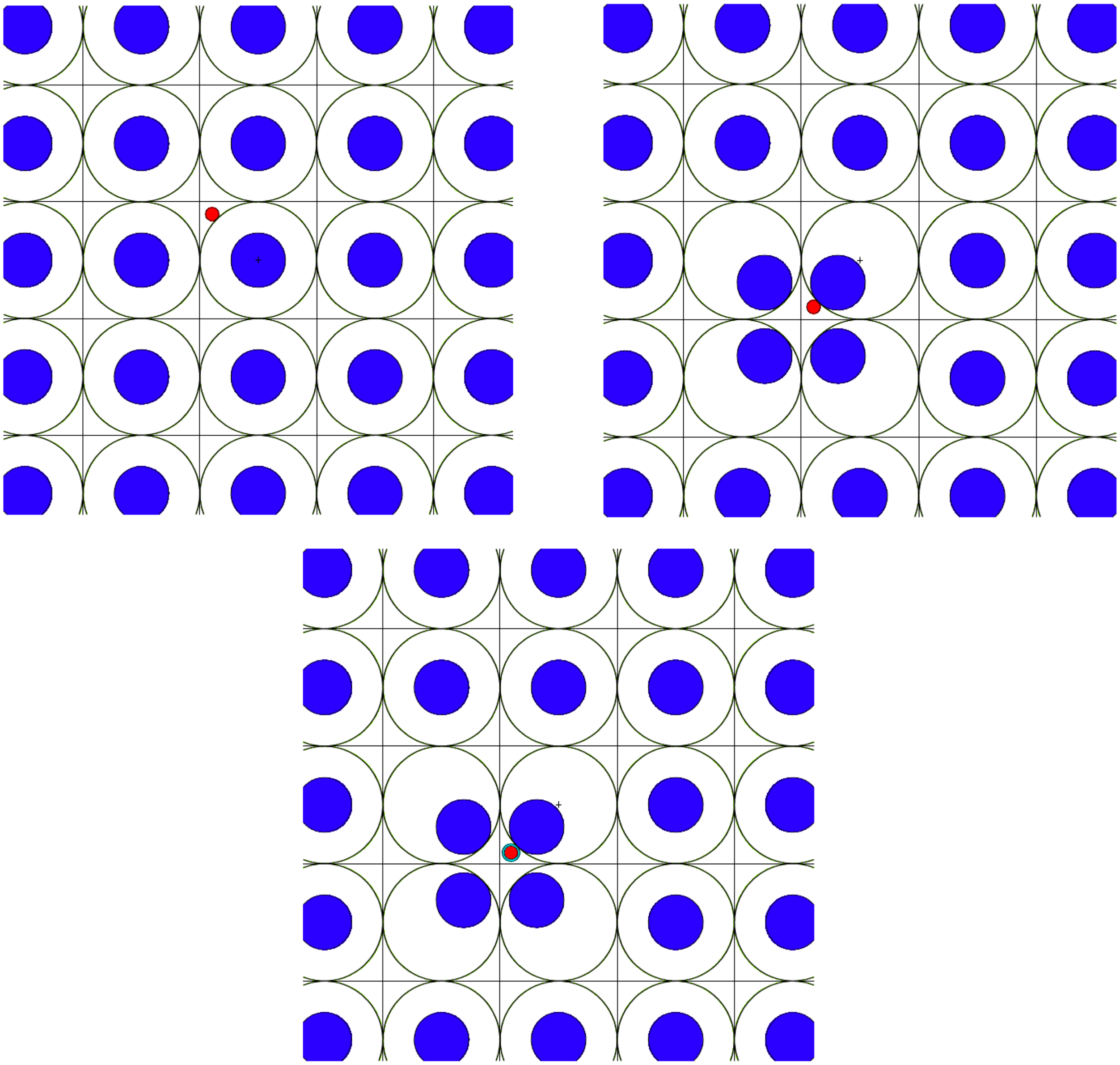


5.1.5 Interaction Upsets

Given that the normal conditions modeled herein demonstrate that infinite arrays of drums in contact remain subcritical, it is clear a priori that interactions with other Low FGE waste drums will remain subcritical. Furthermore, Section 5.1.3 demonstrates that interactions with multiple High FGE drums (300 FGE each) also remain subcritical. However, in order to investigate the interaction effects of other fissionable material three sets of cases are executed that model a 4.5 kg ^{239}Pu metal unit interacting with an infinite planar, three-high array of waste drums with 200 FGE each.

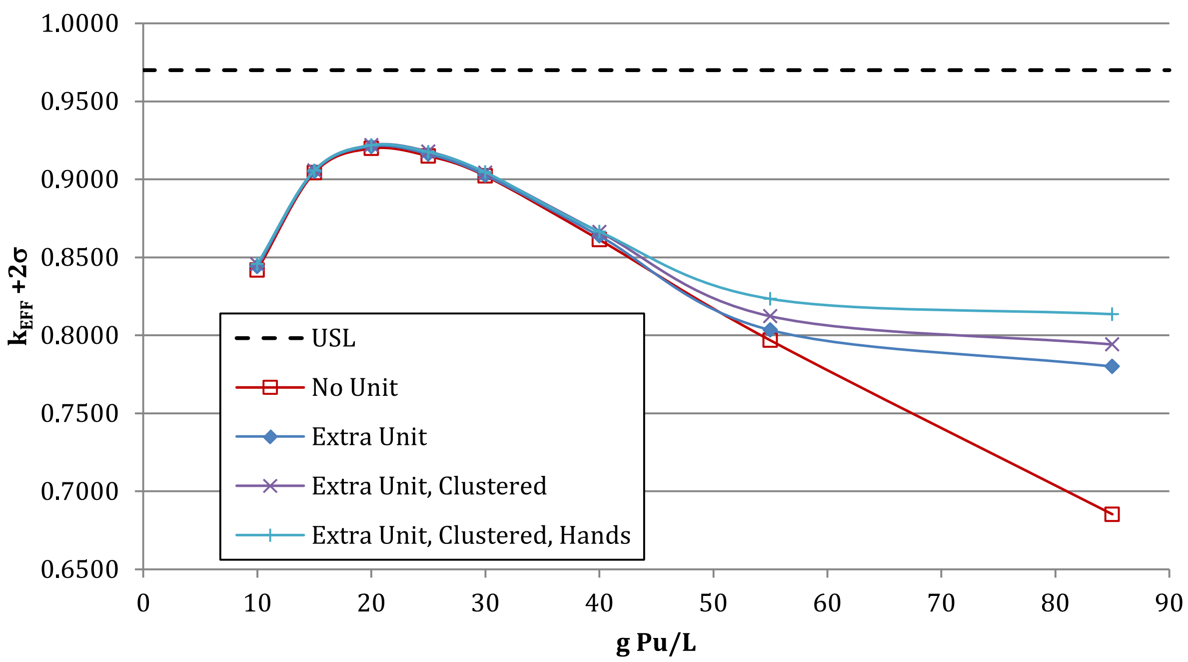
In all three series of cases, the metal unit is modeled as a cylinder with an H/D ratio of 1.0 placed in direct contact with a bottom tier drum in the array, centered vertically with the drum. The first series models the 4.5 kg unit to be bare and the waste units to be centered in their drums, as depicted in the first image of Figure 11. The second series models the waste units in the adjacent drums to be clustered towards the interacting 4.5 kg unit, as depicted in the second image of Figure 11. The third series is identical to the second, except that the interacting unit is modeled with 1 cm thick water reflection, as depicted in the final image of Figure 11. Note that, similar to the mass upsets modeled in Section 5.1.3, all these cases model a reflected finite 7 by 7 by 3-high array to approximate an interacting 4.5 kg unit in each individual group of 147 drums in an infinite array.

Figure 11: Interaction Models



The results, presented in Figure 12, demonstrate that the interacting unit has only negligible effects on adjusted k_{eff} until the waste becomes significantly undermoderated. At fissile concentrations above this point, k_{eff} increases significantly with respect to the cases with no interacting unit. However, the maximum adjusted k_{eff} for each series of cases is still calculated at the optimum waste unit moderation and remains negligibly different from the maximum k_{eff} calculated for normal conditions (Δk = 0.001 to 0.002).

Figure 12: Infinite 3-high Arrays of 55-gallon Drums (200 FGE) (Interacting Unit)



The results also demonstrate that clustering units increases reactivity, as does the addition of water reflection to the interacting item. An additional, abbreviated set of cases is also executed that modifies a subset of the cases with clustering and water reflection (15 to 30 g/L) to model all waste and interacting units at the bottom of the drums (to enhance concrete reflection). These cases resulted in negligible difference in k_{eff} from the similar cases presented in Section 5.1.4 (Δk = -0.001 at optimum moderation).

Given that all cases described in this section remain below the USL, this interaction upset will remain subcritical. Note that it is recognized that higher k_{eff} values could potentially be calculated if the waste units in drums adjacent to the interacting unit were modeled at extreme H/D ratios. However, modeling the waste as optimal density spheres is a very conservative modeling assumption that bounds any actual geometry, given the nature of waste (as described in Sections 2.0 and 4.3). Therefore, it is judged that modeling the waste as full density spheres in drums surrounding an interacting unit in direct contact (with waste units clustered towards the interacting unit) bounds any credible configuration for such an interaction upset.

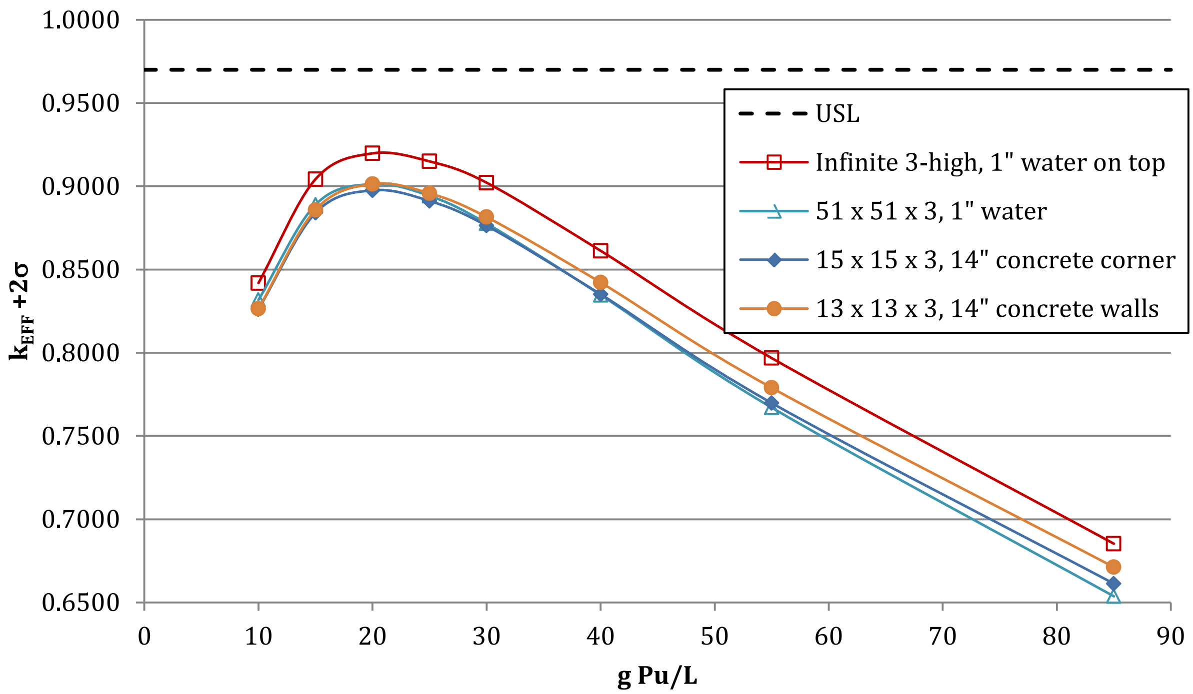
5.2 Finite Arrays of 55-gallon Drums with 200 FGE Each

In Section 5.1, infinite planar, three-high arrays of 55-gallons drums are modeled. In reality, any actual array of waste containers will necessarily be finite in extent. In this section, the safety margin associated with infinite arrays is investigated and balanced against changes in reflection.

First, very large, finite planar, three-high arrays are modeled with 1" of full-density water reflection on five sides and 60 cm concrete below. Array size is increased until the maximum adjusted k_{eff} approaches the value calculated for infinite arrays in Section 5.1 (k_{eff} = 0.92). Since the reactivity of a finite array clearly increases monotonically with array size (as leakage decreases), only the final results are depicted herein (i.e., intermediate scoping results for smaller arrays are not depicted).

Results are presented in Figure 13 for a 51 by 51 by 3-high array of drums. The maximum adjusted k_{eff} is calculated to be 0.90 at an optimal concentration of 20 g/L. Therefore, even an array of this size (e.g., 7,803 drums covering an area of over 100 by 100 feet) is still significantly bounded by the infinite array results (Δk = -0.02).

Figure 13: Drums in Infinite and Finite Arrays (200 FGE)



Next, finite planar, three-high arrays are modeled in a concrete corner. For these cases, 14" of concrete reflection is modeled on two sides of the array[g], 12" of full-density water is modeled on two sides of the array, 12" of concrete is modeled above the array, and 60 cm of concrete is modeled below the array. Array size is increased until the maximum adjusted k_{eff} approaches the value calculated for infinite arrays.

Results are presented in Figure 13 for a 15 by 15 by 3-high array of drums. The maximum adjusted k_{eff} is calculated to be 0.90 at an optimal concentration of 20 g/L. Therefore, even arrays of this size (e.g., 675 drums covering an area of over 30 by 30 feet) positioned in a

[g] Per Reference 15, the exterior bearing walls of PF-4 are 14" thick concrete.

concrete corner are still significantly bounded by the modeled infinite arrays (Δk = -0.02). These results demonstrate that an array of 55-gallon drums with 200 FGE will remain subcritical even if staged inside a building or vault with thick concrete walls on two sides of the array (plus floor and ceiling), as long as the array is no larger than 15 by 15 by 3-high. In addition, given that the modeled array is the most reactive configuration of 675 drums limited to three-high stacking, this conclusion applies generally to any collection of ≤ 675 drums stacked ≤ 3-high.

An abbreviated series of cases is also executed that replaces the Los Alamos Mix concrete with PF-4 concrete with 40% water. The change in concrete mixture results in a negligible increase in maximum k_{eff} (Δk = 0.006).

Finally, finite planar, three-high arrays are modeled with concrete reflection on all sides. For these cases, 14” of concrete reflection is modeled on four sides of the array, 12” of concrete is modeled above the array, and 60 cm of concrete is modeled below the array. Array size is increased until the maximum adjusted k_{eff} approaches the value calculated for infinite arrays.

Results are presented in Figure 13 for a 13 by 13 by 3-high array of drums. The maximum adjusted k_{eff} is calculated to be 0.90 at an optimal concentration of 20 g/L. Therefore, even arrays of this size (e.g., 507 drums covering an area of over 25 by 25 feet) surrounded on all sides by thick concrete are still significantly bounded by the modeled infinite arrays (Δk = -0.02). These results demonstrate that an array of 55-gallon drums with 200 FGE will remain subcritical even if staged inside a building or vault with thick concrete on all sides of the array, as long as the array is no larger than 13 by 13 by 3-high. In addition, given that the modeled array is the most reactive configuration of 507 drums limited to three-high stacking, this conclusion applies generally to any collection of ≤ 507 drums stacked ≤ 3-high.

An abbreviated series of cases is also executed that replaces the Los Alamos Mix concrete with PF-4 concrete with 40% water. The change in concrete mixture results in a negligible increase in maximum k_{eff} (Δk = 0.006).

Given the relatively large safety margins calculated above (Δk = -0.02), it is judged that the following finite arrays are bounded by the calculations performed for infinite planar, three-high arrays in Section 5.1, for both normal conditions and evaluated upsets:

- ≤ 675 drums stacked ≤ 3-high in a 14” concrete corner (12” concrete above and 60 cm concrete below)
- ≤ 507 drums stacked ≤ 3-high with 14” concrete walls on four sides (12” concrete above and 60 cm concrete below)

Therefore, any conclusions derived for infinite arrays in Section 5.1 also apply to these finite arrays, as long as the array size is adequately controlled or bounded.

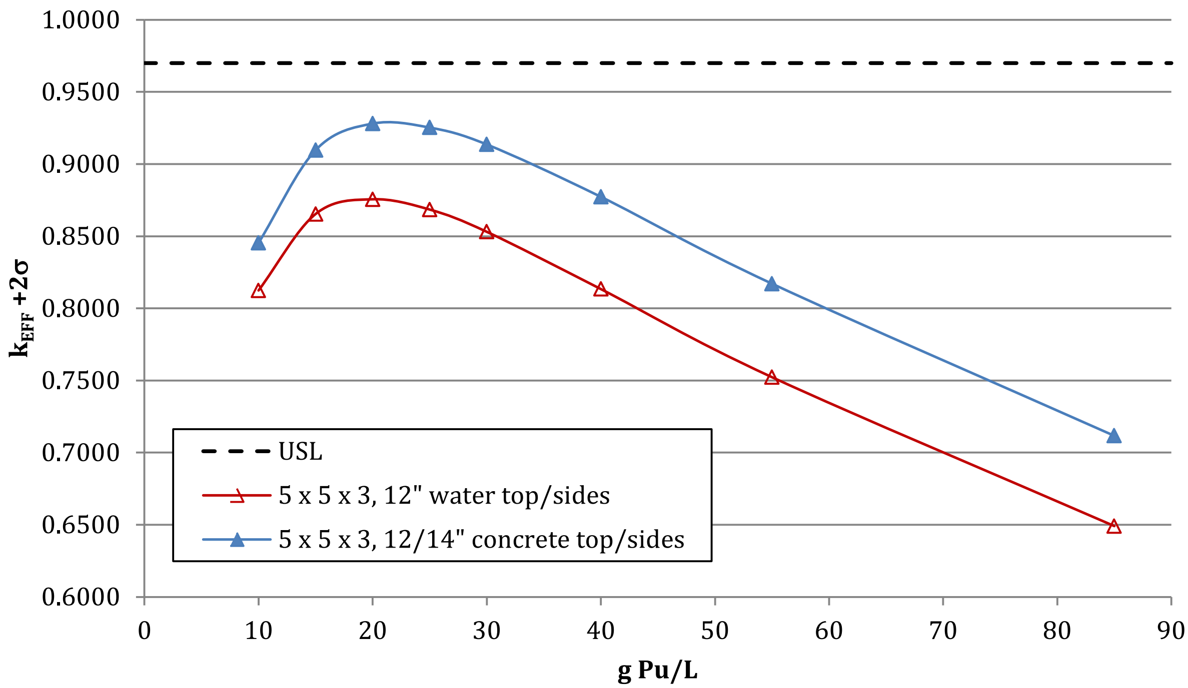
5.3 Finite Arrays of 55-gallon Drums with 300 FGE Each

The calculations in Sections 5.1 and 5.2 assume that each drum nominally contains ≤ 200 FGE ^{239}Pu, based on the WIPP WAC limit for TRU waste in 55-gallon drums (Reference 10).

However, during actual waste packaging and nondestructive assay operations, it is anticipated that some drums may contain greater quantities of fissionable material (i.e., High FGE drums). These drums are normally staged in isolated arrays prior to performing sort, segregate, size reduction, and repackaging operations to meet the WIPP WAC for offsite disposal.

To support such operations, finite arrays of 5 by 5 by 3-high 55-gallon drums are modeled, with each drum nominally containing 300 FGE (modeled herein as 100% ^{239}Pu). Two reflection schemes are modeled: 1) 60 cm concrete below and 12” full density water above and on all four sides or 2) 60 cm concrete below, 12” concrete above, and 14” concrete on all four sides. All other modeling assumptions are as described previously. Results are presented in Figure 14 for both reflection schemes.

Figure 14: Drums in Finite Arrays (300 FGE)



The results demonstrate that reactivity is maximized at an optimal concentration of 20 g/L, which is the same optimal concentration calculated in Sections 5.1 and 5.2. The maximum adjusted k_{eff} is 0.88 for water reflection and 0.93 for concrete reflection. Since these values are well below the USL, these configurations will remain subcritical.

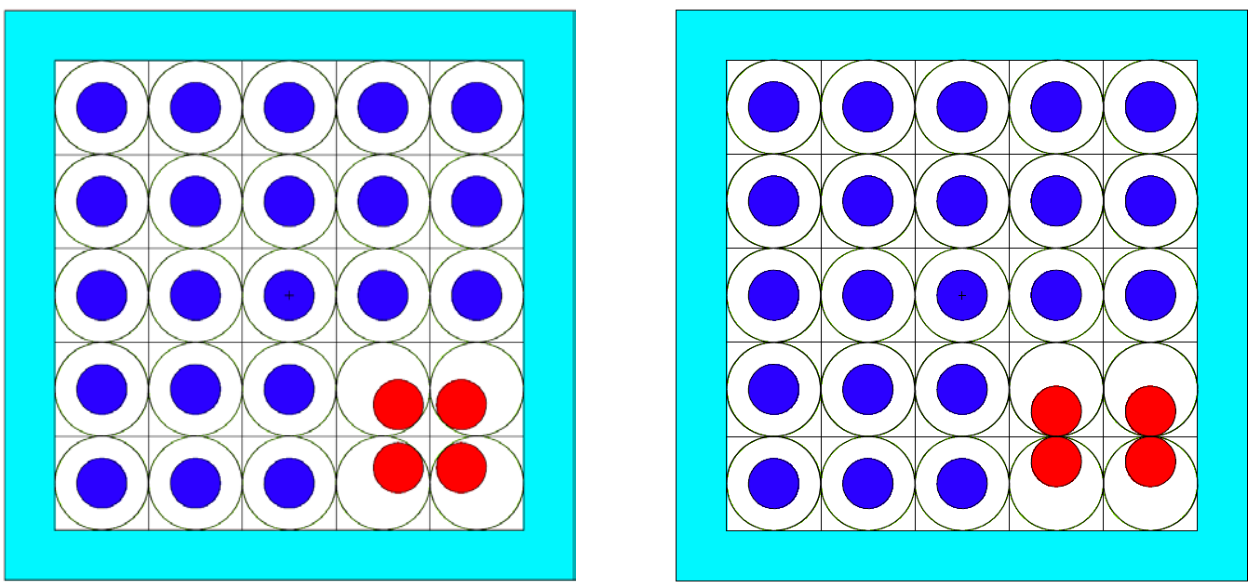
An abbreviated series of cases is also executed that replaces the Los Alamos Mix concrete with PF-4 concrete with 40% water for the concrete reflection scheme. The change in concrete mixture results in a negligible increase in maximum k_{eff} ($\Delta k = 0.004$).

As discussed previously, these results also bound drums larger than 55-gallons with ≤ 300 FGE each, as well as the use of 6” or 12” POCs. Further, since a 5 by 5 by 3-high array of 55-gallon drums has a near ideal configuration with respect to leakage (L/H = 1.08), these results apply to any High FGE drum array with ≤ 75 drums.

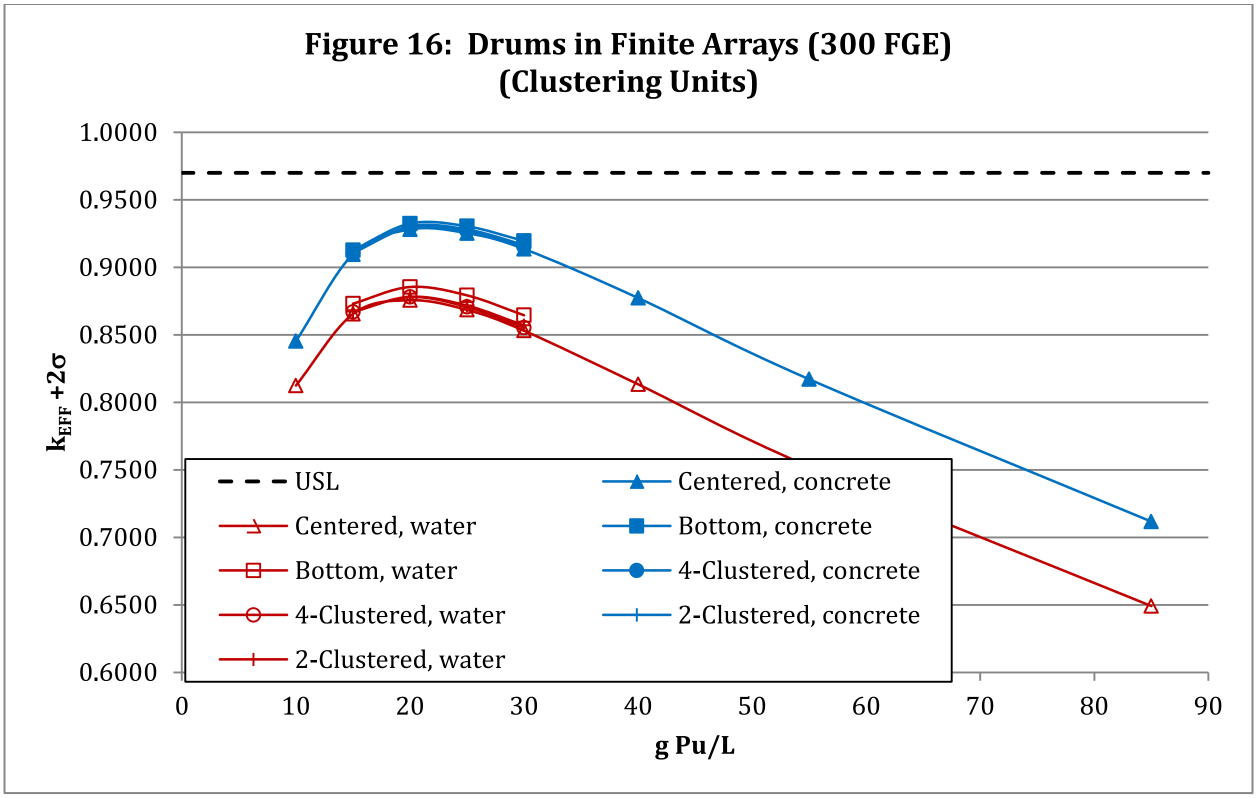
Note that Figure 14 also demonstrates that the adjusted k_{eff} drops significantly even at fissile concentrations close to the optimum (e.g., Δk = -0.02 to -0.01 at concentrations < 15 g/L or > 30 g/L). As described in Section 4.3, it is not judged to be credible that multiple drums could achieve optimum moderation in close proximity to each other. Therefore, modeling the waste as an optimally moderated solution is judged to represent significant safety margin.

The models described above all assume that each spherical waste unit is centered in its drum, and any significant clustering of spherical waste units in a significant number of proximate drums is judged to be not credible given the actual nature of waste. Nonetheless, three series of cases are executed to evaluate the effects of varying the distribution of waste in the drums. First, the spherical waste units are modeled at the bottom of each drum, in closer proximity to the concrete floor. Second, four drums in each tier of the array are modeled with their fissile units clustered towards each other, as depicted in the first image of Figure 15. Third, two pairs of drums in each tier of the array are modeled with their fissile units clustered towards each other, as depicted in the second image of Figure 15.

Figure 15: Clustering Model



The results are depicted in Figure 16. Modeling the fissile units at the bottom of the drums increases k_{eff} by a small amount for the water reflection scheme (Δk = 0.01) and by a negligible amount for the concrete reflection scheme (Δk = 0.004). Both clustering configurations result in negligible k_{eff} increases for both schemes (Δk = 0.002 to 0.003). Therefore, centered fissile units are modeled hereafter in this section, unless otherwise noted. Note that the overmass results of Section 5.3.2 demonstrate that the location of the modified drums (i.e., in the corner of the array as modeled here or in the center of the array) has a negligible effect on k_{eff}.



Given the conservative modeling constraints employed for High FGE drum arrays above, these results are judged to greatly bound normal conditions. With respect to potential upsets, it is judged that the reflection conditions modeled for normal conditions bound any credible reflection in close proximity to an array of High FGE drums. Further, the moderation upset evaluated in Section 5.1.2 demonstrates that interstitial water reduces reactivity in infinite drum arrays, and this conclusion is judged to also apply to finite drum arrays. Therefore, the sub-sections below only evaluate upsets involving geometry, mass, and interaction, with respect to finite arrays of High FGE drums.

5.3.1 Geometry Upsets

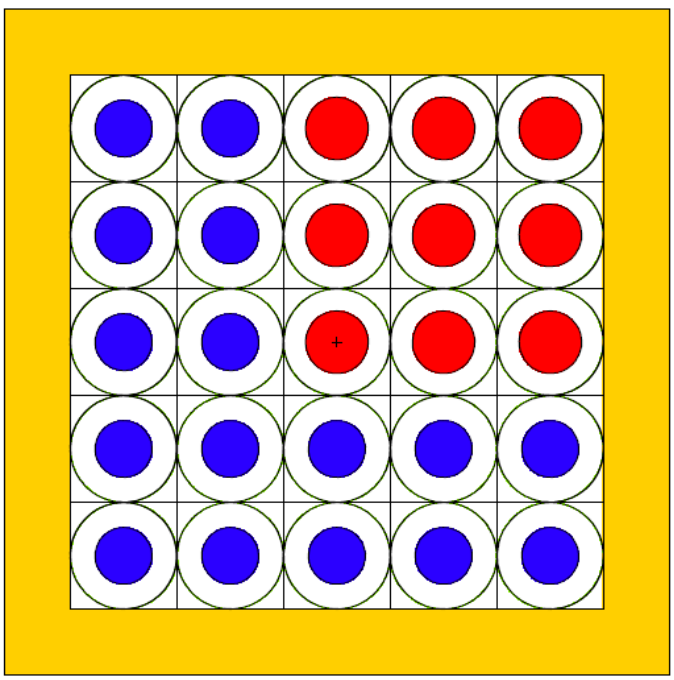
The conservative margins associated with modeled drum dimensions are demonstrated in Section 5.1 for infinite arrays, and similar margins are judged to apply to finite arrays of High FGE drums. The modeled dimensions are judged to bound any minor structural deformation to a limited number of drums due to a low-energy impact (e.g., forklift impact, dropped drum). Further, any credible rearrangement of drums from such an impact would only reduce reactivity given the near ideal configuration of the 5 by 5 by 3-high arrays of drums modeled herein. Finally, the calculations performed in Section 5.1.4 confirm that modeling the waste as spherical units bounds any other geometry, and thus no change to the fissionable material geometry *inside* a drum could impact criticality safety.

5.3.2 Mass Upsets

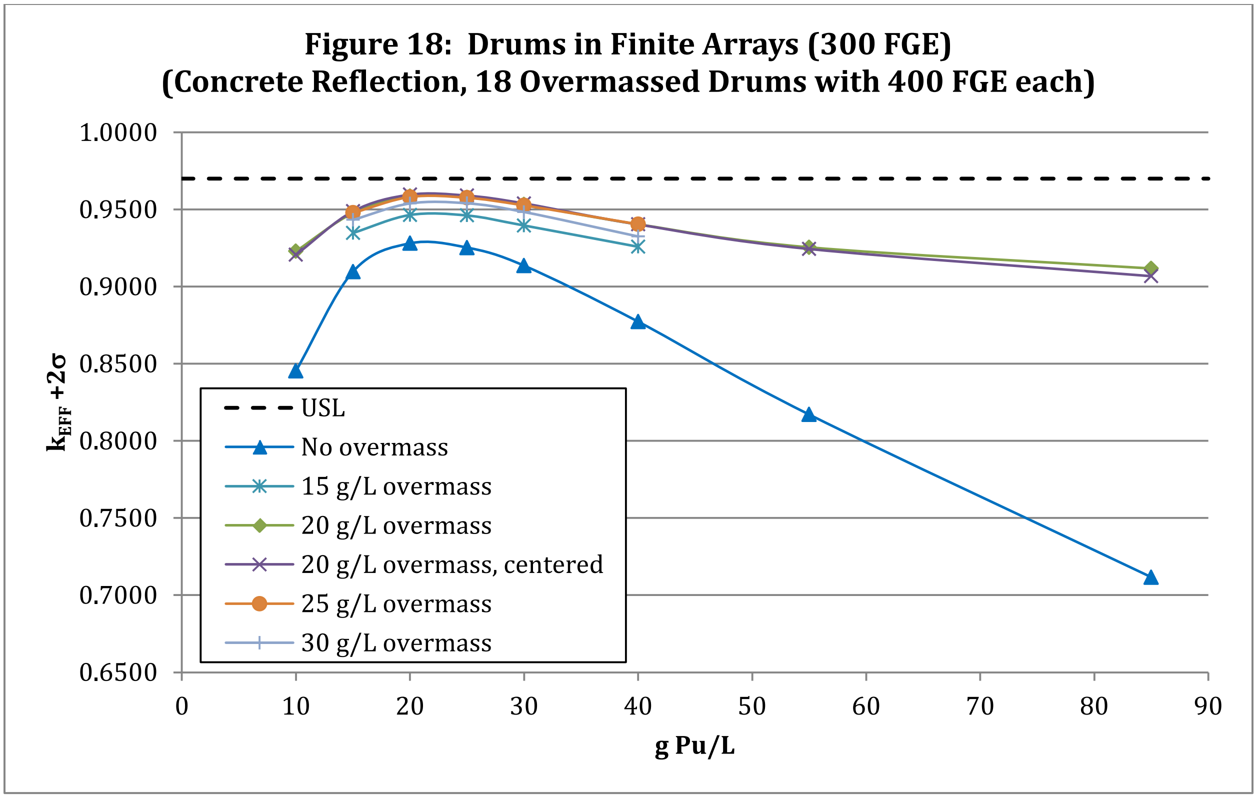
As described in Section 2.0, drums with > 200 FGE are rare, and drums with > 300 FGE are even rarer. Therefore, modeling 75 drums with 300 FGE each coincident in a single compact array is judged to be a very conservative modeling convention with respect to actual fissile mass. Nonetheless, two categories of mass upsets are evaluated herein for High FGE arrays: overmasses in individual drums and > 75 drums in a single array.

With respect to overmassed drums in a High FGE array, two configurations are evaluated. First, 18 drums with 400 FGE each (33% overmass) are modeled in a 3 by 3 by 2-high sub-array in a corner inside the 5 by 5 by 3-high array, as depicted in Figure 17. Since the concrete reflection scheme bounds the water reflection scheme, only the former is modeled for this upset. Note that 18 overmassed drums is equivalent to nearly 25% of the maximum number of drums allowed in a single High FGE array, while a 3 by 3 by 2-high sub-array is a near ideal configuration with respect to leakage (L/H = 0.98). Therefore, this configuration is judged to be very conservative.

Figure 17: 400 FGE Overmassed Drum Model in a High FGE Array

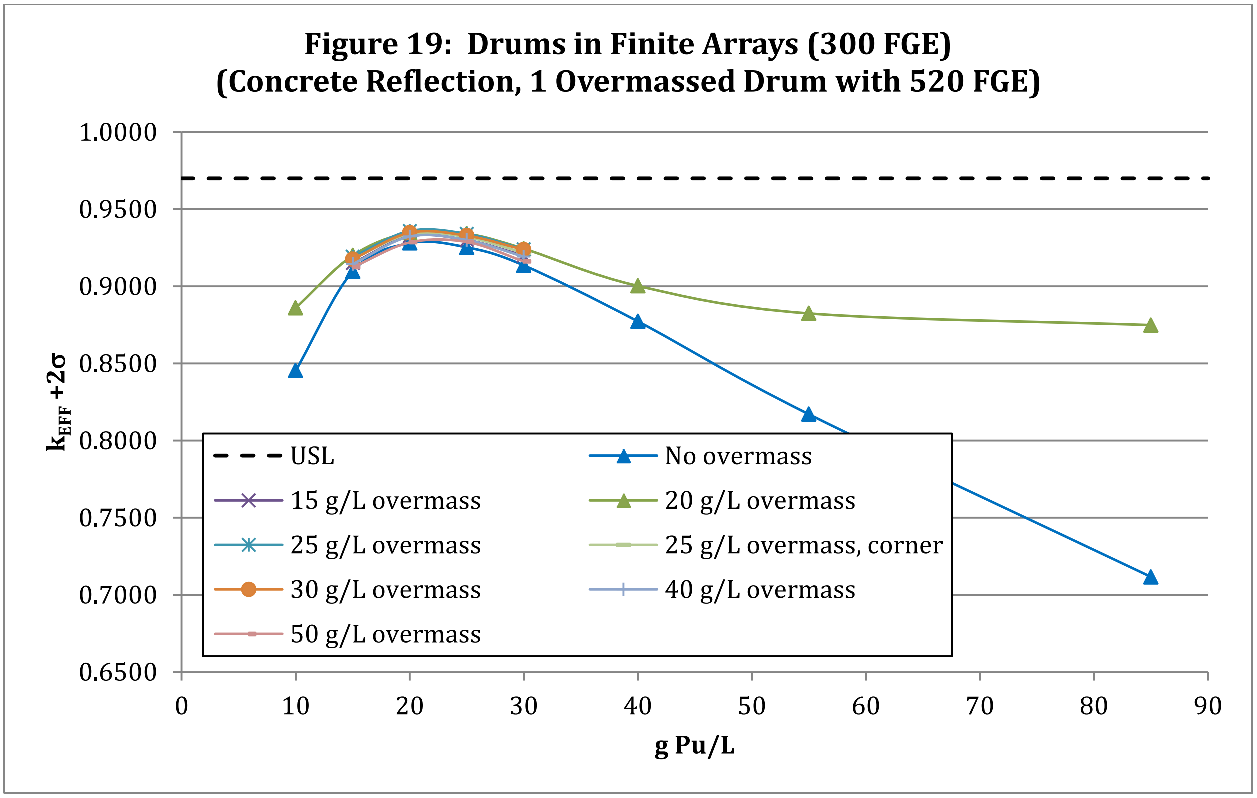


The results are presented in Figure 18. Each distinct curve depicts adjusted k_{eff} as a function of the fissile concentration of the normal drums while the fissile concentration of the overmassed drums is held at a constant value. The results demonstrate that reactivity is maximized when both the normal and overmassed drums are modeled at 20 g/L. At this point, the maximum adjusted k_{eff} is ~0.96. Although this represents a significant increase in reactivity ($\Delta k = 0.03$), the adjusted k_{eff} remains below the USL. Therefore, a mass upset involving up to 18 drums with ≤ 400 FGE each in a High FGE array will remain subcritical.



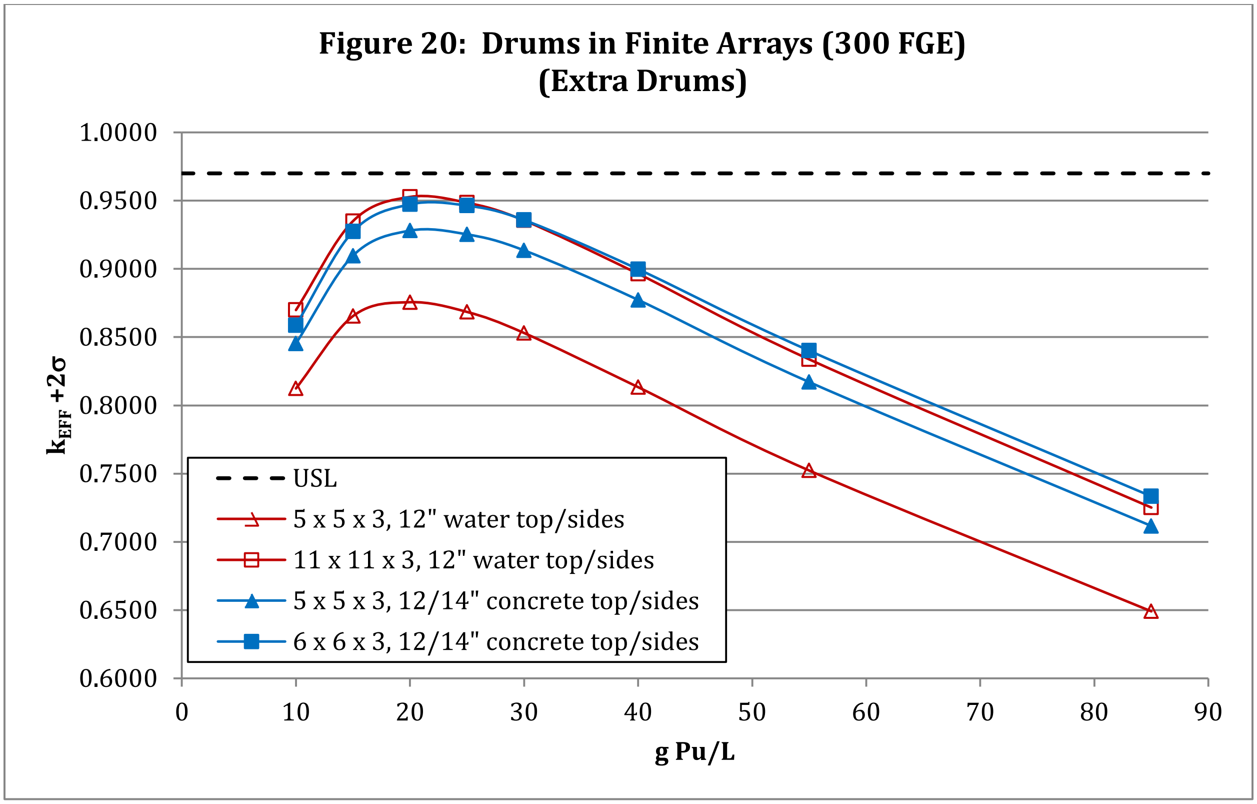
Note that Figure 18 also depicts the results of one series of cases modeling the 3 by 3 by 2-high overmassed sub-array in the center of the High FGE array rather than the corner. These cases result in a negligible increase in the maximum adjusted k_{eff} ($\Delta k = 0.001$). Further, an abbreviated series of cases is also executed that replaces the Los Alamos Mix concrete with PF-4 concrete with 40% water for the limiting cases. The change in concrete mixture results in a negligible increase in maximum k_{eff} ($\Delta k = 0.004$).

The second overmassed drum configuration models a single overmassed drum with 520 FGE in the center of the bottom tier of the High FGE array. The results, presented in Figure 19, demonstrate that reactivity is maximized when the normal drums are modeled at 20 g/L and the overmassed drum is modeled at 25 g/L. At this point, the maximum adjusted k_{eff} is ~0.94. This represents a small increase in reactivity ($\Delta k = 0.01$) with the adjusted k_{eff} remaining below the USL. Therefore, a mass upset involving one drum with ≤ 520 FGE will remain subcritical.



Note that Figure 19 also depicts the results of one series of cases modeling the overmassed drum in a corner of the bottom tier rather than the center. These cases result in a negligible decrease in the maximum adjusted k_{eff} (Δk = -0.002).

The High FGE drum arrays evaluated herein are modeled as 75 drums in a 5 by 5 by 3-high configuration. To evaluate the impact of having too many drums in a single High FGE array, two series of cases are executed: an 11 by 11 by 3-high array with the water reflection scheme (363 drums) and a 6 by 6 by 3-high array with the concrete reflection scheme (108 drums). The results are presented in Figure 20.



The results demonstrate that even with large increases in the number of drums in a single High FGE array (288 extra drums with water reflection, 33 extra drums with concrete reflection), the maximum adjusted k_{eff} (0.95) will remain below the USL. Therefore, such configurations will remain subcritical.

5.3.3 Interaction Upsets

High FGE drums interacting in a single array are considered normal conditions and are demonstrated to be subcritical above. Since High FGE arrays are modeled as finite, interactions between two such arrays are possible. Guidance from ANSI/ANS-8.7 states that "two subarrays when separated by no less than the smallest dimension of the facing surfaces of the subarrays may be evaluated as individual reflected arrays." Therefore, given that a three-high stack of 55-gallon drums or SWBs is approximately 9 feet tall, spacing High FGE arrays ≥ 10 feet from other High FGE or Low FGE arrays would result in negligible interaction.[h]

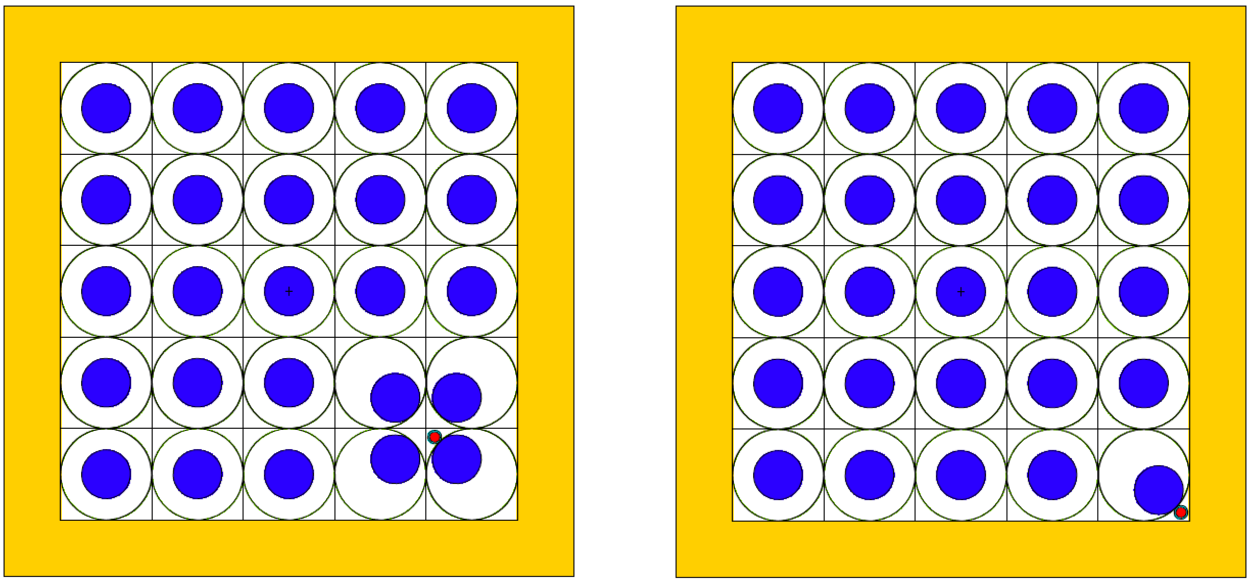
Further, Section 5.3.2 demonstrates that an extra 33 to 288 High FGE drums (depending on reflection) in a High FGE array would remain subcritical, while Section 5.1.3 demonstrates that up to 18 High FGE drums (300 FGE) in an infinite planar, three-high array of Low FGE drums

[h] Waste arrays are generally limited to three-high stacking or lower, based on practical considerations and industrial safety practices.

(200 FGE) also remain subcritical. These configurations are judged to bound any incidental interactions between a High FGE array and other waste drums.[i]

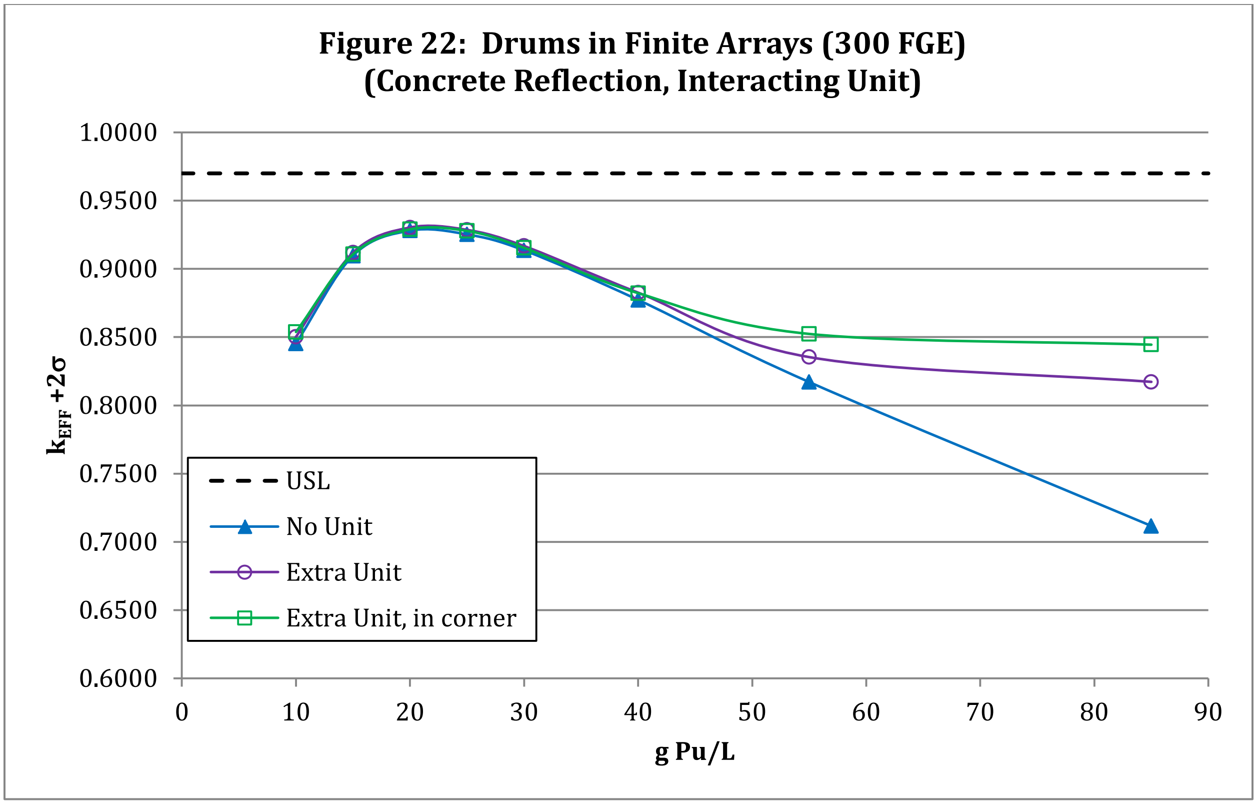
Therefore, the only interaction upset evaluated herein models a single 4.5 kg ^{239}Pu metal unit inside a High FGE array. Based on the results of Section 5.1.5, this unit is modeled as a cylinder with an H/D ratio of 1.0, wrapped in 1 cm of water, and placed in direct contact with a bottom tier drum in the array. The unit is centered vertically with the drum units, and the adjacent drums are clustered towards the unit. The model is depicted in the first image of Figure 21. Alternatively, an additional series of cases models the interacting unit in the corner of the array, as depicted in the second image of Figure 21. Note that, since the concrete reflection scheme bounds the water reflection scheme, only the former is modeled for this upset.

Figure 21: Interaction Models for High FGE Arrays



The results, presented in Figure 22, demonstrate that the interacting unit has only negligible effects on adjusted k_{eff} until the waste becomes significantly undermoderated. At fissile concentrations above this point, k_{eff} increases significantly with respect to the cases with no interacting unit. However, the maximum adjusted k_{eff} for each series of cases is still calculated at the optimum waste unit moderation and remains negligibly different from the maximum k_{eff} calculated for normal conditions (Δk = 0.001 to 0.002). Given that all cases described in this section remain below the USL, this interaction upset will remain subcritical.

i Based on the analyses of Section 5.4, this conclusion also applies to arrays of SWBs, which are bounded by infinite arrays of drums.



5.4 Infinite Three-High Arrays of SWBs with 350 FGE Each

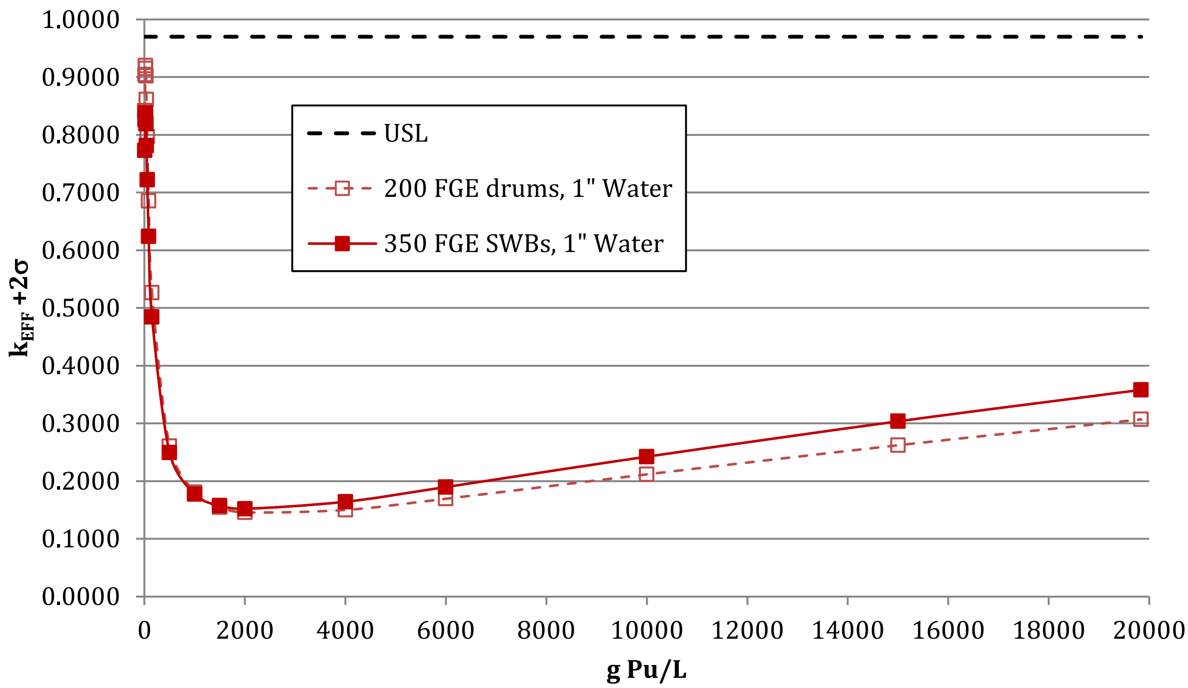
Given that the volume and footprint of an SWB are both approximately nine times larger than those for a 55-gallon drum, while only four or less drums are typically overpacked in a single SWB, Reference 1 judged that the results derived for infinite planar, three-high arrays of 55-gallon drums containing ≤ 200 FGE each may be conservatively extended to similar arrays of SWBs with ≤ 350 FGE each[j], as well as commingled arrays of drums and SWBs. The 350 FGE mass limit is judged to provide significant safety margin because 350 FGE in a single SWB would typically result in a much smaller fissile density than 200 FGE in a 55-gallon drum.

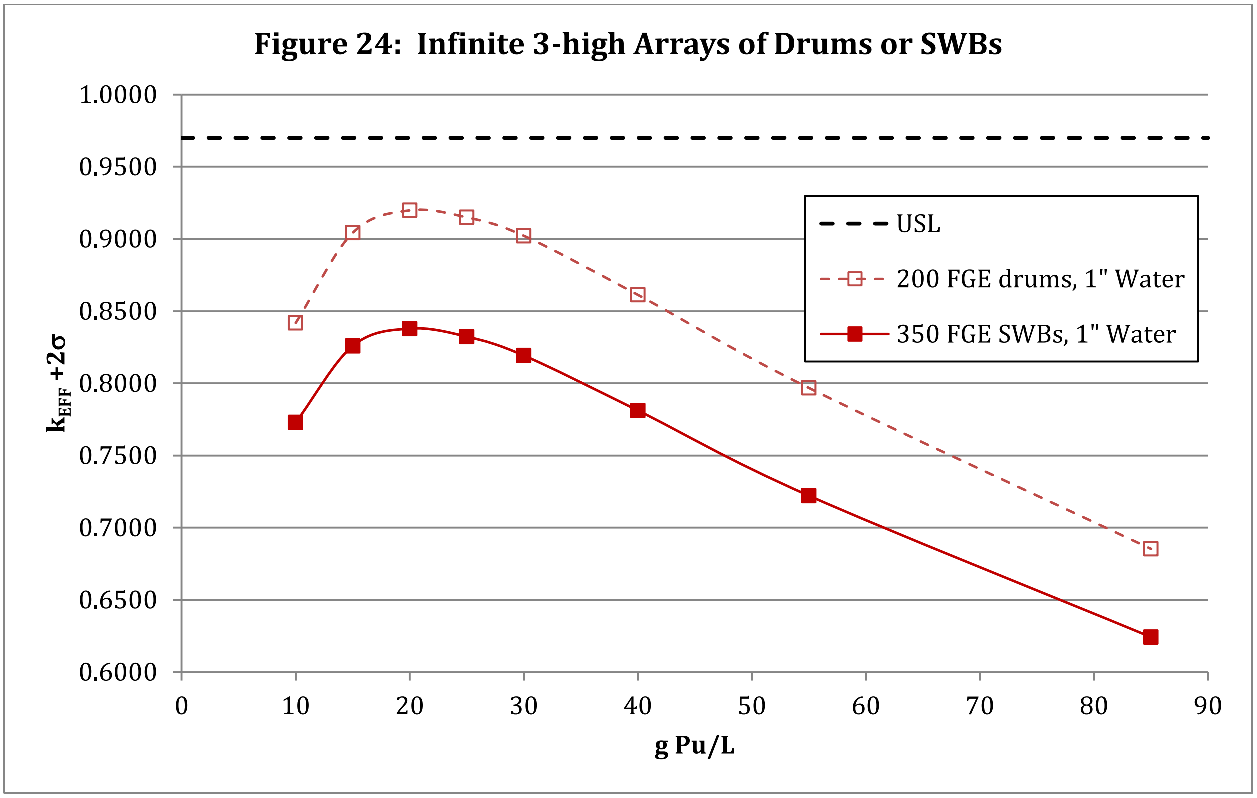
To validate this judgement herein, SWBs are modeled in infinite planar, three-high, square-pitch arrays, with the containers in contact. Each SWB is modeled with the dimensions given in Section 4.2, with half-thick 18 gauge steel walls. TRU waste is modeled as a spherical ^{239}Pu-water solution in the center of each SWB. The fissile concentration of the solution is varied from 10 g/L ^{239}Pu to 19,840 g/L ^{239}Pu (i.e., theoretical metal density), with each SWB modeled to contain 350 FGE ^{239}Pu (modeled herein as 100% ^{239}Pu). Full concrete (60 cm) reflection is modeled below the array and 1” of full-density water reflection is modeled above the array, to match the nominal boundary conditions modeled in Section 5.1 for infinite arrays of drums.

[j] Note that the WIPP WAC (Reference 10) currently limits SWBs to ≤ 325 FGE each. Since both mass limits are currently in use in different areas onsite, the higher mass limit will be evaluated herein.

The results are presented in Figure 23 for the entire range of modeled concentrations, while Figure 24 depicts the concentration range yielding the maximum adjusted k_{eff} values.

Figure 23: Infinite 3-high Arrays of Drums or SWBs



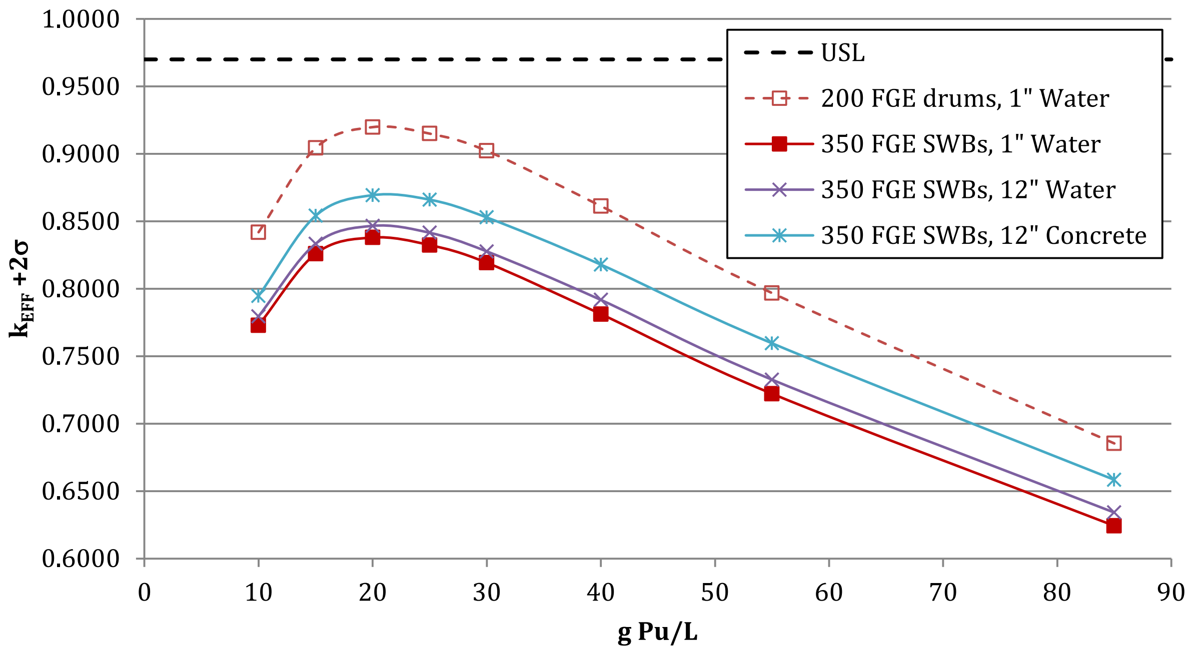


The results demonstrate that reactivity for arrays of SWBs increases with increasing fissile concentration until optimum moderation is achieved. As concentration increases further, reactivity decreases until approximately 2,000 g/L. After this point, reactivity increases monotonically until full metal densities are achieved. The maximum adjusted k_{eff} is 0.84 at an optimum moderation of 20 g/L ^{239}Pu, while the adjusted k_{eff} at theoretical metal density is only 0.36. Since these values are well below the USL, these configurations will remain subcritical.

At very undermoderated conditions (i.e., > 1,500 g/L), the results further demonstrate that arrays of SWBs are more reactive than similar arrays of 55-gallon drums (maximum $\Delta k = 0.05$, at theoretical metal density). However, at lower fissile concentrations, where adjusted k_{eff} is maximized, arrays of drums significantly bound similar arrays of SWBs ($\Delta k = 0.08$ for maximum adjusted k_{eff} at optimal moderation). Therefore, the Reference 1 judgment that 55-gallon drums with ≤ 200 FGE bound SWBs with ≤ 350 FGE is confirmed, and these types of containers may be commingled in infinite planar, three-high arrays. In addition, note that, per the same arguments made in Section 5.1, these results also bound containers larger than SWBs with ≤ 350 FGE each (direct-loaded or overpacked), as well as the use of 6" or 12" POCs.

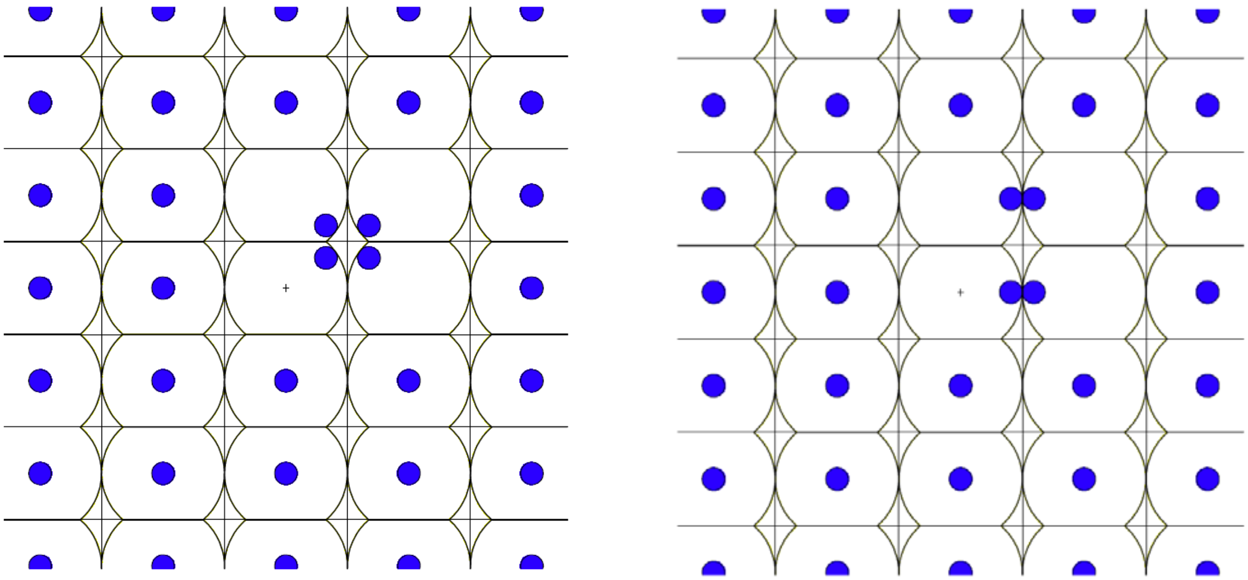
Figure 25 presents the results of two additional series of cases that replace the top 1" water reflector with 12" of water or concrete. The results demonstrate that these reflection schemes still result in maximum adjusted k_{eff} values well below those calculated for drums with 1" water reflection. A single case is also executed that modifies the base case with the maximum adjusted k_{eff} (20 g/L) to replace the Los Alamos Mix concrete with PF-4 concrete with 40% water, resulting in a negligible increase in k_{eff} ($\Delta k = 0.004$). Therefore, infinite arrays of SWBs staged in close proximity to thick water or concrete reflection during normal conditions will also remain subcritical.

Figure 25: Infinite 3-high Arrays of Drums or SWBs (Alternate Reflection)



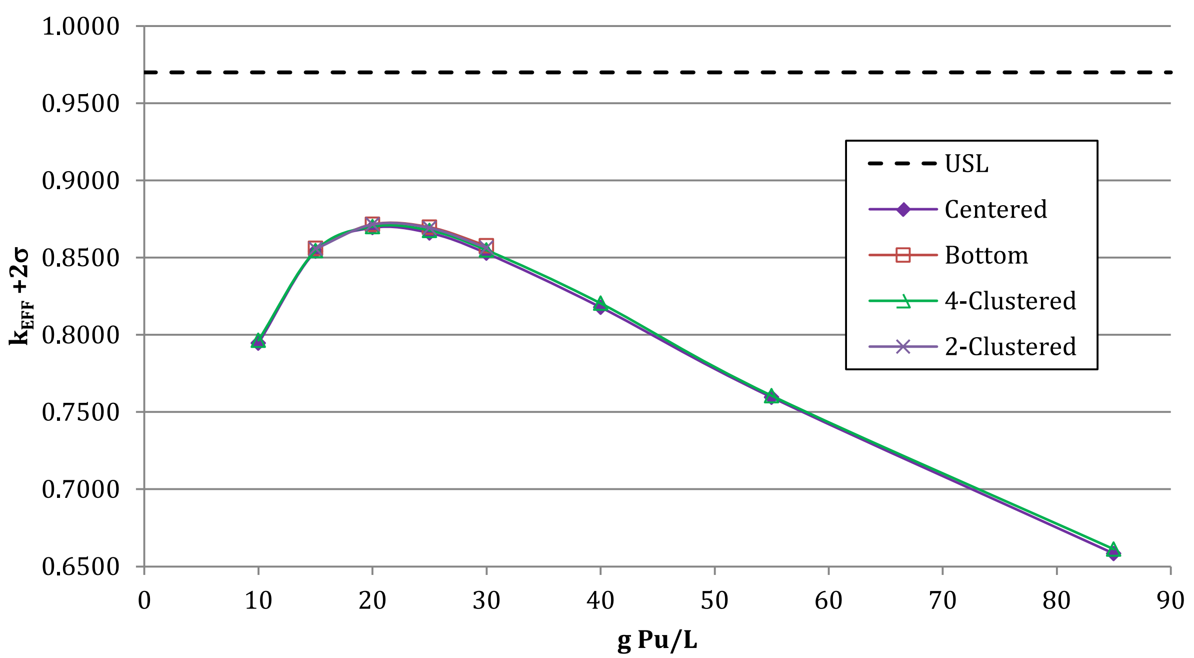
The calculations for normal conditions also model each spherical waste unit to be centered in its SWB, and any significant clustering of spherical waste units in a significant number of proximate SWBs is judged to be not credible given the actual nature of waste. Nonetheless, three series of cases are executed to evaluate the effects of varying the distribution of waste in the SWBs. First, the spherical waste units are modeled at the bottom of each SWB, in closer proximity to the concrete floor. Second, four SWBs in each tier of the array are modeled with their fissile units clustered towards each other, as depicted in the first image of Figure 26. Third, two pairs of drums in each tier of the array are modeled with their fissile units clustered towards each other, as depicted in the second image of Figure 26. Note that 12” concrete reflection is modeled above the array for both series of cases. For clustering configurations, a reflected finite 7 by 7 by 3-high array is modeled to approximate 12 clustered waste units in each individual group of 147 SWBs in an infinite array.

Figure 26: Clustering Model



The results are depicted in Figure 27. Both configurations result in negligible k_{eff} increases (Δk = 0.001 to 0.002 for optimal moderation). Therefore, centered fissile units are modeled hereafter in this section, unless otherwise noted.

Figure 27: Infinite 3-high Arrays of SWBs (Concrete Reflection, Clustering Units)



Given the conservative modeling constraints employed for infinite arrays of SWBs above, these results are judged to greatly bound normal conditions. With respect to potential upsets, it is judged that the reflection conditions modeled for normal conditions bound any credible reflection in close proximity to an array of SWBs. Further, the moderation upset evaluated in Section 5.1.2 demonstrates that interstitial water reduces reactivity in infinite drum arrays, and this conclusion is judged to also apply to SWB arrays. Therefore, the sub-sections below only evaluate upsets involving geometry, mass, and interaction.

5.4.1 Geometry Upsets

The large calculated margin between the maximum adjusted k_{eff} of infinite planar, three-high arrays of SWBs and drums ($\Delta k = 0.08$ for 1” water reflection or $\Delta k = 0.05$ for 12” concrete reflection) demonstrate that the subcritical conclusion for normal operations with SWBs is not sensitive to small changes in SWB dimensions. This margin, as well as the reduced SWB dimensions modeled herein, are judged to bound any minor structural deformation to a limited number of SWBs due to a low-energy impact (e.g., forklift impact, dropped drum). Further, any credible rearrangement of SWBs from such an impact would only reduce reactivity from the uniform, infinite planar, three-high array of SWBs in contact modeled for normal conditions. Although a rearrangement of a large enough collection of SWBs in four or more tiers could possibly increase reactivity, no credible event is postulated herein that could create a large enough array to challenge the normal conditions modeled herein. Similarly, given practical considerations and industrial safety practices, it is judged to be not credible that SWBs would be inadvertently stacked four-high in an array. Finally, the calculations performed in Section 5.1.4 confirm that modeling the waste as spherical units bounds any other geometry, and thus no change to the fissionable material geometry *inside* a SWB could impact criticality safety.

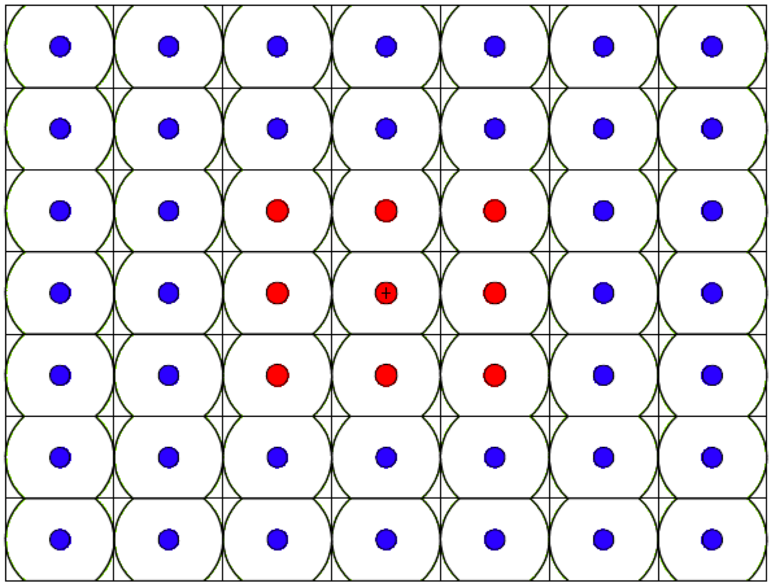
5.4.2 Mass Upsets

Based on the information described in Section 2.0, waste containers with 350 FGE would be very rare in reality. Therefore, modeling every SWB in an infinite planar, three-high array to simultaneously contain 350 FGE is judged to be a very conservative modeling convention with respect to actual fissile mass.

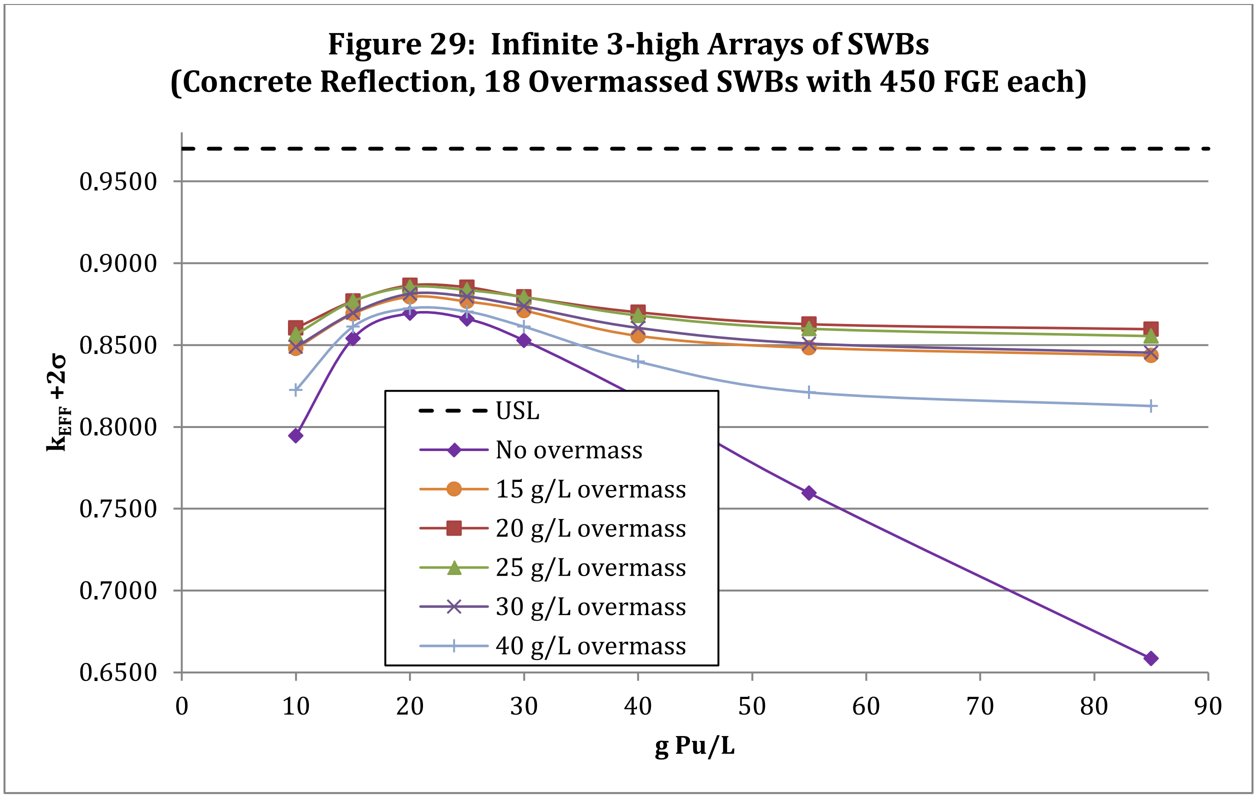
Nonetheless, an overmass upset is explicitly evaluated herein that postulates that 18 SWBs at 450 FGE each (~30% overmass) are inadvertently present in an array. To bound this configuration, a reflected finite 7 by 7 by 3-high array is modeled with a subset of 18 SWBs with 450 FGE each modeled as a 3 by 3 by 2-high sub-array in the center of the bottom two tiers of the larger array. This approximates an infinite planar, three-high array with groups of 18 overmassed SWBs in each larger collection of 147 SWBs. 12” concrete reflection is modeled above the array.

Since each group of 3 by 3 by 2 overmassed SWBs are repeated infinitely throughout the array (representing over 12% of the total modeled SWBs), this configuration is judged to be very conservative. A top view of the bottom tier of the array is depicted in Figure 28, where red represents overmassed SWBs.

Figure 28: 450 FGE Overmassed SWB Model



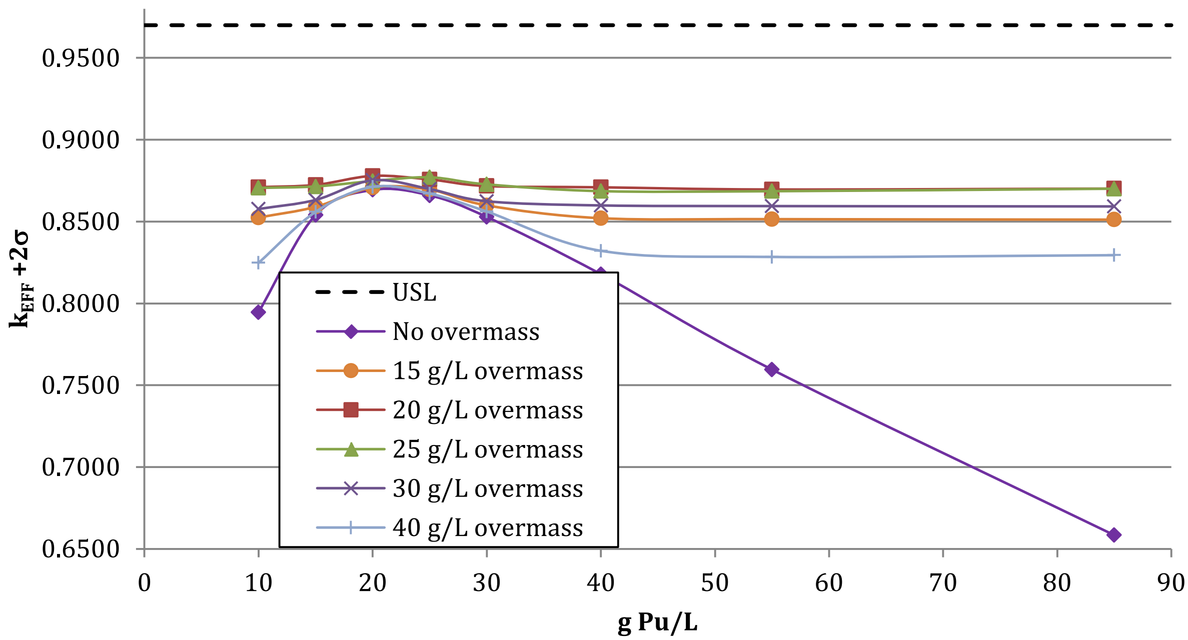
The results are presented in Figure 29. Each distinct curve depicts adjusted k_{eff} as a function of the fissile concentration of the normal SWBs while the fissile concentration of the overmassed SWBs is held at a constant value. The results demonstrate that reactivity is maximized when both the normal and overmassed SWBs are modeled at 20 g/L. At this point, the maximum adjusted k_{eff} is ~0.89. Although this represents a significant increase in reactivity ($\Delta k = 0.02$), the adjusted k_{eff} remains below the USL. Therefore, a mass upset involving up to 18 SWBs with ≤ 450 FGE each will remain subcritical.



One additional overmass upset is modeled using the same finite 7 by 7 by 3-high array of SWBs. In these series of cases, a single overmassed SWB in the bottom tier is modeled to contain 520 FGE, with the finite array reflected to approximate an infinite planar, three-high array with one overmassed SWB in each larger collection of 147 SWBs.

The results, presented in Figure 30, demonstrate that reactivity is maximized when both the normal and overmassed SWBs are modeled at 20 g/L. At this point, the maximum adjusted k_{eff} is ~0.88. This represents a small increase in reactivity ($\Delta k = 0.01$) with the adjusted k_{eff} remaining below the USL. Therefore, a mass upset involving one SWB with ≤ 520 FGE will remain subcritical.

Figure 30: Infinite 3-high Arrays of SWBs
(Concrete Reflection, 1 Overmassed SWB with 520 FGE)

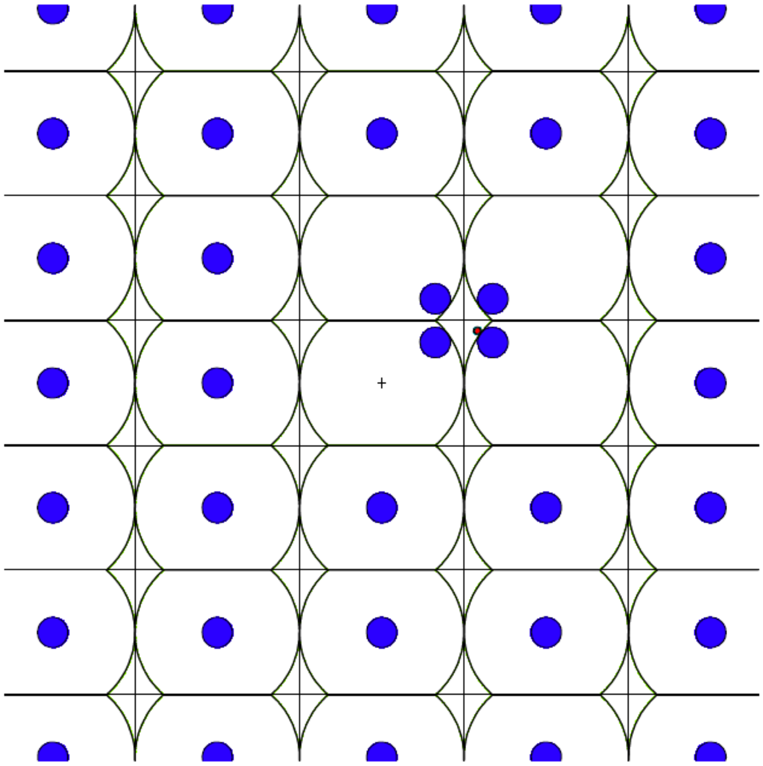


5.4.3 Interaction Upsets

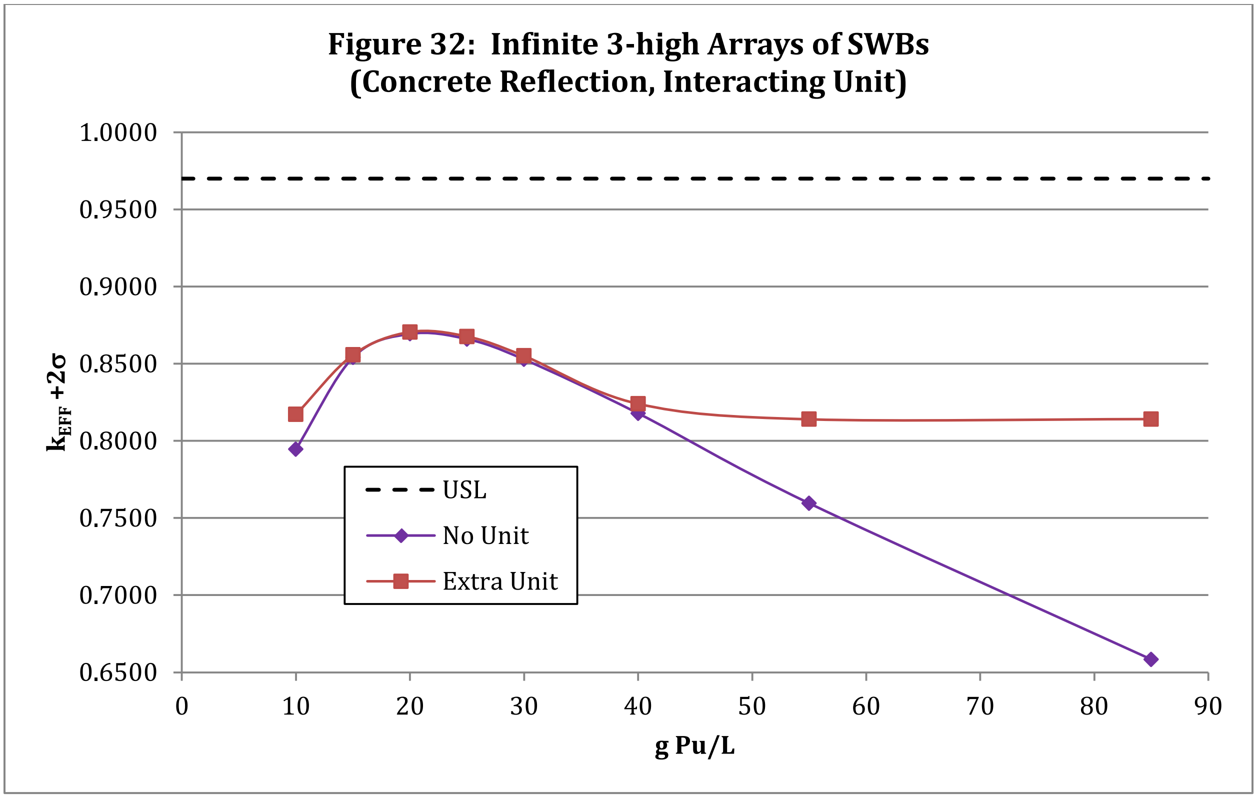
The normal conditions modeled above demonstrate that infinite arrays of SWBs in contact remain subcritical and are bounded by similar arrays of Low FGE drums. Therefore, it is clear a priori that interactions between SWBs and other Low FGE waste containers will remain subcritical. Further, interactions with High FGE drums are evaluated separately in Section 5.3.3 and are determined to remain subcritical.

Therefore, the only interaction upset evaluated herein models a single 4.5 kg ^{239}Pu metal unit inside an array of SWBs with 350 FGE each. Based on the results of Section 5.1.5, this unit is modeled as a cylinder with an H/D ratio of 1.0, wrapped in 1 cm of water, and placed in direct contact with a bottom tier SWB in the array. The unit is centered vertically with the waste units, and the adjacent four SWBs are clustered towards the unit. The model is depicted in Figure 31. Note that a reflected finite 7 by 7 by 3-high array is modeled to approximate one interacting unit in each individual group of 147 SWBs in an infinite array, with 12” concrete reflection modeled above the array.

Figure 31: Interaction Model for SWB Arrays



The results, presented in Figure 32, demonstrate that the interacting unit has only negligible effects on adjusted k_{eff} until the waste becomes significantly undermoderated. At fissile concentrations above this point, k_{eff} increases significantly with respect to the cases with no interacting unit. However, the maximum adjusted k_{eff} is still calculated at the optimum waste unit moderation and remains negligibly different from the maximum k_{eff} calculated for normal conditions ($\Delta k = 0.001$). Given that all cases described in this section remain below the USL, this interaction upset will remain subcritical.

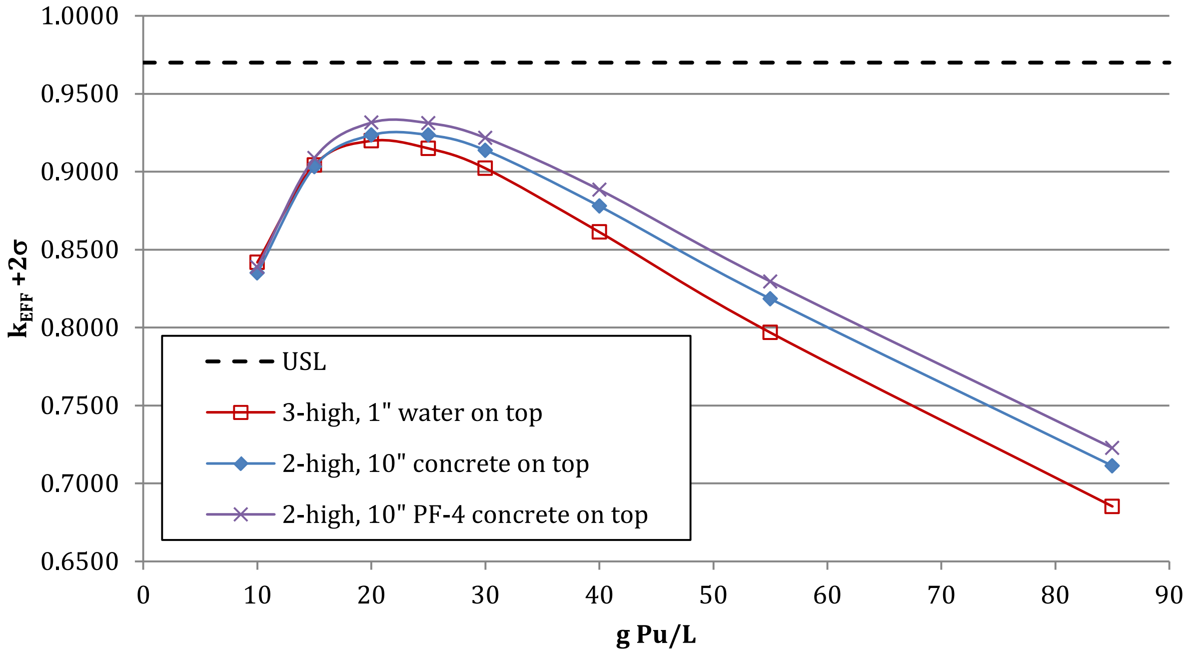


5.5 Infinite Two-High Arrays of 55-gallon Drums with 200 FGE Each

In this section, the infinite planar, three-high arrays of 55-gallon drums modeled in Section 5.1 are modified to model infinite planar *two*-high arrays of 55-gallon drums. In addition, the nominal 1" water reflection on top of the array is replaced with 10" of concrete reflection.[k] This configuration may be used to bound drum arrays in large concrete rooms such as are present in PF-4. The results are presented in Figure 33.

[k] Per Reference 15, the ceilings in PF-4 are ≤ 10" thick concrete.

Figure 33: Infinite 2- or 3-high Arrays of 55-gallon Drums (200 FGE)



The results demonstrate that reactivity is maximized at an optimal concentration of 25 g/L, with a maximum adjusted k_{eff} of 0.92. The adjusted k_{eff} is negligibly greater than that calculated for three-high arrays ($\Delta k = 0.004$) at optimal moderation, with larger increases present at higher fissile concentrations. Figure 33 also presents a series of cases that replaces the Los Alamos Mix concrete with PF-4 concrete with 40% water. The change in concrete mixture results in a negligible increase in maximum k_{eff} ($\Delta k = 0.008$). However, since this configuration will likely be most useful in PF-4, all subsequent cases in this section conservatively model PF-4 concrete with 40% water. Since all adjusted k_{eff} values are well below the USL, this configuration will remain subcritical.

Given the conservative modeling constraints employed above, these results are judged to greatly bound normal conditions. With respect to potential upsets, it is judged that the reflection conditions modeled for normal conditions bound any credible reflection in close proximity to an array of drums. Further, the moderation upset evaluated in Section 5.1.2 demonstrates that interstitial water reduces reactivity in infinite three-high drum arrays, and this conclusion is judged to also apply to two-high arrays. Therefore, the sub-sections below only evaluate upsets involving geometry, mass, and interaction.

Note that, based on the conclusions of Section 5.4, the results presented here for infinite planar, two-high arrays of 55-gallon drums with ≤ 200 FGE each are judged to bound infinite planar, two-high arrays of SWBs with ≤ 350 FGE each, for both normal conditions and evaluated upsets. However, note that the results of Section 5.4 already demonstrate that the normal conditions and evaluated upsets modeled for infinite planar, *three*-high arrays of SWBs remain subcritical, even with 12” concrete above the array.

5.5.1 Geometry Upsets

With respect to geometry upsets, the previous evaluations for infinite three-high arrays of drums, finite arrays of High FGE drums, and infinite three-high arrays of SWBs all demonstrate that the modeled geometry upsets (i.e., fissile unit shape and distribution) have negligible effect on k_{eff}. With one exception, the conclusions from those evaluations are judged to equally apply to infinite two-high arrays of drums, and no new calculations are performed for such upsets.

With respect to two-high arrays, one additional credible upset is identified involving stacking height. It is still judged that no energetic event could credibly rearrange a large enough collection of drums in greater than two tiers to challenge the reactivity of the normal conditions modeled herein (i.e., uniform, infinite planar, two-high array of drums in contact). Nonetheless, despite practical considerations and industrial safety practices, it is judged to be credible although unlikely that a few drums could be inadvertently stacked three-high before being discovered.

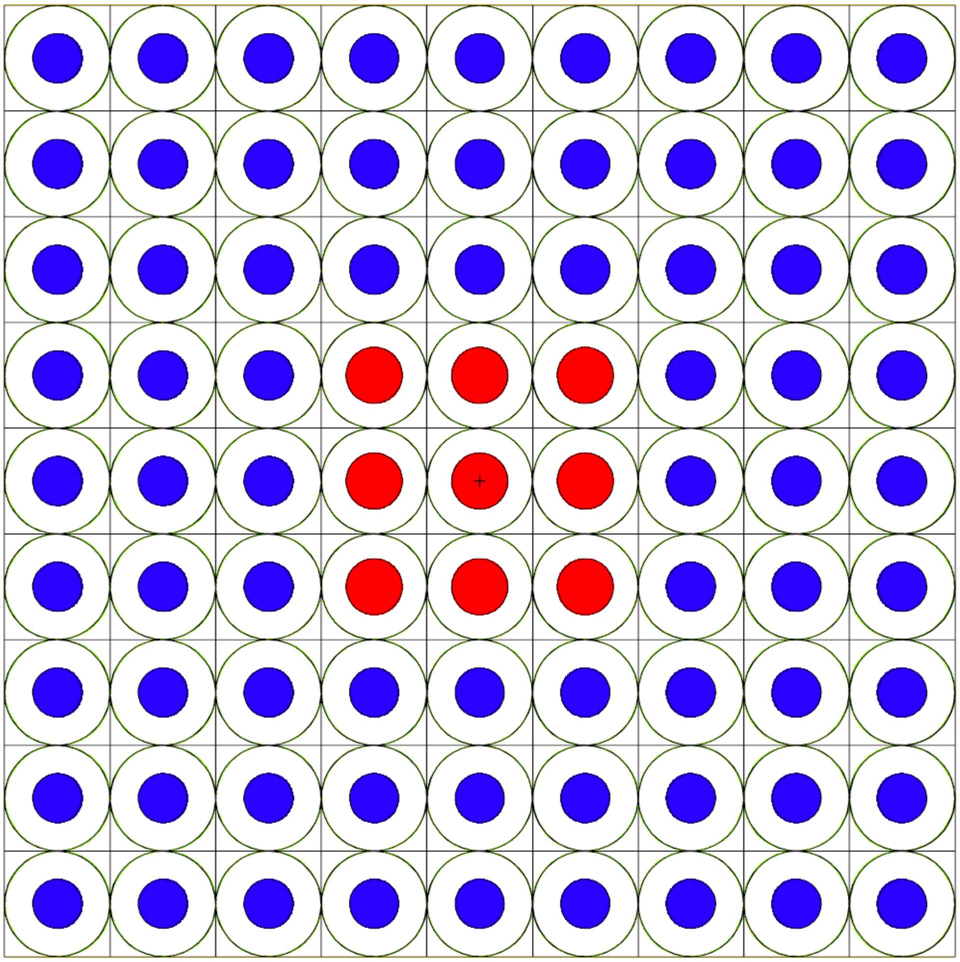
However, Section 5.2 models large finite arrays of drums stacked three-high in the presence of concrete reflection. Specifically, finite arrays with ≤ 507 drums stacked ≤ 3-high with 14” concrete walls on four sides, 12” concrete above, and 60 cm concrete below are judged to be bound by the subcritical calculations performed for infinite planar, three-high arrays in Section 5.1, for both normal conditions and evaluated upsets. This configuration is judged to greatly bound any limited over-stacking of a few drums in a nominally two-high array. Therefore, this upset will remain subcritical.

5.5.2 Mass Upsets

As described in Section 2.0, the average fissile loading of waste drums is expected to be significantly lower than the 200 FGE per drum modeled herein. Therefore, modeling every drum in an infinite planar, two-high array to simultaneously contain 200 FGE is judged to be a very conservative modeling convention with respect to actual fissile mass.

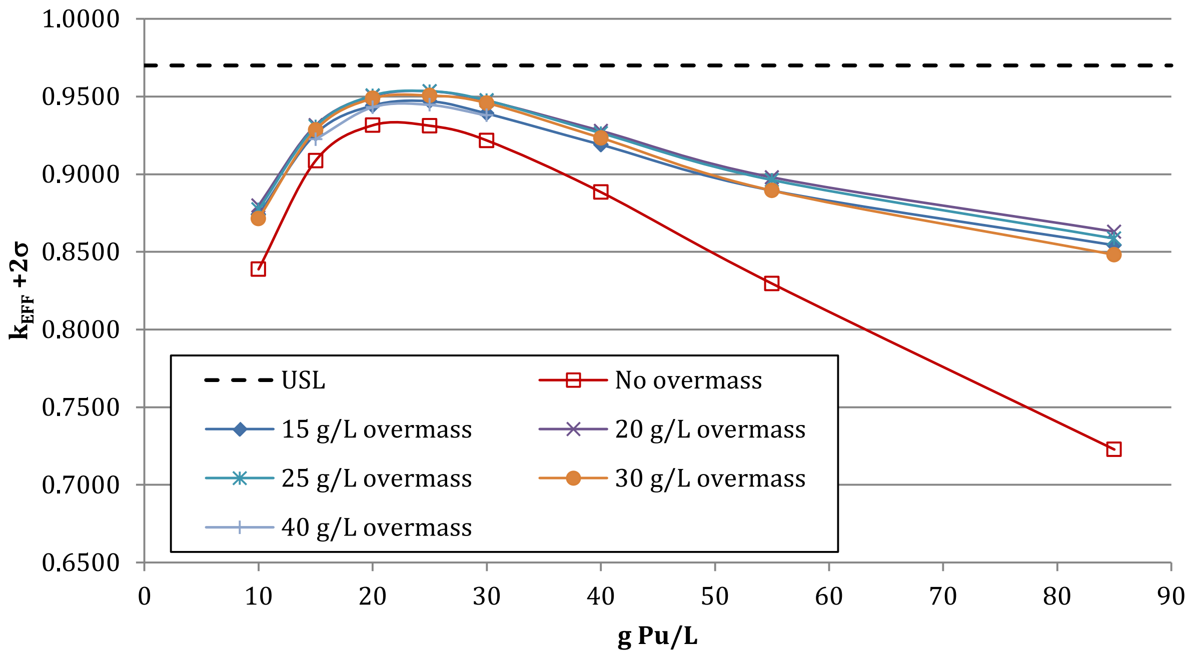
Nonetheless, an overmass upset is explicitly evaluated herein that postulates that 18 drums at 300 FGE each (50% overmass) are inadvertently present in an array. To bound this configuration, a reflected finite 9 by 9 by 2-high array is modeled with a subset of 18 drums with 300 FGE each modeled as a 3 by 3 by 2-high sub-array in the center of both tiers of the larger array. This approximates an infinite planar, two-high array with groups of 18 overmassed drums in each larger collection of 162 drums (i.e., 9 by 9 by 2). Since each group of 3 by 3 by 2 overmassed drums are modeled in a near ideal configuration with respect to leakage (L/H = 0.98) and are repeated infinitely throughout the array (representing over 11% of the total modeled drums), this configuration is judged to be very conservative. A top view of the bottom tier of the array is depicted in Figure 34, where red represents overmassed drums.

Figure 34: 300 FGE Overmassed Drum Model



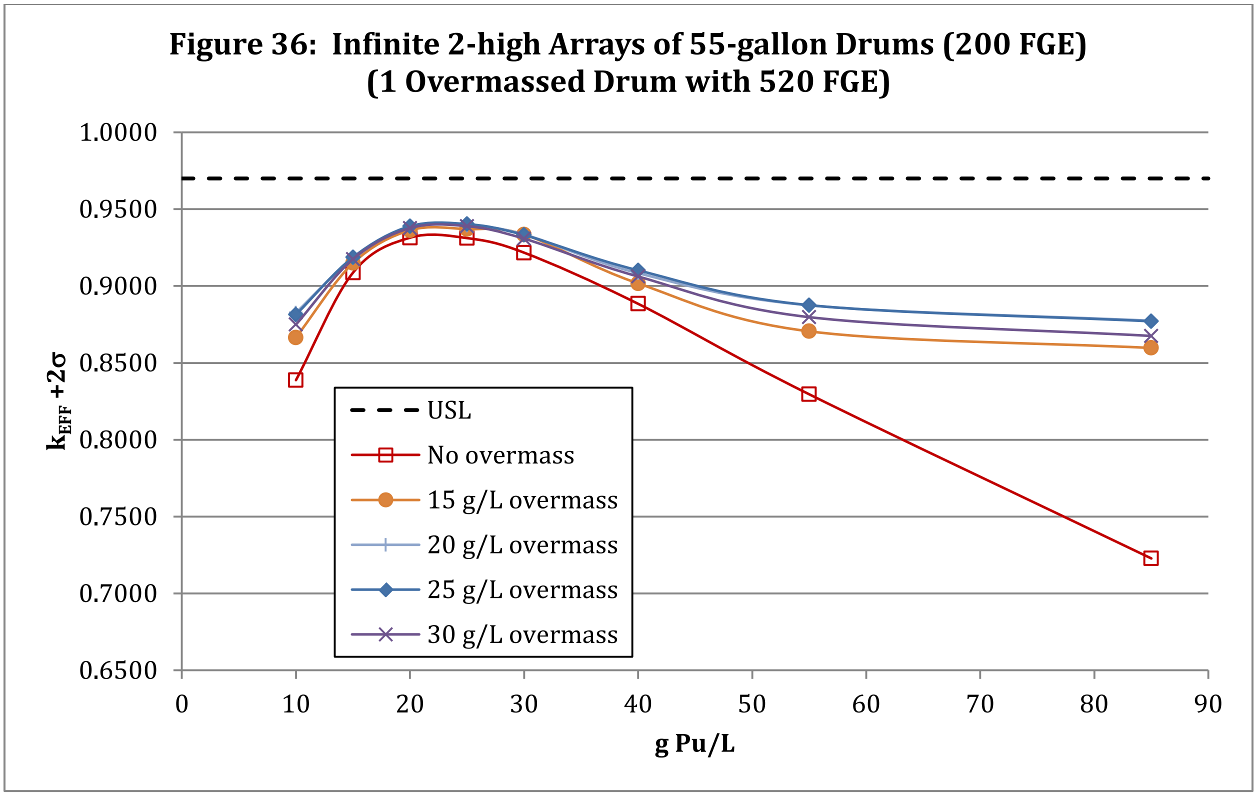
The results are presented in Figure 35. Each distinct curve depicts adjusted k_{eff} as a function of the fissile concentration of the normal drums while the fissile concentration of the overmassed drums is held at a constant value. The results demonstrate that reactivity is maximized when both the normal and overmassed drums are modeled at 25 g/L. At this point, the maximum adjusted k_{eff} is ~0.95. Although this represents a significant increase in reactivity ($\Delta k = 0.02$), the adjusted k_{eff} remains below the USL. Therefore, a mass upset involving up to 18 drums with ≤ 300 FGE each will remain subcritical.

Figure 35: Infinite 2-high Arrays of 55-gallon Drums (200 FGE)
(18 Overmassed Drums with 300 FGE each)



One additional overmass upset is modeled using the same finite 9 by 9 by 2-high array of drums. In these series of cases, a single overmassed drum in the bottom tier is modeled to contain 520 FGE, with the finite array reflected on four sides to approximate an infinite planar, three-high array with one overmassed drum in each larger collection of 162 drums.

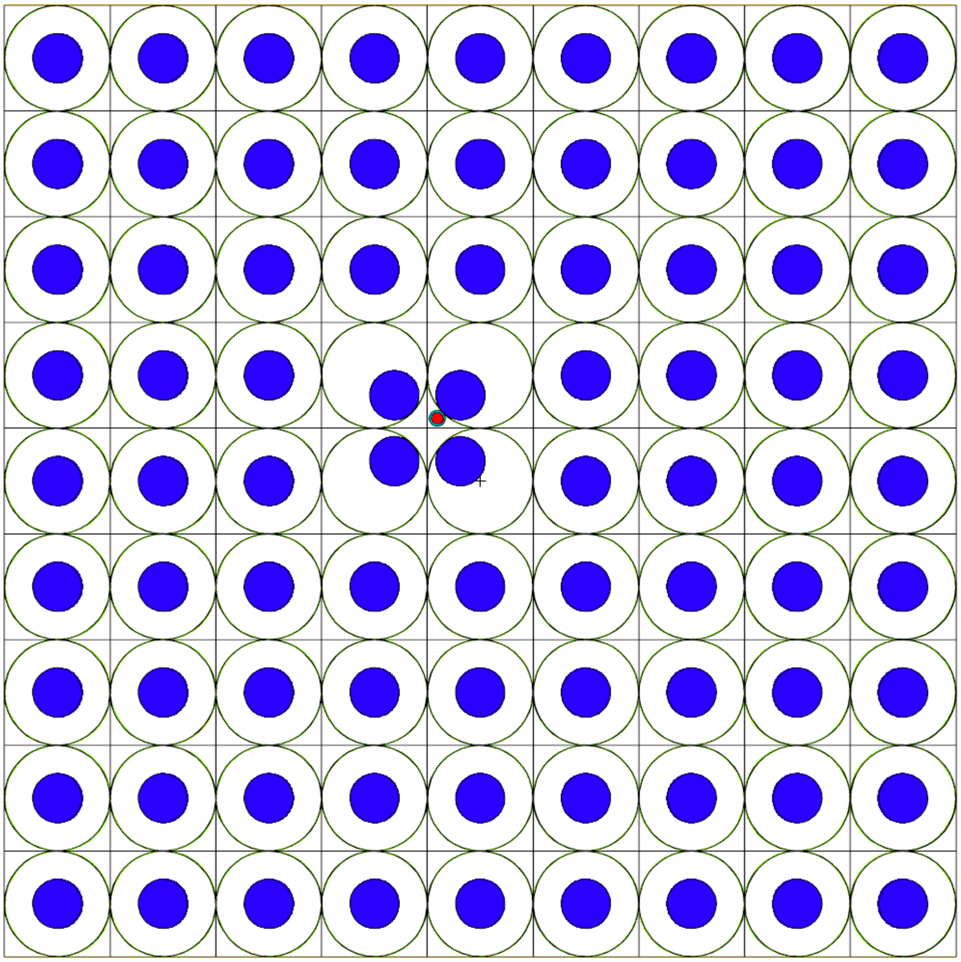
The results, presented in Figure 36, demonstrate that reactivity is maximized when both the normal and overmassed drums are modeled at 25 g/L. At this point, the maximum adjusted k_{eff} is ~0.94. This represents a small increase in reactivity ($\Delta k = 0.01$) with the adjusted k_{eff} remaining below the USL. Therefore, a mass upset involving one drum with $\leq$ 520 FGE will remain subcritical.



5.5.3 Interaction Upsets

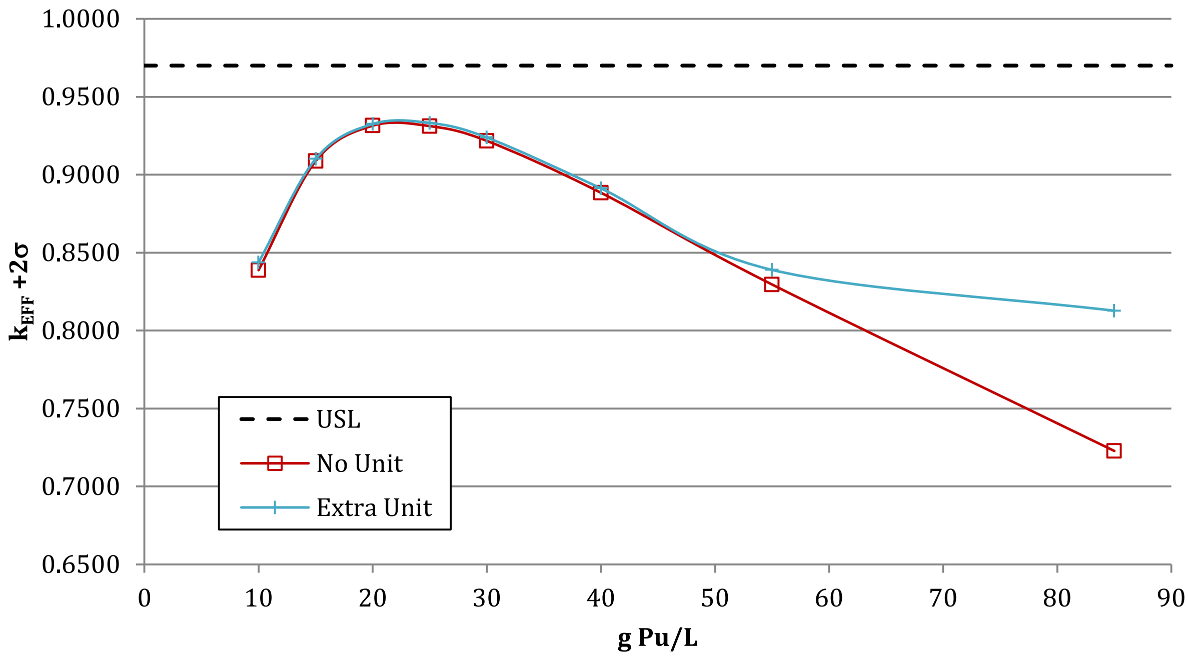
Given that the normal conditions modeled herein demonstrate that infinite arrays of drums in contact remain subcritical, it is clear a priori that interactions with other Low FGE waste drums will remain subcritical. Furthermore, Section 5.5.2 demonstrates that interactions with multiple High FGE drums (300 FGE each) also remain subcritical. Therefore, the only interaction upset evaluated herein models a single 4.5 kg ^{239}Pu metal unit inside the array. Based on the results of Section 5.1.5, this unit is modeled as a cylinder with an H/D ratio of 1.0, wrapped in 1 cm of water, and placed in direct contact with a bottom tier drum in the array. The model is depicted in Figure 37. Note that a reflected finite 9 by 9 by 2-high array is modeled to approximate one interacting unit in each individual group of 162 drums in an infinite array.

Figure 37: Interaction Model



The results, presented in Figure 38, demonstrate that the interacting unit has only negligible effects on adjusted k_{eff} until the waste becomes significantly undermoderated. At fissile concentrations above this point, k_{eff} increases significantly with respect to the cases with no interacting unit. However, the maximum adjusted k_{eff} is still calculated at the optimum waste unit moderation and remains negligibly different from the maximum k_{eff} calculated for normal conditions ($\Delta k = 0.002$). Given that all cases described in this section remain below the USL, this interaction upset will remain subcritical.

Figure 38: Infinite 2-high Arrays of 55-gallon Drums (200 FGE) (Interacting Unit)



6.0 Conclusion

Parametric calculations of TRU waste container arrays are performed herein to determine subcritical configurations and to evaluate potential upsets. The conclusions are summarized below for several types of containers. Note that these conclusions are generally consistent with previous analyses of waste container staging (e.g., Reference 1).

55-gallon drums with ≤ 200 FGE each

Infinite planar, three-high arrays of 55-gallon drums with ≤ 200 FGE each are demonstrated to remain subcritical based on the following conservative assumptions:

- Every drum contains 200 g ^{239}Pu as an optimally moderated spherical solution of full density plutonium metal and water
- No waste matrix material or ^{240}Pu modeled
- Drums in contact, with conservative dimensions and half the nominal wall thickness
- Full (60 cm) concrete reflection modeled below the array and 1” full-density water reflection modeled above the array

For such arrays, the following upsets are evaluated and demonstrated to remain subcritical:

- Reflection: 12” of full density water modeled above the array
- Moderation: interstitial water at densities of 0 to 1.0 g/cc

- Mass: 18 drums with 300 FGE each or one drum with 520 FGE in the array
- Geometry: vertical and radial clustering of waste units in adjacent drums
- Interaction: one 4.5 kg ^{239}Pu metal unit in the array

Furthermore, the conclusions above for normal conditions and evaluated upsets are also judged to apply to the following finite drum configurations involving additional concrete reflection:

- ≤ 675 drums stacked ≤ 3-high in a 14" concrete corner (12" concrete above and 60 cm concrete below)
- ≤ 507 drums stacked ≤ 3-high with 14" concrete walls on four sides (12" concrete above and 60 cm concrete below)

Infinite planar, two-high arrays of 55-gallon drums with ≤ 200 FGE each are demonstrated to remain subcritical based on the following conservative assumptions:

- Every drum contains 200 g ^{239}Pu as an optimally moderated spherical solution of full density plutonium metal and water
- No waste matrix material or ^{240}Pu modeled
- Drums in contact, with conservative dimensions and half the nominal wall thickness
- Full (60 cm) concrete reflection modeled below the array and 10" concrete reflection modeled above the array

For such arrays, the following upsets are evaluated and demonstrated to remain subcritical:

- Moderation: interstitial water at densities of 0 to 1.0 g/cc
- Mass: 18 drums with 300 FGE each or one drum with 520 FGE in the array
- Geometry: vertical and radial clustering of waste units in adjacent drums
- Interaction: one 4.5 kg ^{239}Pu metal unit in the array

55-gallon drums with ≤ 300 FGE each

Finite arrays of ≤ 75 55-gallon drums with ≤ 300 FGE each are demonstrated to remain subcritical based on the following conservative assumptions:

- Every drum contains 300 g ^{239}Pu as an optimally moderated spherical solution of full density plutonium metal and water
- No waste matrix material or ^{240}Pu modeled
- Drums in contact, with conservative dimensions and half the nominal wall thickness
- Two reflection schemes are modeled: 1) 60 cm concrete below and 12" full density water above and on all four sides or 2) 60 cm concrete below, 12" concrete above, and 14" concrete on all four sides

For such arrays, the following upsets are evaluated and demonstrated to remain subcritical:

- Moderation: interstitial water at densities of 0 to 1.0 g/cc

- Mass: 18 drums with 400 FGE each or one drum with 520 FGE in the array
- Mass: > 75 drums in the array (363 drums for water reflection or 108 drums for concrete reflection)
- Geometry: vertical and radial clustering of waste units in adjacent drums
- Interaction: one 4.5 kg ^{239}Pu metal unit in the array

SWBs with ≤ 350 FGE each

Infinite planar, three-high arrays of SWBs with ≤ 350 FGE each are demonstrated to remain subcritical (and to be significantly bounded by similar arrays of 55-gallon drums with ≤ 200 FGE each[1]) based on the following conservative assumptions:

- Every SWB contains 350 g ^{239}Pu as an optimally moderated spherical solution of full density plutonium metal and water
- No waste matrix material or ^{240}Pu modeled
- SWBs in contact, with conservative dimensions and less than half the nominal wall thickness
- Full (60 cm) concrete reflection modeled below the array and 1" full-density water, 12" full-density water, or 12" concrete reflection modeled above the array

For such arrays, the following upsets are evaluated and demonstrated to remain subcritical:

- Moderation: interstitial water at densities of 0 to 1.0 g/cc
- Mass: 18 SWBs with 450 FGE each or one SWB with 520 FGE in the array
- Geometry: vertical and radial clustering of waste units in adjacent SWBs
- Interaction: one 4.5 kg ^{239}Pu metal unit in the array

General

Finally, note that the analyses herein also conclude the following:

- Commingling of 55-gallon drums with ≤ 200 FGE and SWBs with ≤ 350 in infinite planar, three-high arrays is bounded by the results given above.
- The 55-gallon drum/SWB results also bound larger drums/containers with identical mass limits (direct-loaded or overpacked), as well as the use of 6" or 12" POCs.

7.0 References

1. HSR-6-02-049, *Criticality Safety Evaluation of Waste Drums and Standard Waste Boxes Bearing Special Nuclear Material Contaminated Waste at the Los Alamos National Laboratory (LANL)*, 2002-08-05.

[1] In fact, Section 5.4 demonstrates that *normal conditions and all evaluated upsets* for infinite planar three-high arrays of SWBs with ≤ 350 FGE each are bounded by the *normal conditions* modeled for infinite planar three-high arrays of drums with ≤ 200 FGE each.

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