



A REVIEW OF CRITICALITY SAFETY ANALYSIS FOR UNDER-MODERATED LOW ENRICHED URANIUM (LEU) DIOXIDE, HIGH ENRICHED URANIUM (HEU) NITRATE & PLUTONIUM OIL

¹C.E.Okon, ²Y. E. Chad-Umoren

¹School of Physics & Astronomy, University of Manchester, UK.

²Department of Physics, University of Port Harcourt, Nigeria.

Abstract: This report is focused on the review of criticality analysis and predictions of the fissile waste generated from a secret nuclear facility. Those wastes were loaded into sixteen 55 gallon drums and placed in a barge but due to political and economic turmoil of that time, the tank were left and forgotten until the present day. After concluding all the safety measures regarding the drums and identifying the fissile materials in each drum, the final stage was to transfer all the drums by boat-mounted crane to an adjacent vessel. In trying to achieve these, the positioning of the drums in the sister vessel was also put into consideration to avoid the system going critical. Our results from the other displacements show how close the system was to being critical. In this regards, the arrangement of the drums has been model in such a way that they are in a sub-critical and safe position ready for transportation.

Key Words: Critical Geometry, Effective Multiplication Factor, Fissile Material.

I. Introduction

Nuclear criticality safety is the art of avoiding a nuclear excursion. In a system containing fissile material, the neutrons released may go on to produce more neutrons by further fission or be lost through absorption in non-fissile nuclides, or may leave the fissile part of the system to be absorbed in surrounding materials (leakage). A useful way of quantifying how close a system is to being critical is through a factor known as k-effective, the ratio of the rate of neutron production (by fission) to the rate of neutron losses (by absorption plus leakage). At a point of criticality the k-effective is equal to unity. For super-critical systems k-effective is greater than 1.0, and less than 1.0 in sub-critical systems.

A. Factors affecting the criticality of a system

The balance between neutron production and neutron absorption, which is the key to ensuring criticality safety, is influenced by many factors such as^[2],

Density: The amount of fissionable material that is needed for criticality purpose depends strongly on the density of the material. When the system density is reduced, neutron leakage is increased.

Reflection: certain materials which act as reflectors can be used to surround the fissile material. This facilitates the reflection of the neutrons back into the fissile volume. Water for example is an effective neutron reflector.

Geometrical Shape: the system geometry can also be used to consider the potential for criticality. For material of any specified composition there exists a cylinder diameter below which criticality cannot be achieved. As an example, for highly enriched uranium nitrate at any achievable concentration, criticality cannot be achieved in a water-reflected stainless steel or boro-silicate glass cylinder of 6 inches (15cm) diameter.

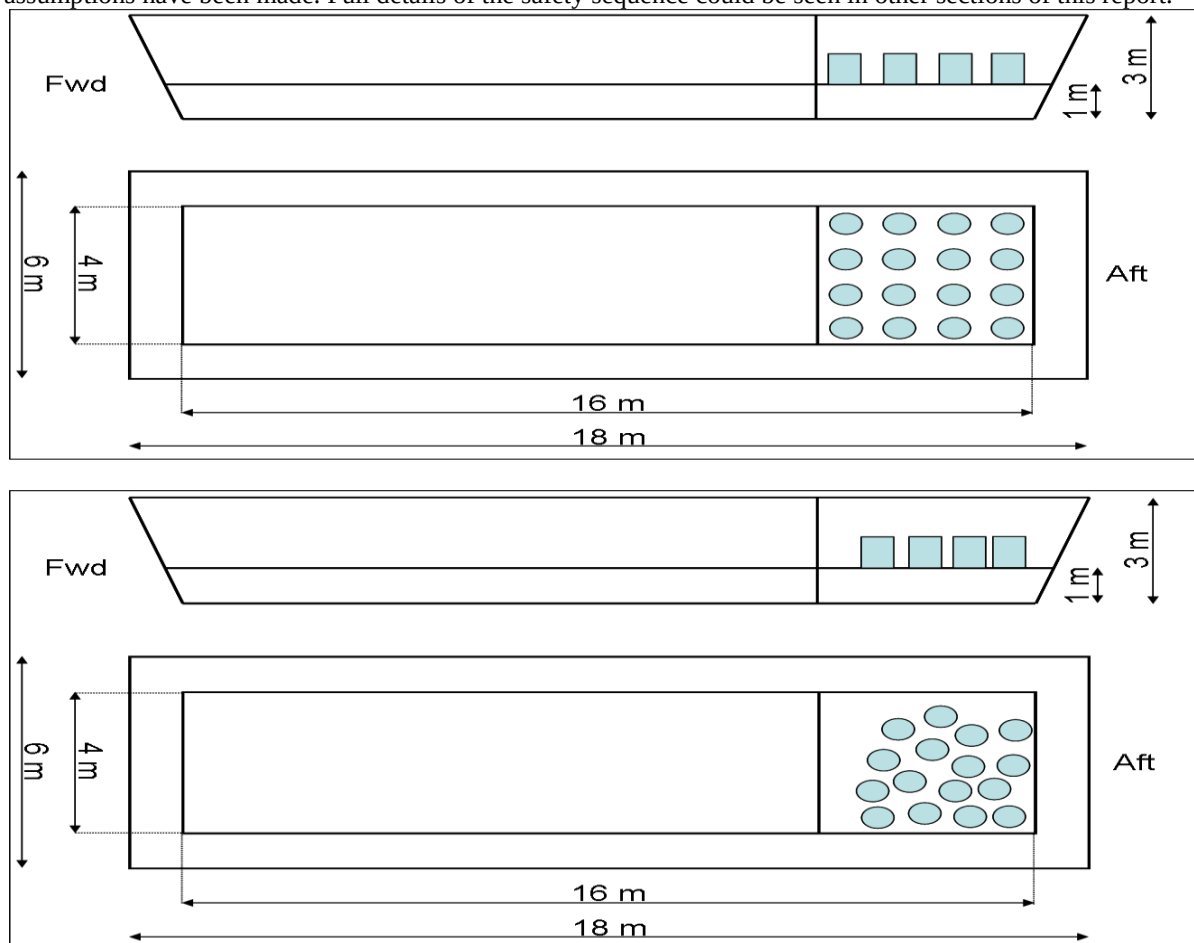
Enrichment: the tendency of a neutron to react with a fissile nucleus is highly influenced by the amount of enrichment of the fissile and non-fissile nuclei in a system. Low enrichment means there is a less likelihood for the system to be critical, while high enrichment is like to cause the system going critical.

Mass: fission increases when the total number of fissile nuclei increases. When there is less fissile material in a certain volume or geometrical arrangement, the mass of such system is said to be a subcritical mass and no chain reaction can be maintained. The threshold by which criticality cannot occur is known as the critical mass.

II. Aims & Objective

The figure above shows the dimension of the barge and positioning of the drums containing the fissile materials as being clustered in one corner of the barge. The fissile materials were orderly arranged on the barge and well labelled for easy identification. Since it was abandoned for years, the drums were displaced from its orderly 4*4 arrays (as can be seen in the figure below) due to excessive corrosion and listing. Due to recent inspection of the

site, it has now become necessary for the fissile materials to be transported to a proper repository site, the aim of this research is to design a safety measures as criticality safety engineer, on how this fissile materials could be re-arranged for preparatory for transport without the materials going critical. An analysis on the situation if a drum drops into the water during the transfer process will be discussed. In trying to achieve these, certain assumptions have been made. Full details of the safety sequence could be seen in other sections of this report.

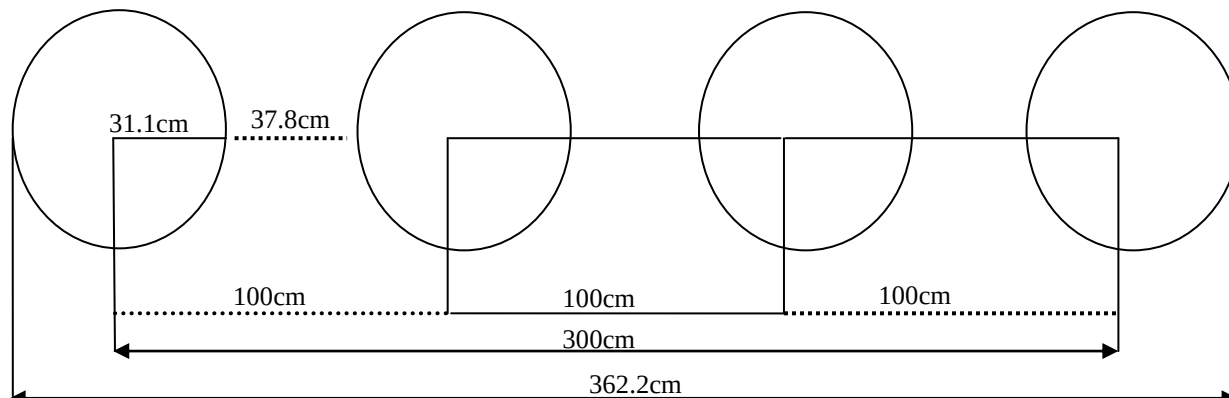


III. Basic Assumptions Deduce

Things to bear in mind:

- Drum at its current disordered position are sub-critical and must remain sub-critical
- Total number of drums and nature of the fissile material containing in each drum
- Volume of each drum and the diameter
- Material used for the drum

From the question, we are made to understand that, though it has been proven that the drums contain LEU, HEU and Pu-Oil, we are not certain on which drum contain which since the labelling has been worn off. Based on this information, it is very necessary to make some assumptions on the distribution of the displaced drums, position of the damaged drum, volume and type of the leaked liquid.



The fissile wastes were loaded in to 55 gallon (208 litres) drums. From the literature, I found out that an ideal 55 gallon (208 litres) drum has the following dimension

Drum Outer Diameter	-	62.2cm (Radius = 31.1)
Drum Inner Height	-	85.1cm
Drum Outer Height	-	90.1cm

I assumed the material used for the drum to be a Duplex stainless steel 2205 (UNS S31803). I choose this material because it is a mixture of two different groups of stainless steel (Ferrite and Austenite). These materials are highly resistance to corrosion and also have high strength. Duplex 2205 is a nitrogen enhanced stainless steel with density of 7.8g/cm³. It is made up of other elements such as Chromium, Molybdenum, Nickel, manganese, Silicon, phosphorus, sulphur and iron. (www.sbecpl.com/products/stainless-steel/duplex-2205/).

A. LEU DRUM

From the question, it was stated that for the LEU drum, the tubes were welded to the bottom of each drum such that the minimum separation of each tube from the drum wall and its two neighbours is equal. Based on this information, I assumed that the cylindrical tube were align to have a close contact with its nearest neighbour and the walls of the drum as can be seen in fig. 3.1 below. I also assumed a separation distance from the bottom of the drum to be 0.01cm to take into account of proper welding. Other dimensions are;

Tube Inner Diameter	-	15cm (Radius = 7.5)
Tube outer Diameter	-	15.5cm (Radius = 7.75)

Minimum Inner Diameter of the Drum is calculated from figure 3.1 as 36.2cm

Maximum Inner Diameter of the Drum is calculated from figure 3.2 as 56.2cm (Radius = 28.1)

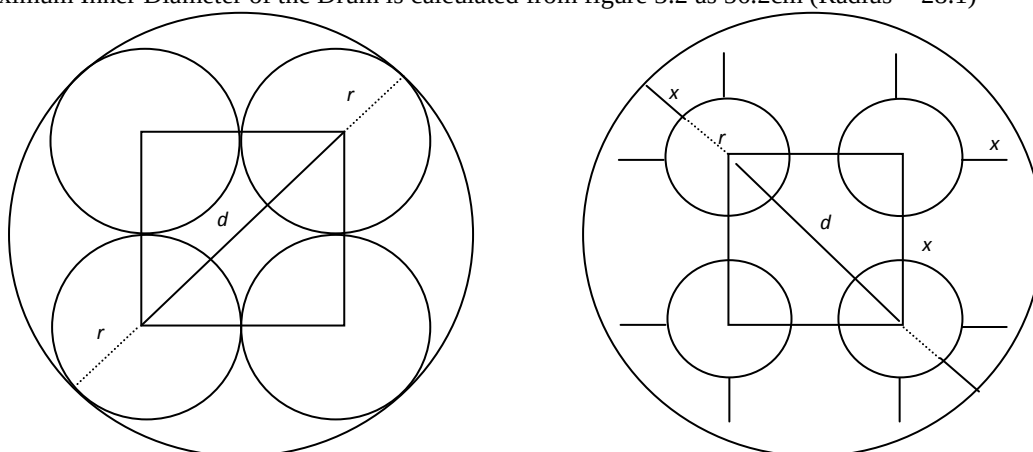


Fig. 3.1 (Diagonal (d) = 21.2cm, Radius (r) = 7.5cm) Fig. 3.2 (Diagonal (d) = 29.48cm, Radius (r) = 7.5cm, Separation (x) = 5.86cm)

The Area of a square is given by the formular $A = S^2$ where S is the length of one side.

But if the length of the diagonal is known, the

area is half the product of the diagonals.

Since both diagonals are congruent, this simplifies;

$$A = \frac{d^2}{2} \text{ where } d \text{ is the length of either diagonal}$$

$$d^2 = 2S^2$$

$$d = \sqrt{2 * S^2}$$

$$\text{where } s = x + 2r$$

$$\text{but } 2x + 2r + d = 2R \dots \dots \dots (a)$$

$$2x + 15 + \sqrt{2} * (x + 15) = 56.2$$

$$x = 5.86\text{cm}$$

substitute $x = 5.86$ into (a), we can solve for d .

$$\therefore d = 29.48\text{cm}$$

LEU Fissile Material Mass & Number Density; 3% enriched UO₂ has a density of 10.87g/cm³, contained in a tube of inner diameter 15cm and height 84.8cm.

The volume of the tube is given as the volume of a cylinder $V = \pi r^2 h = 1.5 * 10^4 \text{cm}^3$

$$\therefore \text{the mass of UO}_2 \text{ powder} = \text{Density} * \text{Volume}$$

$$= 10.87 * 1.5 * 10^4 = 162.89\text{kg}$$

Molecular weight of enriched uranium, which is 3% U – 235 and 97% U – 238

$$\therefore \frac{1}{M_u} = \frac{\epsilon_{u-235}}{M_{u-235}} + \frac{\epsilon_{u-238}}{M_{u-238}} \dots \dots \dots (1)$$

ϵ is the enrichment

$$M_u = 237.96 \text{ g/mol}$$

Mass of U – 235 in UO_2 powder is given as;

$$M_{u-235} = \left[\frac{M_U}{M_{UO_2}} * \text{mass of } UO_2 \text{ powder} \right] * \epsilon$$

$$M_{u-235} = 4.96 \text{ kg}$$

Number density of natural uranium in UO_2 with density of 10.87 g/cm^3

$$N_u = N_{UO_2} = \frac{\rho_{UO_2} * N_{AV}}{M_{UO_2}} \dots \dots \dots (2)$$

$$N_u = 2.42 * 10^{22} \text{ atoms/cm}^3$$

$$\rho_U = \rho_{UO_2} * \frac{M_U}{M_{UO_2}} \dots \dots \dots (3)$$

$$\rho_U = 9.58 \text{ g/cm}^3$$

$$N_{U-235} = \left(\frac{\rho_U * N_{AV}}{M_{u-235}} \right) * \epsilon$$

$$N_{U-235} = 2.45 * 10^{22} \text{ atoms/cm}^3$$

$$N_{U-238} = \left(\frac{\rho_U * N_{AV}}{M_{u-238}} \right) * \epsilon$$

$$= 2.35 * 10^{22} \text{ atoms/cm}^3$$

B. HEU DRUM

HEU Fissile Material Number Density & Mass; 93% enriched uranium nitrate $UO_2(NO_3)_2$ has a density of 2.81 g/cm^3 , contained in a tube of inner diameter 56.2 cm and height 85.1 cm .

Number density of $UO_2(NO_3)_2$

$$N_{UO_2(NO_3)_2} = \frac{\rho_{UO_2(NO_3)_2} * N_{AV}}{M_{UO_2(NO_3)_2}}$$

$$N_u = 4.29 * 10^{21} \text{ atoms/cm}^3$$

Molecular weight of enriched uranium, which is 92% U – 235 and 8% U – 238

$$\therefore \frac{1}{M_u} = \frac{\epsilon_{u-235}}{M_{u-235}} + \frac{\epsilon_{u-238}}{M_{u-238}}$$

ϵ is the enrichment

$$M_u = 235.25 \text{ g/mol}$$

$$\rho_U = \rho_{UO_2(NO_3)_2} * \frac{M_U}{M_{UO_2(NO_3)_2}}$$

$$\rho_U = 1.678 \text{ g/cm}^3$$

$$N_{U-235} = \left(\frac{\rho_U * N_{AV}}{M_{u-235}} \right) * \epsilon$$

$$N_{U-235} = 3.95 * 10^{21} \text{ atoms/cm}^3$$

$$N_{U-238} = \left(\frac{\rho_U * N_{AV}}{M_{u-238}} \right) * \epsilon$$

$$N_{U-238} = 3.40 * 10^{20} \text{ atoms/cm}^3$$

The total mass of $UO_2(NO_3)_2$

*= Density (mass concentration) * Volume*

The highly enriched uranium nitrate solution has

metal – to – water ratio of about 1: 500 which

is equivalent to the ratio of

U: H = 1: 1000, when the total volume of

the solution in the drum is 208 litres and the

mass concentration is 43.96 g/L .

Therefore the total mass of $UO_2(NO_3)_2$ in the drum

$$= 43.96 * 208 = 9144 \text{ g} = 9.144 \text{ kg}$$

Mass of U – 235 in $UO_2(NO_3)_2$ is given as;

$$M_{u-235} = \left[\frac{M_U}{M_{UO_2(NO_3)_2}} * \text{mass of } UO_2(NO_3)_2 \right] * \epsilon$$

$$M_{u-235} = \left[\frac{235.27}{394.03} * 9144 \right] * 0.93 = 5023g = 5.02kg$$

Considering uranium nitrate solution $UO_2(NO_3)_2$ with U:H = 1:2000, when the total volume of the solution in the drum is 208 litres and the mass concentration is 21.98 g/L.

Therefore the total mass of $UO_2(NO_3)_2$ in the drum = $21.98 * 208 = 4571g = 4.571kg$

Mass of U – 235 in $UO_2(NO_3)_2$ is given as;

$$M_{u-235} = \left[\frac{M_U}{M_{UO_2(NO_3)_2}} * \text{mass of } UO_2(NO_3)_2 \right] * \epsilon$$

$$M_{u-235} = 2510g = 2.51kg$$

All my calculations regarding uranium nitrate will be made having in mind the two ratio proportions.

C. PU DRUM

Plutonium Fissile Material Mass; let's consider the finely-ground mixed plutonium metal waste in oil at a concentration of about $<10g \sim 9.0g \text{ Pu L}^{-1}$. Since the mass concentration of plutonium is known and the volume occupied by the fissile material is 208L.

Therefore the total mass of plutonium in the drum = $9.0 * 208 = 1872g = 1.872kg$

IV. Methodology

Two approaches have been considered in this report. The hand calculation methods in criticality safety (This involve Buckling Conversion and Surface Density) and the computer simulations using MONK. These methods will be used to compare and ascertain the sub-criticality of the system as well as establishing the limiting conditions for each fissile units and arrays of units.

A. Hand Calculation Method in Criticality Safety

For the purpose of this assignment, certain assumptions have been made and some parameters which has been calculated has also been outline below;

Assumptions;

Fission Cross Section for thermal neutron U – 235 (σ_f) = $582.6 * 10^{-24} \text{ cm}^2$

Absorption Cross Section for U – 235 (σ_{a-235}) = $680.9 * 10^{-24} \text{ cm}^2$

Scattering Cross Section for U – 235 (σ_{s-235}) = $14.3 * 10^{-24} \text{ cm}^2$

Average number of neutron produced per fission

for U – 235 = 2.425

Absorption Cross Section for U – 238 (σ_{a-238}) = $2.68 * 10^{-24} \text{ cm}^2$

Absorption Cross Section for Hydrogen (σ_{a-H}) = $3.33 * 10^{-25} \text{ cm}^2$

Scattering Cross Section for Hydrogen (σ_{s-H}) = $20.49 * 10^{-24} \text{ cm}^2$

Scattering Cross Section for Oxygen (σ_{s-O}) = $3.76 * 10^{-24} \text{ cm}^2$

Absorption Cross Section for Oxygen (σ_{a-O}) = $5.4 * 10^{-28}$

Assumed the fast fission factor $\epsilon = 1.02$, for a homogenous system

The resonance escape probability (P) is calculated as = 0.886, see calculations below.

A.1 Infinite Multiplication Factor

HEU DRUM:

The safety of this system can be analyzed by calculating some of the parameters associated with the criticality safety management. Those parameters are calculated below;

❖ The reproduction factor can be calculated using the below equation;

$$\eta = \frac{N_{u-235} * \sigma_f * v_{u-235}}{N_{u-235} * \sigma_{a-235} + N_{u-238} * \sigma_{a-238}} \dots\dots\dots (4)$$

Where;

Number Density of U – 235 = $3.95 * 10^{21} \text{ atoms/cm}^3$

Number Density of U – 238 = $3.40 * 10^{20} \text{ atoms/cm}^3$

Number Density of H_2O = $3.34 * 10^{22} \text{ atoms/cm}^3$

$$\eta = 2.074$$

❖ *The thermal utilization factor (f);*

$$f = \frac{(N_{u-235} * \sigma_{a-u235}) + (N_{u-238} * \sigma_{a-u238})}{\Sigma_a^F + (N_{H_2O} * 2\sigma_{a-H})} \dots \dots \dots (5)$$

OR

$$= \frac{\epsilon * (\sigma_{a-u235} + \sigma_{s-u235}) + (\epsilon * \sigma_{a-u238})}{[\epsilon * (\sigma_{a-u235} + \sigma_{s-u235}) + (\epsilon * \sigma_{a-u238})] + \sigma_{a-H}} \dots (6)$$

The highly enriched uranium nitrate solution has metal – to – water ratio of about 1: 500 which is equivalent to the ratio of U: H = 1: 1000 we will either use the equation (6) taking into consideration the enrichments (ϵ) and its ratio proportion.

$$f = \frac{x\sigma_a^F}{x\sigma_a^F + \sigma_a^H}$$

$$x = 1/1000 = 0.001$$

$$x\sigma_a^F = 6.397984 * 10^{-25}$$

$$f = 0.6577$$

❖ *The resonance escape factor can be calculated using the below equation [3];*

$$P(E) = \exp \left[-\frac{1}{\xi} \int \frac{\Sigma_{aF}}{\Sigma_{aF} + \Sigma_s} \frac{dE}{E} \right] \dots \dots \dots (7)$$

$$P = \exp \left[-\frac{1}{\xi} * \frac{\Sigma_{aF}}{\Sigma_{aF} + \Sigma_s} * \ln E \right]$$

Where E could be assumed to be the epithermal fission energy 0.05eV

$$P = \exp \left[\frac{3.7}{\xi} * \frac{\Sigma_{aF}}{\Sigma_{aF} + \Sigma_s} \right] \dots \dots \dots (8)$$

where;

ξ is known as the average lethargy gain per scattering event.

For water moderator ξ ≅ 1. See calculation and prove below.

For mixture of several materials[4],

$$\xi = \sum_{i=1}^N \frac{\xi_i \Sigma_{si}}{\Sigma_{si}} \dots \dots \dots (9)$$

Where N is the number of isotopes in the mixture and Σ_{si} is the macroscopic scattering cross section For the i-th isotope in the mixture.

ξ_H for water is equal to 0.920

ξ_u for Uranium is equal to 0.008482

$$\xi = \frac{(N_u * \sigma_{s-235} * \xi_u) + (N_H * \sigma_H * \xi_H)}{(N_u * \sigma_{s-235}) + (N_H * \sigma_H)}$$

$$\xi = 0.919$$

$$\Sigma_a^F = 2.69$$

$$\therefore P = \exp \left[\frac{3.0}{0.919} * \frac{2.69}{2.69 + 24.25} = 0.886 \right]$$

❖ The K_{∞} factor can be calculated using the eqn;

$$K_{\infty} = f * \eta * \epsilon * p$$

$$\therefore K_{\infty} = 1.23$$

Based on the above condition, the system can only get critical if the sum value for both fast and thermal non leakage probability is ≥ 0.9 . Also, if we consider the drum having a surrounding water jacket which gave a reflector effect. And the drum height does not change but the radius is increased. Increase in diameter could have effect on the effective multiplication factor.

Recall from Fig. 30 of Appendix A, that the critical diameter of an infinite cylinder of $H:U = 1000:1$ is about 300mm which is much smaller than the diameter of a standard 208L drum.

Lets now consider that the nitrate solution has metal – to – water ratio of about 1: 1000 which is equivalent to the ratio of $U:H = 1: 2000$ we will either use the equation (6) taking into consideration the enrichments (ϵ) and its ratio proportion.

$$f = \frac{x\sigma_a^F}{x\sigma_a^F + \sigma_a^H}$$

$$x = 1/2000 = 5 * 10^{-4}$$

$$x\sigma_a^F = 3.199 * 10^{-25}$$

$$f = 0.490$$

❖ The resonance escape factor can be calculated;

$$P = \exp \left[\frac{3.7}{\xi} * \frac{\Sigma_{aF}}{\Sigma_{aF} + \Sigma_s} \right] \dots \dots \dots (10)$$

where;

ξ is known as the average lethargy gain per scattering event.

For water moderator $\xi \cong 1$ [4]. See calculation and prove below.

For mixture of several materials,

$$\xi = \sum_{i=1}^N \frac{\xi_i \Sigma_{si}}{\Sigma_{si}} \dots \dots \dots (11)$$

Where N is the number of isotopes in the mixture and Σ_{si} is the macroscopic scattering cross section for the i -th isotope in the mixture.

ξ_H for water is equal to 0.920

ξ_u for Uranium is equal to 0.008482

$$\xi = \frac{(N_u * \sigma_{s-235} * \xi_u) + (N_H * \sigma_H * \xi_H)}{(N_u * \sigma_{s-235}) + (N_H * \sigma_H)}$$

$$\xi = 0.919$$

$$\sum_a^F = 2.69$$

$$\therefore P = \exp \left[\frac{3.0}{0.919} * \frac{2.69}{2.69 + 24.25} = 0.886 \right]$$

❖ The K_{∞} factor can be calculated using eqn;

$$K_{\infty} = f * \eta * \epsilon * p$$

$$\therefore K_{\infty} = 0.918$$

A.2 Buckling Conversion Method

According to Ref. [6] “the buckling conversion method is based on the solutions to diffusion equation that relates the spatial neutron flux distribution in a neutron-multiplying medium to a parameter called geometric buckling, B_g ”. For a finite cylinder with radius r and height h , the geometric buckling is given as;

$$B_g^2 = \frac{\pi^2}{(h + 2\gamma)^2} + \frac{(2.405)^2}{(r + \lambda)^2} \dots \dots \dots (12)$$

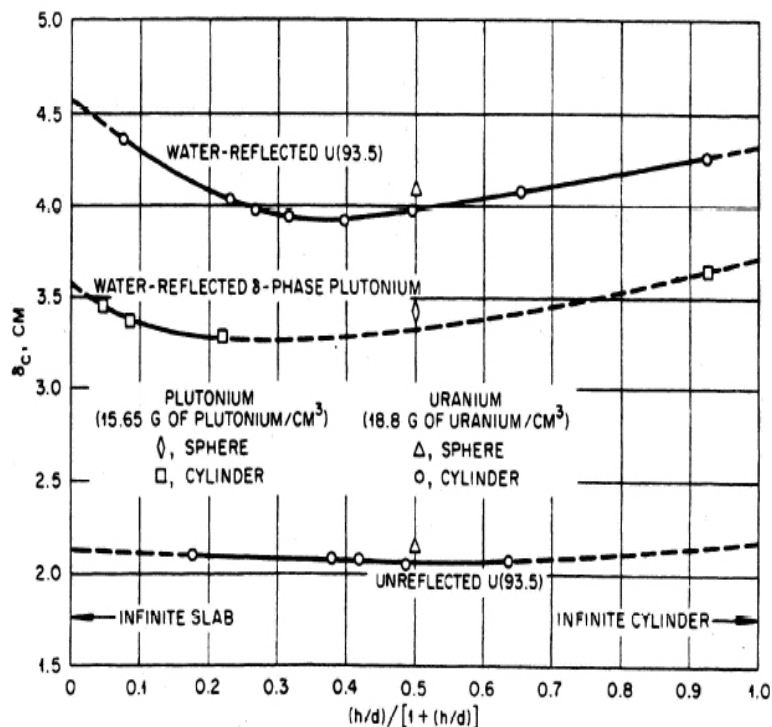


Fig. 4.1: Graph showing the effective extrapolation distances for cylinders ^{235}U (93.5wt %) [6].

HEU DRUM:

The above graph (Fig. 4.1) is a very useful tool in buckling calculation for the critical mass of water-reflected cylinders. It is useful because it can be used to find the extrapolation distance for the cylinder. Although the percentage enrichment for my system is 93wt%, the error recorded will be very insignificant, based on this conclusion, I adopted this graph for my analysis.

From equation (10) & graph above, certain parameters has been defined as shown below;

h = inner height of the drum containing the HEU

fissile material = 85.1cm

d = inner diameter of the drum containing the HEU

fissile material = 56.2cm

r = inner radius of the drum containing the HEU

fissile material = 28.1cm

$\gamma = \frac{h}{d}$ = height – to – diameter ratio = 1.51

$\frac{h}{d} / \left(1 + \frac{h}{d}\right) = 0.60$

λ = effective extrapolation distance read from the graph above is given as = 4.1cm

Therefor the geometric buckling of the cylindrical vol.,

$$B_g^2 = \frac{\pi^2}{(h + 2\gamma)^2} + \frac{(2.405)^2}{(r + \lambda)^2}$$

$$B_g^2 = 6.85 \times 10^{-3} \text{cm}^{-1}$$

Therefore effective multiplication factor;

$$K_{eff} = \frac{K_{\infty}}{1 + M^2 B_g^2} \dots \dots \dots (13)$$

Where;

$$K_{\infty} = 1.230 \text{ (U:H = 1:1000)}$$

$$K_{\infty} = 0.918 \text{ (U:H = 1:2000)}$$

M^2 = migration area of the neutrons

(about 25 – 30cm for $H/\text{fissile atom} \geq 20$). I assumed 27cm.

$$K_{eff} = 1.04 \dots \dots \dots \text{ (U:H = 1:1000)}$$

$$K_{eff} = 0.77 \dots \dots \dots \text{ (U:H = 1:2000)}$$

Also, the material buckling of the cylindrical volume of the solution is given as;

$$B_m^2 = \frac{K_\infty - 1}{M^2} \dots \dots \dots (14)$$

$$B_m^2 = \frac{1.23 - 1}{27} = 8.519E - 3 \text{ cm}^{-1}$$

LEU DRUM:

The buckling calculation for the critical mass of un-reflected cylinder and the effective multiplication factor for LEU fissile drum is given thus;

h = inner height of the drum containing the HEU

fissile material = 84.8cm

d = inner diameter of the drum containing the HEU

fissile material = 15cm

r = inner radius of the drum containing the HEU

fissile material = 7.5cm

$\gamma = \frac{h}{d}$ = height – to – diameter ratio = 5.65

$\frac{h}{d} / \left(1 + \frac{h}{d}\right) = 0.85$

λ = effective extrapolation distance read from the graph above (Fig. 5.1) is given as = 2.21cm

Therefor the geometric buckling of the cylindrical vol.,

$$B_g^2 = \frac{\pi^2}{(h + 2\gamma)^2} + \frac{(2.405)^2}{(r + \lambda)^2}$$

$$B_g^2 = 6.26 * 10^{-2} \text{ cm}^{-1}$$

A.3 Surface Density Method

“Surface density method is used to determine safe parameters for arrays including the fissile mass per array units, spacing of the units or the maximum safe number of units that can be stacked”^[6]. The safe dimension of the unit volume is thus given by the below equation.

$$d = 1.36 \left[\frac{n * m}{\sigma_0 * (1 - 1.3f)} \right]^{\frac{1}{2}} \dots \dots \dots (15)$$

σ_0 = surface density

= the slab thickness * fissile mass concentration

f = the ratio of the mass of the unit to the critical mass

n = the number of units stacked

m = fissile mass

PU DRUM ARRAY:

Mass concentration = $9 * 10^{-3} \text{ g/cm}^3$

Slab thickness = 64.4cm

Fissile mass = 1872g

Critical mass = 5000g

$$f = \frac{1872}{5000} = 0.3744$$

$$\sigma_0 = 64.4 * 9.0E - 3 = 0.579$$

FOR $n=1$ (4*1 ARRAY)

$$d = 1.36 \sqrt{\frac{1872}{0.579 * (1 - 1.3 * 0.3744)}} = 107.94 \text{ cm}$$

FOR $n=2$ (2*2 ARRAY)

$$d = 1.36 \sqrt{\frac{2 * 1872}{0.579 * (1 - 1.3 * 0.3744)}} = 152.65 \text{ cm}$$

HEU DRUM ARRAY (U: H → 1: 1000)

Mass concentration = $4.596 * 10^{-2} \text{ g/cm}^3$

Slab thickness = 50cm

Fissile mass ($u - 235$) = 5023g

Critical mass = 7000g

$$f = \frac{5023}{7000} = 0.7176$$

$$\sigma_0 = 50 * 4.596E - 2 = 2.3$$

FOR n=1 (4*1 ARRAY)

$$d = 1.36 \sqrt{\frac{5023}{2.3 * (1 - 1.3 * 0.7176)}} = 245.326cm$$

FOR n=2 (2*2 ARRAY)

$$d = 1.36 \sqrt{\frac{2 * 5023}{2.3 * (1 - 1.3 * 0.7176)}} = 346.93cm$$

HEU DRUM ARRAY ($U:H \rightarrow 1:2000$)

Mass concentration = $2.198 * 10^{-2} g/cm^3$

Slab thickness = 50cm

Fissile mass ($u - 235$) = 2510g

Critical mass = 7000g

$$f = \frac{2510}{7000} = 0.3586$$

$$\sigma_0 = 50 * 2.198E - 2 = 1.099$$

FOR n=1 (4*1 ARRAY)

$$d = 1.36 \sqrt{\frac{2510}{1.099 * (1 - 1.3 * 0.3586)}} = 88.96cm$$

FOR n=2 (2*2 ARRAY)

$$d = 1.36 \sqrt{\frac{2 * 2510}{1.099 * (1 - 1.3 * 0.3586)}} = 125.80cm$$

B. MONK Simulation

B.1 SINGLE LEU (UO_2 Dry Powder) DRUM:

Out of the sixteen (16) drums, eight (8) of those drums were filled with under-moderated low-enriched dry UO_2 powder. Inside each drum this powder was contained in four (4) steel tubes. MONK was used to model the drum and the fissile material contained in it for different percentage enrichments as can be seen in Fig. 4.2 & Fig. 4.3 below. Appendix 1 shows the MONK code for this single LEU drum. Fig. 4.2 below is used to describe the variation of the effective multiplication factor which depends on the percentage enrichment of ^{235}U .

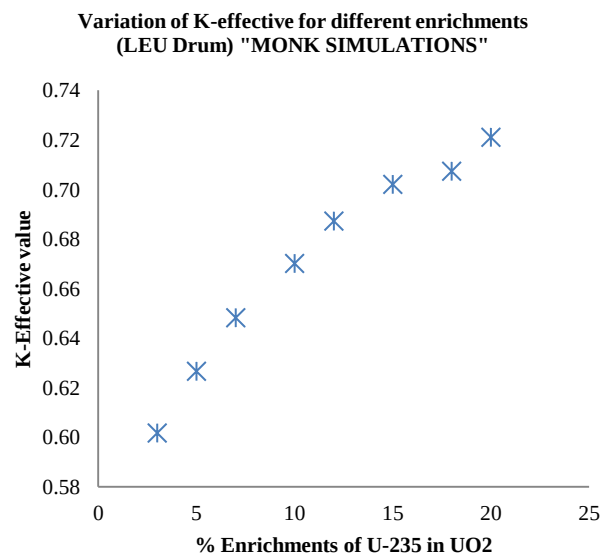


Fig. 4.2: Variation of K-effective for different enrichment (LEU Drum)

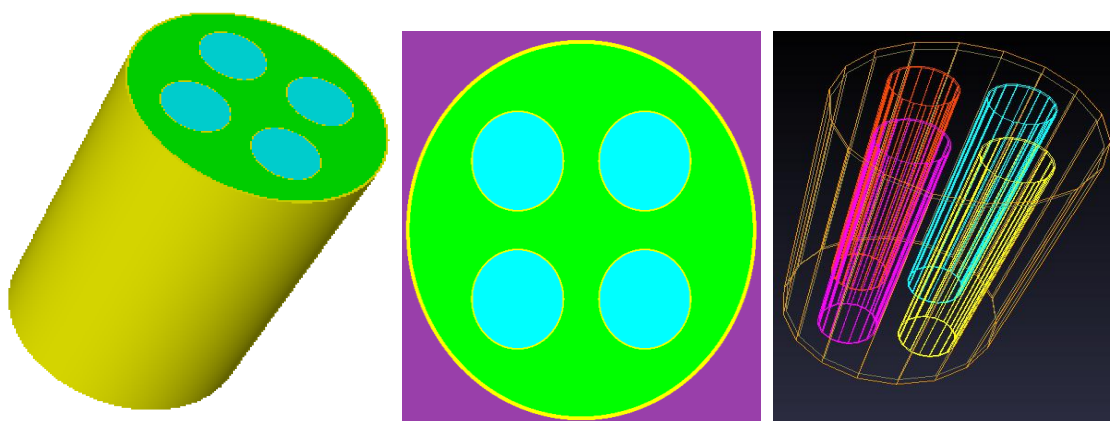


Fig. 4.3: MONK modelling for the LEU drum with fissile material (see code in Appendix 1)



B.2 SINGLE HEU $UO_2(NO_3)_2$ DRUM:

Also, out of the sixteen (16) drums, four (4) of those drums contained highly-enriched uranium nitrate solution with a metal to water ratio of roughly 1:500. MONK was used to model the drum and the fissile material contained in it for different percentage enrichments as can be seen in Fig.4.4 & Fig. 4.5 below. Appendix 2 shows the MONK code for this single HEU drum. Figure 4.4 is used to describe the variation of the effective multiplication factor which depends on the percentage enrichment of ^{235}U .

Variation of K-effective for different enrichments (HEU Drum) "MONK SIMULATIONS"

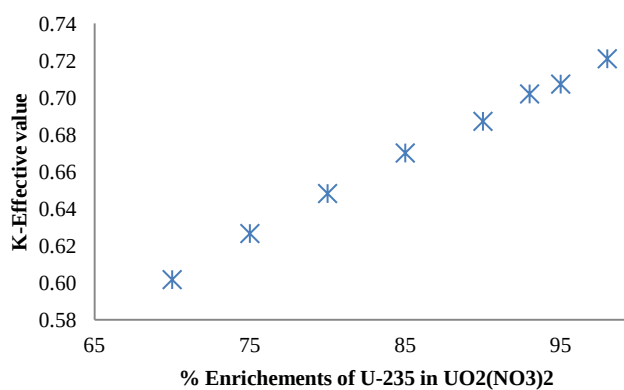


Fig. 4.4: Variation of K-effective for different enrichment (HEU Drum)

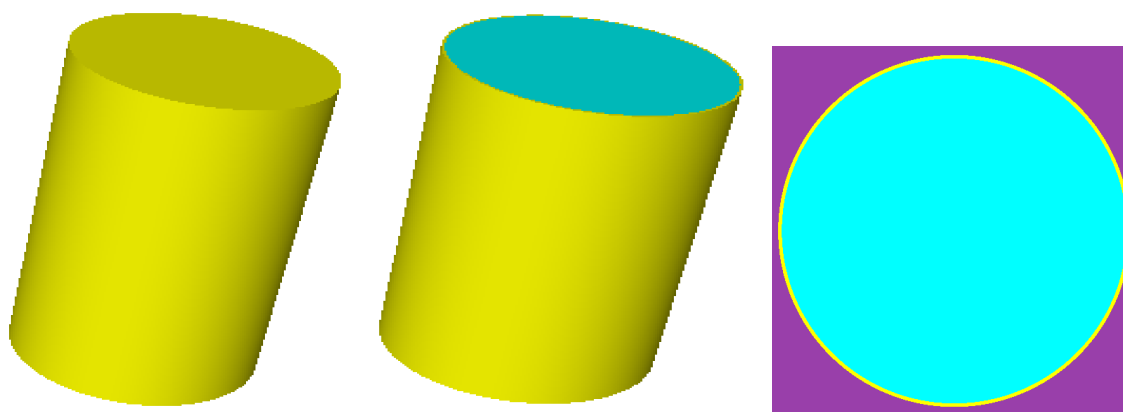


Fig.4.5: MONK modelling for the LEU drum with fissile material (see code in Appendix 2)



B.3 SINGLE Pu – OIL DRUM:

Also, out of the sixteen (16) drums, four (4) of those drums were fully- filled drums of finely-ground mixed plutonium metal wastes in oil at a concentration of about $<10\text{g Pu L}^{-1}$. MONK was used to model the drum and the fissile material contained in it as can be seen in Fig.4.6 below. Appendix 3 shows the MONK code for this single Pu drum. The multiplication factor for this drum is; ($K_{\text{eff}} = 0.3677$ STDV = 0.0010).

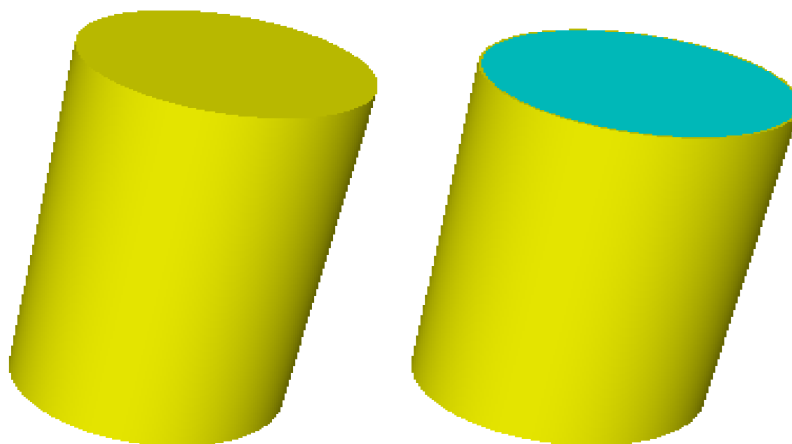


Fig. 4.6: MONK modelling for the Pu Drum (see code in Appendix 3)



B.4 ENTIRE DRUM ARRAY:

The proposed removal process is for the entire drum, so it is necessary to ensure that the whole system on the barge is at a subcritical state. In other to check these, the K-eff for the entire system was calculated using MONK. It could also be assumed that one of the damaged drums that was heavily corroded and leaked at the bottom could be the HEU drum. Before starting the removal process, I assumed that all the 16 drums were closed to each other. MONK modelling was carried out based on these assumptions as can be seen in the figures below. The effective multiplication factor for this as gotten from MONK is $K_{\text{eff}} = 0.9120$ (STDV=0.0010)

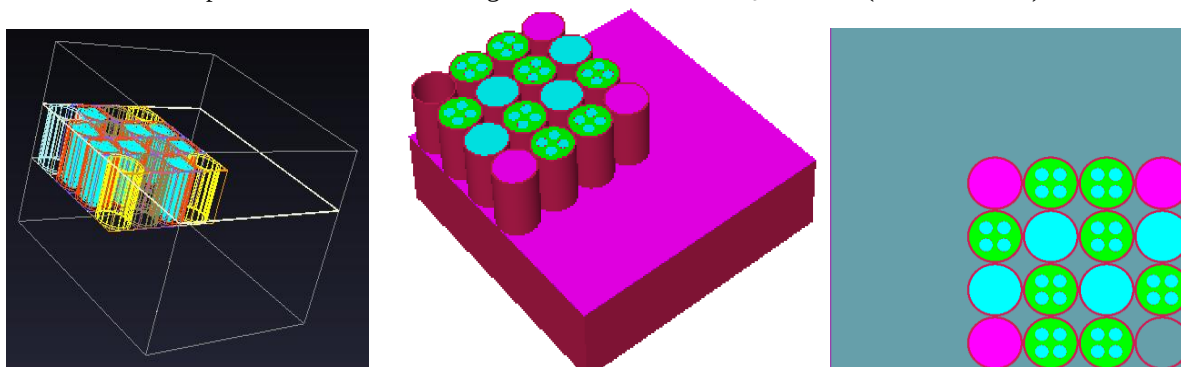
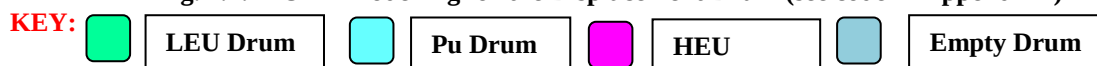


Fig. 4.7: MONK modelling for the Displacement Drum (see code in Appendix 4)



B.5 TRANSFER PROCESS:

The removal process will require two crew members to board the barge in order to control the drums and to load the crane. While another two members will receive each drum on the other vessel.

DISPLACEMENT DRUM WITH WATER REFLECTOR:

Fig. 5.8 below is the modelling from MONK showing the displacement of the drums with a water reflected wall. The effective multiplication factor for this as gotten from MONK is $K_{\text{eff}} = 0.9359$ (STDV=0.0010). These results confirm the effect of a reflector in criticality safety. The K_{eff} value is higher for this system than that for Fig. 4.7. This result could be used to explain the criticality status of the system as the operators approaches the drum. Note that the operators need to wear some reflective material that can reflect the neutrons back to into the fissile volume as they approach the drum. The criticality mass for the fissile material needs to be put into consideration. See look-up fig. 20 (Appendix A) & Fig. 50 (Appendix B).

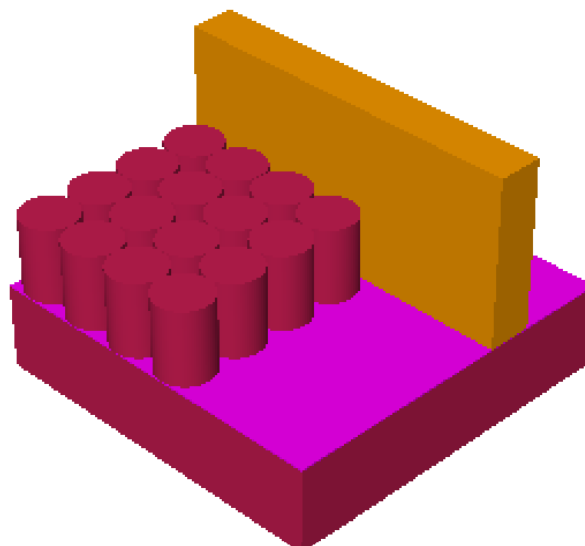


Fig. 4.8: MONK modelling for the Displacement Drum with water wall (see code in Appendix 5)

FINAL DRUM ARRAY:

After concluding all the safety measures regarding the drums and identifying the fissile materials in each drum, the final stage is to transfer all the drums by boat-mounted crane to an adjacent vessel. In trying to achieve these, the positioning of the drums in the sister vessel should also be put into consideration to avoid the system going critical. Our results from the other displacements shows how close the system is to being critical. In this regards, the arrangement of the drums has been model in such a way that they are in a sub-critical and safe position ready for transportation. Fig. 4.9 shows the final arrangement of the drum in the sister vessel.

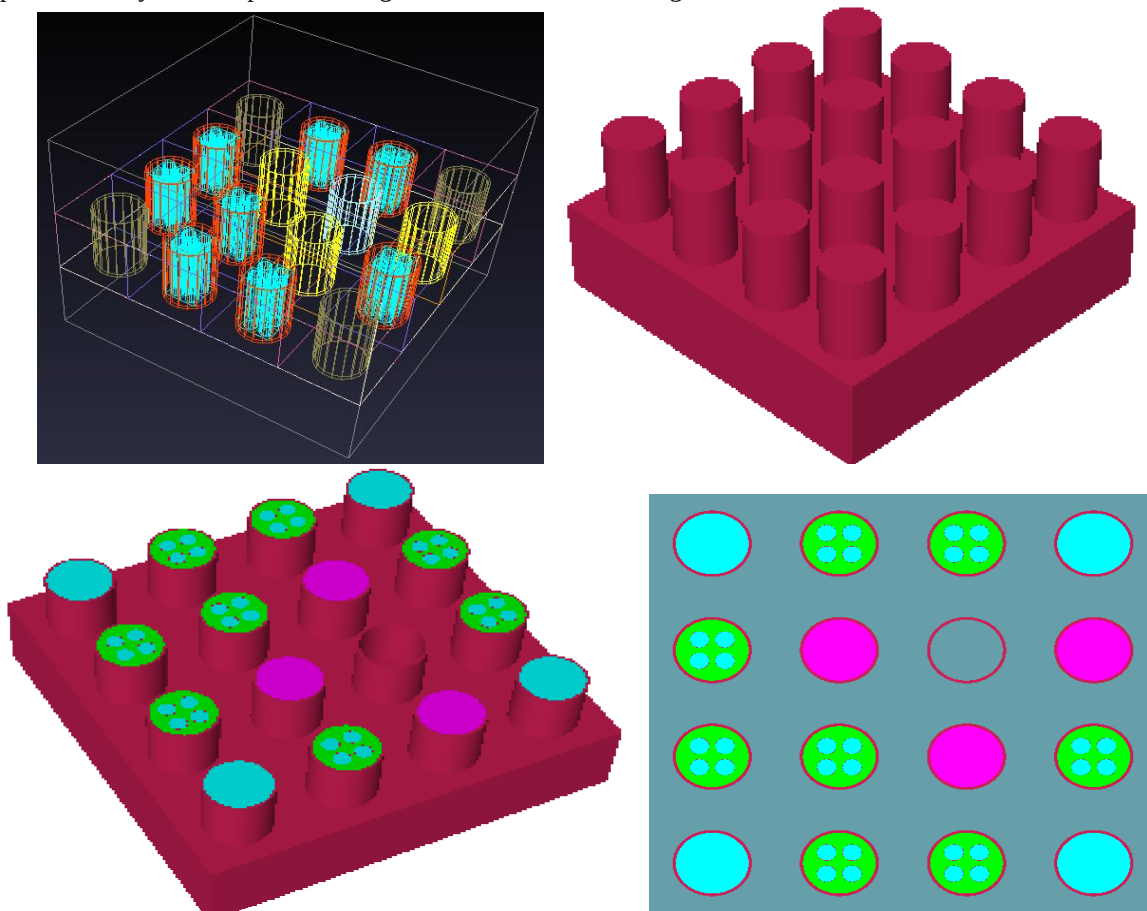


Fig. 4.9: MONK modelling for the Final Drum Arrangement on the sister vessel (see code in Appendix 6)

KEY:  **LEU Drum**  **Pu Drum**  **HEU**  **Empty Drum**

Based on the above arrangement, the drums are very safe and are in sub-critical conditions. The multiplication factor from MONK shows that, with this arrangement, $K_{\text{eff}} = 0.8452$ (STDV 0.0010). As you can see, the

positioning of the drum differs from the initial assumed position. From my analysis, this is the safest way by which those drums can be positioned in on the sister vessel. I assumed that the leaked drum was HEU. For criticality safety, i placed all the Pu-drum at the edge, while the two of the four drums containing HEU are kept in the middle.

V. Conclusion

The criticality safety analysis for the transfer of the fissile materials loaded in 55 gallon drums have been carried out by hand calculation and MONK simulation. In the hand calculation method, i was able to calculate the geometric buckling and the material buckling as well as the multiplication values for the system. I also used MONK to run the simulations and deduce the criticality status of the system in the whole process. From our results regarding the transfer process, we realised that the system was in a subcritical state and the value of the $K_{eff} = 0.9120$, as the operators approaches the drum the value increases to 0.9359. The final arrangement of the drum shows that the system is in a safe sub-critical condition with the effective multiplication factor of 0.8452 (STDV 0.0010). The figure below (Fig.4.10) shows the K-eff value for different enrichments with respect to the transfer process.

- Displacement 1 shows different values for K_{eff} for different enrichment when the operators has not approach the drums.
- Displacement 2 shows different values for K_{eff} for different enrichments as the operators approach the drums.
- Final array shows different values for K_{eff} for different enrichment as the drums are finally placed on the sister barge.

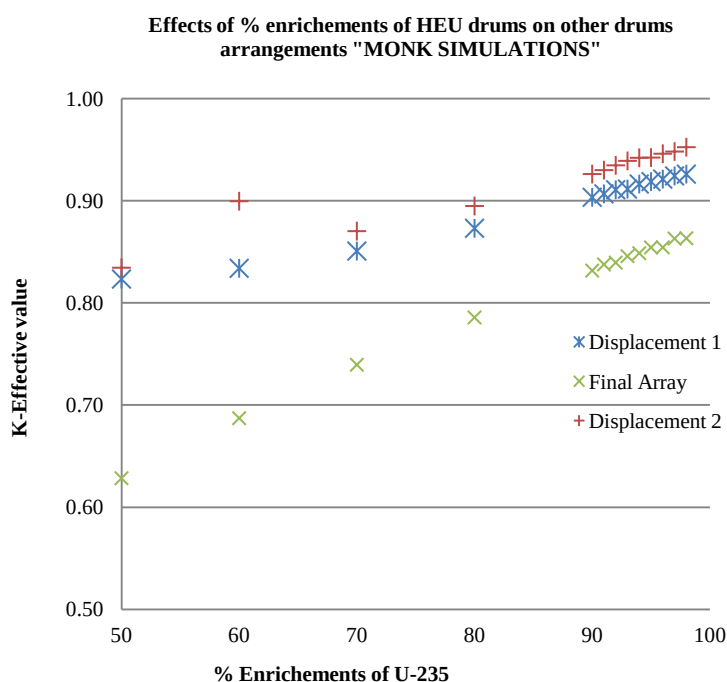


Fig. 4.10: Effect of % enrichments of U-235

References

- [1] Nuclear Safety Guide TID-7016 Revision 2.
- [2] John R. Lamarsh, Introduction to Nuclear Engineering, 3rd Edition.
- [3] Tatjana Jevremovic, Nuclear Principles in Engineering
- [4] M. Ragheb, Fermi Age Theory. (www.scribd.com/doc/34904923/Fermi-Age-Theory)

Appendix A

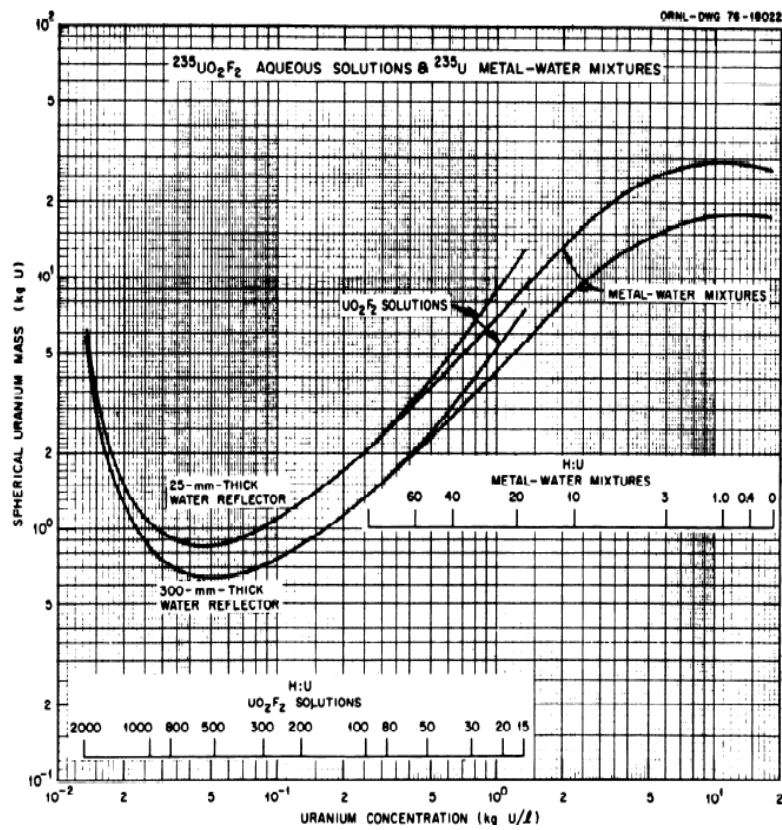


Fig. 20: Subcritical mass limit for individual cylinder of homogeneous water-reflected and moderated ^{235}U

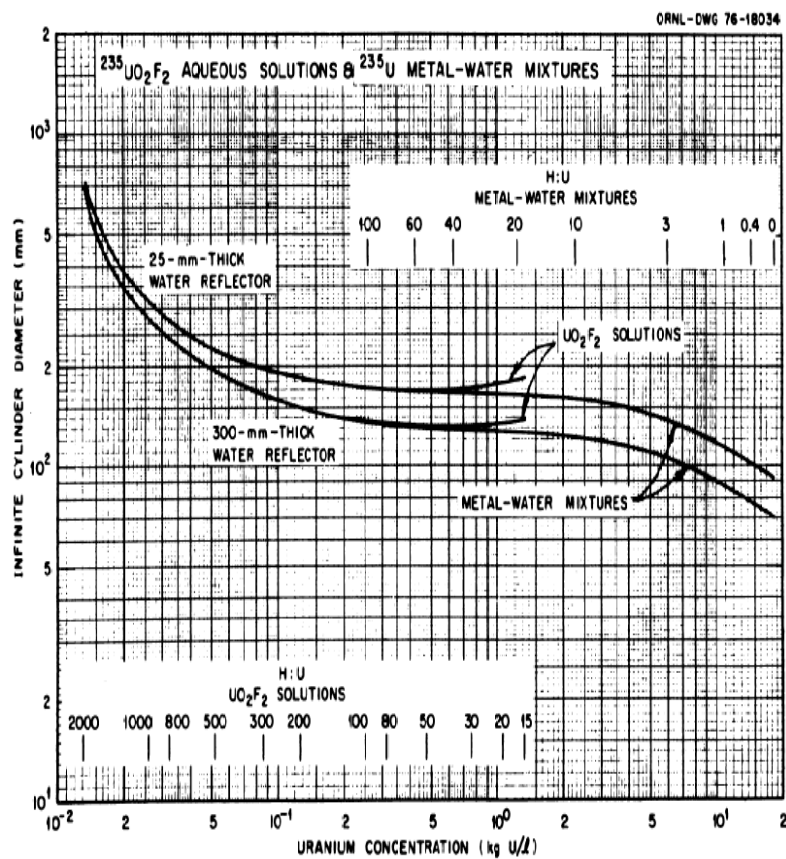


Fig. 30: Subcritical diameter limit for individual cylinder of homogeneous water-reflected and moderated ^{235}U

***APPENDIX 1: Low-Enriched Uranium (LEU) Dry Powder Drum (Charles Monk)**

BEGIN MATERIAL SPECIFICATION

TYPE DICE

NORMALISE ! Normalize proportions where necessary

ATOMS

*Material 1 - UO₂ (Density 10.87 g/cm³)

MIXTURE 1

U235 PROP 0.03

U238 PROP 0.97

O PROP 2.0

*Material 2 - Duplex Stainless Steel 2205 (UNS S31803)

(Density 7.8 g/cm³)

MIXTURE 2

Ni PROP 0.055

Cr PROP 0.22

Mo PROP 0.03

C PROP 0.0003

Mn PROP 0.02

Si PROP 0.01

P PROP 0.0003

N PROP 0.0015

S PROP 0.0002

Fe PROP 0.6627

*Material 3 - Sand-Silicon Dioxide (Density 2.65 g/cm³)

MIXTURE 3

Si PROP 1

O PROP 2

WEIGHT

MATERIAL 1 Density 10.87 Mixture 1

MATERIAL 2 Density 7.80 Mixture 2

MATERIAL 3 Density 2.65 Mixture 3

END

*****BE

GIN MATERIAL GEOMETRY

PART 1 NEST

ZROD M1 0.0 0.0 0.10 7.5 84.8

ZROD M2 0.0 0.0 0.01 7.75 84.89

PART 2 UNTIL 4 CLONE 1

PART 5 CLUSTER

ZROD P 1 -10.6 -10.6 0.01 7.75 84.89

ZROD P 2 -10.6 10.6 0.01 7.75 84.89

ZROD P 3 10.6 -10.6 0.01 7.75 84.89

ZROD P 4 10.6 10.6 0.01 7.75 84.89

ZROD M 3 0.0 0.0 0.0 28.1 85.1

PART 6 NEST

ZROD P 5 0.0 0.0 0.0 28.1 85.1

ZROD M 2 0.0 0.0 -2.0 31.1 90.1

END

BEGIN CONTROL DATA

STAGES -15 100 1000 STDV 0.001

END

BEGIN SOURCE GEOMETRY

ZONEMAT ALL/MATERIAL 1

END

***APPENDIX 2: High-Enriched Uranium (HEU) Nitrate Solution Drum**

BEGIN MATERIAL SPECIFICATION

TYPE DICE

NORMALISE ! Normalize proportions where necessary

ATOMS

*Material 1 - UO₂(NO₃)₂ - (DENSITY 2.81 g/cm³)

MIXTURE 1

U235 PROP 0.93

U238 PROP 0.07

N PROP 2.0

O PROP 8.0

*Material 2 - Duplex Stainless Steel 2205 (UNS S31803)

(Density 7.8 g/cm³)

MIXTURE 2

Ni PROP 0.055

Cr PROP 0.22

Mo PROP 0.03

C PROP 0.0003

Mn PROP 0.02

Si PROP 0.01

P PROP 0.0003

N PROP 0.0015

S PROP 0.0002

Fe PROP 0.6627

WEIGHT

MATERIAL 1 Density 2.81 Mixture 1

MATERIAL 2 Density 7.80 Mixture 2

END

BEGIN MATERIAL GEOMETRY

PART 1 NEST ! HEU DRUM

ZROD M1 0.0 0.0 2.5 28.6 85.1

ZROD M2 0.0 0.0 0.0 31.1 90.1

END

BEGIN CONTROL DATA

STAGES - 15 100 1000 STDV 0.001

END

BEGIN SOURCE GEOMETRY

ZONEMAT

PART 1 /MATERIAL 1

END

***APPENDIX 3: Plutonium Metal Waste Drum (Charles MONK)**

BEGIN MATERIAL SPECIFICATION

TYPE DICE

NORMALISE ! Normalize proportions where necessary

ATOMS

*Material 1 - Plutonium oil - (DENSITY 0.800 g/cm³)

MIXTURE 1

Pu239 PROP 0.011875

Pu240 PROP 0.000625

C PROP 0.8359

H PROP 0.1509

B PROP 0.000625

*Material 2 - Duplex Stainless Steel 2205 (UNS S31803)

(Density 7.8 g/cm³)

MIXTURE 2

Ni PROP 0.055

Cr PROP 0.22

Mo PROP 0.03

C PROP 0.0003

Mn PROP 0.02

Si PROP 0.01

P PROP 0.0003

N PROP 0.0015

S PROP 0.0002

Fe PROP 0.6627

WEIGHT

MATERIAL 1 Density 0.800 Mixture 1

MATERIAL 2 Density 7.80 Mixture 2

END

BEGIN MATERIAL GEOMETRY

PART 1 NEST ! HEU DRUM

ZROD M1 0.0 0.0 2.5 28.6 85.1

ZROD M2 0.0 0.0 0.0 31.1 90.1

END

BEGIN CONTROL DATA

STAGES - 15 100 1000 STDV 0.001

END

BEGIN SOURCE GEOMETRY

ZONEMAT

PART 1 /MATERIAL 1

```

END
*****
*APPENDIX 4: DISPLACEMENT Drum (Charles MONK)
*****
BEGIN MATERIAL SPECIFICATION
TYPE DICE
NORMALISE ! Normalise proportions where necessary
ATOMS
*Material 1 - Plutonium oil - (DENSITY 0.800 g/cm^3)
MIXTURE 1
  Pu239  PROP  0.011875
  Pu240  PROP  0.000625
  C      PROP  0.8359
  H      PROP  0.1509
  B      PROP  0.000625
*Material 2 - UO2 (Density 10.87 g/cm^3)
MIXTURE 2
  U235  PROP  0.03
  U238  PROP  0.97
  O      PROP  2.0
*Material 3 - Sand-Silicon Dioxide (Density 2.65 g/cm^3)
MIXTURE 3
  Si     PROP  1.0
  O      PROP  2.0
*Material 4 - UO2(NO3)2 - (DENSITY 2.81 g/cm^3)
MIXTURE 4
  U235  PROP  0.93
  U238  PROP  0.07
  N      PROP  2.0
  O      PROP  8.0
*Material 5 - Duplex Stainless Steel 2205 (UNS S31803)
(Density 7.8 g/cm^3)
MIXTURE 5
  Ni     PROP  0.055
  Cr     PROP  0.22
  Mo     PROP  0.03
  C      PROP  0.0003
  Mn     PROP  0.02
  Si     PROP  0.01
  P      PROP  0.0003
  N      PROP  0.0015
  S      PROP  0.0002
  Fe     PROP  0.6627
WEIGHT
MATERIAL 1  Density 0.800  Mixture 1
MATERIAL 2  Density 10.87  Mixture 2
MATERIAL 3  Density 2.65  Mixture 3
MATERIAL 4  Density 2.81  Mixture 4
MATERIAL 5  Density 7.80  Mixture 5
END
*****
BEGIN MATERIAL GEOMETRY
PART 1 NEST ! HEU DRUM
ZROD M4  0.0  0.0  2.5  28.6  85.1
ZROD M5  0.0  0.0  0.0  31.1  90.1
PART 2 NEST ! LEU TUBE
ZROD M1  0.0  0.0  0.10  7.5  84.8
ZROD M5  0.0  0.0  0.01  7.75  84.95
BOX M3  -10.6 -10.6  0.0  20.0  20.0  85.0
PART 3 ARRAY 2 2 1
2 2
2 2
PART 4 NEST !LEU DRUM
BOX P3  -20.0 -20.0  2.01  40.0  40.0  85.0
ZROD M3  0.0  0.0  2.0  28.6  85.1
ZROD M5  0.0  0.0  0.0  31.1  90.1
PART 5 NEST ! PU DRUM
ZROD M1  0.0  0.0  2.5  28.6  85.1
ZROD M5  0.0  0.0  0.0  31.1  90.1
PART 6
ZROD 1   0.0  0.0  0.0  31.1  90.1
BOX 2   -31.1 -31.1  0.0  62.2  62.2  1.25
BOX 3   -31.1 -31.1  0.0  62.2  62.2  90.1
ZONES

```

```

P1 +1
M4 +2 -1
M0 +3 -1 -2
PART 7
ZROD 1   0.0  0.0  0.0  31.1  90.1
BOX 2   -31.1 -31.1  0.0  62.2  62.2  1.25
BOX 3   -31.1 -31.1  0.0  62.2  62.2  90.1
ZONES
P4 +1
M4 +2 -1
M0 +3 -1 -2
PART 8
ZROD 1   0.0  0.0  0.0  31.1  90.1
BOX 2   -31.1 -31.1  0.0  62.2  62.2  1.25
BOX 3   -31.1 -31.1  0.0  62.2  62.2  90.1
ZONES
P5 +1
M4 +2 -1
M0 +3 -1 -2
PART 9 NEST ! EMPTY DRUM
ZROD M0  0.0  0.0  2.5  28.6  85.1
ZROD M5  0.0  0.0  0.0  31.1  90.1
PART 10
ZROD 1   0.0  0.0  0.0  31.1  90.1
BOX 2   -31.1 -31.1  0.0  62.2  62.2  1.25
BOX 3   -31.1 -31.1  0.0  62.2  62.2  90.1
ZONES
P9 +1
M4 +2 -1
M0 +3 -1 -2
PART 11 ARRAY 4 4 1
6 7 7 10
8 7 8 7
7 8 7 8
6 7 7 6
PART 12
BOX 1   151.2  0.0  0.00  248.8  248.8  90.1
BOX 2    0.0  0.0  0.0  400.0  400.0  1.25
BOX 3    0.0  0.0  0.0  400.0  400.0  200.0
ZONES
P11 +1
M4 +2 -1
M0 +3 -2 -1
PART 13
BOX 1    0.0  0.0  100.0  400.0  400.0  200.0
BOX 2    0.0  0.0  000.0  400.0  400.0  300.0
ZONES
P12 +1
M5 +2 -1
END
*****
BEGIN CONTROL DATA
STAGES -15 100 1000 STDV 0.001
END
*****
BEGIN SOURCE GEOMETRY
ZONEMAT
ZONE 1 PART 1 /MATERIAL 4
ZONE 1 PART 4 /MATERIAL 2
ZONE 1 PART 5 /MATERIAL 1
END
*****
*APPENDIX 5: DISPLACEMENT Drum with Water Wall
(Charles Okon: MONK)
*****
BEGIN MATERIAL SPECIFICATION
TYPE DICE
NORMALISE ! Normalise proportions where necessary
ATOMS
*Material 1 - Plutonium oil - (DENSITY 0.800 g/cm^3)
MIXTURE 1
  Pu239  PROP  0.011875
  Pu240  PROP  0.000625
  C      PROP  0.8359

```

```

      H      PROP 0.1509
      B      PROP 0.000625
*Material 2 - UO2 (Density 10.87 g/cm^3)
MIXTURE 2
      U235   PROP 0.03
      U238   PROP 0.97
      O      PROP 2.0
*Material 3 - Sand-Silicon Dioxide (Density 2.65 g/cm^3)
MIXTURE 3
      Si     PROP 1.0
      O      PROP 2.0
*Material 4 - UO2(NO3)2 - (DENSITY 2.81 g/cm^3)
MIXTURE 4
      U235   PROP 0.93
      U238   PROP 0.07
      N      PROP 2.0
      O      PROP 8.0
*Material 5 - Duplex Stainless Steel 2205 (UNS S31803)
(Density 7.8 g/cm^3)
MIXTURE 5
      Ni     PROP 0.055
      Cr     PROP 0.22
      Mo     PROP 0.03
      C      PROP 0.0003
      Mn     PROP 0.02
      Si     PROP 0.01
      P      PROP 0.0003
      N      PROP 0.0015
      S      PROP 0.0002
      Fe     PROP 0.6627
*Material 6 - Water-H2O (Density 1.000 g/cm^3)
MIXTURE 6
      H      PROP 2.0
      O      PROP 1.0
WEIGHT
MATERIAL 1      Density 0.800      Mixture 1
MATERIAL 2      Density 10.87      Mixture 2
MATERIAL 3      Density 2.65      Mixture 3
MATERIAL 4      Density 2.81      Mixture 4
MATERIAL 5      Density 7.80      Mixture 5
MATERIAL 6      Density 1.000      Mixture 5
END
*****
BEGIN MATERIAL GEOMETRY
PART 1 NEST ! HEU DRUM
ZROD M4 0.0 0.0 2.5 28.6 85.1
ZROD M5 0.0 0.0 0.0 31.1 90.1
PART 2 NEST ! LEU TUBE
ZROD M1 0.0 0.0 0.10 7.5 84.8
ZROD M5 0.0 0.0 0.01 7.75 84.95
BOX M3 -10.6 -10.6 0.0 20.0 20.0 85.0
PART 3 ARRAY 2 2 1
2 2
2 2
PART 4 NEST !LEU DRUM
BOX P3 -20.0 -20.0 2.01 40.0 40.0 85.0
ZROD M3 0.0 0.0 2.0 28.6 85.1
ZROD M5 0.0 0.0 0.0 31.1 90.1
PART 5 NEST ! PU DRUM
ZROD M1 0.0 0.0 2.5 28.6 85.1
ZROD M5 0.0 0.0 0.0 31.1 90.1
PART 6
ZROD 1 0.0 0.0 0.0 31.1 90.1
BOX 2 -31.1 -31.1 0.0 62.2 62.2 1.25
BOX 3 -31.1 -31.1 0.0 62.2 62.2 90.1
ZONES
P1 +1
M4 +2 -1
M0 +3 -1 -2
PART 7
ZROD 1 0.0 0.0 0.0 31.1 90.1
BOX 2 -31.1 -31.1 0.0 62.2 62.2 1.25
BOX 3 -31.1 -31.1 0.0 62.2 62.2 90.1
ZONES
P4 +1

```

```

M4 +2 -1
M0 +3 -1 -2
PART 8
ZROD 1 0.0 0.0 0.0 31.1 90.1
BOX 2 -31.1 -31.1 0.0 62.2 62.2 1.25
BOX 3 -31.1 -31.1 0.0 62.2 62.2 90.1
ZONES
P5 +1
M4 +2 -1
M0 +3 -1 -2
PART 9 NEST ! EMPTY DRUM
ZROD M0 0.0 0.0 2.5 28.6 85.1
ZROD M5 0.0 0.0 0.0 31.1 90.1
PART 10
ZROD 1 0.0 0.0 0.0 31.1 90.1
BOX 2 -31.1 -31.1 0.0 62.2 62.2 1.25
BOX 3 -31.1 -31.1 0.0 62.2 62.2 90.1
ZONES
P9 +1
M4 +2 -1
M0 +3 -1 -2
PART 11 ARRAY 4 4 1
6 7 7 6
7 8 7 8
8 7 8 7
6 7 7 10
PART 12
BOX 1 151.2 0.0 0.00 248.8 248.8 90.1
BOX 2 0.0 0.0 0.0 400.0 400.0 1.25
BOX 3 0.0 0.0 0.0 400.0 400.0 200.0
BOX 4 100.0 0.0 0.0 50.0 400.0 200.0
ZONES
P11 +1
M4 +2 -1
M6 +4 -2
M0 +3 -2 -1 -4
PART 13
BOX 1 0.0 0.0 100.0 400.0 400.0 200.0
BOX 2 0.0 0.0 000.0 400.0 400.0 300.0
ZONES
P12 +1
M5 +2 -1
END
*****
BEGIN CONTROL DATA
STAGES -15 100 1000 STDV 0.001
END
*****
BEGIN SOURCE GEOMETRY
ZONEMAT
ZONE 1 PART 1 /MATERIAL 4
ZONE 1 PART 4 /MATERIAL 2
ZONE 1 PART 5 /MATERIAL 1
END
*****
*APPENDIX 6: FINAL DRUM ARRAY (Charles MONK)
*****
BEGIN MATERIAL SPECIFICATION
TYPE DICE
NORMALISE ! Normalise proportions where necessary
ATOMS
*Material 1 - Plutonium oil - (DENSITY 0.800 g/cm^3)
MIXTURE 1
      Pu239   PROP 0.011875
      Pu240   PROP 0.000625
      C      PROP 0.8359
      H      PROP 0.1509
      B      PROP 0.000625
*Material 2 - UO2 (Density 10.87 g/cm^3)
MIXTURE 2
      U235   PROP 0.03
      U238   PROP 0.97
      O      PROP 2.0
*Material 3 - Sand-Silicon Dioxide (Density 2.65 g/cm^3)
MIXTURE 3

```

```

Si    PROP 1.0
O     PROP 2.0
*Material 4 - UO2(NO3)2 - (Density 2.81 g/cm^3)
MIXTURE 4
  U235  PROP 0.93
  U238  PROP 0.07
  N     PROP 2.0
  O     PROP 8.0

*Material 5 - Duplex Stainless Steel 2205 (UNS S31803)
(Density 7.8 g/cm^3)
MIXTURE 5
  Ni    PROP 0.055
  Cr    PROP 0.22
  Mo    PROP 0.03
  C     PROP 0.0003
  Mn    PROP 0.02
  Si    PROP 0.01
  P     PROP 0.0003
  N     PROP 0.0015
  S     PROP 0.0002
  Fe    PROP 0.6627
WEIGHT
MATERIAL 1  Density 0.800  Mixture 1
MATERIAL 2  Density 10.87  Mixture 2
MATERIAL 3  Density 2.65  Mixture 3
MATERIAL 4  Density 2.81  Mixture 4
MATERIAL 5  Density 7.80  Mixture 5
END
*****
BEGIN MATERIAL GEOMETRY
PART 1 NEST ! HEU DRUM
ZROD M4 0.0 0.0 2.5 28.6 85.1
ZROD M5 0.0 0.0 0.0 31.1 90.1
PART 2 NEST ! LEU TUBE
ZROD M1 0.0 0.0 0.10 7.5 84.8
ZROD M5 0.0 0.0 0.01 7.75 84.95
BOX M3 -10.6 -10.6 0.0 20.0 20.0 85.0
PART 3 ARRAY 2 2 1
2 2
2 2
PART 4 NEST ! LEU DRUM
BOX P3 -20.0 -20.0 2.01 40.0 40.0 85.0
ZROD M3 0.0 0.0 2.0 28.6 85.1
ZROD M5 0.0 0.0 0.0 31.1 90.1
PART 5 NEST ! PU DRUM
ZROD M1 0.0 0.0 2.5 28.6 85.1
ZROD M5 0.0 0.0 0.0 31.1 90.1
PART 6
ZROD 1 0.0 0.0 0.0 31.1 90.1
BOX 2 -50.0 -50.0 0.0 100.0 100.0 90.1
ZONES
P1 +1

M0 +2 -1
PART 7
ZROD 1 0.0 0.0 0.0 31.1 90.1
BOX 2 -50.0 -50.0 0.0 100.0 100.0 90.1
ZONES
P4 +1
M0 +2 -1
PART 8
ZROD 1 0.0 0.0 0.0 31.1 90.1
BOX 2 -50.0 -50.0 0.0 100.0 100.0 90.1
ZONES
P5 +1
M0 +2 -1
PART 9 NEST ! EMPTY DRUM
ZROD M0 0.0 0.0 2.5 28.6 85.1
ZROD M5 0.0 0.0 0.0 31.1 90.1
PART 10
ZROD 1 0.0 0.0 0.0 31.1 90.1
BOX 2 -50.0 -50.0 0.0 100.0 100.0 90.1
ZONES
P9 +1
M0 +2 -1
PART 11 ARRAY 4 4 1
8 7 7 8
7 7 6 7
7 6 10 6
8 7 7 8
PART 12
BOX 1 0.0 0.0 0.0 400.0 400.0 90.1
BOX 2 0.0 0.0 0.0 400.0 400.0 200.0
ZONES
P11 +1
M0 +2 -1
PART 13
BOX 1 0.0 0.0 100.0 400.0 400.0 200.0
BOX 2 0.0 0.0 000.0 400.0 400.0 300.0
ZONES
P12 +1
M5 +2 -1
END
*****BE
GIN CONTROL DATA
STAGES -15 100 1000 STDV 0.001
END
*****
BEGIN SOURCE GEOMETRY
ZONEMAT
ZONE 1 PART 1 /MATERIAL 4
ZONE 1 PART 4 /MATERIAL 2
ZONE 1 PART 5 /MATERIAL 1
END
*****

```