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A Critical Analysis of Molten Salt Reactor (MSR) Safety Systems

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Abstract

A criticality analysis of Molten Salt Reactor (MSR) safety systems is carried out in this research. These systems are design to work in the event of an accident scenario, where a solid freeze plug (frozen fuel salt) melts, and the fuel salts volume drains into a number of storage tanks of non-critical geometry. For the purpose of this research, MONK Version 9A Monte Carlo Program by ANSWERS Software Service was used to carry out the criticality analysis for the drain tanks using the design geometry and specifications of the Molten Salt Research Experiment (MSRE) at the Oak Ridge National Laboratory (ORNL), Tennessee-USA. We assumed the composition of the fluoride salt mixture in the fuel drain tank to be: 42.16wt% LiF, 35.79wt% BeF, 21wt% ZrF_4, 1.02wt% UF_4, and 0.02wt% PuF_3. The safety margin for subcriticality was determined. The results obtained showed that the four storage tanks were significantly subcritical, as expected. The effective multiplication factor (K_{eff}) as calculated by MONK for a salt volume of 1,905,870cm^3 stored in four drain tanks of capacity 2,271,100cm^3 (each) with a diameter of 127cm is 0.9076 (subcritical).

Keywords: Effective Multiplication Factor, Criticality Safety, Critical Geometry.

Introduction

Much of the development work on molten-salt system has been done at Oak Ridge National Laboratory (ORNL), Tennessee. The motivation for the work, like that of other fluid-fuelled systems, is the ability to utilize economically, through breeding and simple fuel processing, all grades of uranium and thorium. Molten salts, like liquid-metal fuels, do not suffer from the high vapour pressure of aqueous fuels and therefore do not require high reactor pressurization. They are capable of operation at higher temperatures than aqueous or liquid-metal fuels[2]. This reactor operates with a liquid fuel. Liquid (or molten) salts have characteristics that make them particularly suitable for use as primary and/or secondary coolants for nuclear reactors. The link between its chemical technology and the reactor physics distinguish it from other reactors currently in used today.

The main importance of this reactor can be considered in terms of the reactor safety[5];

- Catastrophic loss of coolant accidents are extremely unlikely because the system operates at a very low pressures (atmospheric pressure).
- The fuel with less than 1% ^{233}U is only critical in the graphite moderated core region. And when cooled, it becomes a solid trapping the radioactive material.
- The high fuel burnup results in less nuclear waste per unit of electricity generated.
- There is no possibility of “failure” or “rupture” of the fuel elements.

The salt mixture, lithium fluoride (LiF) and beryllium fluoride (BeF), commonly known as FLiBe, has a boiling point of about 1430^{o}C and the melting point of about 459^{o}C. It has a large working operating temperature range for the reactor. For example, it is solid at room temperature but at reactor’s operating temperature of about 700^{o}C it becomes liquid and also has a large margin before it is vaporized[5].

Aim and Objective

The aim of this research is to carry out a critical analysis of a molten salt reactor safety system using MONK Version 9A Monte Carlo Program by ANSWERS Software Service and the tank design geometry and specifications of the Molten Salt Research Experiment (MSRE) at the Oak Ridge National Laboratory. The objective of this research is to analyse those parameters that needs to be considered in order to cool down the storage tank filled with hot fuel, by removal of the decay heat so as to maintain the integrity of the tank and keep the fuel in a subcritical state.

Limitations of Study

In an actual plant we have to analyze the transient (i.e. how long it will take the fuel to completely drain to the drain tank) but for this project the sub-criticality analysis assumes that the fuel has been completely drained into the tank. The cooling system and the heater assembly surrounding each tank or any other structural material or machinery in the cell is not considered in the analysis. Material geometry/specifications used for the component dimensions were gotten from the reports from related articles on Molten Salt Breeder Reactor (MSBR) & Molten Salt Reactor Experiment (MSRE).

Basic Reactor Emergency Safety Systems

Freeze Plug

The freeze plug is kept actively frozen by an external cooling fan blowing air into the area. In an event of total loss of power, the Freeze Plug (valve) melts, and the bulk of core salt drains by gravity into the drain tank with passively cooled configuration where nuclear fission and melt down is not possible[6].

Critically Safe Fuel Drain Tanks:

The fuel drain tank is necessary in the case of pump power failure because even if the reactor is immediately scrammed, decay-heat generation may raise the core temperatures to intolerable levels as the fuel salt, being its own coolant, is no longer in motion[3]. The capacity of one fuel drain tank is enough to hold all the fuel cell in the entire reactor but for safety reasons the fuel can be distributed equally into two or more fuel tanks linked together. The tank is design with a pump bowl to accommodate any excess of coolant salt volume. Each bowl is provided with an overflow line directed to the first coolant-salt drain tank. The jet pump is used to pump back the salt from the tank to the circulation system. Once in the tank, the fuel salt is cooled by the fluoroborate (as in the case of MSBR) secondary coolant salt through U-tubes which extend into the tank from headers located at the top of the tanks. For MSBR, the maximum cooling requirements are 60 Mw(t) but the system is design for 300Mw(t). The fluoroborate coolant is circulated by natural convection (since power failure may have caused the initial emergency). The heat is then dumped into the atmosphere via air coolers and chimneys[3].

Methodology

MONK 9A Simulation

MONK is a Monte Carlo neutronics computer program used in the study of nuclear criticality safety and reactor physics analysis[1]. The version of MONK used for this dissertation is MONK Version 9A, the ANSWERS Software Package.

Since the goal of criticality safety is to assure that all operations are subcritical, the ability to adjust the balance routinely is, of course, very necessary. Thus, any methods that favour some combination of low production and high absorption and leakage may be employed. The production rate for neutrons depends on the amount and type of each fissionable material present in a system[4].

Drain Tanks Design Specification

The material used for the drain tank design is Hastelloy. Hastelloy material was designed as a “super alloy” or high temperature alloy. It suffers much less loss of ductility under neutron irradiation compared to stainless steel. This material is developed for corrosion resistance of oxidising and reducing agent. The material integrity cannot be perturbed when exposed to very high temperature. It is designed to survive under high-temperature and high-stress service. The primary ingredient of this material is nickel, but it also contains chromium, molybdenum, carbon, manganese, silicon titanium, copper, sulphur, iron and boron. The material has a density of 8.08 g/cm^3, melting point of 1323-1371°C, thermal conductivity of 10.1-12.5 W/m-K and a heat capacity of 0.427J/g°C, The chemical composition by proportion of Hastelloy alloy used for this design is as shown below[7] (the format is taken from the MONK input file, and the values are fractional compositions by mass):

Ni	PROP	0.66
Cr	PROP	0.10
Mo	PROP	0.15
C	PROP	0.0004
Mn	PROP	0.01
Si	PROP	0.01
Ti	PROP	0.00865
Cu	PROP	0.0035
S	PROP	0.0002
Fe	PROP	0.05
B	PROP	0.0001

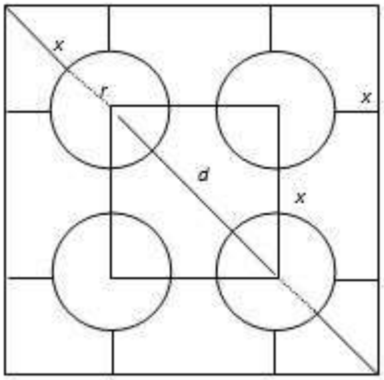
Stated below are the drain tanks design parameters[3];

Drain Tank Capacity	=	2,271 litres (2.271 m^3)
Drain Tank Inner diameter	=	1.27m
Drain Tank Outer diameter	=	1.312m

Drain Tank inner height = 2.1844m
Fuel Salt Density = 2.02 g/cm3
Total Fuel Salt Volume = 1,905.9 litres ($1.906\ m^3$)
Water bath height = 4.00m

The MONK input files have been prepared using the above material geometry and specifications, and are provided in Appendix 2A of this report. The results are displayed in tabular form in Appendix 1A, and a graphical interpretation of the results is provided below in this report.

Design Assumption: the drain tanks are welded to the bottom of the cell such that the minimum separation of each tank from the cell wall and its two neighbours are equal.



Diagonal (d) as calculated below = 243.34cm
Inner tank diameter is 127cm and the radius (r) = 63.5cm
Maximum length of the diagonal (D) is 460.48cm
Separation (x) as calculated below = 45.07cm

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 diogonal is known, the area is half of the digonals.

Since both digonals are congruent, this simplified to:

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

$$d = \sqrt{2 * S^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$where\ s = x + 2r$$

$$but\quad 2x + 2r + d = D$$

$$2x + 127 + \sqrt{2} * (x + 127) = 460.48$$

$$x = \frac{333.48 - 179.60}{3.414} = 45.07cm$$

$$substitute\ x = 45.07cm\ into\ (1), we\ can\ solve\ for\ d.$$

$$\therefore d = 243.34cm$$

The above calculated figures were also used for the MONK modelling.

One of the assumptions made in this design is that, the total fuel salt is equally distributed into four drain tanks of equal dimensions. Therefore, the input files are written for different values of fuel volumes to ascertain the critical volume and critical diameter.

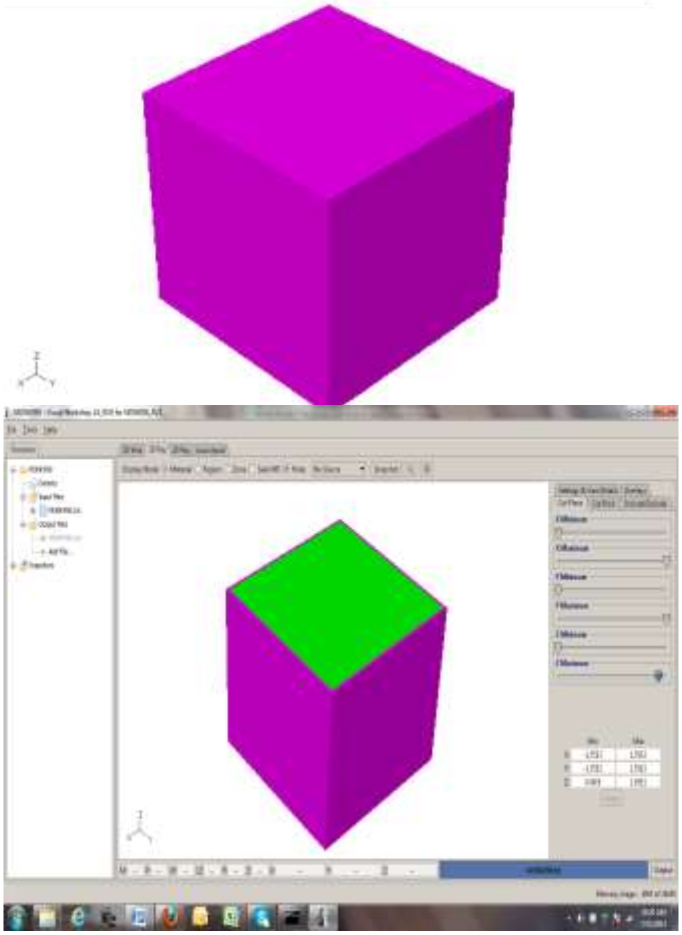


Fig.1: MONK modelling for the MSR Drain Tanks (see code in Appendix B)

🟪 Stainless Steel Tank Bath 🟩 Water

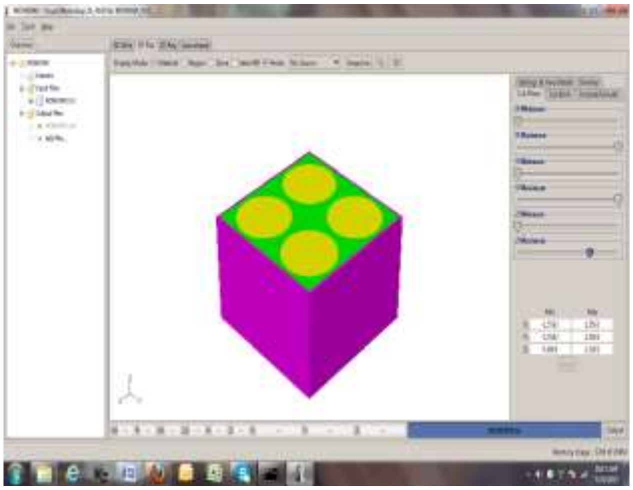


Fig.2: MONK Modelling for 4-MSR Drain Tanks (see code in Appendix B)

🟪 Stainless Steel Tank 🟩 Water 🟧 Hastelloy Material

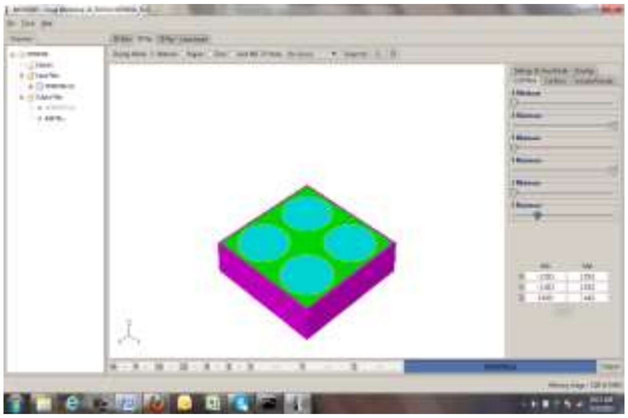


Fig.3: MONK Modelling for 4-MSR Drain Tanks (see codes in Appendix B)

🟪 Stainless Steel Bath 🟩 Water 🟦 Fuel Salt

Results

Appendix A contains data as calculated by MONK for four MSR drain tanks. The graphical representations of different calculated parameters are shown in the figures (3-8) below.

Table 1 (see appendix A), is the critical volume data obtained for four drain tanks. The total volume of the fuel salts is about 1.9059 m^3 while the drain tank capacity is about 2.2711 m^3. It is assumed that the salt volume is divided equally into the four drain tanks of the same dimensions.

According to table 1, the first column contains data for the salt volume. By distributing the total fuel volume into the four drain tanks equally, it means that each drain tank will contain about 0.4765 m^3. In order to carry out a comparative analysis, MONK simulations were run for series of data as can be seen in Table 1 of Appendix A.

The second column contains data for the salt depth. The salt depth represents the inner height occupied by the salt volume in each tank. This data was calculated using equation 2 below since a cylindrical geometry is considered. For a salt volume of 0.4765 m3 the height occupied by this volume in the tank of 127cm in diameter is about 37.6cm. Salt depths occupied by other salt volumes are also calculated as can be seen in Table1 of Appendix A.

$$h = \frac{V}{\pi r^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

$$V = Salt\ Volume$$

$$r = Tank\ inner\ radius$$

The fourth column shows the tank radius of 63.5cm. This constant value indicates that the inner diameter of the drain tank does not change.

The sixth column shows the effective multiplication factor as calculated by MONK, which is the value that determines the state of criticality of the system by putting neutron leakage into considerations. This value was calculated for different salt volumes and their corresponding salt depth.

The last column is the property that is used to determine the amount of neutrons that leaked out of the system. It is a dimensionless property known as the Geometric Buckling. For a cylinder of radius r and height h, the property is mathematically stated thus;

$$B_g^2 = \left(\frac{2.405}{r}\right)^2 + \left(\frac{\pi}{h}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Table 2 (see appendix A), is the MONK data for critical diameter. This data shows how the criticality of the system is affected by varying the diameter of the drain tank. It is assumed that for each diameter, the salt volume is full to capacity. The effective multiplication factor for each diameter, the salt volume and the geometric buckling are all calculated for comparative analysis.

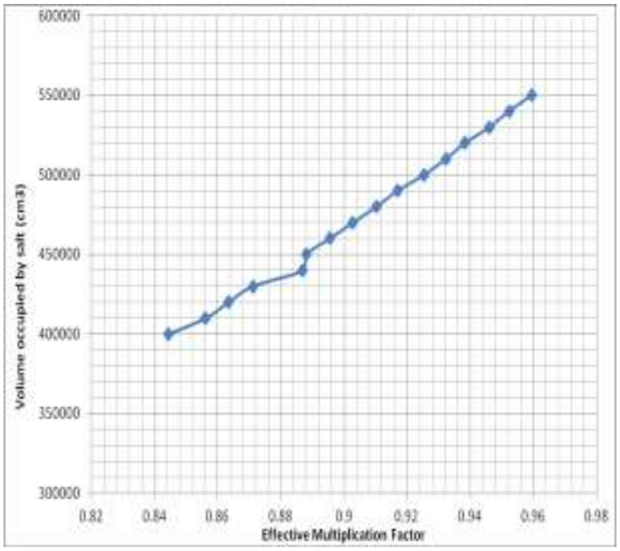


Fig.3: Plot Showing Salt Volume vs K-effective (4-Drain Tanks using MONK 9A)

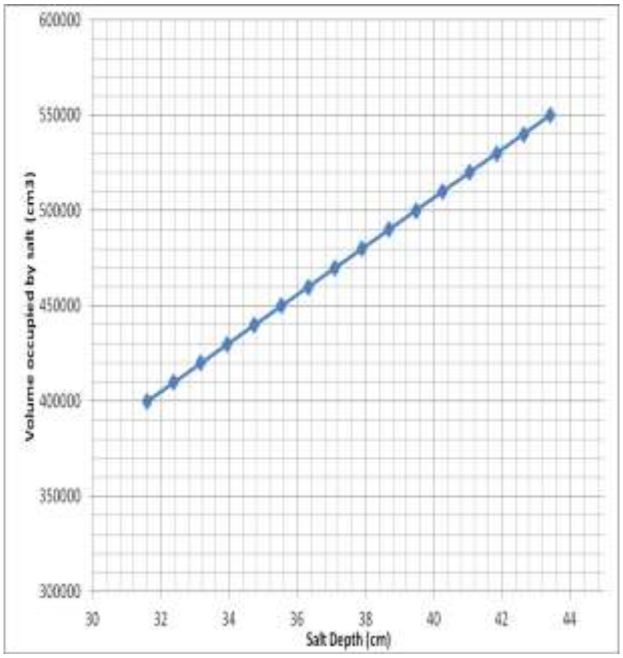


Fig.4: Plot Showing Salt Volume vs Salt Depth (4-Drain Tanks using MONK 9A)

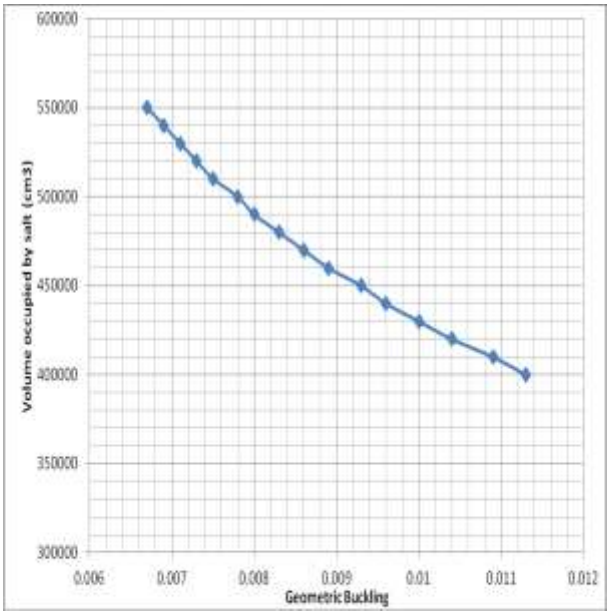


Fig.5: Plot Showing Salt Volume vs Geometric Buckling (4-Drain Tanks using MONK 9A)

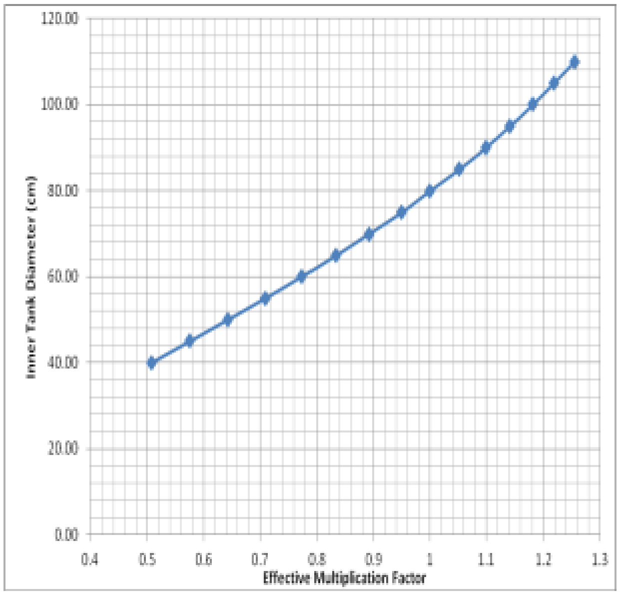


Fig.6: Plot Showing Inner Tank Diameter vs K-effective (4-Drain Tanks using MONK 9A)

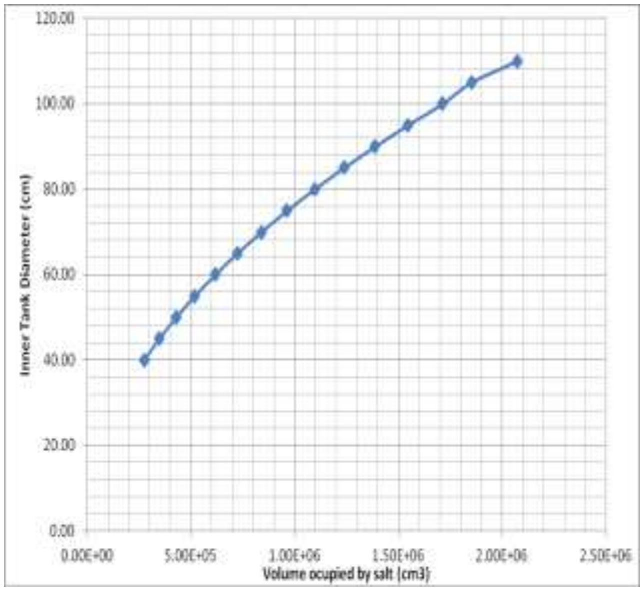


Fig.7: Plot Showing Inner Tank Diameter vs Salt Volume (4-Drain Tanks using MONK 9A)

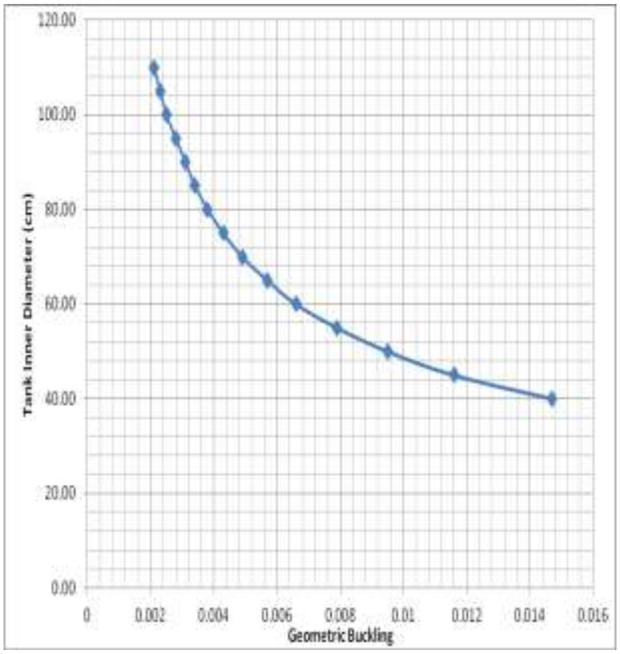


Fig.8: Plot Showing Inner Tank Diameter vs Geometric Buckling (4-Drain Tanks using MONK 9A)

Discussion of Results

The determination of sub-critical limits as part of nuclear criticality safety management is fundamental for ensuring that the processes involving fissile material remain safe.

Figure 3 & 4 is a plot showing how the effective multiplication factor changes as the salt volume is increased. One of the factors that affect the criticality of a fissile system is the quantity of the fissile salt contained in a storage facility of a specific geometry. Since one of the assumptions made in the design for the case of four drain tanks is that the fuel salt is distributed equally into the tanks of equal dimension. An estimate of about 476,468 cm3 is the volume of salt contained in each tank. The effective multiplication factor in this case was calculated by interpolating the simulated data between 470,000cm^3 and 480,000cm^3.

By Interpolation

$$y = y_1 + (x - x_1) * \left(\frac{y_2 - y_1}{x_2 - x_1}\right)$$

$$where, x = volume(cm^3) occupied\ by\ salt$$

$$y = effective\ multiplication\ factor\ (k_{eff})$$

$$x = 476467.5cm^3$$

$$y_1 = 0.9028$$

$$y_2 = 0.9102$$

$$x_1 = 470000cm^3$$

$$x_2 = 480000cm^3$$

$$\therefore y = 0.9076$$

The graph shows that, although there is a corresponding increase in the effective multiplication factor as the volume increases, the system still remains in a stable and subcritical state. This demonstrates that all the salts volume drained from the reactor core could be stored in the four tanks and remain in a safe and subcritical condition without affecting the veracity of the tanks or resulting to any risk factor.

Figure 5 is the plot showing the salt volume and the geometric buckling. This property measures the amount of neutrons that leaked out of the system. It is also used to determine the state of criticality. The geometric buckling reduces with increasing salt volume.

Figure 6 is the plot showing the effect of varying the inner diameter of the tank on the criticality of the system. Let us consider the case where the fuel salt depth in the tank is full to capacity by varying the diameter of the tank as well as the spacing between each tank. Results of data captured from Appendix A table 2 shows that as the diameter of the tank is reduced, there is a wide spacing between each tank thereby enhancing efficient heat removal and circulation of the coolant by natural convection. This also contributes in keeping the system in a subcritical state and also avoids the leakage of neutrons from one tank to another. Equation 4 below is used to calculate the critical diameter for each tank.

$$r = \sqrt{\frac{V}{\pi h}} \quad \text{..} (4)$$

$$r = \sqrt{\frac{476467.5}{\pi * 218}} = 26.37cm$$

For the tank diameter of 52.78cm occupying a salt volume of 476467.5cm3, the effective multiplication factor is calculated as 0.6791. When the diameter is increased, the spacing between each tank is narrowed thereby affecting the effective removal of decay heat and the circulation of coolant. As can be seen from figure 5.4, the K-effective increases as the tank gets compacted to each other. The effective multiplication factor in this case was calculated by interpolating the simulated data between 25.00cm and 27.00cm.

By Interpolation

$$y = y_1 + (x - x_1) * \left(\frac{y_2 - y_1}{x_2 - x_1}\right)$$

$$where, x = tank\ inner\ radius$$

$$y = effective\ multiplication\ factor\ (k_{eff})$$

$$x = 26.37cm$$

$$y_1 = 0.6426$$

$$y_2 = 0.7093$$

$$x_1 = 25cm$$

$$x_2 = 27cm$$

$$\therefore y = 0.6791$$

We can hereby conclude that, the credible upset geometric configuration from a critical safety standpoint occurs when the tank diameter is increased and the spacing between each tank neighbours is very close. This causes the maximum possible reflection in the fuel drain tank cell given the assumed constraint of less water ingress.

<u>Deductions for 4-Drain Tanks</u>

- **For tank diameter of 127cm, the effective multiplication factor (K_{eff}) = 0.9074 at the depth of about 37cm (1/6 of each tank capacity) for a salt volume of 476467.5cm^3 per tank ≈1,905,870cm^3 (i.e for 4-tanks).**
- **For tank diameter of 52.74cm, the effective multiplication factor (K_{eff}) = 0.6791 at the depth equal to 218cm (tank inner height) for a salt volume of 476467.5cm^3 per tank ≈1,905,870cm^3 (i.e for 4-tanks)**

Figure 7 & 8, shows a plot of the inner diameter against the salt volume and the geometric buckling respectively. As the inner diameter of the drain tank is increased it gives room for more salt volume to be accommodated and the leakage also decreases as the inner diameter is increased.

Conclusion

Criticality safety is concerned with preventing both criticality and supercriticality. It seeks to assure that operations with fissionable materials outside of reactor core are always subcritical.

The primary aim and objective of this work was to determine the degree of subcriticality of the molten salt drain tank. To accomplish this, a model of the fuel drain tank was created using MONK 9A. This model includes the fuel salt, fuel drain tanks, and water bath. The model did not include the cooling system or any other structural material. The results obtained showed that the four storage tanks were significantly subcritical, as expected. The effective multiplication factor (K_{eff}) as calculated by MONK for a salt volume of 1,905,870cm^3 stored in four drain tanks of capacity 2,271,100cm^3 (each) with a diameter of 127cm is 0.9076 (subcritical).

Recommendations for Future Work

Having considered my limitations in this research, I thereby recommend that this research could be improved upon by looking at the following;

1. The thermal hydraulic analysis of the drain tanks.
2. Effort could also be made to design the drain tanks of a noncritical spherical geometry and also putting into consideration the cooling system and other parameters associated with it

Also by calculating the transient temperature behaviour of the drain tank.

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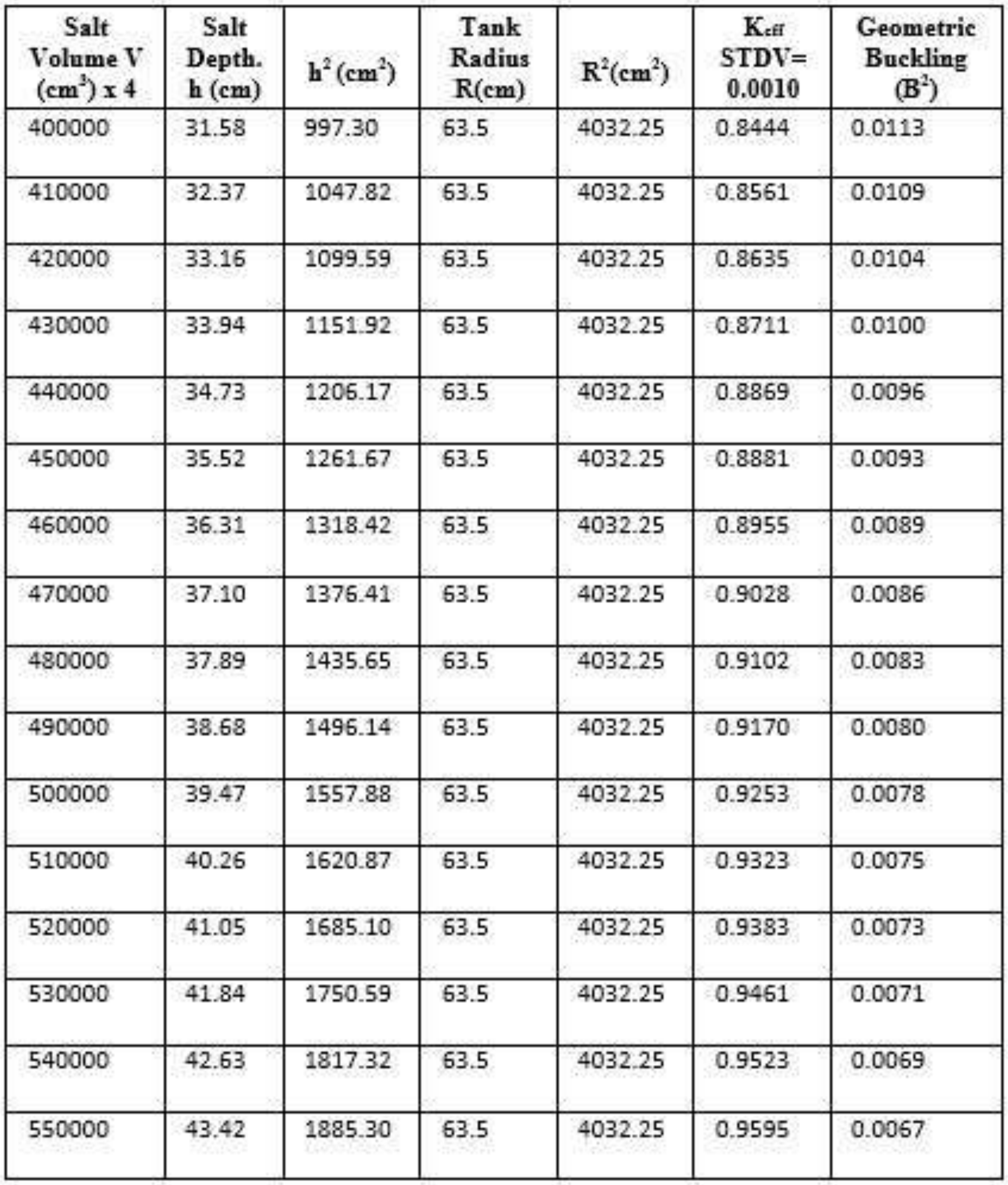
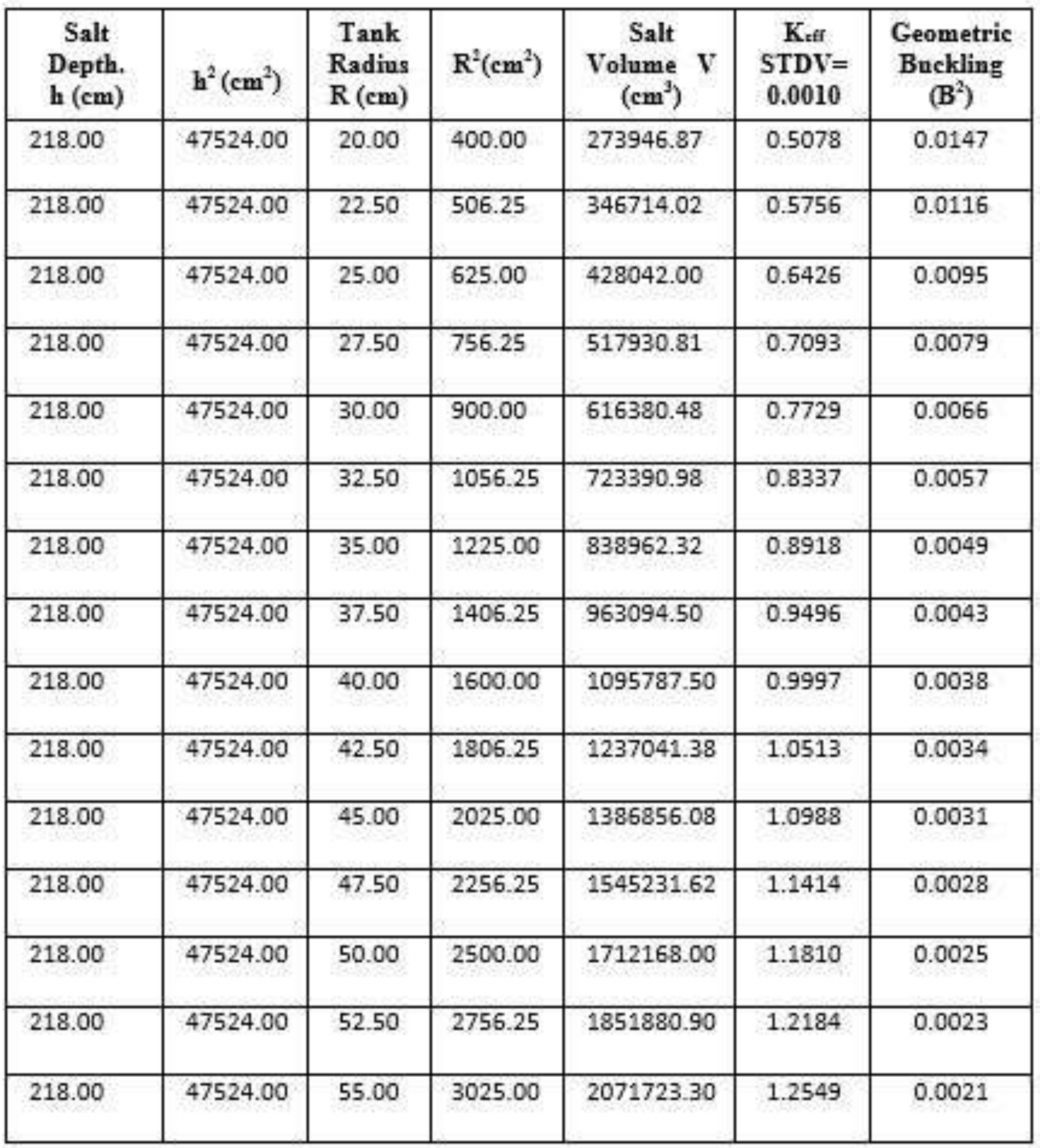
APPENDIX A

Table 1: MONK Data for Critical Volume obtained for Four(4) Drain Tanks (Total Salt Volume: 1,905,870 cm^3)



Salt Volume V (cm^3) x 4	Salt Depth. h (cm)	h^2 (cm^2)	Tank Radius R(cm)	R^2(cm^2)	K$_{eff}$ STDV= 0.0010	Geometric Buckling (B^2)
400000	31.58	997.30	63.5	4032.25	0.8444	0.0113
410000	32.37	1047.82	63.5	4032.25	0.8561	0.0109
420000	33.16	1099.59	63.5	4032.25	0.8635	0.0104
430000	33.94	1151.92	63.5	4032.25	0.8711	0.0100
440000	34.73	1206.17	63.5	4032.25	0.8869	0.0096
450000	35.52	1261.67	63.5	4032.25	0.8881	0.0093
460000	36.31	1318.42	63.5	4032.25	0.8955	0.0089
470000	37.10	1376.41	63.5	4032.25	0.9028	0.0086
480000	37.89	1435.65	63.5	4032.25	0.9102	0.0083
490000	38.68	1496.14	63.5	4032.25	0.9170	0.0080
500000	39.47	1557.88	63.5	4032.25	0.9253	0.0078
510000	40.26	1620.87	63.5	4032.25	0.9323	0.0075
520000	41.05	1685.10	63.5	4032.25	0.9383	0.0073
530000	41.84	1750.59	63.5	4032.25	0.9461	0.0071
540000	42.63	1817.32	63.5	4032.25	0.9523	0.0069
550000	43.42	1885.30	63.5	4032.25	0.9595	0.0067

Table 2: MONK Data for Critical Diameter obtained for Four(4) Drain Tanks (Total Salt Volume: 1,905,870 cm³)



Salt Depth. h (cm)	h^2 (cm^2)	Tank Radius R (cm)	R^2(cm^2)	Salt Volume V (cm^3)	K_{eff} STDV= 0.0010	Geometric Buckling (B^2)
218.00	47524.00	20.00	400.00	273946.87	0.5078	0.0147
218.00	47524.00	22.50	506.25	346714.02	0.5756	0.0116
218.00	47524.00	25.00	625.00	428042.00	0.6426	0.0095
218.00	47524.00	27.50	756.25	517930.81	0.7093	0.0079
218.00	47524.00	30.00	900.00	616380.48	0.7729	0.0066
218.00	47524.00	32.50	1056.25	723390.98	0.8337	0.0057
218.00	47524.00	35.00	1225.00	838962.32	0.8918	0.0049
218.00	47524.00	37.50	1406.25	963094.50	0.9496	0.0043
218.00	47524.00	40.00	1600.00	1095787.50	0.9997	0.0038
218.00	47524.00	42.50	1806.25	1237041.38	1.0513	0.0034
218.00	47524.00	45.00	2025.00	1386856.08	1.0988	0.0031
218.00	47524.00	47.50	2256.25	1545231.62	1.1414	0.0028
218.00	47524.00	50.00	2500.00	1712168.00	1.1810	0.0025
218.00	47524.00	52.50	2756.25	1851880.90	1.2184	0.0023
218.00	47524.00	55.00	3025.00	2071723.30	1.2549	0.0021

APPENDIX B

MONK Input File for Four(4) Drain Tanks

```
*APPENDIX B1 (Charles Monk)
*******************************************
*******************************
BEGIN MATERIAL SPECIFICATION
TYPE DICE
NORMALISE ! Normalise proportions where
necessary
ATOMS
*Material 1 - LiF-BeF2-ZrF4-UF4 (Density 2.02
g/cm^3)
MIXTURE 1
        Li      PROP  1
        Be      PROP  1
        Zr      PROP  1
        U233  PROP  0.93
        U234  PROP  0.07
```

```
            F           PROP   90
*Material 2 - Hastelloy G2 (Density 8.03 g/cm^3)
MIXTURE 2
            Ni      PROP   0.66
            Cr      PROP   0.10
            Mo      PROP   0.15
            C       PROP   0.0004
            Mn      PROP   0.01
            Si      PROP   0.01
            Ti      PROP   0.00865
            Cu      PROP   0.0035
            S       PROP   0.0002
            Fe      PROP   0.05
            B       PROP   0.0001
*Material 3 - Water-H2O (Density 1.000 g/cm^3)
MIXTURE 3
       H        PROP   2.0
       O        PROP   1.0
*Material 4 - Duplex Stainless Steel 2205 (UNS
S31803) (Density 7.8 g/cm^3)
MIXTURE 4
       Ni      PROP   0.66
       Cr      PROP   0.15
       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 2.03      MIXTURE 1
MATERIAL 2     DENSITY 8.03      MIXTURE 2
MATERIAL 3     DENSITY 1.00      MIXTURE 3
MATERIAL 4     DENSITY 7.80      MIXTURE 4

END
********************************************
******************************

BEGIN MATERIAL GEOMETRY
PART 1 NEST
ZROD M1   0.0   0.0  1.5  63.5   31.58
ZROD M2   0.0   0.0  1.0  65.6   218.0
BOX  M3 -75.0 -75.0  0.0  150.0   150.0  280.0

PART 2 ARRAY 2 2 1
1 1
1 1

PART 3 NEST
BOX P2 -150.0  -150.0  10.0  300.0  300.0  280.0
BOX M4 -155.0  -155.0  0.0   310.0  310.0  310.0
END
********************************************
**************

BEGIN CONTROL DATA
STAGES -15 1000 1000 STDV 0.001
END
********************************************
**************

BEGIN SOURCE GEOMETRY
ZONEMAT
PART 1 /MATERIAL 1
END
********************************************
**************
```