



COMPARATIVE MODELLING OF MOLTEN SALT REACTOR (MSR) PASSIVE COOLED DRAIN TANKS

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Abstract: This paper provides a technical evaluation and modelling, including a criticality analysis, of Molten Salt Reactor (MSR) passive cooled drain tanks. 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. MONK Version 9A Monte Carlo Program by ANSWERS Software Service was used to carry out the 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% ZrF₄, 1.02wt% UF₄, and 0.02wt% PuF₃. A comparative analysis was carried out for a single drain tank and four drain tanks. The safety margin for subcriticality associated with the MSR fuel storage tanks under normal and credible upset conditions was determined. The results obtained showed that the effective multiplication factor as calculated by MONK for a salt volume of 1,905,870cm³ stored in four drain tanks of capacity 2,271,100cm³ (each) with a diameter of 127cm is 0.9076 (subcritical), while the same salt volume stored in a single tank of the same dimension is 1.298 (supercritical).

I. Introduction

A molten salt reactor is one of the promising future generation nuclear reactor concepts. 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. This reactor is included in the Generation IV reactors family^[4].

Molten fuel salt consists of mixtures of fuel and other salts (to act as diluents and to lower melting temperatures) used in molten form. The salts must fulfil various stringent requirements such as low neutron cross sections, thermal and radiolytic stability, low corrosion, and good heat-transfer and -fluid-flow characteristics^[5]. Fluorides seem to provide the best compromises for molten-fuel choice because fluorine has a relatively high scattering cross section for neutrons, higher volumetric specific heats and higher thermal conductivities. It has extremely low absorption for neutrons and is also very electronegative and mono-isotopic. Fluoride salts being ionically bonded, are very resistant (i.e. exhibit very little change) to radiation damage resulting from the gamma radiation, alpha radiation or neutron flux^[3].

It is believed that the system UF₄-BeF₂-LiF-NaF (i.e. fuel salt) offers the best combination of properties for use in molten-salt reactors. The molten fluoride salt has a triple function.

- It provides the fissile material needed to produce energy
- It is the heat transfer medium (i.e. excellent nuclear reactor coolant)
- It is the fuel reprocessing medium.

The salt mixture is a liquid with very high specific heat of about 2.42kJ/kg°C and very low viscosity, which is ideal for heat exchange medium.

II. Aim and Objective

The aim of this research is to carry out a comparative analysis by modelling a molten salt reactor passive cooled drain tanks, to determine the margin and acceptable level of sub-criticality for fuel storage tanks under normal and credible upset conditions using MONK. Considering a reactor shut down for maintenance, or an accident scenario, or any abnormality that might cause the fuel temperature to go above the maximum set limit, the freeze valve gets melted (open) and the fuel is drained into the drain tank(s) of non-critical geometry. Discharging fuel salt to the drain tank empties fissile materials and fission products from the primary system.

The objective of this research is to compare the level of subcriticality for a single tank and four drain tanks, taking into considerations those parameters that will enhance cooling of the storage tanks filled with hot fuel so as to maintain the integrity of the tank and keeping the fuel in a credible condition. For a molten salt reactor, the cooling process is achieved by natural convection.

III. Limitations of Study

The modelling did not take into consideration the cooling system and the heater assembly surrounding each tank or any other structural material or machinery in the cell. 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).

IV. Passive Cooled Drain Tanks:

A typical empty fuel drain tank modelled with Hastelloy material using MONK, as seen in Fig.1&2 is connected to the core inlet via a line, housed in a separate cell. This cell is situated below the reactor cell in order for the fuel salt to drain by gravity.

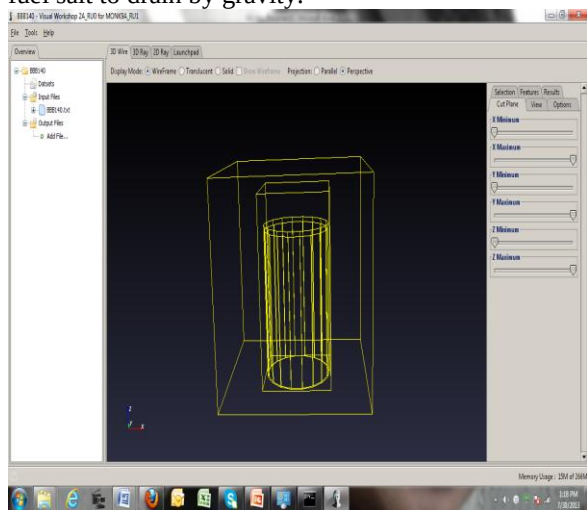


Fig.1: Single Fuel Drain Tanks Modelled Using MONK (3D Wire Mode)

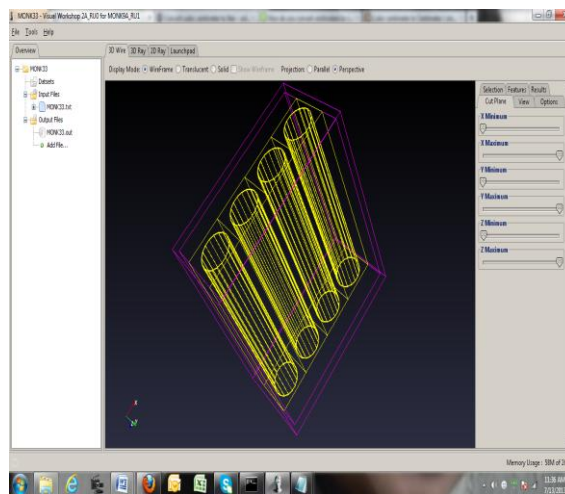


Fig.2: Four Fuel Drain Tanks Modelled Using MONK (3D Wire Mode)

V. Methodology

The version of MONK used for this dissertation is MONK Version 9A, the ANSWERS Software Package.

The primary aim for which MONK is used for this research is to calculate the effective neutron multiplication factor (K_{eff}). The actual number of neutrons tracked determines the statistical precision associated with the simulated value of $K^{[1]}$. In this simulation, all calculations were run to Standard Deviations of 0.001 using the default super history powering algorithm with 1000 neutrons per stage.

The effective multiplication factor is one that takes leakage into considerations. Neutron leakage is dependent on system geometry and density. For a given composition and quantity of material, a geometry of increased surface area or decreased density enhances leakage. Controlling leakage by geometry is especially important to nuclear criticality safety. The leakage effect, however, is dominant in determining the stage of criticality of the system^[1].

A. Drain Tanks Design Specification:

The drain tanks are made with Hastelloy material. It is designed to use a mixed water-steam coolant that circulates by natural convection. The reason for selecting this passively cooled safety system design is that it is relatively easy to get natural convection; it is excellent in transferring heat; and has good radiation and thermal stability. The drain tank is cylindrical in shape, design such that it can hold sufficiently, in a noncritical geometry, all the salt that is contained in the fuel circulating system. The drain tank is connected to the bottom of the reactor vessel by a drain line equipped with a freeze-plug type of "valve" which can be melted to allow gravity drain the entire primary circulating system in about 7 min. To prevent overheating due to stagnant salt, a small circulation of fuel salt is usually maintained in the drain line between the reactor and the freeze valve^[2]. The cell wall (water bath) is designed using stainless steel surrounded by ordinary concrete for shielding. The chemical composition by proportion of this material used for this design is as shown below^[6]:

Ni	PROP	0.66
Cr	PROP	0.10
Mo	PROP	0.15
C	PROP	0.0004

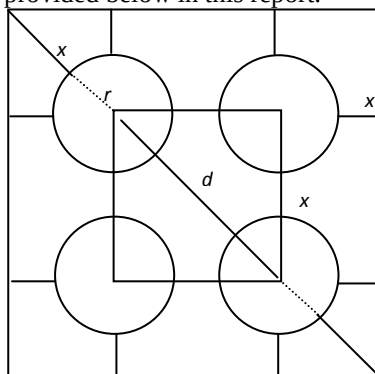
Mn	PROP	0.01
Si	PROP	0.01
Ti	PROP	0.00865
Cu	PROP	0.0035
S	PROP	0.0002
Fe	PROP	0.05
B	PROP	0.0001

Hastelloy alloys are designed for use in pressure vessels and nuclear reactors. Hastelloy N was developed specifically for use in MSBR system^[7]. Among the major constituents, chromium is the least resistant to attack by the fluorides. Molybdenum content gives good strength without embrittlement, though the embrittlement problem can be overcome due to the presence of titanium and boron which forms borides that would be dispersed as precipitates and not particularly segregate at the grains boundaries.

Stated below are the drain tanks design parameters^[2],

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/cm ³
(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

= S² 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 to;

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

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

where s = x + 2r

but 2x + 2r + d = D

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

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

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

$$\therefore d = 243.34 \text{ cm}$$

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

A series of different values have been assumed for the fuel volume, and the fuel depth occupied in the tank is calculated for each volume. Full details of the results interpretations and discussions are also contained in this report. 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. Also, the design was carried out for a single tank to ascertain the effectiveness and the credibility of using single drain tank for the storage of all the fuel salt without affecting the integrity of the tank. Comparative analysis was carried out to check the level of sub-criticality by calculating the effective multiplication factors in both cases.

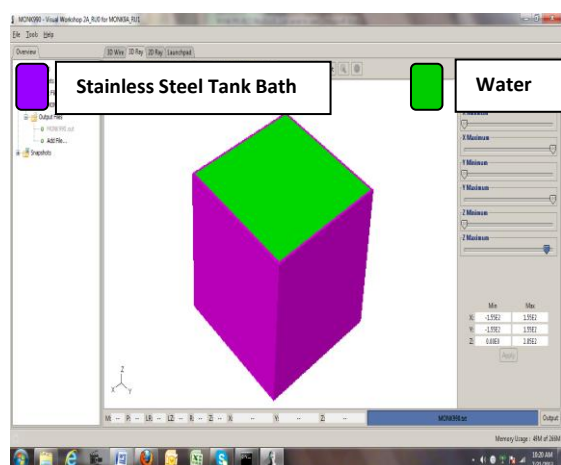
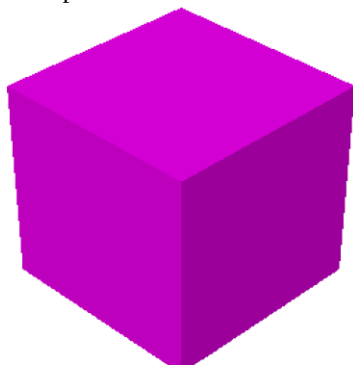


Fig.1: MONK modelling for the MSR Drain Tanks (see code in Appendix B)

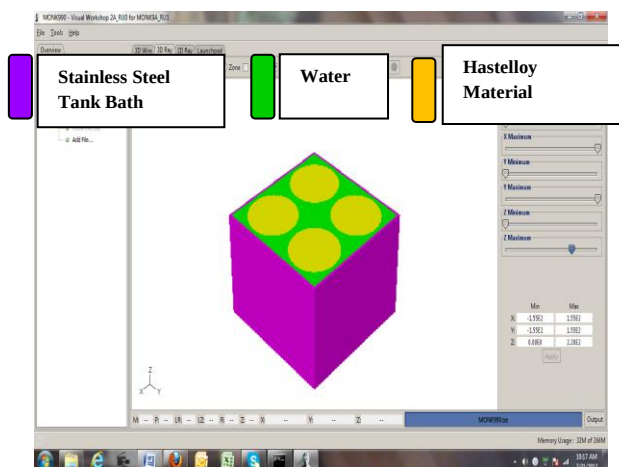


Fig.2: MONK Modelling for 4-MSR Drain Tanks (see code in Appendix B)

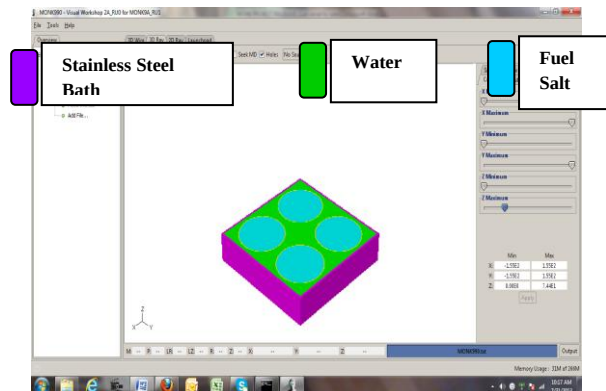


Fig.3: MONK Modelling for 4-MSR Drain Tanks (see codes in Appendix B)

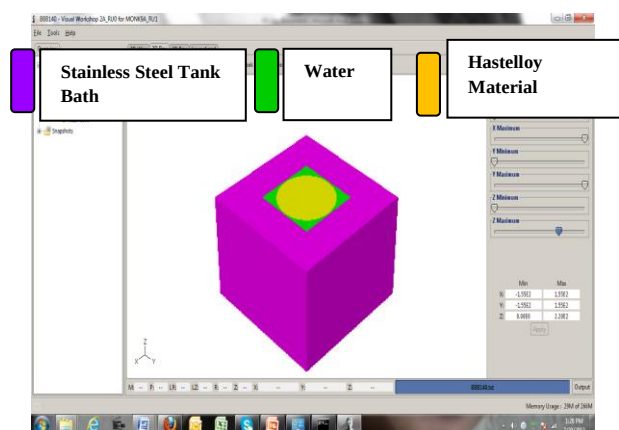


Fig.4: MONK Modelling for a single MSR Drain Tanks (see code in Appendix B)

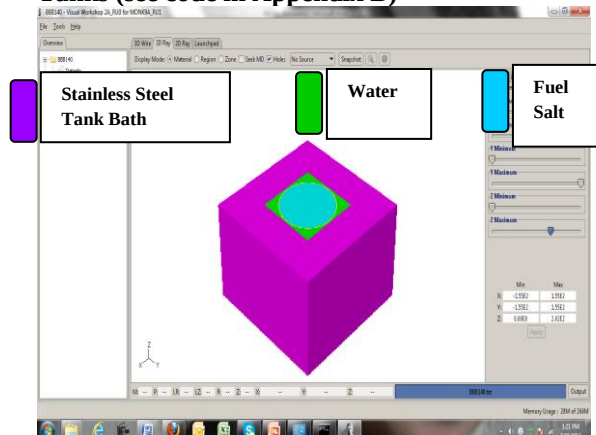


Fig.5: MONK Modelling for a single MSR Drain Tanks (see codes in Appendix B)

VI. Results

Appendix A contains data as calculated by MONK for a single MSR drain tank and for four MSR drain tanks. The graphical representations of different calculated parameters are shown in the figures (5.1-5.12) 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 m³ while the drain tank capacity is about 2.2711 m³. 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 m³. 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.

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

$V = \text{Salt Volume}$

$r = \text{Tank inner radius}$

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;

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

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.

Table 3 & 4 (see app. A pages) lists the MONK data calculated for a single drain tank. This data shows the effect of using a single drain tank for the storage of all the fuel salt. The total volume of the fuel salts in a tank of diameter 127cm is about 1.9059 m³ while the drain tank capacity is about 2.2711 m³. The effective multiplication factor for different salt volume, the salt depth and the geometric buckling are all calculated for comparative analysis. Table 4, is the analysis carried out for a single tank by varying the diameter to ascertain the state of criticality.

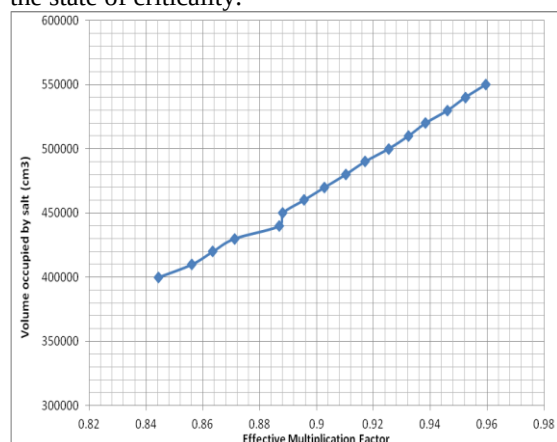


Fig.6: Plot Showing Salt Volume vs K-effective (4-Drain Tanks using MONK 9A)

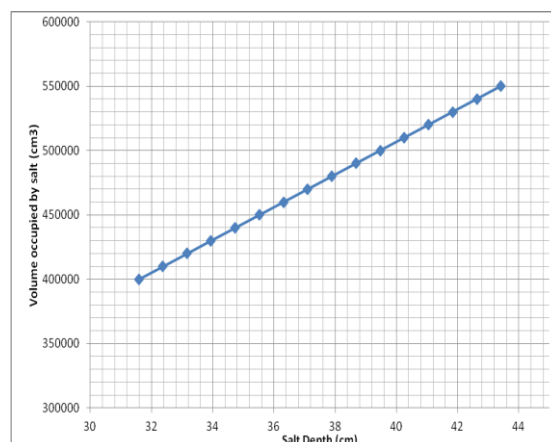


Fig.7: Plot Showing Salt Volume vs Salt Depth (4-Drain Tanks using MONK 9A)

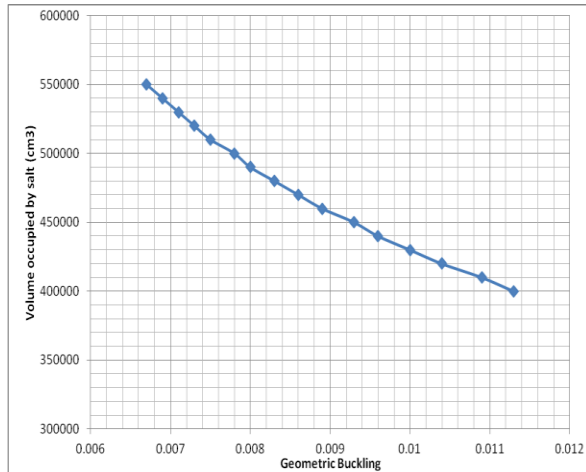


Fig.8: Plot Showing Salt Volume vs Geometric Buckling (4-Drain Tanks using MONK 9A)

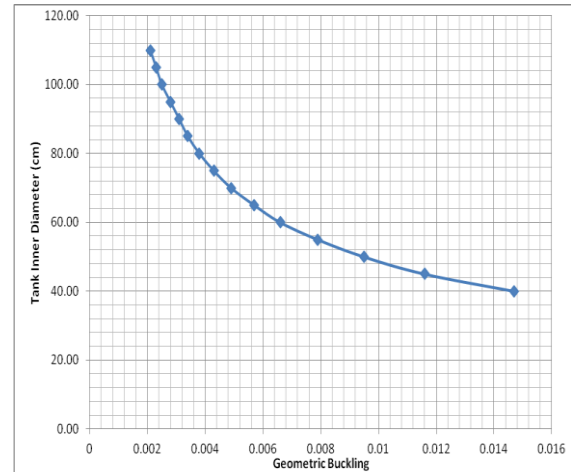


Fig.11: Plot Showing Inner Tank Diameter vs Geometric Buckling (4-Drain Tanks using MONK 9A)

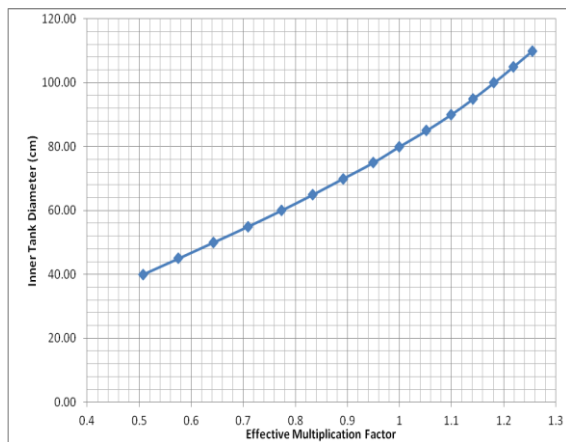


Fig.9: Plot Showing Inner Tank Diameter vs K-effective (4-Drain Tanks using MONK 9A)

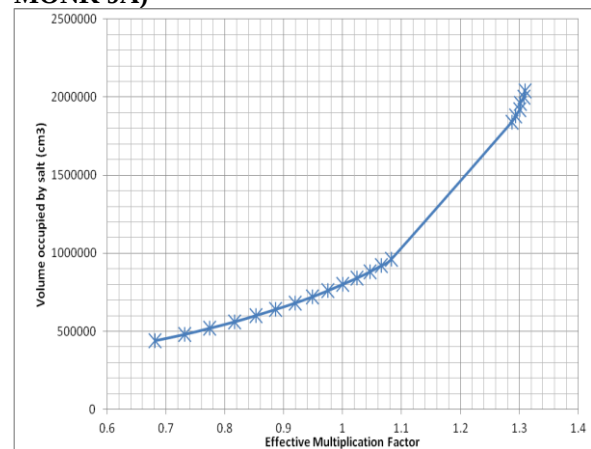


Fig.12: Plot Showing Salt Volume vs K-effective (1-Drain Tank using MONK 9A)

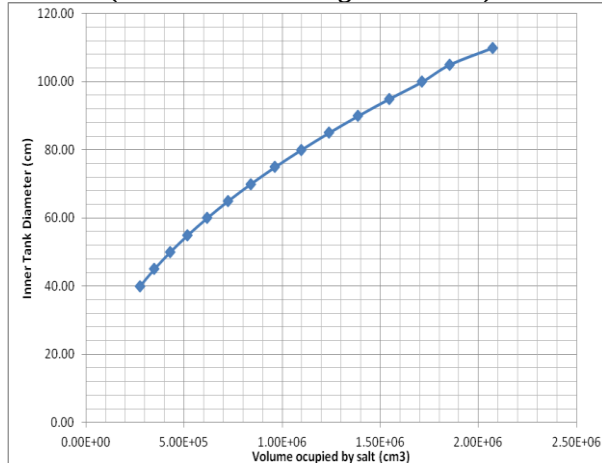


Fig.10: Plot Showing Inner Tank Diameter vs Salt Volume (4-Drain Tanks using MONK 9A)

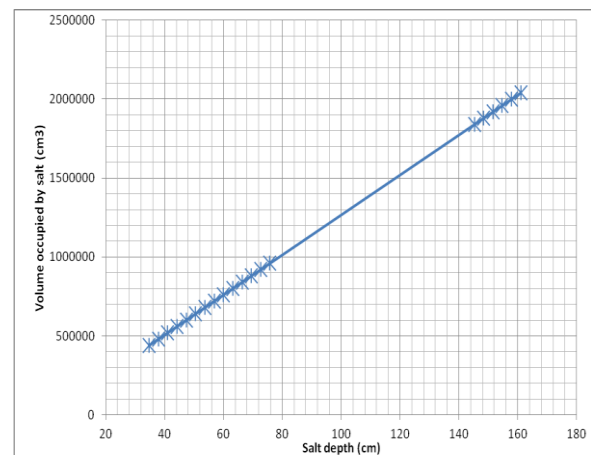


Fig.13: Plot Showing Salt Volume vs Salt Depth (1-Drain Tank using MONK 9A)

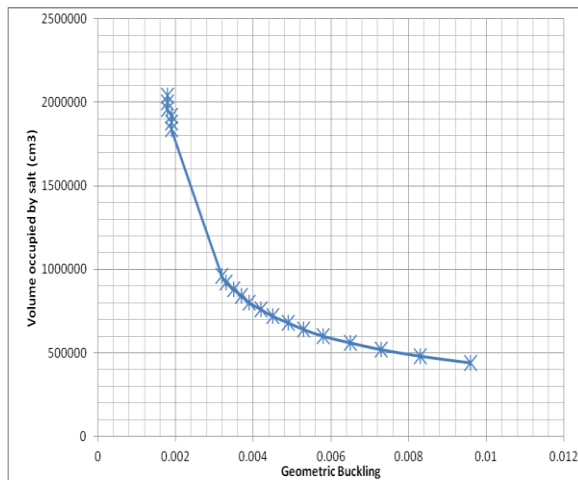


Fig.14: Plot Showing Salt Volume vs Geometric Buckling (1-Drain Tank using MONK 9A)

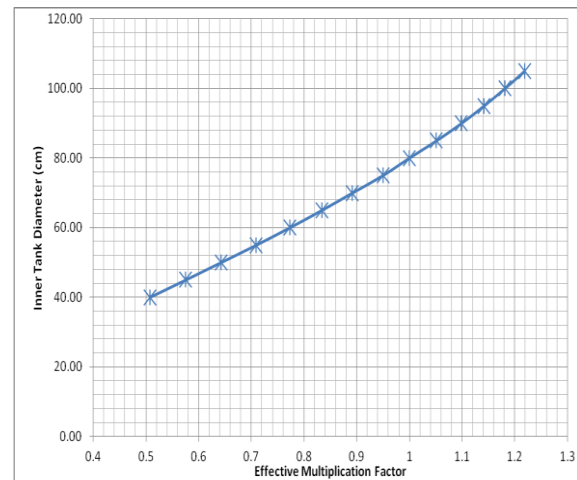


Fig.15: Plot Showing Inner Tank Diameter vs K-effective (1-Drain Tank using MONK 9A)

VII. 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 6 & 7 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 470,000cm³ and 480,000cm³.

By Interpolation

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

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

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

$$x = 476467.5 \text{ cm}^3$$

$$y_1 = 0.9028$$

$$y_2 = 0.9102$$

$$x_1 = 470000 \text{ cm}^3$$

$$x_2 = 480000 \text{ cm}^3$$

$$\therefore y = 0.9076$$

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 8 is the plot showing the salt volume and the geometric buckling. This property as mentioned before in chapter 5 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 9 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.

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

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

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})

$$x = 26.37 \text{ cm}$$

$$y_1 = 0.6426$$

$$y_2 = 0.7093$$

$$x_1 = 25 \text{ cm}$$

$$x_2 = 27 \text{ cm}$$

$$\therefore y = 0.6791$$

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.

Deductions for 4-Drain Tanks

➤ 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 476467.5cm³ per tank $\approx 1,905,870\text{cm}^3$ (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 476467.5cm³ per tank $\approx 1,905,870\text{cm}^3$ (i.e for 4-tanks)

Figure 10 & 11, 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.

Figure 12 is the graphical representation of the data calculated for a single drain tank. The plot shows the volume occupied by fuel salt and their corresponding effective multiplication factors. From the single drain tank analysis, the effective multiplication factor for the salt volume of 1,905,870cm³ contained in a tank of diameter 127cm is 1.298. This results show that, the system is in a supercritical condition. Data from Table 3 also show that the single tank can only accommodate a maximum fuel salt volume of about 760,000cm³ – 790,000cm³ for the system to remain in a subcritical state. Data ranging from 1000000cm³ - 1800000cm³ is too clustered so that it will be difficult to trace the data point. As a result, numerical values within that range are not presented on the graph and table of values, hence the discontinuity in data as seen in **fig.12, 13 and 14**.

The effective multiplication factor in the case of a single drain tank was calculated by interpolating the simulated data between the salt volume of 1,880,011.42cm³ and 1,920,041.32cm³.

By Interpolation

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

where, x = volume(cm³)occupied by salt

y = effective multiplication factor (k_{eff})

$$x = 1,905,870\text{cm}^3$$

$$y_1 = 1.2937$$

$$y_2 = 1.3006$$

$$x_1 = 1,880,011.42 \text{ cm}^3$$

$$x_2 = 1,920,041.32 \text{ cm}^3$$

$$y = 1.2937 + (1,905,870 - 1,880,011.42) * \left(\frac{1.3006 - 1.2937}{1,920,041.32 - 1,880,011.42} \right)$$

$$\therefore y = 1.298$$

For a comparative analysis, it is evident that less neutron leakage is recorded when the fuel salts are drained into four drain tanks compare to the same volume of salt stored in a single tank. Data for the salt depth as seen in **fig.13** and that of the geometric buckling as seen in **fig.14** and also by varying the inner diameter of the drain tank to ascertain the state of criticality as seen in **fig.15** can also be used for the comparative analysis.

In summary, to achieve a subcritical condition, it is best to store the salt in four different tanks instead of storing all the salts in a single drain tank.

VIII. CONCLUSION

The state of a neutron chain-reacting system can be described conveniently in terms of its effective multiplication factor. Neutron reflectors decrease the net leakage by scattering back neutrons that would otherwise have been lost. The primary aim and objective of this work is 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 does not include the cooling system or any other structural material. The comparative analysis for a single tank and four drain tanks gives a reliable justification on the accuracy of the design and why it is recommendable from the safety point of view to design and use more than one drain tank for the storage of the fluoride salt in case of emergency scenario.

Reactor safety is an important element in the issue that concerns accepting nuclear future. There is a disparity of viewpoints between nuclear technologist and those of the public who are worried about reactor safety. The public looks at the large consequences imputed to a low probability accident and concludes that reactor are clearly unsafe, whereas the nuclear energy industry looks at the low probabilities calculated for a large consequence accident and concludes that reactors are exceedingly safe.

The MSR has many favourable safety features. The drain tank serves conveniently as a flow volume to which salt can be continuously overflowed from the primary pump bowl. At the drain tank the supply and return connections to the chemical processing facility will be made. The same jet pump arrangement used to fill the primary system from the drain tank could also be used to transfer salt to the chemical facility. These completely eliminate the need for pressurizing the tank for salt transfer. With this arrangement, salt can be taken from the tank for processing separately of reactor operation.

IX. Recommendations for Future Work

Though this research did not consider the cooling system in its design, for the purpose of future research, I would also recommend that to design the cooling system, the following objectives have to be considered:

1. It must be capable of keeping the highest drain tank temperature well within the safe operating range even under the worst condition of transient heat loads.
2. The system must be dependable, with a minimum of reliance on the electric power supply or operator initiated actions.
3. The cooling system should cause a minimal risk for freezing of either the fuel salt or the cooling system coolant.

It is decided that the above objectives would be best met by storage of the salt in a tank having a coolant circulated by ordinary convection, since a storage tank with a convective cooling system was used with good results in the MSRE.

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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 cm³)

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

Table 3: MONK Data for Critical Volume obtained for a Single(1) Drain Tank (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)
34.70	1204.09	63.5	4032.25	439568.74	0.6818	0.0096
37.90	1436.41	63.5	4032.25	480105.34	0.7322	0.0083
41.00	1681.00	63.5	4032.25	519375.17	0.7745	0.0073
44.20	1953.64	63.5	4032.25	559911.76	0.8160	0.0065
47.36	2242.97	63.5	4032.25	599941.66	0.8525	0.0058
50.52	2552.27	63.5	4032.25	639971.55	0.8865	0.0053
53.68	2881.54	63.5	4032.25	680001.44	0.9191	0.0049
56.84	3230.79	63.5	4032.25	720031.33	0.9486	0.0045
60.00	3600.00	63.5	4032.25	760061.21	0.9754	0.0042
63.15	3987.92	63.5	4032.25	799964.43	0.9997	0.0039
66.31	4397.02	63.5	4032.25	839994.32	1.0244	0.0037

69.47	4826.08	63.5	4032.25	880024.21	1.0462	0.0035
72.63	5275.12	63.5	4032.25	920054.11	1.0656	0.0033
75.78	5742.61	63.5	4032.25	959957.32	1.0826	0.0032
145.25	21097.56	63.5	4032.25	1839981.53	1.2874	0.0019
148.41	22025.53	63.5	4032.25	1880011.42	1.2937	0.0019
151.57	22973.46	63.5	4032.25	1920041.32	1.3006	0.0019
154.72	23938.28	63.5	4032.25	1959944.53	1.3022	0.0018
157.88	24926.09	63.5	4032.25	1999974.42	1.3077	0.0018
161.04	25933.88	63.5	4032.25	2040604.31	1.3103	0.0018

Table 4: MONK Data for Critical Diameter obtained for a Single(1) Drain Tank (Total Salt Volume: 1,905,870 cm³)

Salt Depth. (cm)	h	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	273946.88	0.5077	0.0147
218.00		47524.00	22.50	506.25	346714.02	0.5737	0.0116
218.00		47524.00	25.00	625.00	428042.00	0.6399	0.0095
218.00		47524.00	27.50	756.25	517930.82	0.7060	0.0079
218.00		47524.00	30.00	900.00	616380.48	0.7683	0.0066
218.00		47524.00	32.50	1056.25	723390.98	0.8287	0.0057
218.00		47524.00	35.00	1225.00	838962.32	0.8879	0.0049
218.00		47524.00	37.50	1406.25	963094.50	0.9403	0.0043
218.00		47524.00	40.00	1600.00	1095787.52	0.9942	0.0038
218.00		47524.00	42.50	1806.25	1237041.38	1.0456	0.0034
218.00		47524.00	45.00	2025.00	1386856.08	1.0914	0.0031
218.00		47524.00	47.50	2256.25	1545231.62	1.1326	0.0028
218.00		47524.00	50.00	2500.00	1712168.00	1.1739	0.0025
218.00		47524.00	52.50	2756.25	1887665.22	1.2116	0.0023
218.00		47524.00	55.00	3025.00	2071723.28	1.2491	0.0021
218.00		47524.00	57.50	3306.25	2264342.18	1.2790	0.0020

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/cm³)

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/cm³)

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/cm³)

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
*****

```

MONK Input File for a Single Drain Tank

* APPENDIX B2 (Charles MONK)

BEGIN MATERIAL SPECIFICATION

TYPE DICE

NORMALISE ! Normalise proportions where necessary

ATOMS

*Material 1 - LiF-BeF₂-ZrF₄-UF₄ (Density 2.02 g/cm³)

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/cm³)

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/cm³)

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  20  218
ZROD M2  0.0  0.0  1.0  22  226.0
BOX  M3 -75.0 -75.0  0.0  150.0  150.0  280.0
BOX  M4 -155.0 -155.0  0.0  310.0  310.0  310.0
END
*****

BEGIN CONTROL DATA
STAGES -15 100 1000 STDV 0.001
END
*****

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

```