Design and Nuclear Criticality Safety Evaluation of the Fuel Salt Preparation and Handling Processes for the Molten Salt Nuclear Battery Design

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Authorization to Submit Thesis

This thesis of Trevin A. Lasley, submitted for the degree of Master of Science with a Major in Nuclear Engineering and titled "Design and Nuclear Criticality Safety Evaluation of the Fuel Salt Preparation and Handling Processes for the Molten Salt Nuclear Battery Design," has been reviewed in the final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

A Nuclear Criticality Safety Evaluation was performed for the proposed FLiNaK-UF_4 fuel salt preparation and handling processes to be used in the Molten Salt Nuclear Battery concept. The fuel salt is a mixture of purified eutectic LiF-NaF-KF (respectively 46.5, 11.5, and 42 mole %) and UF_4 fuel with a fuel loading of 18 mole % UF_4 and enrichment of 19.75 mole % ^{235}U. The DOE-STD-3007-2017 technical standard was followed while performing this evaluation to be compliant with the ANSI/ANS-8 series of criticality safety standards. The Monte-Carlo nuclear code Serpent 2, version 2.1.31, was used to perform the calculations for this evaluation to estimate the effective neutron multiplication factor, k_{eff}, of the processes under normal and credible abnormal conditions. The results of this evaluation show that the processes will remain subcritical under both normal and credible abnormal conditions by not exceeding an upper subcritical limit of 0.95. The maximum k_{eff} under normal conditions was 0.58737 ± 0.00085 (95 % confidence) during the transportation of the fuel salt vessels. The maximum k_{eff} under abnormal conditions was 0.82013 ± 0.00134. Any controls and assumptions used for these processes are discussed.

Acknowledgments

Special thanks need to be given to my thesis committee members for their support throughout the entire process. Without their support, this work and thesis would not have been completed in time.

Additional thanks to Joseph Christensen who is a fellow classmate and Nuclear Safety and Criticality Safety Engineer and SHINE Medical Technologies, Inc. Without his mentoring, input, and direction, this thesis would have looked a lot different.

The last acknowledgment goes to my mentor and friend Dr. Matthew Memmott of Brigham Young University for his influence in helping me to become a nuclear engineer.

Dedication

This work is dedicated to my family. First, to my mother and stepdad for raising me up to be the man I am today. The values and work ethic that they have instilled in me have given me the tools to pursue my education and fulfill my goals. Next, to my 10-month-old son for the joy he brings to me. Lastly, to my amazing wife for the love and support she has given me at each step of receiving my master’s degree. She is very much looking forward to having her husband back.

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Statement of Contribution

Special thanks to Trevor Casper for his contribution in determining the length of the salt plug for the fuel salt vessel. Additional thanks to Alberto Cardenas Melgar for his preliminary stress analysis work on the fuel salt vessel in the support structure and the resulting CAD drawings of the system.

Chapter 1: Introduction

1.1 Background

As part of the development of the Molten Salt Nuclear Battery (MsNB) design, the fuel salt preparation and handling processes were designed, and a Nuclear Criticality Safety Evaluation (NCSE) was performed for these processes. These processes include the mixing, storage, transportation, and unloading of the fuel salt for the MsNB.

The fuel handling for the molten salt reactor is relatively unknown with the exception of the Molten Salt Reactor Experiment (MSRE). The thesis gives a proposed process design for fuel salt processing and handling for the MsNB and gives the NCSE performed on these designs to show that it will remain subcritical under normal and abnormal conditions. Before the design and the NCSE are presented, some background is necessary to illustrate the importance of the MsNB design.

1.1.1 Micro-reactors

Micro-reactors, otherwise known as Special Purpose Reactors or very Small Modular Reactors, are factory built, deployable nuclear reactors that can provide heat and power with a heat output up to 50 MWth. The recent interest in micro-reactors has come from the need for smaller, scalable, versatile, and mobile reactors. These reactors are small enough to be easily transported by semi-trailer, plane, helicopter, etc. With the advantage of the reactor's smaller size, they can generate power where previous larger reactors had not been able to. This is what makes these reactors ideal for applications such as military outposts, remote locations, disaster relief, hospitals, mining, etc. If necessary, these reactors can be modulated to increase power output for any desired application. Molten salt technologies are being explored for micro-reactors and the MsNB is a potential molten salt micro-reactor design [1].

In Figure 1.1, a rendered model of the MsNB next to a power conversion unit is shown [2]. The MsNB has a 400 kWth heat output with an estimated 10-year fuel life. It is about 8 feet tall with about a 5-foot-wide diameter and uses natural circulation to cool the core. These and other safety features make it a suitable design for micro-reactor applications.

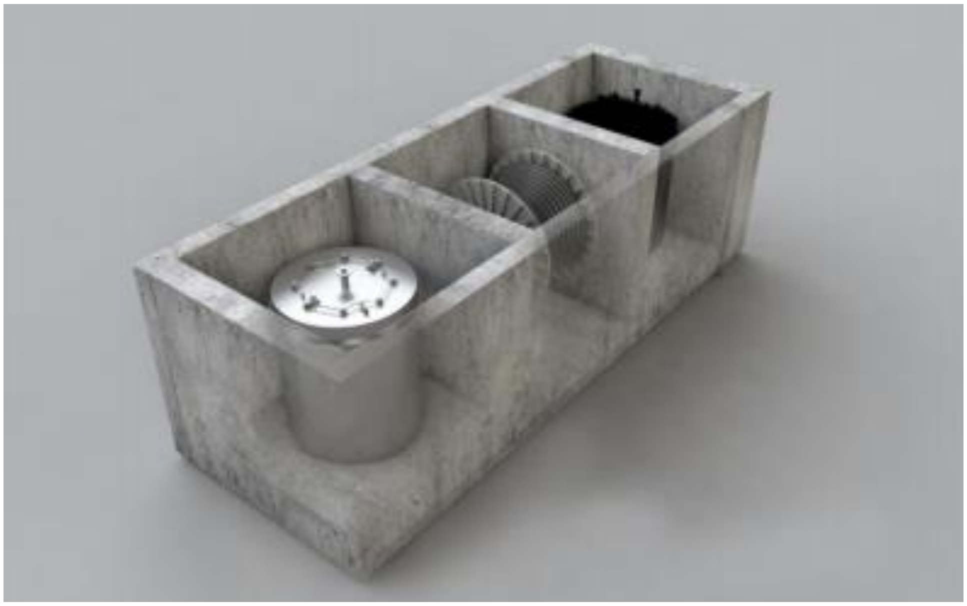

Figure 1.1. Artist rendition of the MsNB next to a power conversion unit.

1.1.2 Molten Salt Reactor Experiment

The Molten Salt Reactor Experiment (MSRE) is a good example of how fuel preparation and handling can be performed safely. The MSRE is one of the first molten salt reactors built at the Oak Ridge National Laboratory. It was developed to test one of the six Generation IV advanced reactor concepts. This reactor first went critical in 1965 and was in operation until 1969. One of the benefits of this reactor is the ability of online refueling provided by the continuous flow of fluid-fueled salt running through the reactor. Figure 1.2 shows a sketch of the inside of the MSRE [3].

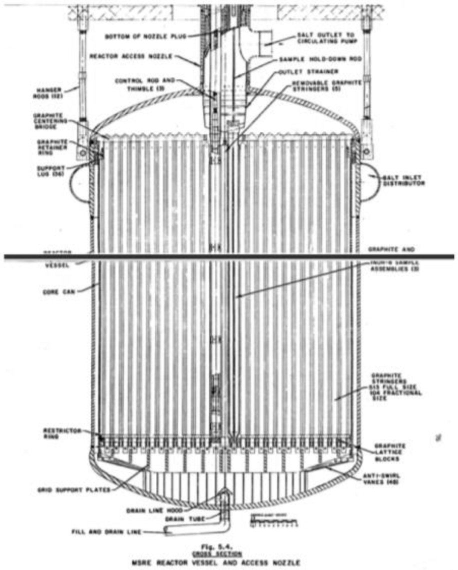

Figure 1.2. Vertical cross-section of the MSRE reactor vessel.

The fuel salt used for the MSRE is nominally comprised of (in mole %) 65 LiF, 29.1 BeF_2, 5 ZrF_4, and 0.9 UF_4. The actual amount of fuel in the mixture was dependent on the amount required to bring the system to the criticality and then the operational limit. Before the fuel salt was added to the reactor, three different batch of salt mixtures were made: 1) the fuel solvent mixture, $^7LiF\text{-}BeF_2\text{-}ZrF_4$ (64.7-30.1-5.2 mole %), 2) the depleted fuel concentrate mixture, $^7LiF\text{-}^{238}UF_4$ (73-27 mole %), and 3) the enriched fuel concentrate mixture, $^7LiF\text{-}^{235}UF_4$ (73-27 mole %). The first two were made in batch processes on-site and the last one was manufactured off-site [4].

The first step of loading the reactor was to load approximately 10,050 lb. of the solvent salt into the reactor from 35 batch containers. Then about 520 lb. of the depleted fuel salt was added from 2 batch containers. Later, the enriched fuel salt was added in increments as part of the zero-power experiments for the reactor system [4].

1.1.3 Nuclear Criticality Safety

Nuclear criticality safety is an area of nuclear engineering that focuses on the prevention of a nuclear accident due to an unintended criticality. An intended criticality is when a controlled self-sustaining nuclear chain reaction is present in a nuclear system. A nuclear power reactor uses this controlled criticality to safely run the reactor and provide heat and power to an energy system.

A measurement used to estimate the criticality of a nuclear system is called the effective multiplication factor or k_{eff}. k_{eff} is described by the following relationship in a neutron core life cycle.

$$k_{eff} = \frac{\#\ of\ neutrons\ at\ some\ point\ in\ the\ cycle}{\#\ of\ neutrons\ at\ the\ same\ point\ in\ the\ previous\ cycle} \tag{1.1}$$

A reaction is self-sustaining when there are enough neutrons left in the cycle to produce more neutrons through fission. Neutron loss is due to multiple factors including absorption and leaving the reactor. When k_{eff} < 1, this means that there are not enough neutrons to maintain a self-sustaining chain reaction and will eventually decrease until there are no more neutrons. When k_{eff} = 1, this means that there is a sufficient number of neutrons at the end of the cycle needed to produce more neutrons for each following cycle. This is a self-sustained chain reaction. When k_{eff} > 1, the reactor is considered supercritical meaning that there are too many neutrons in the cycle and will continue to increase causing an uncontrolled chain reaction. When left unchecked, a supercritical reaction may lead to a criticality accident [5].

Many factors affect the criticality of a reactor. These factors can be described by the two following acronyms: MAGIC MERV and MERMAIDS. MAGIC MERV stands for Mass, Absorption, Geometry, Interaction, Concentration, Moderation, Enrichment, Reflection, and Volume. MERMAIDS stands for Mass, Enrichment, Reflection, Moderation, Absorption, Interaction, Density, and Shape. Temperature is also a factor. Any changes to these parameters can affect how the neutrons develop in the reactor. For example, adding a reflector can reflect a neutron leaving the reactor back into the core thus increasing the probability of a fission reaction to produce more neutrons. Understanding these parameters helps nuclear engineers to make proper decisions in the design process of a nuclear reactor or process [6] [7].

1.2 Theory

1.2.1 Six-Factor Formula

Whether a nuclear system with fissionable material is subcritical, critical, or supercritical was established using the effective multiplication factor, k_{eff}. This value can be calculated using what is called the six-factor formula.

$$k_{eff} = \epsilon p \eta f P_{NL}^{f} P_{NL}^{th} \tag{1.2}$$

where the six factors are the fast fission factor ϵ, the resonance escaper probability p, the thermal fission factor η, the thermal utilization f, the fast non-leakage probability P_{NL}^{f}, and the thermal non-leakage probability P_{NL}^{th} [5].

1.2.1.1 The fast fission factor ϵ

ϵ accounts for the fast fissions in the neutron life cycle. It is the ratio of the total number of neutrons produced due to fission in both the fast and thermal spectrum to the number of neutrons produced only in the thermal spectrum or

$$\epsilon = \frac{\#\, of\ neutrons\ produced\ from\ fast\ and\ thermal\ fission}{\#\, of\ neutrons\ produced\ from\ thermal\ fission\ only} \tag{1.3}$$

Nearly every parameter listed previously in Section 1.1.3 influences the fast fission factor. However, mass, enrichment, concentration, and moderation play a larger role. Fast fission is largely influenced by the amount of ^{238}U present. With more enrichment, this factor is more likely to be close to 1 as the number of ^{238}U atoms decreases. This is also true for a highly moderated system. With an increased moderator amount, it is more likely that a fast neutron will thermalize by interacting with a moderator before a ^{238}U atom. For a typical thermal reactor, $\epsilon = 1.02$ [5] [8].

1.2.1.2 The resonance escape probability p

The resonance escape probability accounts for the number of neutrons that are absorbed in the resonance spectrum region. p is the probability that a fast neutron will slow down to the thermal spectrum without being absorbed in the resonance region. The mass, enrichment, concentration, and moderation also play a large role in this factor. Again, ^{238}U plays a large role in determining this factor due to a larger absorption resonance cross section. With an increased enrichment, the factor is closer to 1. With increased moderation, the neutron is also more likely to thermalize without being absorbed because it has a higher chance of scattering with a moderator atom before absorbing with a U atom. A correlation that can be used to estimate the resonance escape probability is

$$p = \exp\left[-\frac{a}{\xi}\left(\frac{N_A/N_M}{\sigma_{sM}10^{24}}\right)^{1-c}\right] \tag{1.4}$$

where N_A is the atom density of the absorber, N_M is the atom density of the moderator, ξ is the average lethargy per collision from the moderator, and σ_{sM} is the scattering cross section of the moderator. For ^{238}U, a = 2.73 and c = 0.486. From the correlation, one can see that as the number of absorbers increases, the probability of resonance escape decreases. For a typical thermal reactor, p = 0.87 [5] [8].

1.2.1.3 The thermal fission factor η

The next factor is the thermal fission factor η which is the number of neutrons that are produced when thermally absorbed by the fuel. This is calculated using the equation

$$\eta = \nu\frac{\bar{\Sigma}_f^F}{\bar{\Sigma}_a^F} \tag{1.5}$$

where ν is the average number of neutrons produced per fission, $\bar{\Sigma}_f^F$ is the macroscopic fission cross section of the fuel, and $\bar{\Sigma}_a^F$ is the macroscopic absorption cross section of the fuel. This equation gives the average number of neutrons produced from fission multiplied by the probability that an absorbed neutron in the fuel will result in a fission event. This equation is dependent only on the mass of the fuel in the core. A typical thermal reactor value for η is 1.65 [5] [8].

1.2.1.4 The thermal utilization f

This factor accounts for the fact that not all of the thermal neutrons are absorbed by the fuel but also by the non-fuel. The thermal utilization is determined by the ratio of the average rate of thermal absorption in the fuel to the total average rate of thermal absorption in the fuel and non-fuel. This ratio is given by the following equation.

$$f = \frac{\bar{\Sigma}_a^F \phi_T^F V^F}{\bar{\Sigma}_a^F \phi_T^F V^F + \bar{\Sigma}_a^{NF} \phi_T^{NF} V^{NF}} = \frac{\bar{\Sigma}_a^F}{\bar{\Sigma}_a^F + \bar{\Sigma}_a^{NF} (V^{NF}/V^F)(\phi_T^{NF}/\phi_T^F)} \tag{1.6}$$

where ϕ_T^i is the thermal neutron flux densities with V^i being the respective volumes. This equation can then be simplified for a homogeneous core where $\phi_T^F = \phi_T^{NF}$ and $V^F = V^{NF}$. This simplification gives

$$f = \frac{\bar{\Sigma}_a^F}{\bar{\Sigma}_a^F + \bar{\Sigma}_a^{NF}} = \frac{\bar{\sigma}_a^F}{\bar{\sigma}_a^F + \bar{\sigma}_a^{NF} (N^{NF}/N^F)} \tag{1.7}$$

where $\bar{\sigma}_a^F$ is the microscopic absorption cross section of the fuel and non-fuel and N^i is the atomic density of the fuel and non-fuel.

As expected, this factor is dependent on the mass and concentration parameters. The factor can range from zero with little or no fuel to unity with only fuel. A typical thermal reactor value for f is 0.71 [5] [8].

1.2.1.5 The fast non-leakage probability P_{NL}^f

Another factor of the six-factor formula that determines the k_{eff} value is the fast non-leakage probability P_{NL}^f. Some fast neutrons will inevitably leak out of the system. P_{NL}^f is the probability that a fast neutron will not leak as it slows from the fast to the thermal region. This probability can be calculated by the following equation for a bare core.

$$P_{NL}^f = \exp\left(-B_g^2 \tau_T\right) \tag{1.8}$$

where B_g^2 is the geometric buckling and τ_T is the *Fermi age* to thermal energies. τ_T is understood as one-sixth the mean squared distance from the point that a fast neutron is born and begins to slow to the point that the neutron becomes thermal. Mathematically this can look like the following.

$$\tau = \frac{1}{6}\langle r^2 \rangle \tag{1.9}$$

The geometry of the core and the moderator are the leading factors for this equation. For a finite cylindrical core, the geometric buckling is about

$$B_g^2 = \left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{H}\right)^2 \tag{1.10}$$

where R is the radius of the core and H is the height of the core. As the radius and/or height increases $B_g^2 \to 0$ and $P_{NL}^f \to 1$. This is also the case for a more effective moderator which will give a smaller value of τ_T. The greater the moderator the shorter the distance the neutron can travel. For a typical thermal reactor, P_{NL}^{f} = 0.97 [5] [8].

1.2.1.6 The thermal non-leakage probability P_{NL}^{th}

The last factor is similar to the fast non-leakage probability only for the thermal neutron spectrum. The estimate for a bare core is given by the following equation.

$$P_{NL}^{th} = \frac{1}{1 + L_T^2 B_g^2} \tag{1.11}$$

where L is the thermal neutron diffusion length or the one half the length from when the neutron thermalizes to the point when it is absorbed in the core. This is defined as $L \equiv \sqrt{D/\Sigma_a}$ where D is the thermal diffusion coefficient. In a homogenous mixture of fuel and moderator the square of the thermal neutron diffusion length can be given as

$$L_T^2 \equiv \frac{\bar{D}}{\bar{\Sigma}_a} = \frac{\bar{D}^M}{\bar{\Sigma}_a^F + \bar{\Sigma}_a^M} = \frac{\bar{D}^M}{\bar{\Sigma}_a^M} \frac{\bar{\Sigma}_a^M}{\bar{\Sigma}_a^F + \bar{\Sigma}_a^M} = L_M^2 \left(1 - \frac{\bar{\Sigma}_a^F}{\bar{\Sigma}_a^F + \bar{\Sigma}_a^M}\right) = L_M^2(1 - f) \tag{1.12}$$

where L_M is the thermal neutron diffusion length in the moderator and f is the thermal utilization factor from before. The parameters that play a large role in this factor are the mass of the fuel, moderator, concentration, and geometry of the system. With an increased concentration of fuel, $f \to 1$ and $P_{NL}^{th} \to 1$. The reverse gives greater dependence on the geometric buckling where we can see as the core size increase or $B_g^2 \to 0$, $P_{NL}^{th} \to 1$. This is expected based on the fast non-leakage probability discussion. A typical value for P_{NL}^{th} in a thermal reactor is 0.99 [5] [8].

1.2.2 Neutron Life Cycle

The factors of the six-factor formula help to describe the life cycle of a neutron in a nuclear system. This life cycle is shown in Figure 1.3 [5].

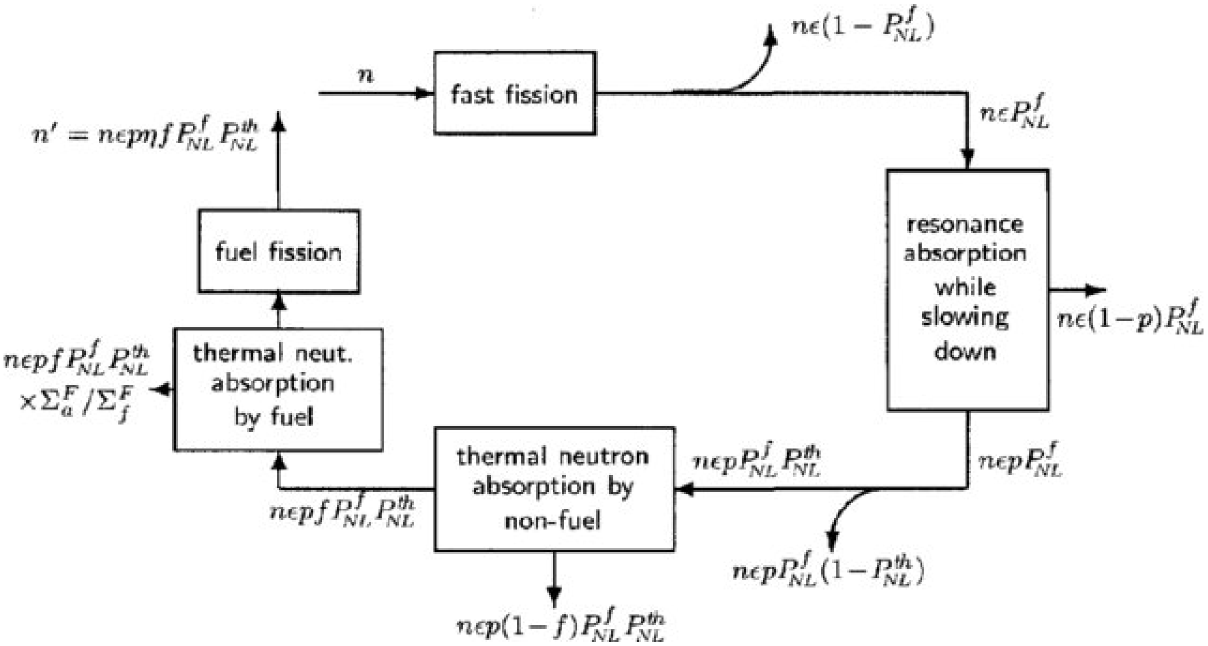

Figure 1.3. The neutron life cycle showing the contributions of the factors in the six-factor formula.

The beginning of the neutron life cycle begins with fast neutrons being produced in the system. The probability of these fast neutrons being absorbed and create more fast neutrons is determined by the fast fission factor ϵ. These fast neutrons can then either exit the core, P_{NL}^{f}, or be absorbed in the resonance region while slowing down to the thermal spectrum, p. Once the fast neutron has thermalized, more neutron loss can occur via escaping the core, P_{NL}^{th}, or by being absorbed in the non-fuel, f. The remaining neutrons are then either absorbed by the fuel which may or may not result in a fission event, η. The neutrons that do cause a fission event produce more fast neutrons which start the next generation of the neutron life cycle. Thus, k_{eff} is determined to see if enough neutrons survived the cycle to maintain a self-sustaining reaction, too many neutrons were produced and a runaway reaction occurs, or not enough neutrons were produced, and the reaction is not self-sustaining [5].

1.2.3 The Neutron Transport Equation

Another equation of note that describes the gain and loss of neutrons in a nuclear system is the neutron transport equation. This equation is given as follows.

$$\begin{aligned}\frac{1}{v}\frac{\partial\varphi}{\partial t} + \widehat{\Omega}\cdot\nabla\varphi + \Sigma_t(r,E)\varphi\big(r,E,\widehat{\Omega},t\big) &= \frac{\chi(E)}{4\pi}\int_{4\pi} d\widehat{\Omega}' \int_0^{\infty} dE'\,\nu(E')\Sigma_f(E')\varphi\big(r,E',\widehat{\Omega}',t\big) \\ &+ \int_{4\pi} d\widehat{\Omega}' \int_0^{\infty} dE'\,\Sigma_s\big(E'\to E,\widehat{\Omega}'\to\widehat{\Omega}\big)\varphi\big(r,E',\widehat{\Omega}',t\big) + S\big(r,E,\widehat{\Omega},t\big)\end{aligned} \tag{1.13}$$

where v is the neutron velocity vector, φ is the angular neutron flux, t is the time, $\widehat{\Omega}$ is the unit vector, Σ_t is the macroscopic total cross section, r is the position vector, E is the energy, $\chi(E)$ is the probability density function for neutrons of exit energy E from all neutrons produced by fission, ν is the average number of neutrons produced per fission event, Σ_f is the macroscopic fission cross section, Σ_s is the macroscopic scattering cross section, and S is the neutron source term.

The first term of the equation is the time rate of change for the neutrons in a system. The rate of change can tell us whether the system is subcritical, critical, or supercritical. For example, if the rate of change is positive then the system may be either increasing to a critical state. If the rate continues to increase, this may indicate a supercritical system. The second term of the equation gives the movement of neutrons going into or out of the system. The non-leakage probability factors are related to this term. The third term describes any interaction that the neutron may have while in the system. Factors that relate to this term are p, and f due to the loss of neutrons from resonance and thermal neutron absorption. Absorption is one of the ways that a neutron may interact with other atoms inside the system without leading to fission [8].

On the right side of the equation, the first term gives the production of neutrons due to a fission event. Both ϵ and η relate to this term due to the production of neutrons from fast and thermal fission. The second term describes the gain of neutrons due to the in-scattering of neutrons from other energies or directions. These neutrons may be part of the beginning of a new neutron life cycle. The final term is a generic source term of neutrons other than fission [8]. For the processing of fissionable material, this value should be zero.

1.3 Process Nuclear Criticality Accidents

If a runaway or uncontrolled nuclear fission chain reaction were to occur outside of a nuclear reactor, the accident would be considered a process nuclear criticality accident. A process accident could occur in a storage vessel, process vessel, experiments, etc. An example is given in the following section.

1.3.1 JCO Fuel Fabrication Plant

On September 30, 1999, a process criticality accident occurred at the JCO Fuel Fabrication plant in Japan. It involved a uranyl nitrate solution in a precipitation tank, with multiple excursions (i.e., runaway chain reactions), two fatalities, and one significant exposure. The plant where the accident occurred was used to fabricate uranyl nitrate from U_3O_8 and nitric acid. The accident was a result of the operators not following the authorized procedure to fabricate the uranyl nitrate fuel but by instead executing a procedure that was thought to be faster and more efficient. Figure 1.4 shows a diagram of the authorized procedure and the executed procedure that led to the accident [9].

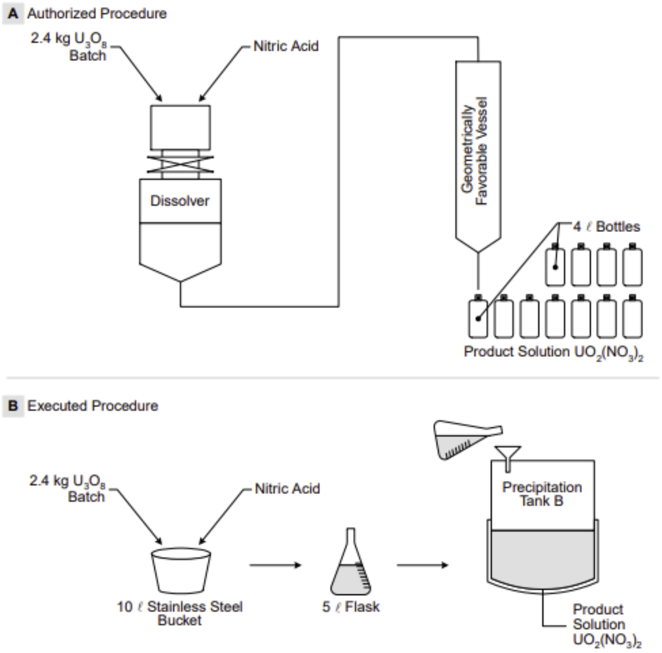

Figure 1.4. JCO Fuel Fabrication Process Procedure

1.3.1.1 Authorized Procedure

The goal of the process was to prepare 16.8 kg of U(18.8) as a 370 g/L uranyl nitrate solution. The uranyl nitrate solution was then to be used in the Joyo experimental breeder reactor at the Oarai site of the Japan Cycle Development Institute. This process was performed at an inner-city location for one of the JCO company sites in Toki-mura, Ibarakin prefecture, Japan.

The authorized procedure, as shown in Figure 1.4, was a batch process performed by taking 2.4 kg of U_3O_8 and nitric acid and mixing the reactants in a dissolver. Impurities in the solution were then removed using tributyl phosphate (TBP) and nitric acid or water. Once the impurities were removed, the mixture was then conveyed to a geometrically safe storage vessel where ammonia gas was bubble through the solution to precipitate ammonium diuranate (ADU), $(NH_4)_2U_2O_7$. The precipitate was separated from the solution using a pan filter and the uranyl nitrate solution was then dispensed into 4 L bottles for delivery. The ADU was then heated up to produce U_3O_8 which was recycled back into the dissolver [9] [10].

1.3.1.2 Executed Procedure

This process criticality accident was a result of the operators not performing the authorized procedure described above but by executing a different procedure that was thought to be more efficient. The executed procedure used two modifications to the authorized process. The first deviation was that U_3O_8 and nitric acid were mixed in an open 10 L stainless steel bucket. This modification was made to save about an hour of dissolution time. The second, most critical deviation was the transfer of the uranyl nitrate solution to an unfavorable geometric precipitation vessel. The reasoning behind this change was due to some difficulty filling up the 4 L bottles from the geometrically safe storage columns. The drainpipe from the columns was only about 10 cm above the ground. Additionally, the precipitation vessel had a stirrer to give a uniform solution and was easier to dispense the solution into the 4 L bottles. This last modification was made only a day before the accident.

On the day leading up to the accident, four 2.4 kg dissolution batches were performed. Each solution was transferred to a 5 L flask which was used to hand pour the solution via a funnel in an open port on the top of the precipitation tank. One operator would pour the solution and a second operator would hold the funnel. The precipitation tank had a capacity of about 100 L with a 450 mm diameter and 610 mm height. After the four batches were added, the work was completed for the day.

The day of the accident, September 30th started with the operators mixing the final three batches to complete the order. The fifth and the sixth batch were added to the precipitation vessel with no incident. During the pouring of the seventh batch, the uranyl nitrate solution in the precipitation vessel went prompt critical, a blue flash was seen, and the gamma alarms sounded in both this facility and the neighboring commercial buildings. All personnel were then evacuated at the sounding of the alarm. The critical excursions then continued for the next twenty hours until actions were taken by government officials [9] [10].

Due to the length of the critical excursions, this accident was most likely a cyclic critical event. Meaning that the solution would go prompt critical, get hot and boil, become subcritical due to the expansion of the solution and loss of moderator, and then go prompt critical again when the solution settled down into a more reactive state. Prompt critical means that a system will go critical when induced by prompt fission neutrons or the neutrons first produced immediately after the fission event. Most likely, the solution continued to go through this prompt critical cycle until enough fission products were produced and then decay into their daughter products. As part of this decay process, more neutrons can be emitted from the decay to cause additional fission events. These neutrons are called delayed neutrons. The prompt and delayed neutrons allowed for the solution to remain critical until action was taken to stop the excursions twenty hours later. The excursions were eventually stopped when the officials recognized that they could decrease reactivity by removing the cooling water from the jacket around to precipitation vessel [8].

1.3.1.3 Consequences

Many consequences directly followed the first critical excursion and the following excursions during the next twenty hours. The first direct consequences came from the severe overexposure that the three operators received while preparing the uranyl nitrate solution. The operator holding the funnel received an estimated dose of 16 to 20 GyEq and the operator pouring the solution received about 6 to 10 GyEq. The third operator received a dose of about 1 to 4.5 GyEq and was only a few meters away at a desk. The three operators were placed under special medical care where the operator holding the funnel died 82 days later, the operator pouring the solution died 210 days after the accident, and the third operator left the hospital three months later.

One thing of note for this process criticality accident was that it was the first process criticality accident to have a measurable dose outside of the facility to the public. This is because the accident occurred at an inner-city facility. After about 4.5 hours into the accident, radiation readings from a nearby facility read a combined neutron and gamma dose rate of about 5 mSv/hour. Residents within 350 m were then asked to evacuate. After 12 hours, residents within a 10 km radius were asked to stay indoors. This was due to airborne fission product activity. Of the estimated 200 residents that were evacuated around the site, 90% of them received a dose less than 5 mSv dose and the remaining 10% received no more than 25 mSv. From the airborne fission products contamination, they were short-lived, and the maximum readings gave a dose rate of less than 0.01 mSv/hr.

A final consequence of this accident was the Government’s decision to cancel JCO’s license of operation. Other consequences may include the impact on the perception of risk of the local community and the decrease in trust for the nuclear energy sector [9] [10].

1.3.1.4 Lessons Learned

The main contributing factor that led to this accident was the lack of understanding of how the fissile solution would behave differently in the used vessel compared to the intended vessel. This was a lack of understanding by the personnel at all levels of the company. This lack of understanding by the upper levels can be seen by the pressure given by the company on the operators to produce fuel more quickly and efficiently. The last factor was the overall mindset of the potential dangers of process criticality accidents compared to reactor criticality accidents. This accident shows the importance of following an authorized procedure when filling up a vessel with a fissile solution [9] [11].

Lessons that can be learned from this accident for the fuel salt preparation and handling processes are the importance of using authorized equipment and following authorized procedures. The purpose of an

NCSE is to provide tools and knowledge so that accidents like these will not occur during the fuel cycle processes of the MsNB.

1.4 Standards and Regulations

The NCSE was performed by following the Department of Energy Technical Standard DOE-STD-3007-2017: Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities. The purpose of the document is to provide a standard of how an NCSE should be completed. Following this standard helps to create an NCSE that follows the American National Standards Institute/American Nuclear Society (ANSI/ANS-8) series of criticality safety standards and other DOE Orders [12].

Two standards from ANSI/ANS-8.1-2014 that best explain the purpose of generating the NCSE document are the Process Analysis (PA) standard and the Double-Contingency Principle (DCP). From Section 4.1.2 of the ANSI/ANS-8.1-2014 document, the PA standards state that,

> “Before a new operation with fissionable material is begun, or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions.”

Section 4.2.2 of the same document states,

> “Process designs should incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible. [13]”

With these standards in mind, the outline of the thesis and NCSE is as follows:

1. Introduction
2. The description of the equipment, materials, and processes to be evaluated.
3. The methodology and validation of calculation methods used in the evaluation.
4. The process analysis to document the normal and abnormal conditions. The DCP is also applied in this section.
5. A summary of controls and assumptions used in the process.
6. A summary and conclusion of the NCSE
7. A list of cited references.
8. Any needed appendices.

Following this outline, the Nuclear Criticality Safety Evaluation of the fuel salt preparation and handling processes is given below.

Chapter 2: Description

Before the fuel salt for the MsNB can be employed, it must be prepared, stored, transported, and loaded into the battery. Proposed descriptions for each of these processes will be provided in this chapter. Each description will describe the equipment/materials involved, the process used, and the process boundaries. These descriptions will provide the foundation for the normal and credible abnormal conditions to be analyzed later in this paper.

2.1 Fuel Salt Preparation

2.1.1 Equipment/Materials

The equipment to be used in the first process is shown in Figure 2.1. It consists of the eutectic FLiNaK salt, UF_4 fuel, Argon gas, the mixing/storage vessel, and the support structure. Four of these units will be used to prepare the fuel salt to be used in the MsNB. The image on the right of Figure 2.1 gives a glimpse of the interior of the mixing vessel. Inside can be seen the four baffles and the two 45-degree pitched axial impellers.

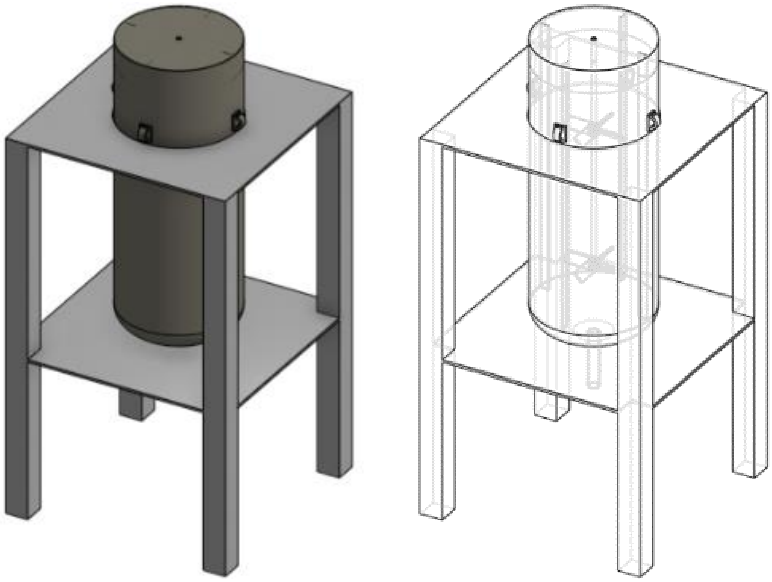

Figure 2.1. Fuel Salt Preparation Vessel.

2.1.1.1 The Fuel Salt

The estimated total amount of fuel salt needed for the MsNB is 3,364.915 kg. The fuel salt is made of purified eutectic FLiNaK salt (LiF-NaF-KF, respectively 46.5, 11.5, 42 mole%) and UF_4 fuel [14]. The eutectic salt will be highly enriched in Lithium 7 at 99.99 mole% to reduce the production of Hydrogen-3. The other isotopic constituents will consist of naturally abundant isotopes. The fuel is of the HALEU variant at 19.75 mole % Uranium-235. With an 18 mole % UF_4 fuel leading, the isotopic composition of the fuel salt in mole fraction and mass fraction is given in Table 2.1.

Table 2.1. Isotopic constituents of the FLiNaK-UF_4 eutectic fuel salt.

Isotope	Mole Fraction	Mass Fraction
^{6}Li	0.00001500	0.00000253
^{7}Li	0.14993898	0.02956273
^{19}Fl	0.60652368	0.32381767
^{23}Na	0.03708539	0.02395921
^{39}K	0.12631092	0.13830726
^{41}K	0.00911554	0.01049309
^{235}U	0.01402457	0.09263585
^{238}U	0.05698593	0.38122165

The density of the fuel salt is an important specification for estimating the criticality of the preparation vessel. The density correlation for the eutectic FLiNaK salt is given in Equation 2.1 [14] The correlation for UF_4 dissolved in the molten salt is given in Equation 2.2 [15].

$$\rho_{FLiNaK} = 2.5793 - 0.000624\,T \tag{2.1}$$

$$\rho_{UF_4} = 7.784 - 0.000992\,T \tag{2.2}$$

where ρ_i is the density of material i in g/cm^3 and T is the temperature in Kelvin (K). It should be noted that the theoretical density of UF_4 is 6.7 g/cm^3 and the production bulk density ranges from about 2.0 to 4.5 g/cm^3 [16] [17].

There is currently not any data readily available for the combined density of FLiNaK and UF_4. However, the average density of the fuel salt can be estimated using the formula given by Felder and Rousseau which assumes volume additivity. This assumption is justified by treating the fuel and the molten salt as independent of each other and that they do not mix chemically and only physically. This equation is shown in Equation 3 [18].

$$\frac{1}{\bar{\rho}} = \sum_{i=1}^{n} \frac{x_i}{\rho_i} \tag{2.3}$$

where $\bar{\rho}$ is the average density in g/cm^3 and x_i is the mass faction of material i. Using this equation, equations 1 and 2, and the data from Table 2.1, the average density can be calculated as a function of temperature for FLiNaK-UF_4. At the operating temperature of 600 °C, the density is 3.643 g/cm^3.

Another important characteristic of the fuel salt is the solubility of fuel in the salt. Just like dissolving sugar in water, the solubility of UF_4 in FLiNaK increases with temperature. A correlation for UF_4 solubility in eutectic FLiNaK is given in the following equation [19].

$$\log S = 4.23 - \frac{2496.9}{T} \tag{2.4}$$

where S is the solubility in mole % and T is the temperature in K with the temperature ranging from 823.15 to 973.15 K.

Mixing/Storage Vessel

The mixing/storage vessel is made of 304 stainless steel (SS304) and consists of a straight cylindrical body, a 2:1 elliptical-bottom head, a flat-top head, a drainpipe, two 45-degree pitched axial flow impellers, and four baffles. The impeller blades are currently also made of SS304. The parameters of each of these components were determined using basic rules of thumb for a mixing vessel. These rules of thumb take the diameter of the tank, D, and the fluid height, H, to base the other dimensions off these parameters. Using these rules of thumb, the parameters of the mixing vessel were determined as follows [20] [21]:

- Two 45-degree Pitched Impeller Blades
    - Diameter = 1/2 D
    - Width = 1/10 D
    - Thickness = 1/50 D
    - Two impellers: 1.3 < H/D < 2.5 (for uniform suspension of fast-settling solids)
    - Lower Impeller Height = 1/6 H, measured from the bottom of the tank
    - Upper Impeller Height = 1/3 H, measured from the top of the tank
- Baffles
    - Width = 1/12 D
    - Offset Gap = 1/72 D
- Elliptical Head Depth = 1/4 D

One of the factors that may lead to a critical excursion is an unfavorable geometry of the vessel. To account for this factor, the diameter of the vessel was determined by comparing it with the estimated effective neutron multiplication factor, k_{eff}, of the vessel, using the three-dimensional continuous-energy Monte Carlo particle transport code, Serpent 2.1.31 [22]. Nuclear systems are considered subcritical when the value of k_{eff} is less than 1. The Serpent input code for this comparison is given in the Appendix. Some parameters that were controlled in this comparison were the height of the vessel, the liquid height, and a constant volume. The height of the vessel was kept between 5 and 10 cm above the liquid height, to the nearest 5 cm increments, as the diameter changed. The liquid height was limited so that the H/D never exceed 2.5 which would require three impellers. Three impellers are not recommended for liquid-solid mixing of fast-settling solids [20]. The results of this comparison are given in Table 2.2 and Figure 2.2.

Table 2.2. Vessel Diameter vs k_{eff} Comparison

Diameter (cm)	k_{eff}	$+2\sigma$	-2σ	Liquid Height (cm)	Vessel Height (cm)	H/D
47	0.25721	0.25801	0.25641	137.928	146.75	2.93
48	0.26354	0.26442	0.26266	132.477	142.00	2.76
49	0.27121	0.27205	0.27037	127.364	137.25	2.60
50	0.27717	0.27795	0.27639	122.561	132.50	2.45
51	0.28308	0.28402	0.28214	118.045	127.75	2.31
52	0.28822	0.28904	0.28740	113.794	123.00	2.19
53	0.29451	0.29531	0.29371	109.787	118.25	2.07
54	0.30023	0.30105	0.29941	106.007	113.50	1.96
55	0.30520	0.30618	0.30422	102.437	108.75	1.86
56	0.31081	0.31177	0.30985	99.057	109.00	1.77
57	0.31367	0.31453	0.31281	95.864	104.25	1.68
58	0.31832	0.31918	0.31746	92.840	99.50	1.60
59	0.32149	0.32247	0.32051	89.968	99.75	1.52
60	0.32647	0.32745	0.32549	87.249	95.00	1.45
61	0.32921	0.33011	0.32831	84.668	90.25	1.39
62	0.33209	0.33313	0.33105	82.211	90.50	1.33
63	0.33535	0.33629	0.33441	79.704	85.75	1.27
64	0.33694	0.33786	0.33602	77.478	86.00	1.21
65	0.33931	0.34031	0.33831	75.362	81.25	1.16
66	0.34211	0.34305	0.34117	73.341	81.50	1.11
67	0.34385	0.34473	0.34297	71.419	76.75	1.07
68	0.34348	0.34434	0.34262	69.581	77.00	1.02
69	0.34410	0.34514	0.34306	67.826	77.25	0.98
70	0.34417	0.34511	0.34323	66.154	72.50	0.95

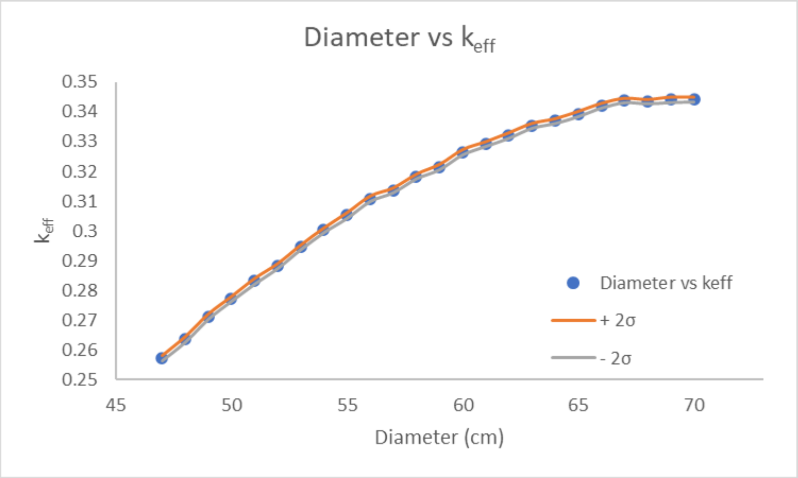

Figure 2.2. Vessel diameter vs k_{eff} comparison.

As shown in Figure 2.2, the vessel geometry became less favorable and more reactive with increasing diameter. Additionally, three impellers would be needed for diameters less than 50 cm. From this comparison, 50 cm was chosen as the diameter of the vessel. It should be noted at the time of this comparison the fuel loading for the MsNB was 15 mole % UF_4. The results for 18 mole % should be similar and the current k_{eff} for a 50 cm diameter vessel is 0.32094 ± 0.00068. (95% confidence is given in this value. This format will be used for the rest of the thesis.)

For the thickness of the vessel and drainpipe walls and the four baffles, ¼ inch SS304 plate will be used. This is a standard size plate that can be shaped into the desired shape of the vessel. Stress tests will need to be performed to ensure the safety of the vessel at this thickness. As part of the preliminary design, the minimum thickness was calculated using a formula given by Section III, Division 1, of the ASME Boiler and Pressure Vessel Code. This formula with an additional factor accounting for corrosion allowance is given in the following equation [23].

$$t_{shell} = \frac{PD_i}{2SE - 1.2P} + t_{CA} \tag{2.5}$$

where t_{shell} is the thickness of the shell in cm, P of the pressure of the contents on the shell in g/cm^2, D_i is the inner diameter of the shell in cm, S is the maximum allowable stress in g/cm^2, E is the weld efficiency, and t_{CA} is the corrosion allowance thickness in cm.

The pressure of the vessel is the hydrostatic pressure of the contents on the wall or $P = \rho H$. With a liquid density of 3.643 g/cm^3 and height of 122.551 cm, the pressure is $P = 3.643$ g/cm^3 × 112.551 cm = 446.453 g/cm^2. The maximum allowable stress is dependent on temperature and this value at an operating temperature of 600°C for SS304 is about 594,215 g/cm^2 (58.3 MPa). The weld efficiency ranges from 1.0 for a double-welded butt joint with full radiographing to 0.6 for a single-welded butt joint without backing strips with no radiographing. Typical values for corrosion allowance are between 0.3175 and 0.635 cm and the ASME standard minimum thickness for any process vessel is 0.4763 cm [23]. Using the minimum weld efficiency and the ASME minimum thickness as t_{CA}, the minimum thickness for the mixing/storage vessel was calculated to be about 0.508 cm. This is less than the ¼ inch (0.635 cm) plate and gives credit to using ¼ inch plate for the preparation vessel.

Another variant of Equation 2.5 can be used to calculate the thickness of the elliptical head. This thickness is calculated using the following equation.

$$t_{head} = \frac{PD_iK}{2SE - 0.2P} + t_{CA} \, with \, K = \frac{1}{6}\left[2 + \left(\frac{D_i}{2h}\right)^2\right] \tag{2.6}$$

where t_{head} is the thickness of the elliptical head in cm, K is a dimensionless geometric factor for elliptical heads, and h is the depth of the head in cm. K = 1 for a 2:1 elliptical head. Using the same parameters of the cylindrical shell, the minimum thickness of the head was also estimated to be about 0.508 cm.

The purpose of the drainpipe is to create a salt plug to give the operator control of when the fuel salt drains into the MsNB. When the preparation vessel is connected to the MsNB, the operator first melts the main part of the vessel and then melts the salt plug. Additionally, the salt plug is used with a secondary cap to keep the fuel salt mixture in the vessel. The primary method to solidify the salt plug is by applying an active coolant around the drainpipe. As a safeguard, the length of the drainpipe needs to be determined to ensure that at least 75 % of the salt plug remains solid using natural convection.

The length of the drainpipe was estimated by using a correlation that describes the temperature gradient of an infinitely long cylindrical pin where one end is attached to a bulk heat source. This correlation is given in the following equation [24].

$$T = T_\infty + (T_b - T_\infty)e^{-mx} \, with \, m = \sqrt{\frac{4h}{kD}} \tag{2.7}$$

where T is the temperature along the drainpipe in K, T_∞ is the temperature of the surrounding air in K, T_b is the bulk temperature of the fuel salt vessel in K, x is the position along the length of the pin in cm, h is the natural convection heat transfer coefficient in W/m^2 K, k is the thermal conductivity of the drainpipe in W/m K, and D is the diameter of the drainpipe in cm. The natural free convection heat transfer coefficient for air can range from 10 to 100 W/m^2 K depending on the temperature difference between the pipe surface and surrounding air. The lower value will be used to be conservative. The thermal conductivity of the SS304 is approximately 23.53 W/m K at 600 °C [24]. With T_∞ = 300 K and T_b = 873.15 K, the results of the correlation are given in Figure 2.3. This figure shows that at about 5 cm away from the fuel salt along the drainpipe the temperature reaches the melting point of 454 °C for FLiNaK salt. For a drainpipe length where only 25 % is melted, the length is then estimated to be 20 cm. It was decided to add 5 cm extra as a precaution for a total drainpipe length of 25 cm.

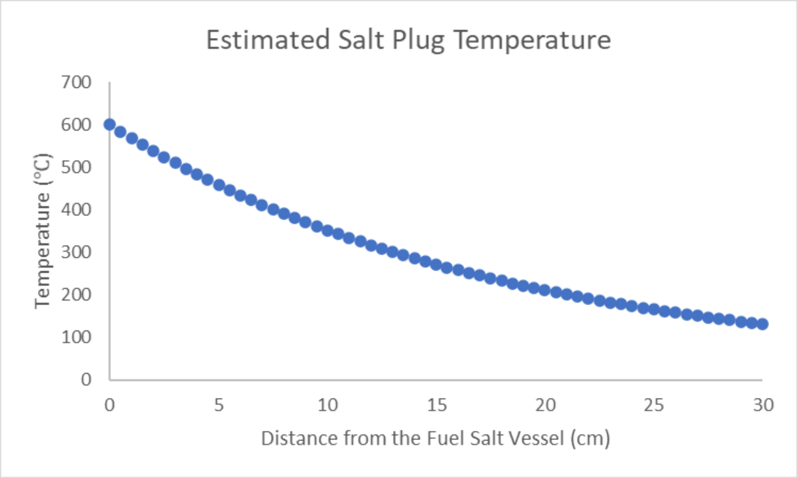

Figure 2.3. Estimated temperature of the salt plug along the drainpipe length.

2.1.1.2 Support Structure

A simple support structure was designed to hold the vessel during the mixing operation and in storage. This structure is made of SS304 and is shown in Figure 2.1. It consists of two plates and four legs. The plates are 1 cm x 100 cm x 100 cm with a 51.3 cm diameter hole in the center of the top plate at a height of 135.1 cm and a 5.3 cm diameter hole in the center of the bottom plate at a height of 37.0 cm. Each of the legs is 10 cm x 10 cm x 135.1 cm. with a hollow interior and a wall thickness of 1 cm. The preparation vessel will rest inside the holes of the support structure as shown in the figure.

Stress studies will also need to be performed for this support structure. In an initial stress study using ANSYS to measure the stress of the vessel and its contents on the structure, the following was found:

- The maximum displacement due to the weight of the vessel on the structure is about 5 mm.
- The hoop stress was about 1.6 MPa and the maximum allowable stress is 58.27 MPa. This gives a safety factor of about 36.4.
- The maximum shear stress was located at the external face of the ellipsoidal cap with a value of about 18 MPa.
- The maximum Von-Mises stress, which is the value of whether a material will yield or fracture, is on the order of 19 MPa.

These findings give further evidence of the safety of the preliminary vessel design. Further stress analysis will need to be performed before this design can be implemented.

2.1.1.3 Argon

Argon gas will fill the remaining gap in the preparation vessel. The pressure of the gas will be near atmospheric and will be regulated by a pressure regulator, tank, and pressure relief valve. The density of the gas at atmospheric pressure is determined by the following relationship [25].

$$\rho_{Ar} = 0.508\, T^{-1.009} \tag{2.8}$$

where ρ_{Ar} is the density of Argon gas in g/cm^3 and T is the temperature in K.

2.1.1.4 Fuel Salt Preparation Vessel Summary

Figure 2.4 shows another view of all the components for the fuel salt preparation vessel and structure. Table 2.3 gives a detailed summary of all the parameters of these components.

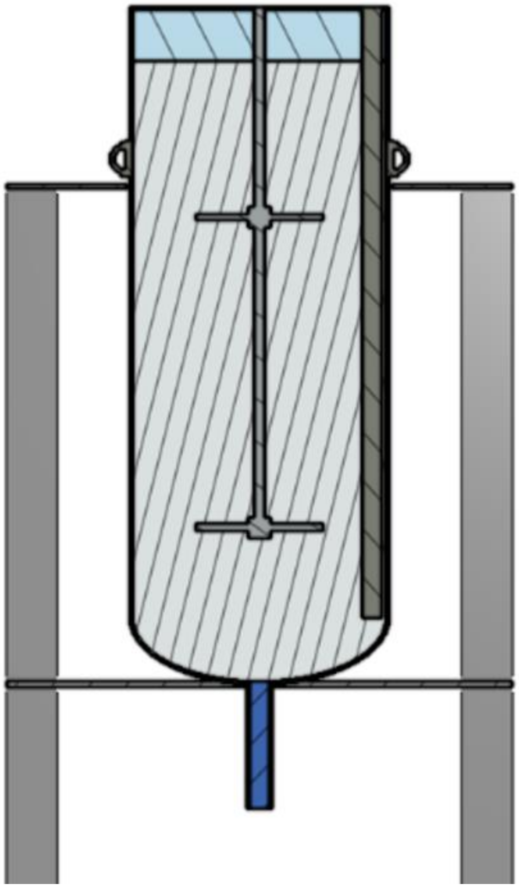

Figure 2.4. Detailed look at the fuel salt preparation vessel and support structure.

Table 2.3. Summary of preparation vessel and structure parameters.

Vessel Parameter	Dimension
Total Amount of Fuel Salt per Vessel, kg	841.229
Fuel ^{235}U Enrichment, mole %	19.75
Fuel UF_4 Loading, mole %	18.0
UF_4 Solubility Limit in FLiNaK at 600 °C, mole %	23.5
FLiNaK-UF_4 Density (Hot), g/cm^3	3.643
FLiNaK-UF_4 Density (Cold), g/cm^3	4.145
Inner Diameter, cm	50.0
Cylinder Height, cm	120.0
Elliptic Head Inner Radius, cm	25.0
Elliptic Head Inner Depth, cm	12.5
Drainpipe Length, cm	25.0
Vessel and Pipe Thickness, cm	0.635
Mixer Rod Length, cm	114.196
Mixer Rod Diameter, cm	1.905
Number of Impellers	2
Upper Impeller Location*, cm	81.701
Lower Impeller Location*, cm	20.425
Total Impeller Diameter, cm	25.0
Number of Blades per Impeller	4
Impeller Blade Angle, degrees	45
Impeller Blade Mount Radius, cm	2.1213
Impeller Blade Mount Height, cm	4.2426
Impeller Blade Length, cm	10.379
Impeller Blade Width, cm	5.0
Impeller Blade Thickness, cm	1.0
Number of Baffles	4
Baffle Length, cm	120
Baffle Width, cm	4.167
Baffle Thickness, cm	0.635
The gap of the Baffle from Vessel Wall, cm	0.694
FLiNaK-UF_4 Height (Hot), cm	122.551
FLiNaK-UF_4 Height (Cold), cm	108.249
Liquid Height to Diameter Ratio (Hot)	2.45
Support Structure Total Height, cm	136.135
Support Plates Width (Square), cm	100
Support Plates Thickness, cm	1
Upper Plate Location from base, cm	135.135
Upper Plate Hole Diameter, cm	~51.3
Lower Plate Location from base, cm	37
Lower Plate Hole Diameter, cm	~5.3
Support Legs Length, cm	135.135
Support Legs Width (Square), cm	10
Support Legs Thickness (Hollow), cm	1

* From the centerline of the blade to the bottom of the vessel.

2.1.2 Process

An empty preparation vessel is first placed inside the support structure in the mixing area. The vessel is then filled with purified molten eutectic FLiNaK salt. The total amount of FLiNaK salt for one vessel is 315.036 kg. Passive and active cooling then form a slat plug in the drainpipe of the vessel and this salt is now considered separate from the rest of the FLiNaK salt. The remaining salt in the vessel is now heated and maintained at the operating temperature of 600 °C. This temperature ensures that the solubility limit of UF_4 in FLiNaK salt is not exceeded as fuel is added to the mixing vessel. Once the salt is up to temperature, the mixer is then turned on. The rotation speed of the mixer will need to be determined experimentally to achieve uniform suspension of the fuel in salt.

The solid UF_4 fuel is then heated to 600 °C and added to the molten salt. The total amount of UF_4 fuel for one preparation vessel is 526.193 kg. To ensure that the mixture remains well mixed and that the fuel dissolves into the salt, the fuel is added slowly in 17.540 kg increment units for a total of 30 units. Once the fuel has dissolved into the salt, the mixer is turned off and the fuel salt is cooled to room temperature. The vessel and structure can then be transferred into storage or prepared for transportation.

With a portion of the FLiNaK salt used as a salt plug, the composition of the remaining FLiNaK-UF_4 needs to be slightly adjusted. The total amount of solid salt in the plug is 0.796 kg with a density of 2.533 g/cm^3. The total amount of fuel salt in the tank of the vessel is 840.433 kg with a density of 3.646 g/cm^3 at 600 °C and 4.148 g/cm^3 at room temperature. The adjusted composition in mass fraction of the FLiNaK-UF_4 salt is given in Table 2.4.

Table 2.4. Adjusted FLiNaK-UF_4 fuel salt composition.

Isotope	Mass Fraction
^{6}Li	0.00000253
^{7}Li	0.02951598
^{19}Fl	0.32368899
^{23}Na	0.02392133
^{39}K	0.13808856
^{41}K	0.01047650
^{235}U	0.09272355
^{238}U	0.38158256

2.1.3 Process Boundaries

The location or facility where this process will take place has not been determined. One possible process that may be in the same facility as the fuel salt preparation process is the salt purification process. This would allow the newly purified salt to be directly placed in the preparation vessel following the salt purification process. Other equipment already onsite would include argon tanks, heating/cooling equipment, and a mixer motor.

2.1.3.1 Material Input

The materials and equipment that would be brought into the fuel salt preparation area are the mixing/storage vessel, the support structure, the purified FLiNaK salt, and the 30 units of UF_4 fuel. The process by which the 30 units of UF_4 fuel will be transferred to the mixing/storage vessel is still to be determined. Any other equipment should not be brought into the preparation area.

2.1.3.2 Material Output

The materials and equipment that would be taken out of the fuel salt preparation area are the mixing/storage vessel, the support structure, and the cooled FLiNaK-UF_4 fuel salt. These components will be moved to the storage area that will be kept in a separated controlled portion of the facility.

2.2 Storage

The fuel salt may be stored in the storage area of the facility. The only materials and equipment brought into and out of the storage area include the mixing/storage vessel, the support structure, and the fuel salt. Each vessel is placed next to the other in a square array. The support structure provides inherent spacing in between vessels to limit interaction. If wanted or if needed, empty vessels and structures may be placed in between filled vessels to further limit interaction.

2.3 Transportation

Four mixing/storage vessels will need to be transported from the facility to the site of the MsNB. One possible solution to achieve this is to place the four vessels inside the 10-160B Type B cask designed by EnergySolutions.

2.3.1 Equipment/Materials

2.3.1.1 10-160B Transport Container

The 10-160B container is an approved DOT, DOE, and NRC cask. The maximum content mass is 6,464 kg (14,250 lb.) and the contents may include [26]:

- Byproduct, source, and special nuclear material, non-fissile or fissile-excepted, as special form or nonspecial form in the form of process solids or resins; either dewatered, solid, or solidified waste; in secondary containers;
- Dewatered, solid, or solidified transuranic-containing wastes; fissile, non-fissile, or fissile-excepted; in secondary containers;
- Miscellaneous radioactive solid waste materials, including special form materials and powdered solids in secondary containers with a maximum decay heat of 200 W.

The main components of the 10-160B cask are the containment vessel (carbon steel, SA-516 Gr. 70), lead shielding, and impact limiters (SS304 shell filled with polyurethane foam). It was designed to protect the contents from the transport environment, a 30-foot drop test, a 40-inch puncture test, a 1475 °F thermal exposure, and a transfer of dissipation of any generated heated from the inside. A cross-section view of the 10-160B Type B container is shown in Figure 2.5 which gives the general dimensions for the container. More clear drawings were withheld because they were considered security-related information [27].

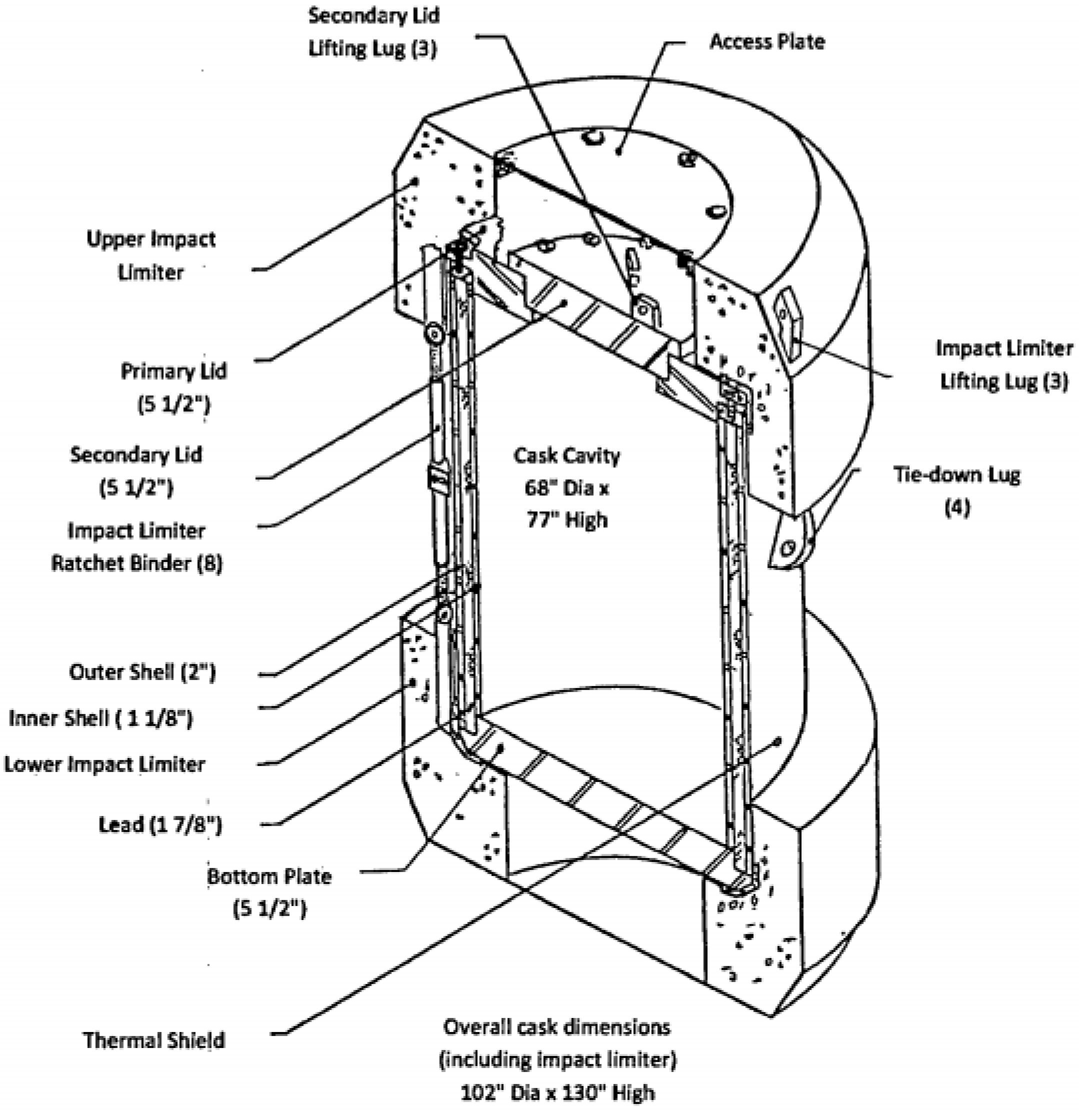

Figure 2.5. 10-160B General Arrangement. (Top thermal shield not shown)

To transport the four mixing/storage vessels, only small modifications were made to the inner cavity of the container. These modifications include two flat plates like the plates of the support structure described in section 2.1.1 and polyurethane foam (PUR) to fill up the void space of the vessel.

2.3.1.2 Support Structure Plates

The plates will most likely be some type of insert that can be placed in the cavity of the vessel to provide support and spacing for the mixing/storage vessels. They are 1 cm thick and have a diameter of 172.72 cm. The bottom of the upper plate is 135.135 cm from the floor of the vessel and has four 51.3 cm diameter holes which are spaced in a 75 cm pitched square array. The bottom of the lower plate is 37 cm from the floor of the vessel and has four 5.3 cm diameter holes with the same square array. The pitch was measured from center to center between two vessels. The layout of the mixing/storage vessels is shown in Figure 2.6.

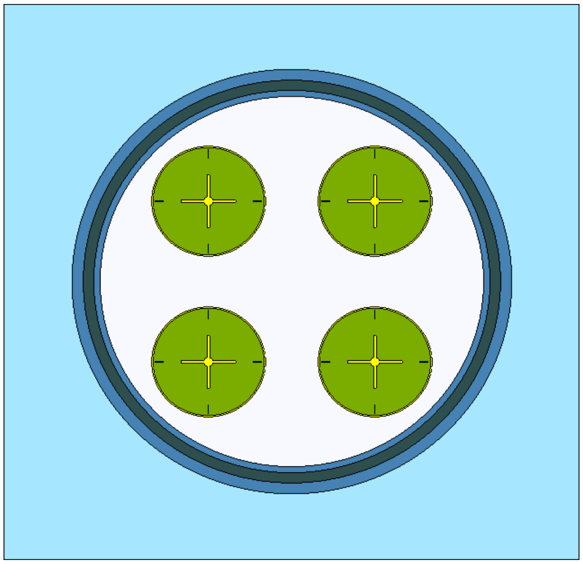

Figure 2.6. Layout of mixing/storage vessels in 10-160B transport vessel.

The pitch between the vessels was decided upon by comparing it with k_{eff}. This is similar to what was done with the diameter of the mixing/storage vessel. The comparison was performed by initially having the vessel grouped in the center of the transport vessel and then increase the pitch 1 cm at a time until they touched the walls of the vessel. The results of the comparison are given in Figure 2.7. It should be noted at the time of this comparison, the fuel loading was 15 mole % UF_4 and the model used air instead of PUR. The results of the comparison using 18 mole % UF_4 and PUR should be similar and the current k_{eff} for a 75 cm pitched square array is 0.58666 ± 0.00094.

As shown in Figure 2.7, the transport vessel layout became more favorable as the pitch increased between mixing/storage vessels. The interaction of the vessels in the center was more reactive which is expected. It was interesting to see that as the vessels approached the walls of the containment, more reflection for the shielding could be seen as the reactivity began to level out and slightly increase. This is most likely due to the high density of the carbon steel and lead shielding of the container's wall. A pitch of 75 cm was chosen due to the low reactivity of the system. It was chosen over a pitch of 80 cm to add more clearance between the wall and fuel salt vessel during the loading and unloading process.

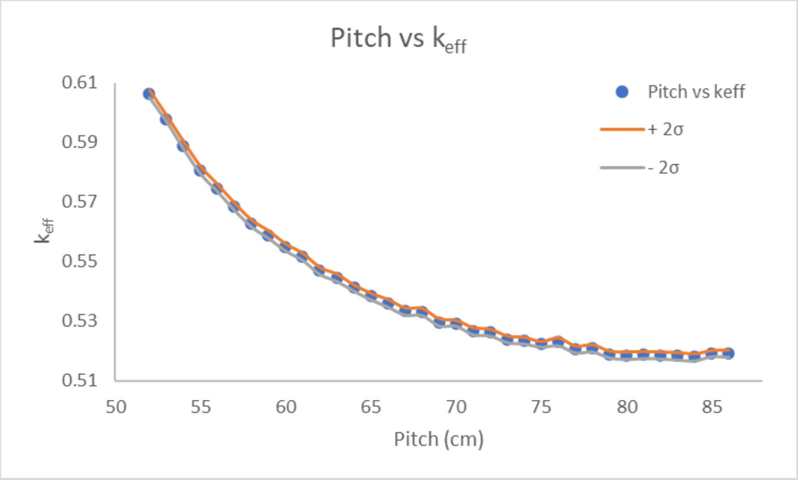

Figure 2.7. Vessel pitch vs k_{eff} comparison.

2.3.1.3 Polyurethane Foam

The PUR foam will fill the remainder of the space in the vessel. Adding the PUR foam has the benefit of adding more cushion to the mixing/storage vessels in case of an accident and limits the number of other materials that can enter the cavity interact with the fuel salt vessels. The density of the PUR foam is 0.021 g/cm^3 and will fill the volume of 3,924,978.3 cm^3 void in the transport cavity [16].

The total mass of the content in the cavity includes the four fuel salt vessels, two support plates, and PUR foam. The four fuel salt vessels have a total mass of 3,923.51 kg. The mass of the fuel salt vessel support plates is 303.31 kg. The mass of the PUR foam is 82.42 kg. This gives a total content mass of 4309.24 kg which leaves 2154.76 kg of leeway for any other needed support for the fuel salt vessels such as bracers or tie-downs.

2.3.2 Process

Four of the fuel salt vessels and support structures are taken from the fuel salt preparation area or the storage area. They are placed one at a time inside the transport vessel and secured. The remaining space is filled with the PUR foam. The cap of the transport vessel is placed as the PUR foam expands to fill the cavity. The transport vessel is then transferred by either ground, rail, or ship. It is not authorized for air transport due to the fissile material [26]. When it arrives at the facility, the fuel salt vessels are removed from the transport vessel and are placed in additional support structures in preparation to unload the fuel salt into the battery.

2.3.3 Process Boundaries

The location of the first part of this process is still to be determined. The mode of transportation will also and depend on the location of the employed MsNB. The only materials involved in the process are the four fuel salt vessels and structures, the transport vessel, the PUR equipment, the moving equipment, and the transportation equipment.

2.4 Unloading

2.4.1 Equipment/Materials

The equipment and materials used in the fuel salt unloading process are the same as those in the preparation process. The only additional components are the MsNB, and any materials utilized to connect the fuel salt vessels to the MsNB. The support structures may be shortened at the site of the MsNB to facilitate the unloading process. Figure 2.8 gives an example of what this process step may look like.

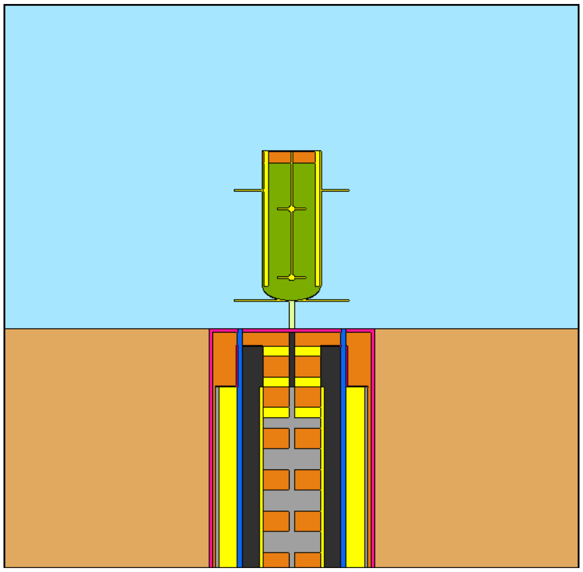

Figure 2.8. Possible layout of the fuel salt vessel unloading process.

2.4.2 Process

The fuel salt vessel and support structure are placed over and connected to the MsNB. The main chamber of the vessel is then heated to 600 °C to melt the fuel salt. After, the salt plug is melted, and the fuel salt is allowed to gravity drain into the MsNB. The Argon pressure regulator keeps the pressure inside the vessel at atmospheric pressure to achieve the gravity drain. Once the fuel salt has drained from the vessel, the vessel can cool to room temperature and is safely unattached from the MsNB. The vessel then may be repurposed for additional use.

2.4.3 Process Boundaries

The boundary conditions for this process are similar to the conditions of the fuel salt preparation process. Equipment already on-site includes the MsNB, the connecting equipment, the argon tanks, and the heating equipment. The materials brought into the process include the fuel salt vessels, the support structures, and the FLiNaK-UF_4 fuel salt. The materials leaving the process boundaries include the empty fuel salt vessels and the support structures. Any other materials and equipment should not be brought into the fuel salt unloading area.

Chapter 3: Methodology and Validation

3.1 Methodology

Serpent, a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code, version 2.1.31, with the ENDF/B-VII cross-section library was used to perform the calculations for this NCSE [22]. The calculations were run on an Ubuntu 20.04.2 LTS Linux operating system. The inputs and outputs are archived on the Linus system in the directory /home/trevin/Serpent/MsNB and the directory OneDrive - University of Idaho\Prep Serpent Codes. Calculation results are stored in the FLiNaK_UF4_Properties.xlsx excel file.

3.2 Validation

One of the main sources used to validate a computational code for criticality safety validation is the International Handbook of Evaluated Criticality Safety Benchmark Experiments. From the Handbook, it states, “The benchmark specifications are intended for use by criticality safety engineers to validate calculation techniques used to establish minimum subcritical margins for operations with fissile materials…” Currently, there are not any benchmarks in the handbook which utilize molten salts and only two of the benchmarks have calculation results using Serpent [28]. This makes validation and establishing the minimum subcritical margin or the upper subcritical limit (USL) of this system more complicated.

3.2.1 Serpent Developers Validations

In an effort to validate the Serpent code, the developers at VTT Technical Research Centre of Finland, Ltd do a comparison of each serpent update with the MCNP by performing a standard set of assembly calculation problems. When using the same cross-section libraries, the k_{eff} and homogenized few-group reaction cross-section are “within the statistical accuracy of the reference results.” Additionally, work is being done to compare the results of Serpent with those from the Handbook. One of these comparisons was done for the LEU-SOL-THERM-007 benchmark. [29].

3.2.1.1 LEU-SOL-THERM-007 Benchmark

The LEU-SOL-THERM-007 is the benchmark of an experiment at the Static Experiment Critical Facility performed in 1995 by the Japan Atomic Energy Research Institute. The experiment was an unreflected, 10%-enriched uranyl nitrate solution in a 60-cm-diameter cylindrical tank with a critical height of 46.83 cm. The uranium concentration in the solution was 0.313 g/cm^3 with a total solution density of 1.4881 g/cm^3. Sample calculations were given in the benchmark to compare different continuous energy (CE) Monte Carlo codes for this system. The codes (and libraries) used were MCNP

4B (CE JENDL-3.2), APOLLO 2-MORET IV (CEA93 Library 172-Group), KENO (238-Group ENDF/B-V), and MCNP (CE ENDF/B-V). The results from the Serpent code, using the ENDF/B-VII library, were also calculated, and the results of the compared codes are given in Table 3.1 [30].

Table 3.1. LEU-SOL-THERM-007 comparison of sample results.

Code (Cross Section Set), Country	k_{eff}
MCNP 4B (CE JENDL-3.2), Japan	1.00150 ± 0.0002
APOLLO 2-MORET IV (CEA93 Library 172-Group), France	0.99508 ± 0.0003
KENO (238-Group ENDF/B-V), United States	0.99600 ± 0.0007
MCNP (CE ENDF/B-V), United States	0.99660 ± 0.0007
Serpent (CE ENDF/B-VII), Finland	0.99451 ± 0.00007

The Serpent results are similar to the other code’s results but are slightly less. This may be due to the updated cross-section library used by Serpent. The benchmark was completed in 1999.

3.2.2 Hand Calculations of the Multiplication Factor, k_{eff}

In an attempt to further validate the Serpent code for the criticality of the proposed processes, hand calculations were performed to try and understand how the six factors of the six-factor formula described in Section 1.2.1 relate to the FLiNaK-UF$_4$ fuel salt preparation vessel.

As part of the Serpent code output files, estimated values for each of the six factors can be found in the output file file_name_res.m. For a preparation vessel where the fuel has already been added and the fuel salt is cooled and solid, the six-factor values are ϵ = 412.649, p = 0.138733, η = 1.92935, f = 0.0117592, P_{NL}^{f} = 0.387319, and P_{NL}^{th} = 0.935712. Using the six-factor formula, k_{eff} = 0.470718.

The first factor of the six-factor formula is the fast fission factor ϵ. An approximation for this factor is given in Equation 3.1 [31].

$$\epsilon \approx 1 + \frac{1-p}{p}\,\frac{u_f \nu_f P_{FAF}}{f \nu_t P_{TAF} P_{NL}^{th}} \tag{3.1}$$

where p is the resonance escape probability, u_f is the fast utilization factor, ν_F is the average number of neutrons from fast fission, P_{FAF} is the probability that a fast neutron is absorbed in the fuel and causes fission, f is the thermal utilization factor, ν_T is the average number of neutrons from thermal fission, P_{TAF} is the probability that a thermal neutron is absorbed in the fuel and causes fission, and P_{NL}^{th} is the thermal non-leakage probability. From Equation 1.5, it is known that $\nu_T P_{TAF} = \eta_T$ which is the thermal fission factor. From this, the average number of neutrons from fast fission ν_f and the probability that a fast neutron is absorbed in the fuel and causes fission P_{FAF} can be written as $\nu_F P_{FAF} = \eta_F$. The equation can then be written as follows.

$$\epsilon \approx 1 + \frac{1-p}{p}\,\frac{u_f \eta_f}{f \eta_t P_{NL}^{th}} \tag{3.2}$$

The fast fission factor approximation is dependent on four of the six factors to calculate k_{eff}. They are p, f, η, and P_{NL}^{th}. The first factor is calculated using Equation 1.4 which is given again in the following equation.

$$p = \exp\left[-\frac{a}{\xi}\left(\frac{N_A/N_M}{\sigma_{sM}10^{24}}\right)^{1-c}\right] \tag{3.3}$$

Normally ξ and σ_{sM} would account for typical moderators, such as water and graphite. For FLiNaK-UF$_4$, we can use the following relationship in Equation 3.4 to calculate the average lethargy of each isotope of the fuel salt other than uranium. σ_{sM} can be estimated by averaging the microscopic total scatter cross sections over the resonance energy region of ^{238}U for each isotope. Then σ_{sM} can be multiplied by the individual atomic density N_i to get the macroscopic total scattering cross section Σ_{sM} for the resonance region. The results of this process are given in Table 3.2 and Table 3.3. Neutron cross section data for these tables and the following tables in this section were provided by the ENDF/B-VIII.0, ENDF/B-VII.1, and JEFF-3.3 cross section libraries [32].

$$\bar{\xi} = \frac{\sum_i^n \xi_i \Sigma_s^i}{\sum_i^n \Sigma_s^i} \tag{3.4}$$

Table 3.2. Lethargy and averaged, constant values of the microscopic total scattering cross sections in the U-238 resonance energy spectrum for the isotopic components of FLiNaK-UF$_4$ excluding Uranium.

Isotope	Lethargy ξ	U-238 Resonance Region $\sigma_{sM}(E\ (MeV))(b)$					Averaged Constant
		10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	$\sigma_{sM}\ (cm^2)$
Li-6	0.268		7.024E-01	7.132E-01	7.165E-01	7.173E-01	7.124E-25
Li-7	0.268	9.840E-01	1.059E+00	1.060E+00	1.029E+00	9.992E-01	1.026E-24
F-19	0.102		3.600E+00	3.637E+00	3.641E+00	3.645E+00	3.631E-24
Na-23	0.0845	3.539E+00	5.130E+00	3.714E+00	3.145E+00	3.132E+00	3.732E-24
K-39	0.0504	1.365E+00	2.088E+00	1.073E+00	1.657E+00	2.002E+00	1.637E-24
K-41	0.0504	9.176E-01	1.011E+00	7.237E-01	1.450E+00	2.341E+00	1.289E-24

Table 3.3. Lethargy, number density, and averaged, constant values of the microscopic and macroscopic total scattering cross sections in the U-238 resonance energy spectrum for the isotopic components of FLiNaK-UF$_4$ excluding Uranium.

Isotope	Lethargy ξ	$\sigma_{sM}\ (cm^2)$	$N_i\ (cm^{-3})$	$\Sigma_{sM}\ (cm^{-1})$
Li-6	0.268	7.124E-25	1.053E+18	7.499E-07
Li-7	0.268	1.026E-24	1.053E+22	1.080E-02
F-19	0.102	3.631E-24	4.258E+22	1.546E-01
Na-23	0.0845	3.732E-24	2.603E+21	9.716E-03
K-39	0.0504	1.637E-24	8.867E+21	1.451E-02
K-41	0.0504	1.289E-24	6.399E+20	8.247E-04
Average/Total	0.1064	2.920E-24	6.521E+22	1.904E-01

For ^{238}U, a = 2.73 and c = 0.486 [5]. N_A is the atom density of the resonance absorber. For this case, N_A is the atomic density of ^{238}U and gives the value of 4.000x10^{21} atoms/cm^3. With these values and the values in the table, p = 0.02948.

The next value for ϵ is the fast utilization. This is given by the equation

$$u_f = \frac{\bar{\Sigma}_R^F V_F \bar{\phi}_F}{\bar{\Sigma}_R^F V_F \bar{\phi}_F + \bar{\Sigma}_R^{NF} V_{NF} \bar{\phi}_{NF}} \; with\; \bar{\Sigma}_R^i = \bar{\Sigma}_a^i + \bar{\Sigma}_{el}^i + \bar{\Sigma}_{il}^i \tag{3.5}$$

where $\bar{\Sigma}_R^i$ is the removal cross section which accounts for absorption, elastic scattering, and inelastic scattering [8]. For a homogenized system, u_f takes the following form similarly seen for the thermal utilization factor.

$$u_f = \frac{\bar{\Sigma}_R^F}{\bar{\Sigma}_R^F + \bar{\Sigma}_R^{NF}} \tag{3.6}$$

Table 3.4. Various macroscopic cross sections of FLiNaK-UF$_4$ in the fast energy spectrum (2MeV).

Isotope	$\bar{\Sigma}_{F,\gamma}(cm^{-1})$	$\bar{\Sigma}_{F,f}(cm^{-1})$	$\bar{\Sigma}_{F,a}(cm^{-1})$	$\bar{\Sigma}_{F,el}(cm^{-1})$	$\bar{\Sigma}_{F,il}(cm^{-1})$	$\bar{\Sigma}_{F,R}(cm^{-1})$
Li-6	1.044E-11	-	1.044E-11	1.041E-06	2.291E-07	1.271E-06
Li-7	4.434E-08	-	4.434E-08	1.435E-02	1.846E-03	1.619E-02
F-19	3.339E-06	-	3.339E-06	9.438E-02	3.678E-02	1.312E-01
Na-23	4.430E-07	-	4.430E-07	4.970E-03	1.441E-03	6.411E-03
K-39	3.723E-06	-	3.723E-06	2.559E-02	7.383E-04	2.633E-02
K-41	1.413E-06	-	1.413E-06	1.490E-03	4.884E-04	1.980E-03
U-235	5.206E-05	1.098E-03	1.151E-03	3.014E-03	3.224E-03	7.389E-03
U-238	1.698E-04	1.909E-03	2.078E-03	1.252E-02	1.331E-02	2.791E-02

Using the cross section data at 2 MeV for the fast neutron spectrum in Table 3.4, u_f = 0.16238.

Table 3.5. Macroscopic absorption cross section of FLiNaK-UF$_4$ in the thermal energy spectrum (0.0253 eV).

Isotope	$\bar{\Sigma}_{T,a}(cm^{-1})$
Li-6	3.592E-08
Li-7	4.396E-04
F-19	3.614E-04
Na-23	1.218E-03
K-39	1.672E-02
K-41	8.286E-04
U-235	5.865E-01
U-238	9.523E-03

The thermal utilization f was determined using the following neutron absorption cross section data at 0.0253 eV in Table 3.5 and Equation 1.7. The calculated value of f is 0.96822.

The average number of neutrons produced from fast fission for ^{235}U and ^{238}U are respectively 2.63 and 2.6. With these values and the fission and the absorption cross sections from Table 3.4, we can solve for η_F using the following equation.

$$\eta_F = \frac{\nu_F^{235}\bar{\Sigma}_{F,f}^{235}}{\bar{\Sigma}_{F,a}^{F}} + \frac{\nu_F^{238}\bar{\Sigma}_{F,f}^{238}}{\bar{\Sigma}_{F,a}^{F}} = \frac{\nu_F^{235}\bar{\Sigma}_{F,f}^{235} + \nu_F^{238}\bar{\Sigma}_{F,f}^{238}}{\bar{\Sigma}_{F,a}^{235} + \bar{\Sigma}_{F,a}^{238}} \tag{3.7}$$

This equation gives η_F = 2.43159

η_T is the thermal fission factor. Using the values in the following table and Equation 1.5 gives η_T = 2.05034.

Table 3.6. Averaged thermal macroscopic fission and absorption cross sections of U-235 and U-238 and the number of fission neutrons from thermal fission.

Element	ν_T	$\bar{\Sigma}_{\mathrm{T,f}}\ (cm^{-1})$	$\bar{\Sigma}_{\mathrm{T,a}}\ (cm^{-1})$
U-235	2.4367	5.080E+02	5.941E+02
U-238	-	-	2.381E+02

The last value that is needed to calculate to approximate ϵ is the thermal non-leakage probability P_{NL}^{th}. The equation from Section 1.2.1 is given below.

$$P_{NL}^{th} = \frac{1}{1 + L_T^2 B_g^2} \tag{3.8}$$

The unknown quantities for this factor are L_T^2 and B_g^2. From the theory section, it was given that $L \equiv \sqrt{\bar{D}/\bar{\Sigma}_a}$. $\bar{D}$ can be calculated using the following equation.

$$\bar{D} = [3(\Sigma_t - \bar{\mu}_0 \Sigma_s)]^{-1} \tag{3.9}$$

where Σ_t is the macroscopic total cross section, $\bar{\mu}_0$ is the average cosine of the scattering angle, and Σ_s is the macroscopic total scattering cross section. Values for these constants were determined using the microscopic cross sections given in the following table for naturally occurring elements at 0.0253 eV and 20 °C [8]. The average $\bar{\mu}_0$ was determined using the following equation.

$$\bar{\mu}_0 = \frac{\sum_i^n \bar{\mu}_{0,i} \Sigma_s^i}{\sum_i^n \Sigma_s^i} \tag{3.10}$$

Table 3.7. Thermal microscopic and macroscopic scattering and total interaction cross sections and $\bar{\mu}_0$ of FLiNaK at 0.0253 eV and 20 °C.

Element	σ_t	σ_s	$\Sigma_t\ (cm^{-1})$	$\bar{\mu}_0$	$\Sigma_s\ (cm^{-1})$
Li-6	72.4	1.4	7.621E-05	0.0953	1.474E-06
Li-7	72.4	1.4	7.620E-01	0.0953	1.474E-02
F-19	3.9	3.9	1.661E-01	0.0351	1.661E-01
Na-23	4.53	4.0	1.179E-02	0.0290	1.041E-02
K-39	3.57	1.5	3.165E-02	0.0171	1.330E-02
K-41	3.57	1.5	2.284E-03	0.0171	9.598E-04
Total			0.9739	0.0379	0.2055

The geometric buckling is determined by Equation 1.10 with a 25 cm radius and a liquid height of 108.25 cm. This height is assuming that the vessel is a straight cylinder with a flat bottom rather than an elliptical head. From these equations and values, P_{NL}^{th} = 0.99437.

The estimated value of ϵ can now be determined to be $\epsilon \approx 7.58497$.

The last factor of the six-factor formula is the fast non-leakage probability P_{NL}^{f}. This value is calculated using the following equation.

$$P_{NL}^{f} = \exp\left(-B_g^2 \tau_T\right) \tag{3.11}$$

The only unknown quantity in this equation is the Fermi age τ_T and limited data of τ_T is available for the elements of FLiNaK salt. Shultis and Faw gives a table with some values of τ_T for typical moderators [5].

Table 3.8. Fermi age for common neutron moderators.

Moderator	$\tau_T\ (cm^2)$
H_2O	27
D_2O	131
Be	102
BeO	100
C	368

Noticing that carbon, fluorine, sodium, and potassium have similar microscopic total cross sections, respectively 4.8, 3.9, 4.53, and 3.57, the Fermi age of carbon will be used to approximate τ_T of FLiNaK salt. Using this value and the previously calculated geometric buckling, $P_{NL}^{f} = 0.02434$. The six-factor formula can then be used to calculate k_{eff} with k_{eff} = 0.01074.

Table 3.9. Comparison of hand calculations versus Serpent estimated values of the Six-Factor Formula.

Parameters	Hand Calculations	Serpent
ϵ	7.58497	412.649
p	0.02948	0.13873
η	2.05034	1.92935
f	0.96822	0.01176
P_{NL}^{f}	0.02434	0.38732
P_{NL}^{th}	0.99437	0.93571
k_{eff}	0.01074	0.47072

Table 3.9 gives a comparison of the hand calculated k_{eff} six-factors to the estimated Serpent values. We can see from the table that both the hand calculated, and the Serpent estimated values give a subcritical calculation. However, there are some drastic differences.

The first difference is seen in the calculation of ϵ. This is the ratio of neutrons produced by fast and thermal fission to the neutrons produced by thermal fission alone. This difference between the two estimations comes from the major difference between the two thermal utilization factors f which accounts for the neutrons absorbed into the fuel vs the fuel and the non-fuel combined. This difference may account for not all of the other absorption cross sections being utilized. Only the radiative capture cross section was used. Other reasons may be due to neutrons being absorbed in the SS304 of the fuel salt vessel which is not accounted for. SS304 was used for the baffles, impellers, and walls of the vessel.

From the hand calculated and Serpent estimation values, the neutron lifecycle is given. The high value of ϵ gives evidence that the neutrons are being absorbed and produced more readily by fast fission. These neutrons are then more likely to leak from the vessel before being thermalized given the low value of P_{NL}^{f}. Further evidence of this is shown in Figure 3.1 where the majority of the neutron flux energy is seen in the fast spectrum. This figure was generated using data from the Serpent output files [22]. The resonance escape probability p shows that most of the remaining fast neutrons are then absorb in the resonance region while slowing down.

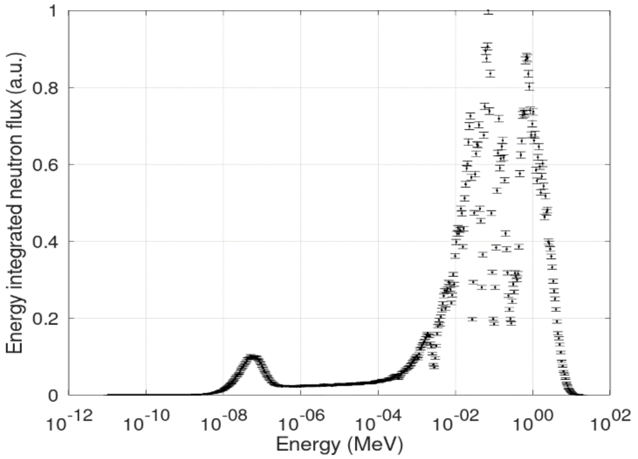

Figure 3.1. Normalized energy integrated neutron flux for the cooled fuel salt vessel.

The newly thermalized neutrons will most likely stay in the vessel because of the high probability given by P_{NL}^{th}. From the Serpent estimation of f, most of these thermal neutrons are then lost by being absorbed by the non-fuel components of the fuel salt vessel. The remaining thermal neutrons are then absorbed by the fuel and the high value of η indicates that the absorbed neutrons will cause a fission event.

Despite these validation results, more validation should be performed to provide further validation for this system. This can be done by benchmarking molten salt critical experiments and adding them to the handbook. Additional guidance to validate neutron calculation methods can be found in ANSI/ANS-8.24-2007. Until better validation is performed, this thesis and the analyses that follow will use a USL of the standard 0.95. This means that calculated $k_{eff} \pm 2\sigma$ values that are less than 0.95 are considered subcritical.

Chapter 4: Process Analysis

In this chapter, the normal and credible abnormal conditions of the fuel salt preparation and handling processes will be analyzed. This is done by establishing set parameters and controls, calculating k_{eff} under normal conditions, identifying hazards through a What-if Analysis, and applying the Double-Contingency Principle. This will show that these processes are subcritical under normal and credible abnormal conditions.

4.1 Parameters

4.1.1 Mass

The total uranium mass is controlled for the fuel salt processes. This is done by limiting the amount of feed material to the 30 units of UF_4 fuel discussed in Section 2.1.2 for the fuel salt preparation and unloading processes. The mass can be controlled in storage by limiting the number of vessels in storage. The mass is controlled in the transportation process by the four required fuel salt vessels for the MsNB.

4.1.2 Geometry

The geometry is controlled for the fuel salt processes. The fuel salt vessel's geometry is controlled by specifying the diameter, height, head depth, and thickness. The space around the vessel is also controlled by the support structure providing a gap between the vessel walls and other materials. The pitch between fuel salt vessels in the transport vessel is controlled by the support plate inserts.

4.1.3 Interaction

The interaction is controlled for the fuel salt processes. The fuel salt vessel interaction with other vessels and materials is controlled using the support structure. This is described in Section 4.1.2.

4.1.4 Volume

The volume is controlled for the fuel salt processes. This is controlled by separating the total required fuel salt for the MsNB into four vessels. This subsequently separates the total volume of UF_4 fuel into four even quantities.

4.1.5 Concentration/Density

The concentration/density is controlled for the fuel salt processes. The specified amount of purified molten salt and the specified amount of UF_4 fuel is added to each vessel. The concentration is also controlled so that the concentration does not exceed the solubility limit at operating temperature.

The density correlation for UF_4 is also a conservative estimate. The theoretical value of UF_4 at room temperature is 6.7 g/cm^3 and the density at 600 °C is 6.92 g/cm^3. The models used in the analysis may have a higher density than in practice. Research into FLiNaK-UF_4 densities should be explored for better correlations.

4.1.6 Neutron Absorption/Poison

Neutron absorbers and poisons are controlled for the fuel salt processes. The only materials in the fuel salt vessel are the eutectic FLiNaK salt, UF_4 fuel, and Ar gas.

4.1.7 Moderation

The moderation is controlled for the fuel salt processes. Water is removed from the salt during the purification process. The moderation provided by the PUR foam in the transport vessel is controlled by limiting the amount of liquid PUR before expansion.

4.1.8 Enrichment

The enrichment of uranium is controlled for the fuel salt processes. The enrichment is 19.75 mole % (19.55 wt %) ^{235}U and is regulated as a HALEU variant for non-proliferation use.

4.1.9 Reflection

The reflection is controlled for the fuel salt processes while the fuel salt vessel is in the support structures. The support structures provide adequate spacing between other materials to prevent reflection back into the fuel salt vessel.

The reflection is regulated during the transfer of the fuel salt vessel to and from the transport vessel but is not controlled. Caution is given so that no reflective material is brought near the fuel salt vessel during this process.

4.1.10 Temperature

The temperature is controlled for the fuel salt processes. The operating temperature during the mixing of the vessels ensures that the solubility limit is not exceeded as the UF_4 fuel is dissolved in the FLiNaK salt.

4.2 Normal Process Conditions

This section gives the normal process conditions for each of the processes described in Chapter 2. The processes were modeled using Serpent to provide a basis for the credible abnormal conditions to be identified in Section 4.3. Base models used for each of these processes are given in Appendix B.

4.2.1 Fuel Salt Preparation Processes

The first condition modeled during this step of the fuel salt preparation process is the mixing of the UF_4 fuel in the vessel. Figure 4.1 shows the initial and final state of the process. The set parameters of the mixing model include the temperature of the fuel, vessel salt, vessel, impellers, and Ar gas at 600 °C with the salt plug, surrounding air, concrete, and ground at room temperature. The total amount of FLiNaK salt is also constant. The UF_4 fuel is added to the mixing vessel in 30 unit increments of 17.540 kg which changes the composition of the fuel salt and the fluid. The volume of the Ar gas is adjusted using the pressure regulator. k_{eff} was calculated at each unit addition of the fuel to the salt. The results as a function of fuel loading concentration in mole % are given in Figure 4.2.

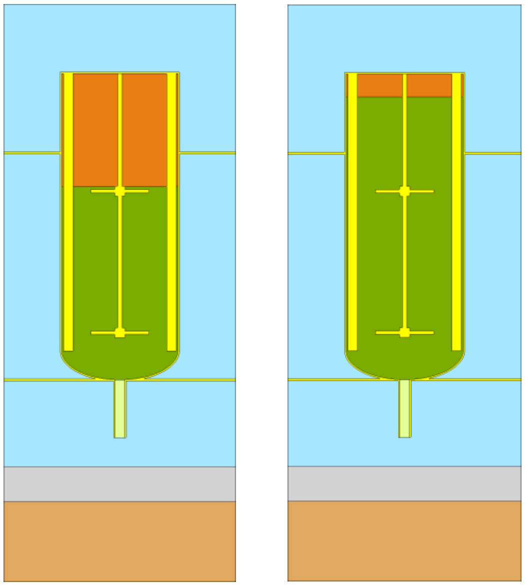

Figure 4.1. Initial and final state of the fuel mixing process.

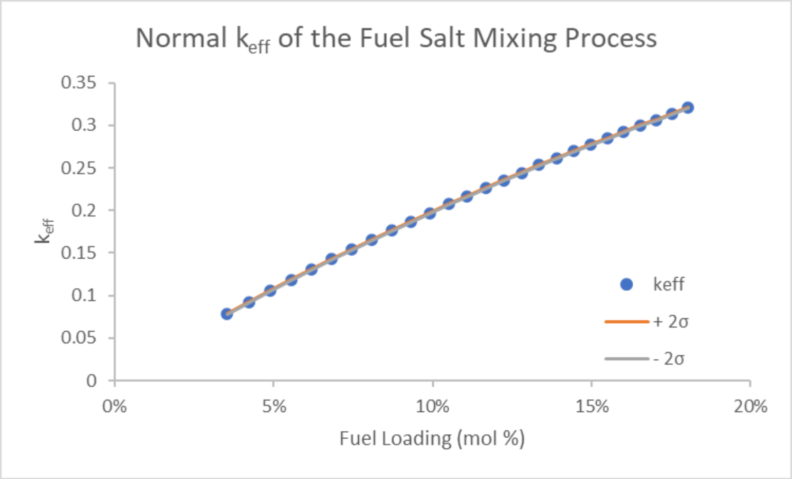

Figure 4.2. Normal k_{eff} of the fuel salt mixing process as a function of fuel loading.

As shown in Figure 4.2, k_{eff} is not measured until the 5th unit is loaded into the mixing vessel. This is because not enough multiplication was available in the model at these low fuel loading concentrations. The maximum normal k_{eff} value for this step of the process is 0.32088 ± 0.00063.

The last condition modeled in this step of the fuel salt preparation process is the cooling of the fuel salt vessel to room temperature. Figure 4.3 shows the initial and final state of this process. The set parameters of the cooling model include the mass and composition of the fuel salt and the temperature of the salt plug and surround materials. The temperature of the fuel salt, vessel, impellers, and Ar gas will be lowered from 600 °C to 454 °C (freezing point) in 10 °C increments and then lowered from 454 °C to room temperature in 25 °C increments. It is assumed that the temperature distribution is uniform throughout the fuel salt. The change in temperature changes the density and volume of the fuel salt as it cools. The volume of the Ar gas is adjusted using the pressure regulator. k_{eff} was calculated at each temperature change. The results as a function of temperature are given in Figure 4.4.

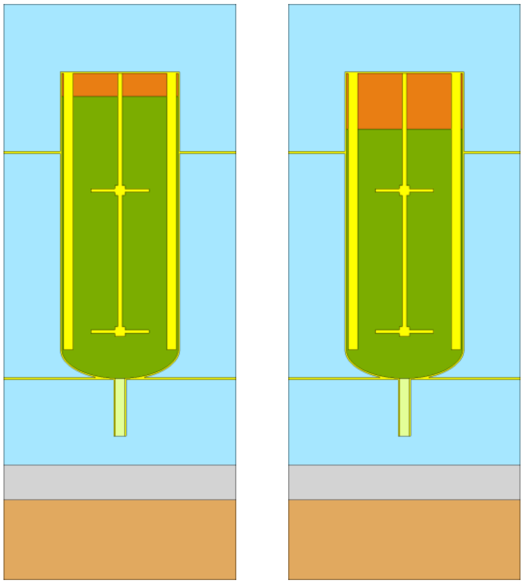

Figure 4.3. Initial and final state of the fuel salt cooling process.

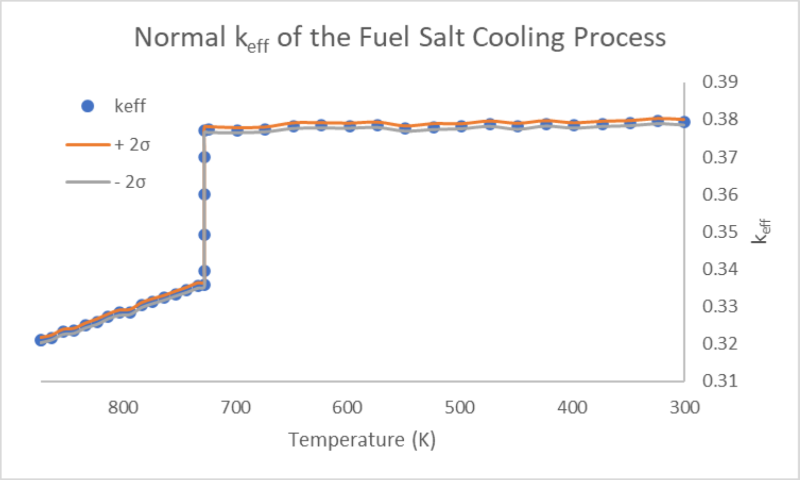

Figure 4.4. Normal k_{eff} of the fuel salt cooling process as a function of temperature.

As shown in Figure 4.4, k_{eff} increases with decreasing temperature which is mainly contributed to the increasing density of the fuel salt. At 727.15 K (454 °C), k_{eff} increases more quickly. This is due to the higher density of fuel as the fuel salt phase changes from liquid to solid. The phase change results in a smaller volume. These values were estimated using the liquid density of FLiNaK-UF_4 at the freezing point to the theoretical density of FLiNaK-UF_4 at room temperature. From the freezing point to room temperature, the density and fuel salt height remained the same while only the temperature decreased. The maximum normal k_{eff} value for this step of the process is 0.37916 ± 0.00071.

4.2.2 Storage Process

The storage model takes the final state of the fuel salt preparation process model and sets the fuel salt vessel in a 4x4 square array. There are 16 total vessels and their support structures, and the structures are in contact with each other with no gaps. Figure 4.5 shows the layout of the 4x4 array. The normal k_{eff} value for this arrangement is 0.46562 ± 0.00087.

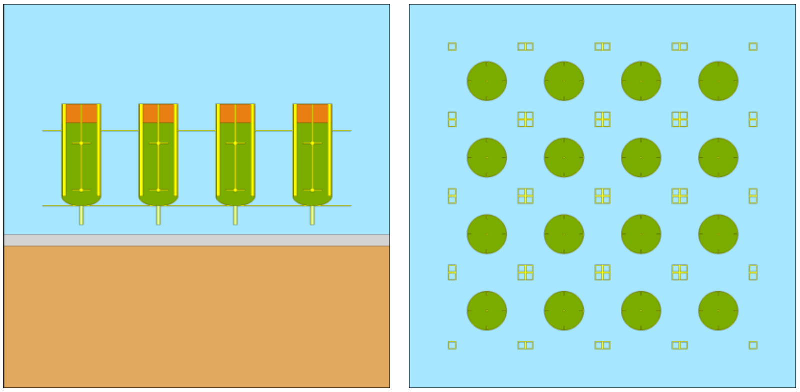

Figure 4.5. Example layout of the cold fuel salt vessels in storage.

4.2.3 Transportation Process

The transportation model takes the final state of the fuel salt preparation vessel model and sets four of the fuel salt vessels in the square array described in Section 2.3.1. There are two models for the transportation process. One with the 10-160B container on the ground and one on the bed of a trailer or rail car. The bed of the trailer/railcar was modeled to resemble a double drop-deck trailer or a depressed deck railcar. Figure 4.6 gives an example of a double drop-deck trailer carrying a 10-160B container [33]. Figure 4.7 and Figure 4.8 give the Serpent models of the 10-160B vessels on the ground and the trailer/railcar bed. Respectively, the normal k_{eff} values for the fuel salt in the 10-160B containers are 0.58603 ± 0.00096 and 0.58737 ± 0.00085. The effect of the neutron reflection from the trailer/railcar shows a little more reactivity than the ground. This is due to the density of the SS304 bed.

Figure 4.6. 10-160B container on a double dropdeck trailer bed.

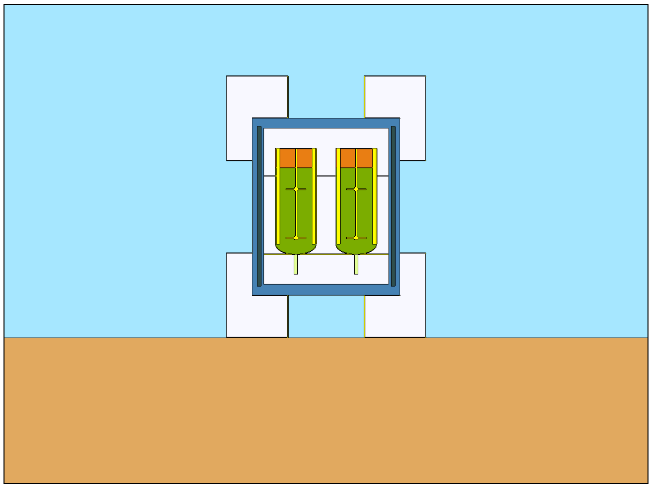

Figure 4.7. Layout of the 10-160B container on the ground.

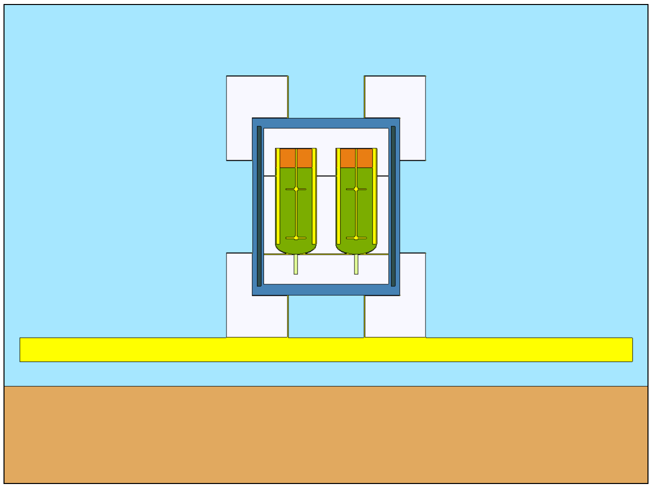

Figure 4.8. Layout of the 10-160B container on the trailer/railcar bed.

4.2.4 Unloading Process

The first condition modeled during the step of the fuel salt unloading process is the melting of the FLiNaK-UF$_4$ fuel salt to prepare it for unloading. Figure 4.9 shows the initial and final state of this process. The set parameters of the heating model include the mass and composition of the fuel salt and the temperature of the salt plug and surround materials. The temperature of the Ar gas is also set at 600 °C with the assumption that it will reach operating temperature before the fuel salt does. The temperature of the fuel salt, vessel, and impellers will be raised from room temperature to 454 °C in 25 °C increments and then raised from 454 °C to 600 °C in 10 °C increments. It is assumed that the temperature distribution is uniform throughout the fuel salt. The change in temperature changes the density and volume of the fuel salt as it heats. The volume of the Ar gas is adjusted using the pressure regulator. k_{eff} was calculated at each temperature change. The results as a function of temperature are given in Figure 4.10.

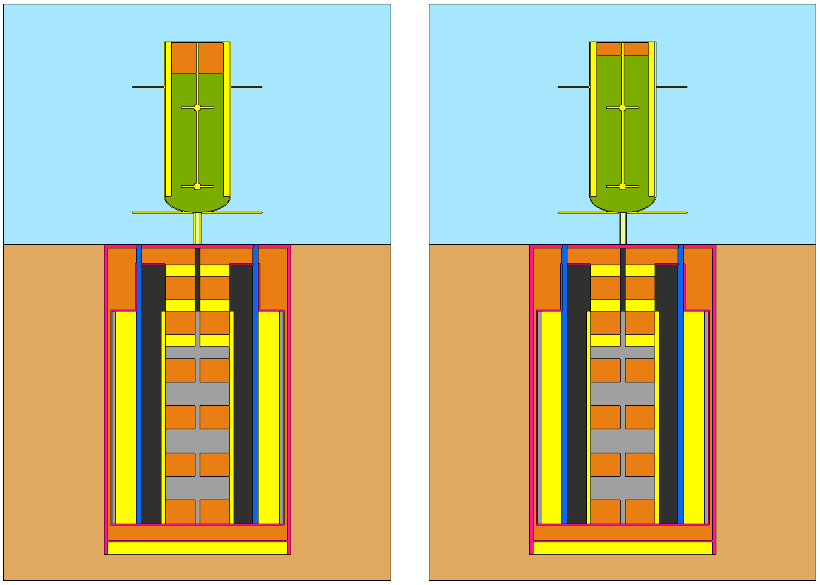

Figure 4.9. Initial and final state of the fuel salt melting process.

As shown in Figure 4.10, k_{eff} decreases with increasing temperature which is mainly contributed to the decreasing density of the fuel salt. This is to be expected since this process is essentially the reverse of the cooling process in Section 4.2.1. The maximum normal k_{eff} value for this step of the process is 0.37972 ± 0.00067. There is a negligible difference due to the reflection of the concrete in the cooling process versus the reflection of the MsNB during the melting process.

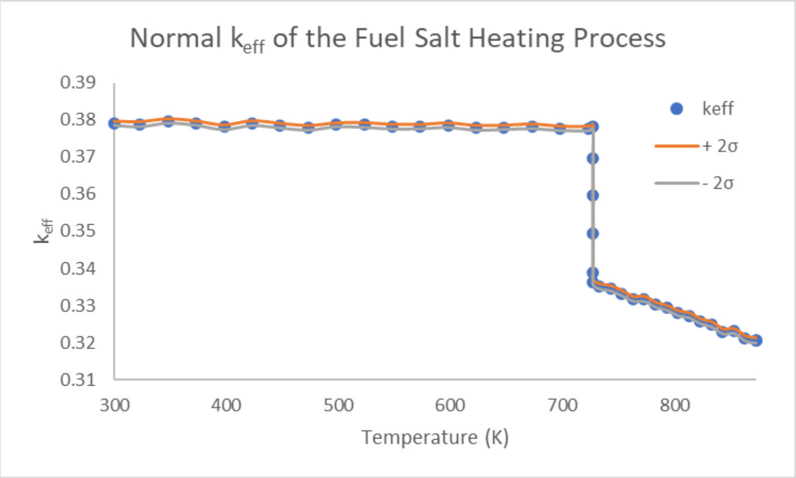

Figure 4.10. Normal k_{eff} of the fuel salt melting process as a function of temperature.

The last normal condition modeled during the step of the fuel salt unloading process is the draining of the fuel salt into the MsNB. The changing parameters are the liquid fuel salt height and the amount of Ar gas in the vessel. This draining of the fuel salt vessel is modeled by calculating k_{eff} at 5 cm increments. The results of this process are shown in Figure 4.11. As shown in the figure, k_{eff} decreases with decreasing fuel salt volume. As the fuel height reached the bottom of the vessel, there was not enough neutron multiplication in the system to calculate k_{eff} for this region. The maximum normal k_{eff} value for this step of the process is 0.31989 $\pm$ 0.00059.

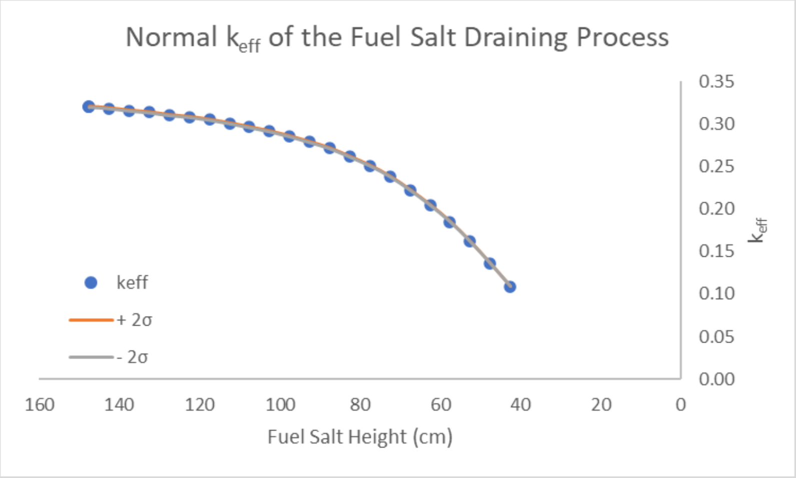

Figure 4.11. Normal k_{eff} of the fuel salt draining process as a function of fuel salt height.

4.3 Identify Credible Abnormal Conditions

The results of Section 4.2 show that the FLiNaK-UF$_4$ fuel salt is below the USL of 0.95 for the normal process conditions. This shows that during the normal processing of the fuel salt, the system remains subcritical. The maximum k_{eff} value of 0.58737 $\pm$ 0.00085 was calculated while the fuel salt was in transport. The next step of the NCSE is to identify credible abnormal conditions for this process that may lead to a critical excursion. This was done by performing a What-if analysis to identify these conditions. An event tree analysis was then performed to better visualize the results of the What-if analysis and apply the double contingency principle.

4.3.1 What-If Analysis

The first step of the What-If analysis is to ask the question “What-If?” The parameters to ask “What-If?” about are the parameters that influence the criticality safety of the system such as those in MAGIC MERV, MERMAIDS, and temperature. Each “What-If?” identifies a hazard and lists them in the What-If hazards identification table. These hazards are also separated into three process zones: 1) the fuel salt preparation and storage processes, 2) the transportation process, and 3) the fuel salt unloading process.

After the potential hazards have been identified, the next step of the analysis is to screen the hazards to determine if they are credible and if they have an impact on the criticality safety of the system. This screening is recorded in the What-If screening results table. If the hazard has been screened as a credible hazard, it is then analyzed in the contingency analysis section of the NCSE [34]. A pre-screening was also done before the hazard was listed in the screening results table. This pre-screening consisted of not listing the hazard if the consequence of the hazard led to a less reactive condition.

The What-If hazards identification table and the What-If screening results table are located in Appendix A. The first few rows of each table are given in Table 4.1 and Table 4.2 as an example of the What-If analysis process. These tables show examples of hazard identification, pre-screening, and screening results.

Table 4.1. What-If Hazards Identification Table Example.

No.	What-If	Causes	Consequences	Preventive Measures	Comments
Process Zone 1: Fuel Salt Preparation and Storage Processes					
1.1	What if too much fuel was added to the vessel?	• Operator error • Mechanical error	• Solubility limit exceeded • Fuel precipitation • Increased criticality	• Vessel volume limits • Set fuel loading increments • Set procedures and training • Regular maintenance	
1.2	What if too little fuel was added to the vessel?	• Operator error • Mechanical error	• Decreased criticality	• Set fuel loading increments • Set procedures and training • Regular maintenance	
1.3	What if the plug was shorter?	• Manufacturer error	• Potential melt and leak of salt/fuel salt on the floor • Potential critical excursion	• Active cooling • Secondary cap • Equipment quality check	
1.4	What if the plug was longer?	• Manufacturer error		• Equipment quality check	
1.5	What if the plug's diameter was wider?	• Manufacturer error	• Potential melt and leak of salt/fuel salt on the floor • Potential critical excursion	• Active cooling • Secondary cap • Equipment quality check	
1.6	What if the plug's diameter was narrower?	• Manufacturer error		• Equipment quality check	
1.7	What if the diameter was wider?	• Manufacturer error	• Longer neutron time in the vessel • Increased criticality	• Equipment quality check	
1.8	What if the diameter was narrower?	• Manufacturer error	• Shorter neutron time in the vessel • Decreased criticality	• Equipment quality check	
1.9	What if the impeller blades were higher?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	• Equipment quality check	
1.10	What if the impeller blades were lower?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	• Equipment quality check	
1.11	What if the impeller blades were wider?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	• Equipment quality check	
1.12	What if the impeller blades were narrower?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	• Equipment quality check	

Table 4.2. What-If Screening Results Table Example

No.	What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
Process Zone 1: Fuel Salt Preparation and Storage Processes						
1.1	What if too much fuel was added to the vessel?	• Operator error • Mechanical error	• Solubility limit exceeded • Fuel precipitation • Increased criticality	Credible		Yes Sec 4.3.1.1
1.3	What if the plug was shorter?	• Manufacturer error	• Potential melt and leak of salt/fuel salt on the floor • Potential critical excursion	Not Credible	• More likely that molten salt without fuel will leak before fuel leaks. • If fuel were to leak out, it will disperse into a less reactive shape than inside the vessel.	No
1.5	What if the plug's diameter was wider?	• Manufacturer error	• Potential melt and leak of salt/fuel salt on the floor • Potential critical excursion	Not Credible	• More likely that molten salt without fuel will leak before fuel leaks. • If fuel were to leak out, it will disperse into a less reactive shape than inside the vessel.	No
1.7	What if the diameter was wider?	• Manufacturer error	• Longer neutron time in the vessel • Increased criticality	Not Credible	• Diameter vs k_{eff} was considered in the design of the vessel. Negligible increase in criticality.	No
1.9	What if the impeller blades were higher?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.10	What if the impeller blades were lower?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.11	What if the impeller blades were wider?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.12	What if the impeller blades were narrower?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1

4.3.1.1 Precipitation of Fuel in the Fuel Salt Vessel

This upset condition may occur if 1) too much fuel was added to the vessel, 2) the impeller blades were at the wrong position in the vessel, 3) the impeller blades had the wrong dimensions, 4) the baffles were the wrong width, 5) the vessel head had the wrong shape or depth, 6) the added UF_4 fuel was too cold, or 7) the fuel salt mixture is below operating temperature. Other causes of fuel precipitation not listed in the What-If analysis include the mixer not turning on, the mixer speed is too slow, the impeller blade broke, or the fuel was added too quickly to the molten salt.

Operation of the mixer may be controlled by performing regular maintenance on the mixer and having set procedures and training to make sure that the mixer is set at the right rotation speed. Same controls can be set so that the fuel is not added too quickly to the molten salt.

The geometrical contingencies can be easily controlled by doing a material quality check on the vessel and impellers before it is employed for use. As discussed in Section 4.1.1, the mass is controlled by limiting the UF_4 feed material to 30 units of fuel. A quality check will be performed to ensure that each unit contains the correct amount of fuel. Additionally, the amount of fuel added to the vessel is limited to the volume of the vessel. If the total volume of the molten mixture exceeds the volume of the vessel, it will backflow into the feed unit and/or into the Ar gas line. Sensors may be placed at the top of the vessel that measures the density of the material. When a material with a density greater than the Ar gas is measured by the sensor, alarms will go off indicating that too much of the fuel salt mixture is in the vessel.

The last unlikely cause depends on the temperature of the fuel/fuel salt. If the temperature is too low, the solubility limit may be exceeded, and the fuel will not completely dissolve. This can be controlled by regular maintenance on the temperature controls, set procedures and training to ensure that the correct temperature is set, and a quality check to calibrate the thermocouples to give an accurate reading.

4.3.1.2 Interaction Between Vessels

This upset condition may occur if the fuel salt vessel interacts with another vessel while mixing, in storage, or transport. In storage, it is expected that the vessel will interact with other vessels. As discussed in Section 4.1.3, the support structures around the gap provide sufficient spacing to prevent an interaction that will lead to a critical incident under normal conditions. Additionally, Section 2.3.1.2 shows that when four fuel salt vessels are in contact with each other the fuel salt remains subcritical. This indicates that when two vessels interact with one another without any space in between, it may be assumed they will remain subcritical. Controls that may be put in place include having set procedures and training to limit the interaction between vessels and having additional neutron-absorbing barriers between vessels to further limit interaction.

4.3.1.3 Increase in Fuel Concentration

This unlikely event could occur if the concentration of the fuel in the salt was larger. This contingency is separate from Section 4.3.1.1 because of the possibility that the solubility limit was not exceeded and there was no fuel precipitation. A higher concentration of fuel could indicate either that there is not enough FLiNaK salt in the vessel or that too much fuel was added to the vessel. If too much fuel was added, controls like those in Section 4.3.1.1 can indicate an excess volume in the mixture. The amount of FLiNaK salt in the vessel can be controlled by set procedures and training, a liquid height indicator, and regular maintenance to keep equipment up to quality.

4.3.1.4 Moderation Introduced to System

This upset could occur if 1) there is flooding in the preparation or storage area, 2) the PUR foam was more compacted in the transport vessel, or 3) the water filled up the transport container before PUR foam was added.

The cause of a flood could be due to a natural disaster or to a mechanical error in the facility (e.g., pipe break). Controls that can be set in place include emergency pumps, elevating the vessels and structures, and regular maintenance in the facility to prevent breaks.

The PUR foam can be controlled by regulating set amounts of liquid PUR to be added to each section of the transport vessel. However, the density of PUR foam is low enough at 0.021 g/cm^3 that any additional amount of liquid PUR before it expands may be negligible to provide more reactivity.

Water entering the transport vessel before PUR is added is unlikely. This may be controlled by having set procedures and training to prevent any adequate source of water to be near the transport vessel during the fuel salt vessel loading and unloading process.

4.3.1.5 Increased Enrichment

This upset could occur if the ^{235}U enrichment exceeded the set value of 19.75 mole %. The UF_4 fuel will most likely be provided by a separate manufacturer or source. The event that the fuel will be too enriched is unlikely. Controls that can be set on the fuel enrichment include regulation controls and a material quality check on the UF_4 fuel.

4.3.1.6 Added Reflective Material

This contingency could occur if 1) the vessel was brought closer to a wall or surface, 2) a group of people surrounded the vessel, 3) some type of reflective material was brought closer to the vessel, 4) a reflector was added to the transport vessel, or 5) the vessel was brought closer to the wall of the transport vessel.

As mentioned in previous sections, the support structure is used as a control to provide additional space for the support structure. This prevents any unwanted material to be brought closer to the outside wall of the vessel. However, further controls will be set in place while the fuel salt vessel is being transferred to and from the transport vessel. Set procedures and training can be used as controls to limit reflective interaction between the vessel and other materials. Additional controls can be set to prevent any unwanted material from entering the transport vessel. As for the fuel salt vessel being brought closer to the wall of the transport vessel, results in Section 2.3.1.2 indicate that the fuel salt remains subcritical as the vessel near the walls of the container.

4.3.1.7 The Temperature Increased in or Around the Transport Container.

This unlikely event could occur if the transport vessel were encased in fire. The potential consequence could be that the fuel salt melts and drains from the vessels and pools on the floor of the container. One of the controls for this contingency is the controls already in place for the 10-160B Type B container. This container is certified for thermal exposure up to 1475 °F (801.7 °C) provided the thermal shield around the container [27]. Another control may include a secondary cap on the end of the drainpipe.

4.3.2 Event Tree Analysis

One of the control parameters for an NCSE is the double-contingency principle. This principle indicates that "process designs should incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible" [13]. An event tree analysis can be performed to identify these types of conditions using the hazards indicated by the What-If analysis.

Four event trees were made for four states of the fuel salt processes: 1) a single hot preparation vessel, 2) a single cold preparation vessel, 3) preparation vessels in storage, and 4) preparation vessels in transport. The hazards analyzed are 1) too much fuel added to the mixing vessel with no precipitation, 2) the fuel precipitated, 3) a reflective material was introduced, 4) flooding, and 5) the fuel salt vessel and support structure tipped over. The event tree takes each of these independent hazards as hazard events and combines them to see if a critical excursion occurs. The top branch of each event tree is given as a basis to show the criticality of the initial state without any hazards [35]. These combinations were modeled using Serpent.

The first event tree considered is the single hot preparation vessel. The first hazard was modeled by taking the normal amount of molten salt and adding enough UF_4 fuel until the total amount reaches the volume limit of the container while it is hot. The fuel loading at this state is 21.6 mole % UF_4. The second hazard was modeled by separating the fuel salt mixture into two levels with all the UF_4 fuel settled at the bottom with the molten FLiNaK salt on top. The density of the fuel on the bottom and the density of the molten salt are their densities at 600 °C as indicated by equations 2.1 and 2.2. The third hazard was modeled by placing a square container around the vessel and fuel structure. The container is made of beryllium oxide (BeO) and is 14.5 cm thick. This is the thickest portion of the reflective material used in the MsNB. The inside walls of the container are touching the top of the fuel salt vessel and the outside of the support structure. The fourth hazard was modeled by replacing the surrounding air with water. The fifth hazard was modeled by placing the vessel and support structure on its side parallel to the concrete floor. Figure 4.12 shows models for each of these independent cases compared to the normal case. Figure 4.14 gives the event tree for these hazards.

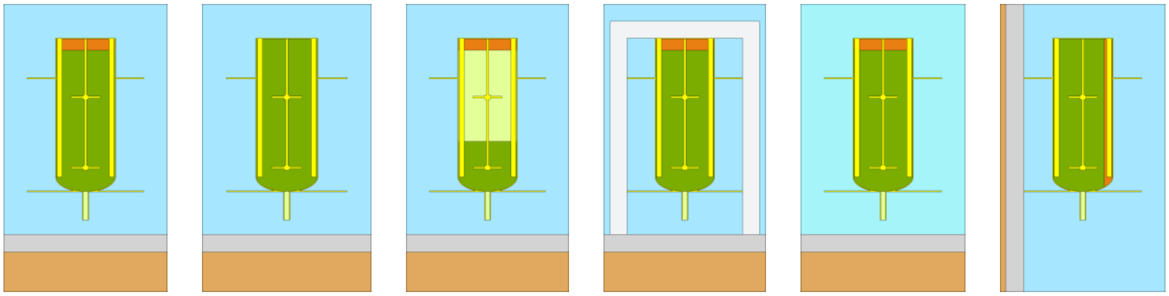

Figure 4.12. Serpent models of the hazards for event tree 1. The first image is the normal case, and the following images are respectively hazard models 1 through 5.

The second event tree is similar to the first. The only difference is that the fuel salt mixture is cold rather than hot. The same amount of salt and fuel is used in both hot and cold cases. The same fuel density was also used in the cold case due to the assumption the precipitated fuel is solid in both cases. Figure 4.13 shows models for each of these independent cases compared to the normal case. Figure 4.15 gives the event tree for these hazards.

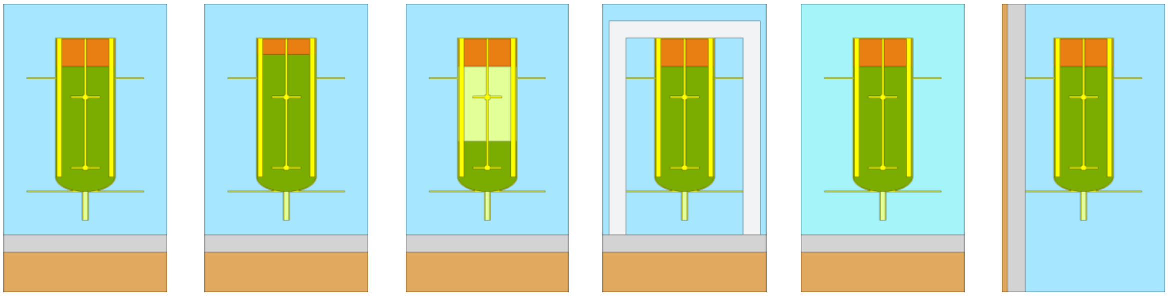

Figure 4.13. Serpent models of the hazards for event tree 2. The first image is the normal case, and the following images are respectively hazard models 1 through 5.

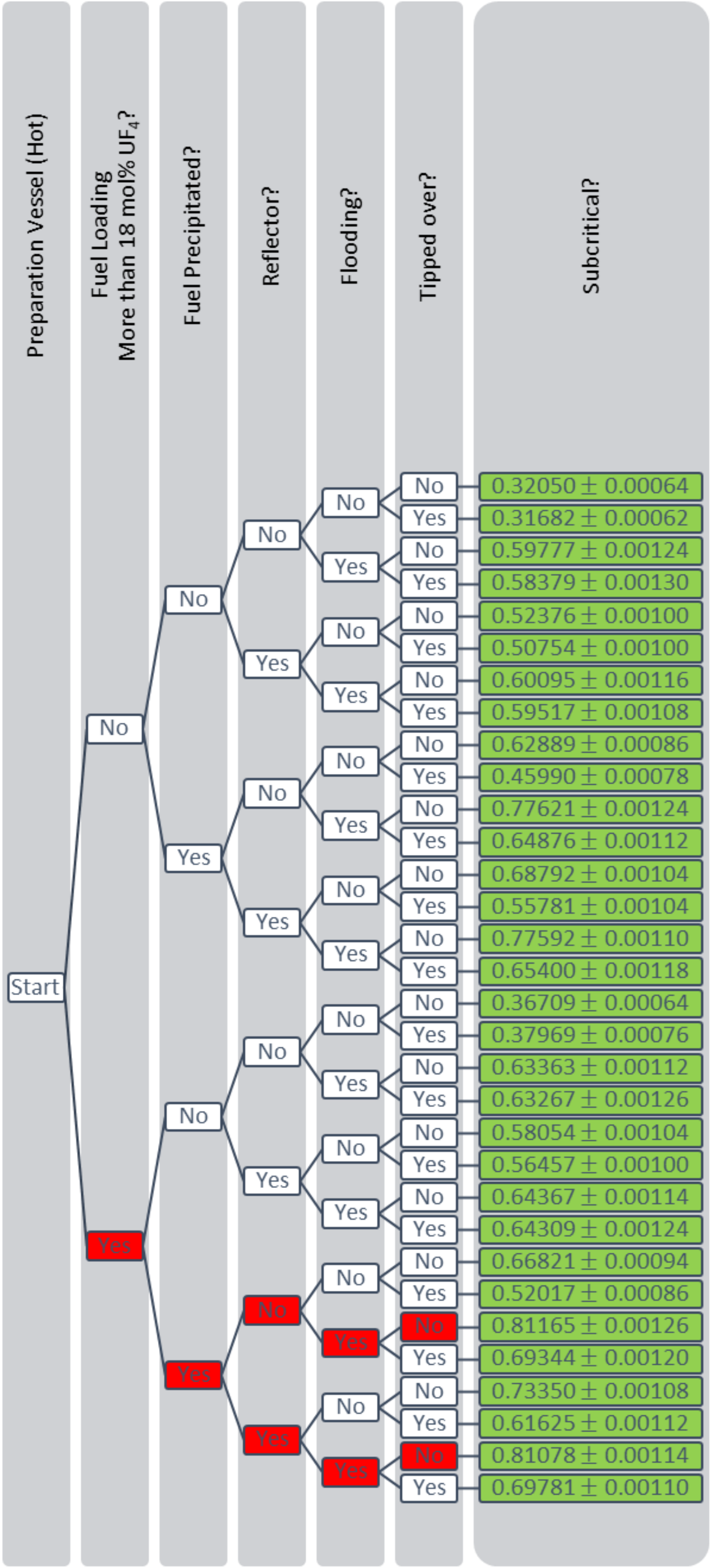

Figure 4.14. Event tree 1. A single hot preparation vessel with potential hazards.

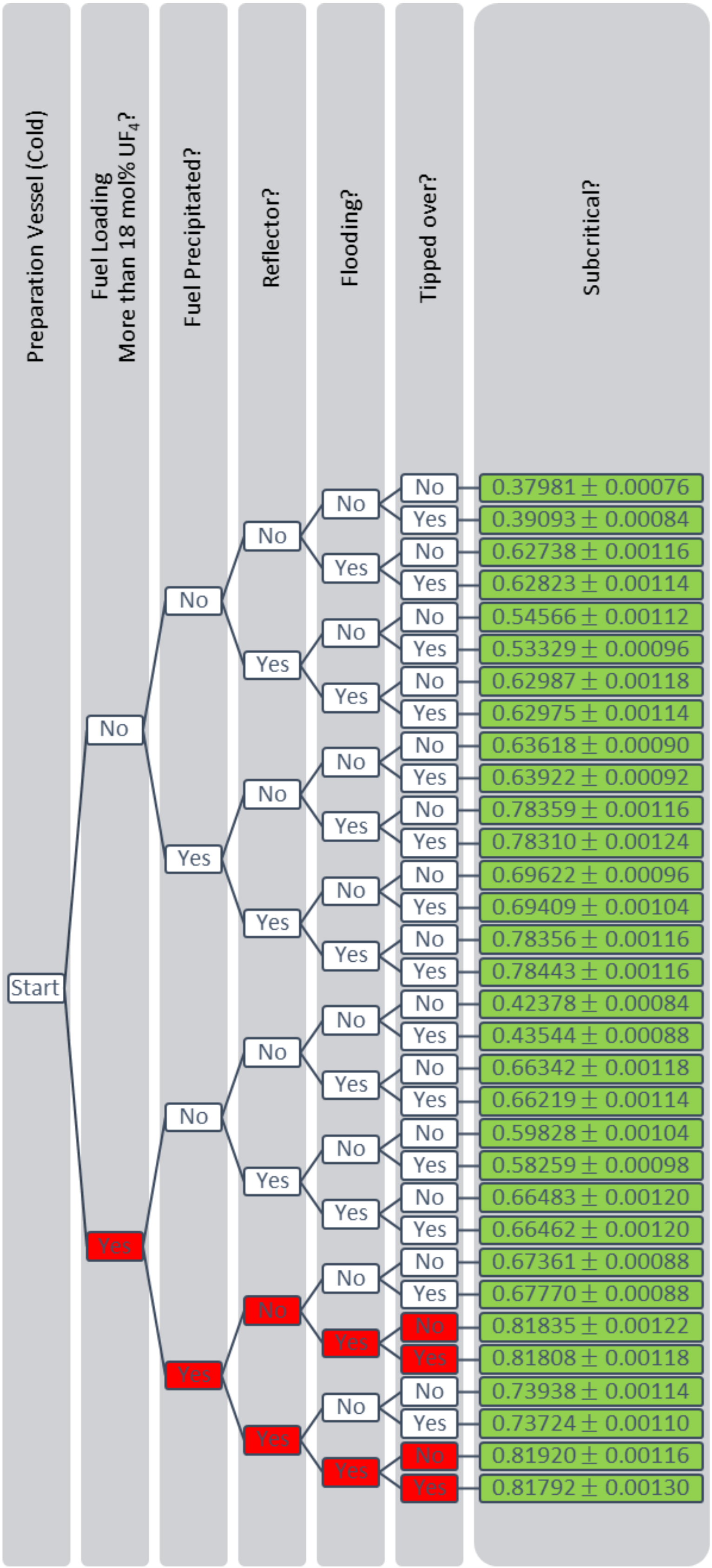

Figure 4.15. Event tree 2. A single cold preparation vessel with potential hazards.

The most critically reactive event paths with k_{eff} greater than 0.80 are shown in red for Figure 4.14 and Figure 4.15. Even though these paths are the most reactive they are still below the USL and are subcritical.

For the hot preparation vessel, the most reactive paths have conditions where there is too much fuel in the vessel, the fuel has precipitated, there is flooding, and the vessels are standing up. The addition of the reflector did not appear to increase the reactivity significantly for these cases. The water provides enough moderation that by the time the neutron was reflected by the BeO, its energy had already thermalized. Figure 4.16 shows this phenomenon where the relative fission power is in shades of red and yellow and the thermal flux (less than 0.625 eV) is in shades of blue.

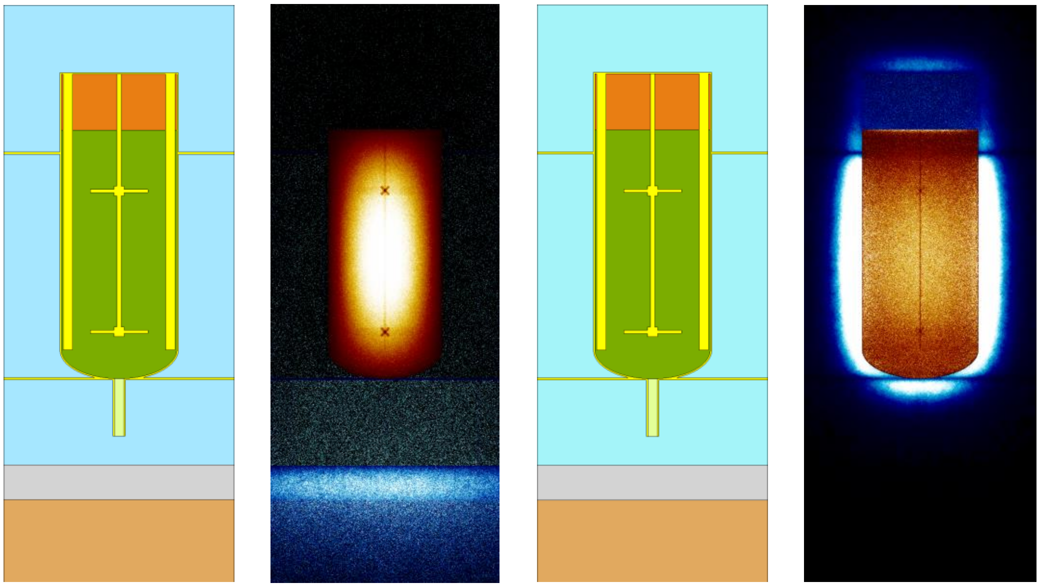

Figure 4.16. Visualization of the neutron thermalization due to moderation by water.

For the cold preparation vessel, the most reactive paths have the same conditions as the hot preparation vessel except the vessel is also reactive when it is tipped over. This can be attributed to the shape of the fuel salt mixture. When the mixture is hot, it is molten and can form its shape to vessel and becomes less reactive. When the mixture is cold, it is a solid mass and does not change shape to fit the new orientation. The cold vessel keeps has the same reactivity upright or on its side.

The third event tree is of the cold vessel in storage. The hazards are the same as those for a single preparation vessel, but it is assumed that the vessel and support structure will remain upright due to the self-support nature of the vessels in the array. It is also assumed that no reflectors will be introduced to the storage area and that controls are in place to prevent this hazard. The vessels are arranged as is described in Section 4.2.2. The resulting event tree is given in Figure 4.17.

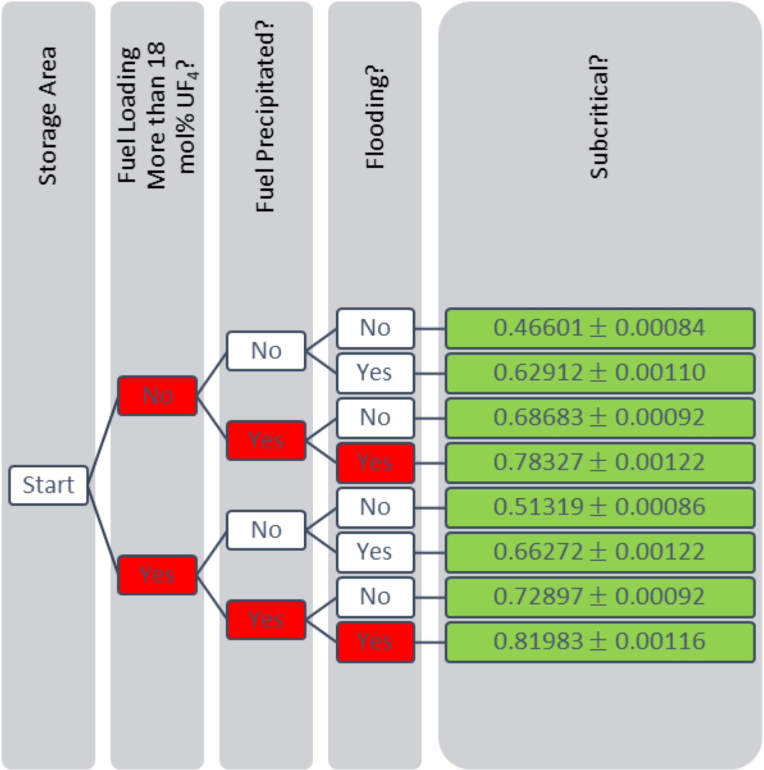

Figure 4.17. Event tree 3. Cold preparation vessels in storage with potential hazards.

The most reactive event paths with k_{eff} greater than 0.75 are shown in red for Figure 4.17. The combination of hazards for the storage area still results in a subcritical system. The conditions that lead to the most reactive paths are when the fuel precipitates and there is flooding in the storage area. The fuel loading also contributes to a more reactive system and the normal process of fuel loading with flooding and precipitation also leads to a slightly less reactive system.

The fourth event tree is of the cold vessels in transportation. The hazards are the same as those for the storage area but on a smaller four-vessel scale with the addition of the PUR foam rather than only air surrounding the vessels. The assumption is also the same that no reflective materials are introduced to the transport vessel and that controls are in place to prevent this hazard. The arrangement of the vessels is described in Section 2.3.1.2. The resulting event tree is given in Figure 4.18.

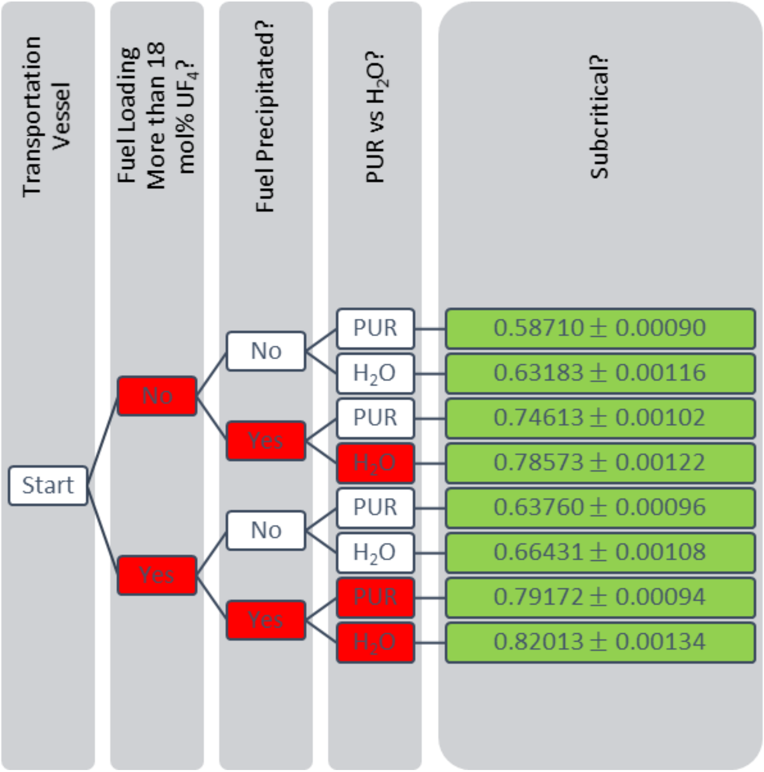

Figure 4.18. Event tree 4. Cold preparation vessels in the transport vessel with potential hazards.

The most reactive event paths with k_{eff} greater than 0.75 are shown in red for Figure 4.18. The combination of hazards for the storage area is still subcritical for this system. The conditions that lead to the most reactive paths are similar to those for the storage area with the addition of the PUR foam with too much fuel and precipitated fuel.

Looking at all four event trees, the contributing conditions that lead to the most reactive system are the combination of too much fuel, fuel precipitation, and flooding. Controls for these are given in Sections 4.3.1.3, 4.3.1.1, and 4.3.1.4, respectively. Giving priority to these controls satisfies the double-contingency principle.

The one hazard that was not addressed in the event tree analysis was having an increase in fuel enrichment. The question can be asked to what enrichment would be sufficient to exceed the USL for the worst-case hazard scenario. A quick case study took the most reactive event path in the transport vessel and increased the fuel enrichment until the USL was exceeded with a k_{eff} value of 0.94887 ± 0.00121. The conditions that led to this case were 1) a fuel enrichment of 28.7 mole % ^{235}U, 2) a fuel loading of 21.6 mole % UF_4, 3) fuel precipitation, and 4) water flooding the transport vessel. As stated before, the event that this will occur is unlikely.

4.4 Conclusions

The fuel salt preparation and handling process have been evaluated both under normal and credible abnormal conditions. This evaluation has shown that the processes have remained subcritical. In addition, the What-if and event tree analyses have shown that the abnormal conditions have satisfied the Double-Contingency Principle or have not been determined to be credible events.

Chapter 5: Summary of Controls and Assumptions

The controls and the assumptions established and determined during the process analysis are summarized in this chapter.

5.1 Passive Design Features

The following are passive design features indicated by the NCSE. These will be applied and maintained for the fuel salt preparation and handling processes.

5.1.1 The fuel is loaded using 30 equal units of UF_4.

This feature provides criticality safety by reducing the density and concentration of fuel to one single unit. It also provides the operator a set number of units to fill the preparation vessel.

5.1.2 The FLiNaK-UF_4 mixture is split into four preparation vessels.

This provides the same features as Section 5.1.1. It provides a set number of preparation vessels needed to fill the MsNB.

5.1.3 The geometry of the preparation vessel is specified.

This passive design feature ensures that the fuel salt will be prepared and stored in a favorable geometry. It also limits the amount of fuel that may be added to the mixing vessel.

5.1.4 The support structure provides additional spacing from other vessels and materials.

This passive design feature provides criticality safety by setting the space between objects around the fuel salt vessel. This helps to limit 1) interaction with other vessels, 2) the effects of moderation during a flood, and 3) the effects of neutron reflection from other materials.

5.1.5 The pitch in the transportation container provides sufficient spacing between vessels and materials.

This feature provides criticality safety in the transportation container to limit the interaction between vessels and the walls of the container.

5.1.6 Only specified amounts of FLiNaK salt and UF_4 fuel are added to each vessel.

This feature ensures that the concentration of fuel salt is correct and critically safe.

5.1.7 Only the FLiNaK salt, UF_4 fuel, and Ar gas are present in the vessel during the mixing operation.

This design feature ensures that are not any unwanted moderator, reflector, or neutron poisons in the fuel salt mixture.

5.1.8 Multiple emergency pumps are installed and maintained in the event of flooding.
The passive design feature helps to limit the effects of moderation.

5.1.9 Set amounts of PUR liquid (before expansion) are specified for each section inside the transportation vessel.
This feature limits the density of the PUR foam which also limits the effects of moderation.

5.1.10 The operating temperature is set at 600 °C.
This passive safety feature ensures that the solubility limit is not exceeded to prevent precipitation of the fuel.

5.1.11 A secondary cap is placed on the drainpipe.
This passive design feature ensures that the fuel salt mixture stays in the vessel in the event of extreme temperatures.

5.1.12 Measuring devices shall be implemented.
These passive design features may include a liquid height sensor, thermocouples, and density sensors to ensure that the correct conditions are maintained for the fuel salt mixing process.

5.2 Active Design Features

The following are active design features indicated in the NCSE. This will be applied and maintained for the fuel salt preparation and handling processes.

5.2.1 Active use of bracers and tie-downs.
If the vessel and structure are stationary for any amount of time, bracers and/or tie-downs will be attached to the support structure as safeguards to prevent it from tipping over in the event of an accident.

5.2.2 Active cooling on salt plug
The drainpipe is sufficiently long that more than 75 % of the length of the plug will remain solid during mixing operations. The cooling provides an additional safeguard.

5.3 Administratively Controlled Limits and Requirements

The following are administrative control limits and requirements that will provide additional safety to personnel at the facility.

5.3.1 Set procedures and training are implemented.
Human reliability is important to ensure the criticality safety of a facility. Proper procedures and training will provide the operators the necessary tools to handle the fuel salt preparation and handling

processes safely. They will ensure that procedure steps such as those specified in Sections 2.1.2 are followed.

5.3.2 Unnecessary materials are restricted from the fuel salt mixing, storage, and transportation areas of the facility.

This administrative control can prevent unwanted materials such as reflectors or moderators from entering controlled spaces.

5.3.3 Regular maintenance implemented.

Regular maintenance is important to ensure that the equipment is working correctly. This includes the vessels, structures, measuring devices, mixers, moving equipment, facility, etc.

5.3.4 Regular material quality checks implemented.

Material quality checks ensure that the parameters of the fuel salt preparation and handling processes are maintained. This includes the vessel and support structure geometry, the enrichment of the UF_4 fuel, the amount of UF_4 fuel in each of the 30 units, calibration of measuring devices, etc.

5.4 Assumptions

The assumptions made during the NCSE are reiterated as follows:

- Volume additivity in the average mixture density equation.
- The fuel is evenly distributed inside the fuel salt mixture.
- The temperature is uniformly distributed inside the fuel salt mixture.
- The drainpipe is an infinitely long cylindrical pin.
- The precipitated fuel’s density is the same for the cold and hot cases in the event tree analysis.
- There are no reflectors present in the storage area and transportation vessel.
- The vessels are self-supporting and do not tip over in the storage area.
- The upper subcritical limit is 0.95.
- The fuel salt preparation process is in an inert, closed system.

Chapter 6: Summary, Future Work, and Conclusion

6.1 Summary

A Nuclear Criticality Safety Evaluation was performed for the fuel salt preparation and handling processes. This evaluation was performed by following the outline given in DOE-STD-3007-2017 to show and document that the process will remain subcritical both in normal and abnormal conditions. A description of the process was given, and the process analysis was done by calculating the criticality of the system under normal conditions using Serpent 2.1.31. These calculations show that the processes are subcritical under normal conditions. The abnormal conditions were identified and screened to determine if they are credible by performing a What-If analysis. Controls to prevent a critical accident were set for these abnormal conditions. After the What-If analysis, an event tree analysis was performed for the credible abnormal conditions to show that the set controls provide safety under the Double-Contingency Principle.

6.2 Future Work

Future work that needs to be performed before these processes can be employed include, and are not limited to, the following:

- Research to determine the actual density correlation of the FLiNaK-UF_4 fuel salt mixture.
- Additional stress analysis to show that the preparation vessel will remain safe under multiple conditions. These additional stress analyses may include a drop test, stress from centrifugal forces, stress from lifting the vessel, etc.
- Experiments to determine the necessary mixer rotation speed and vessel geometry to ensure that the fuel salt mixture is well-mixed.
- Further work to validate molten fuel salt systems.
- Coupling of the Serpent code with other codes such as computational fluid dynamic models are thermodynamic codes. This will give a clearer picture of the reactivity effects of fuel mass distribution and temperature distribution inside the mixing vessel.
- Risk assessment analyses to determine other hazards than those that lead to a criticality accident.
- Additional risk assessment analyses during the transportation process to ensure the criticality safety of this step of the handling process.
- Research into potential uses of the fuel salt preparation vessel for spent fuel reprocessing.

6.3 Conclusion

In conclusion, the proposed fuel salt preparation and handling process designs have been determined to be subcritical under both normal and abnormal conditions. The was determined following the standards and directions given in the DOE-STD-3007-2017 technical standard.

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Appendix A - What-If Analysis Tables

Table A.1. What-If Hazards Identification Table

No.	What-If	Causes	Consequences	Preventive Measures	Comments
Process Zone 1: Fuel Salt Preparation and Storage Processes					
1.1	What if too much fuel was added to the vessel?	• Operator error • Mechanical error	• Solubility limit exceeded • Fuel precipitation • Increased criticality	• Vessel volume limits • Set fuel loading increments • Set procedures and training • Regular maintenance	
1.2	What if too little fuel was added to the vessel?	• Operator error • Mechanical error	• Decreased criticality	• Set fuel loading increments • Set procedures and training • Regular maintenance	
1.3	What if the plug was shorter?	• Manufacturer error	• Potential melt and leak of salt/fuel salt on the floor • Potential critical excursion	• Active cooling • Secondary cap • Equipment quality check	
1.4	What if the plug was longer?	• Manufacturer error		• Equipment quality check	
1.5	What if the plug's diameter was wider?	• Manufacturer error	• Potential melt and leak of salt/fuel salt on the floor • Potential critical excursion	• Active cooling • Secondary cap • Equipment quality check	
1.6	What if the plug's diameter was narrower?	• Manufacturer error		• Equipment quality check	
1.7	What if the diameter was wider?	• Manufacturer error	• Longer neutron time in the vessel • Increased criticality	• Equipment quality check	
1.8	What if the diameter was narrower?	• Manufacturer error	• Shorter neutron time in the vessel • Decreased criticality	• Equipment quality check	
1.9	What if the impeller blades were higher?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	• Equipment quality check	

No.	What-If	Causes	Consequences	Preventive Measures	Comments
1.10	What if the impeller blades were lower?	- Manufacturer error	- Inefficient mixing - Fuel settling - Potential critical excursion	- Equipment quality check	
1.11	What if the impeller blades were wider?	- Manufacturer error	- Inefficient mixing - Fuel settling - Potential critical excursion	- Equipment quality check	
1.12	What if the impeller blades were narrower?	- Manufacturer error	- Inefficient mixing - Fuel settling - Potential critical excursion	- Equipment quality check	
1.13	What if the baffles were wider?	- Manufacturer error	- Inefficient mixing - Fuel settling - Potential critical excursion	- Equipment quality check	
1.14	What if the baffles were narrower?	- Manufacturer error	- Inefficient mixing - Fuel settling - Potential critical excursion	- Equipment quality check	
1.15	What if the vessel head’s depth was lower?	- Manufacturer error	- Inefficient mixing - Fuel settling - Potential critical excursion	- Equipment quality check	
1.16	What if the vessel head’s depth was higher?	- Manufacturer error	- Inefficient mixing - Fuel settling - Potential critical excursion	- Equipment quality check	
1.17	What if the vessel thickness was thinner?	- Manufacturer error	- Less reflection - Decreased criticality	- Equipment quality check	
1.18	What if the vessel thickness was thicker?	- Manufacturer error	- More reflection - Increased criticality	- Equipment quality check	
1.19	What if the vessel cylinder was taller?	- Manufacturer error	- Increased space for expansion and extra fuel - Potential of increased criticality	- Equipment quality check	
1.20	What if the vessel cylinder was shorter?	- Manufacturer error	- Decreased space for expansion and extra fuel	- Equipment quality check	

No.	What-If	Causes	Consequences	Preventive Measures	Comments
1.21	What if the vessel interacts with another vessel while mixing?	• Operator error • Procedure error	• Increased criticality • Potential critical excursion	• Support structures to space out vessels • Set procedures and training	
1.22	What if the vessel interacts with another vessel in storage?	• Operator error	• Increased criticality • Potential critical excursion	• Support structures to space out vessels • Set procedures and training	
1.23	What if the volume of the vessel was larger?	• Manufacturer error	• Increased space for expansion and extra fuel • Longer neutron time in the vessel • Potential of increased criticality	• Equipment quality check	
1.24	What if the volume of the vessel was smaller?	• Manufacturer error	• Decreased space for expansion and fuel • Shorter neutron time in the vessel • Decreased criticality	• Equipment quality check	
1.25	What if the concentration of the fuel in the salt was larger?	• Operator error • Mechanical error	• Solubility limit exceeded • Fuel precipitation • Increased criticality	• Vessel volume limits • Set procedures and training • Regular maintenance	Fuel concentration larger due to lack of molten salt.
1.26	What if the concentration of the fuel in the salt was smaller?	• Operator error • Mechanical error	• Decreased criticality	• Set procedures and training • Regular maintenance	Fuel concentration smaller due to too much molten salt.
1.27	What if a neutron poison was added to the salt?	• Operator error	• Decreased criticality	• Set procedures and training • Label of materials	Accidently added to the vessel.
1.28	What if water was added on top of the cooled fuel salt?	• Human Error	• Increased reflection • Increased moderation • Increased criticality • Potential critical excursion	• Set procedures and training • System checks before operating • Pipe check	Water remaining in the system after leak check. Open valve, etc.
1.29	What if flooding occurred in the mixing area?	• Mechanical error • Natural disaster	• Increased criticality • Potential critical excursion • Rapid cooling, cracked vessel, leak	• Regular maintenance • Emergency pumps • Elevated structure	

No.	What-If	Causes	Consequences	Preventive Measures	Comments
1.30	What if flooding occurred in the storage area?	• Mechanical error • Natural disaster	• Increased criticality • Potential critical excursion	• Regular maintenance • Emergency pumps • Elevated structures	
1.31	What if the ^{235}U enrichment increased?	• Manufacturer error	• Increased criticality • Potential critical excursion	• Material quality check	
1.32	What if the ^{235}U enrichment decreased?	• Manufacturer error	• Decreased criticality	• Material quality check	
1.33	What if the vessel was lowered closer to the floor?	• Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	• Set procedures and training • Regular maintenance • Support structure to limit space from floor	
1.34	What if the vessel was brought closer to a wall or other surface?	• Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	• Set procedures and training • Regular maintenance • Support structure to limit space from other surfaces	
1.35	What if a group of people surrounds the vessel?	• Human error	• Increased reflection • Increased criticality • Potential critical excursion	• Set procedures and training • Support structure to limit space from operators	
1.36	What if some type of reflective material was brought closer to the vessel?	• Operator error	• Increased reflection • Increased criticality • Potential critical excursion	• Set procedures and training • Support structure to limit space from other surfaces	Ex. BeO sheet carried through the facility
1.37	What if the vessel (hot) and structure were horizontal to the floor?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Cracked vessel, leak • Potential critical excursion	• Bracers to prevent the vessel from tipping over • Support structure to limit space from floor • Set procedures and training • Regular maintenance	

No.	What-If	Causes	Consequences	Preventive Measures	Comments
1.38	What if the vessel (cold) and structure were horizontal to the floor?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	• Bracers to prevent the vessel from tipping over • Support structure to limit space from floor • Set procedures and training • Regular maintenance	
1.39	What if the vessel (hot) and structure were horizontal to the floor and surrounded by water?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Rapid cooling, cracked vessel, leak • Potential critical excursion	• Bracers to prevent the vessel from tipping over • Support structure to limit space from floor • Set procedures and training • Regular maintenance	
1.40	What if the vessel (cold) and structure were horizontal to the floor and surround by water?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	• Bracers to prevent the vessel from tipping over • Support structure to limit space from floor • Set procedures and training • Regular maintenance	
1.41	What if a fire occurred in the facility?	• Mechanical error • Electrical error	• Potential plug melt and leak • Potential critical excursion and radiation exposure	• Active cooling • Secondary Cap • Fire suppression system	
1.42	What if the added fuel is cooler than 600 °C?	• Operator error • Mechanical error	• Freezing salt • Fuel precipitation and settling • Increased criticality • Potential critical excursion	• Set procedures and training • Regular maintenance	
1.43	What if the added fuel is hotter than 600 °C?	• Operator error • Mechanical error		• Set procedures and training • Regular maintenance	

No.	What-If	Causes	Consequences	Preventive Measures	Comments
1.44	What if the vessel was too cold before adding the molten salt?	• Operator error • Mechanical error	• Freezing salt • Fuel precipitation and settling • Increased criticality • Potential critical excursion	• Set procedures and training • Regular maintenance	
1.45	What if the vessel was too hot before adding the molten salt?	• Operator error • Mechanical error	• Cracked vessel, leak • Potential critical excursion and radiation exposure	• Set procedures and training • Regular maintenance	
1.46	What if the fuel salt mixture is below operating temperature?	• Operator error • Mechanical error	• Fuel precipitation and settling • Increased criticality • Potential critical excursion	• Set procedures and training • Regular maintenance	
1.47	What if the fuel salt mixture is above operating temperature?	• Operator error • Mechanical error	• Volume expansion • Decreased criticality	• Vessel volume limits • Set fuel loading increments • Set procedures and training • Regular maintenance	
	Process Zone 2: Transportation Process				
2.1	What if the transport vessel's volume was larger?	• Manufacturer error	• Increased space between walls and storage vessels • Less reflection • Decreased criticality	• Equipment quality check	
2.2	What if the transport vessel's volume was smaller?	• Manufacturer error	• Decreased space between walls and storage vessels • More reflection • Potential of increased criticality	• Equipment quality check	
2.3	What if the pitch between storage vessels was larger?	• Manufacturer error • Operator error	• Decreased interaction with other storage vessels • Increased reflection from the wall • Overall decreased criticality	• Equipment quality check • Set procedures and training	

No.	What-If	Causes	Consequences	Preventive Measures	Comments
2.4	What if the pitch between storage vessels was smaller?	• Manufacturer error • Operator error	• Increased interaction with other storage vessels • Decreased reflection from the wall • Overall increased criticality	• Equipment quality check • Set procedures and training	
2.5	What if the shielding was thicker?	• Manufacturer error	• Increased reflection • Increased criticality	• Equipment quality check	
2.6	What if the shielding was thinner?	• Manufacturer error	• Decreased reflection • Decreased criticality	• Equipment quality check	
2.7	What if PUR was more compacted?	• Manufacturer error • Operator error	• Increased moderation • Increased criticality	• Material quality check • Set procedures and training	
2.8	What if PUR was less compacted?	• Manufacturer error • Operator error	• Decreased moderation • Decreased criticality	• Material quality check • Set procedures and training	
2.9	What if the bed of the rail car/trailer was thicker?	• Manufacturer error	• Increased reflection • Potential of increased criticality	• Equipment quality check	
2.10	What if the bed of the rail car/trailer was thinner?	• Manufacturer error	• Decreased reflection	• Equipment quality check	
2.11	What if the transport vessel was taller?	• Manufacturer error	• Decreased reflection from other surfaces	• Equipment quality check	
2.12	What if the transport vessel was shorter?	• Manufacturer error	• Increased reflection from other surfaces • Potential of increased criticality	• Equipment quality check	
2.13	What if PUR was replaced by water?	• Operator error • Mechanical error	• Increased moderation • Increased criticality	• Set procedures and training • Regular maintenance	
2.14	What if the transport vessel was submerged in water?	• Transport accident • Natural disaster	• Increased reflection • Potential of increased criticality	• Set procedures and training • Elevated position • Flooding barrier • Emergency pumps	

No.	What-If	Causes	Consequences	Preventive Measures	Comments
2.15	What if the transport vessel was on its side (horizontal)?	• Natural disaster • Operator error	• Increased reflection • Potential of increased criticality	• Bracers to prevent transport vessel from tipping over • Set procedures and training	
2.16	What if the transport vessel was encased in a fire?	• Natural disaster • Mechanical error • Electrical error	• Potential plug melt and leak onto transport vessel floor • Potential critical excursion and radiation exposure	• Secondary cap • Fire suppression system	
2.17	What if a neutron poison was added to the transport vessel?	• Operator error	• Decreased criticality	• Set procedures and training	
2.18	What if a reflector was added to the transport vessel?	• Operator error	• Increased criticality • Potential of critical excursion	• Set procedures and training	
2.19	What if the storage vessel (cold) was lying horizontal to the floor?	• Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential of critical excursion	• Set procedures and training • Regular maintenance	Ex. During the transfer of storage vessel into or out of transport vessel
2.20	What if too much fuel was added to the storage vessels?	See No. 1.1			
2.21	What if too little fuel was added to the storage vessels?	See No. 1.2			
2.22	What if the storage vessel plug was shorter?	See No. 1.3			
2.23	What if the storage vessel plug was too long?	See No. 1.4			
2.24	What if the storage vessel plug’s diameter was wider?	See No. 1.5			
2.25	What if the storage vessel plug’s diameter was narrower?	See No. 1.6			
2.26	What if the storage vessel’s diameter was wider?	See No. 1.7			
2.27	What if the storage vessel’s diameter was narrower?	See No. 1.8			
2.28	What if the storage vessel’s baffles were wider?	See No. 1.13			
2.29	What if the storage vessel’s baffles were narrower?	See No. 1.14			
2.30	What if the storage vessel head’s depth was lower?	See No. 1.15			

No.	What-If	Causes	Consequences	Preventive Measures	Comments
2.31	What if the storage vessel head's depth was higher?	See No. 1.16			
2.32	What if the storage vessel thickness was thinner?	See No. 1.17			
2.33	What if the storage vessel thickness was thicker?	See No. 1.18			
2.34	What if the storage vessel cylinder was taller?	See No. 1.19			
2.35	What if the storage vessel cylinder was shorter?	See No. 1.20			
2.36	What if the volume of the storage vessel was larger?	See No. 1.23			
2.37	What if the volume of the storage vessel was smaller?	See No. 1.24			
2.38	What if the concentration of the fuel in the salt was larger?	See No. 1.25			
2.39	What if the concentration of the fuel in the salt was smaller?	See No. 1.26			
2.40	What if a neutron poison was added to the salt?	See No. 1.27			
2.41	What if water was added on top of the cooled fuel salt?	See No. 1.28			
2.42	What if the ^{235}U enrichment increased?	See No. 1.31			
2.43	What if the ^{235}U enrichment decreased?	See No. 1.32			
2.44	What if the storage vessel was lowered closer to the floor of the transport vessel?	See No. 1.33			
2.45	What if the vessel was brought closer to a wall of the transport vessel?	See No. 1.34			
2.46	What if a group of people surrounds the transport vessel?	See No. 1.35			
2.47	What if some type of reflective material was brought closer to the transport vessel?	See No. 1.36			
Process Zone 3: Fuel Salt Unloading Process					
3.1	What if the storage vessel and structure were laid horizontal to the battery?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	• Bracers to prevent the vessel from tipping over • Support structure to limit space from the surface • Set procedures and training • Regular maintenance	

No.	What-If	Causes	Consequences	Preventive Measures	Comments
3.2	What if too much fuel was added to the vessel?	See No. 1.1			
3.3	What if too little fuel was added to the vessel?	See No. 1.2			
3.4	What if the plug was shorter?	See No. 1.3			
3.5	What if the plug was too long?	See No. 1.4			
3.6	What if the plug’s diameter was wider?	See No. 1.5			
3.7	What if the plug’s diameter was narrower?	See No. 1.6			
3.8	What if the diameter was wider?	See No. 1.7			
3.9	What if the diameter was narrower?	See No. 1.8			
3.10	What if the baffles were wider?	See No. 1.13			
3.11	What if the baffles were narrower?	See No. 1.14			
3.12	What if the vessel head’s depth was lower?	See No. 1.15			
3.13	What if the vessel head’s depth was higher?	See No. 1.16			
3.14	What if the vessel thickness was thinner?	See No. 1.17			
3.15	What if the vessel thickness was thicker?	See No. 1.18			
3.16	What if the vessel cylinder was taller?	See No. 1.19			
3.17	What if the vessel cylinder was shorter?	See No. 1.20			
3.18	What if the vessel interacts with another vessel in storage?	See No. 1.22			
3.19	What if the volume of the vessel was larger?	See No. 1.23			
3.20	What if the volume of the vessel was smaller?	See No. 1.24			
3.21	What if the concentration of the fuel in the salt was larger?	See No. 1.25			
3.22	What if the concentration of the fuel in the salt was smaller?	See No. 1.26			
3.23	What if a neutron poison was added to the salt?	See No. 1.27			
3.24	What if water was added on top of the cooled fuel salt?	See No. 1.28			
3.25	What if flooding occurred in the storage area?	See No. 1.30			
3.26	What if the ^{235}U enrichment increased?	See No. 1.31			
3.27	What if the ^{235}U enrichment decreased?	See No. 1.32			
3.28	What if the vessel was lowered closer to the floor?	See No. 1.33			
3.29	What if the vessel was brought closer to a wall or other surface?	See No. 1.34			
3.30	What if a group of people surrounds the vessel?	See No. 1.35			

No.	What-If	Causes	Consequences	Preventive Measures	Comments
3.31	What if some type of reflective material was brought closer to the vessel?	See No. 1.36			
3.32	What if the vessel (hot) and structure were horizontal to the floor? (earthquake)	See No. 1.37			
3.33	What if the vessel (cold) and structure were horizontal to the floor? (earthquake)	See No. 1.38			
3.34	What if the vessel (hot) and structure were horizontal to the floor and surrounded by water? (earthquake and flooding)	See No. 1.39			
3.35	What if the vessel (cold) and structure were horizontal to the floor and surround by water? (earthquake and flooding)	See No. 1.40			
3.36	What if a fire occurred in the facility?	See No. 1.41			

Table A.2. What-If Screening Results Table.

No.	What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
Process Zone 1: Fuel Salt Preparation and Storage Processes						
1.1	What if too much fuel was added to the vessel?	• Operator error • Mechanical error	• Solubility limit exceeded • Fuel precipitation • Increased criticality	Credible		Yes Sec 4.3.1.1
1.3	What if the plug was shorter?	• Manufacturer error	• Potential melt and leak of salt/fuel salt on the floor • Potential critical excursion	Not Credible	• More likely that molten salt without fuel will leak before fuel leaks. • If fuel were to leak out, it will disperse into a less reactive shape than inside the vessel.	No
1.5	What if the plug's diameter was wider?	• Manufacturer error	• Potential melt and leak of salt/fuel salt on the floor • Potential critical excursion	Not Credible	• More likely that molten salt without fuel will leak before fuel leaks. • If fuel were to leak out, it will disperse into a less reactive shape than inside the vessel.	No
1.7	What if the diameter was wider?	• Manufacturer error	• Longer neutron time in the vessel • Increased criticality	Not Credible	• Diameter vs k_{eff} was considered in the design of the vessel. Negligible increase in criticality.	No
1.9	What if the impeller blades were higher?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.10	What if the impeller blades were lower?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.11	What if the impeller blades were wider?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.12	What if the impeller blades were narrower?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.13	What if the baffles were wider?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1

No.	What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
1.14	What if the baffles were narrower?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.15	What if the vessel head's depth was lower?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.16	What if the vessel head's depth was higher?	• Manufacturer error	• Inefficient mixing • Fuel settling • Potential critical excursion	Credible		Yes Sec 4.3.1.1
1.18	What if the vessel thickness was thicker?	• Manufacturer error	• More reflection • Increased criticality	Not Credible	• Negligible increase in criticality. Would need to be a significant difference.	No
1.19	What if the vessel cylinder was taller?	• Manufacturer error	• Increased space for expansion and extra fuel • Potential of increased criticality	Not Credible	• Vessel height itself does not lead to increased criticality. Would need an increase in the liquid volume.	No
1.21	What if the vessel interacts with another vessel while mixing?	• Operator error • Procedure error	• Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.2
1.22	What if the vessel interacts with another vessel in storage?	• Operator error	• Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.2
1.23	What if the volume of the vessel was larger?	• Manufacturer error	• Increased space for expansion and extra fuel • Longer neutron time in the vessel • Potential of increased criticality	Not Credible	• Vessel volume itself would not lead to increased criticality. Would need an increase in the liquid volume.	No
1.25	What if the concentration of the fuel in the salt was larger?	• Operator error • Mechanical error	• Solubility limit exceeded • Fuel precipitation • Increased criticality	Credible		Yes Sec 4.3.1.3
1.28	What if water was added on top of the cooled fuel salt?	• Human Error	• Increased reflection • Increased moderation • Increased criticality • Potential critical excursion	Not Credible	• Small surface area and volume of water on top of the salt. Insignificant reflection.	No

No.	What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
1.29	What if flooding occurred in the mixing area?	• Mechanical error • Natural disaster	• Increased criticality • Potential critical excursion • Rapid cooling, cracked vessel, leak	Credible		Yes Sec 4.3.1.4
1.30	What if flooding occurred in the storage area?	• Mechanical error • Natural disaster	• Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.4
1.31	What if the ^{235}U enrichment increased?	• Manufacturer error	• Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.5
1.33	What if the vessel was lowered closer to the floor?	• Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	Not Credible	• Insignificant reflection.	No
1.34	What if the vessel was brought closer to a wall or other surface?	• Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.6
1.35	What if a group of people surrounds the vessel?	• Human error	• Increased reflection • Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.6
1.36	What if some type of reflective material was brought closer to the vessel?	• Operator error	• Increased reflection • Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.6
1.37	What if the vessel (hot) and structure were horizontal to the floor?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Cracked vessel, leak • Potential critical excursion	Not Credible	• Insignificant reflection • Support structure provides space between vessel and floor.	No
1.38	What if the vessel (cold) and structure were horizontal to the floor?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	Not Credible	• Insignificant reflection • Support structure provides space between vessel and floor.	No

No.	What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
1.39	What if the vessel (hot) and structure were horizontal to the floor and surrounded by water?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Rapid cooling, cracked vessel, leak • Potential critical excursion	Credible		Yes Sec 4.3.1.4
1.40	What if the vessel (cold) and structure were horizontal to the floor and surround by water?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.4
1.41	What if a fire occurred in the facility?	• Mechanical error • Electrical error	• Potential plug melt and leak • Potential critical excursion and radiation exposure	Not credible	• If fuel were to leak out, it will disperse into a less reactive shape than inside the vessel.	No
1.42	What if the added fuel is cooler than 600 °C?	• Operator error • Mechanical error	• Freezing salt • Fuel precipitation and settling • Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.7
1.44	What if the vessel was too cold before adding the molten salt?	• Operator error • Mechanical error	• Freezing salt • Fuel precipitation and settling • Increased criticality • Potential critical excursion	Not credible	• The next step of the process after the molten salt is added is to heat and maintain the salt at operating temperature.	No
1.45	What if the vessel was too hot before adding the molten salt?	• Operator error • Mechanical error	• Cracked vessel, leak • Potential critical excursion and radiation exposure	Not credible	• If fuel were to leak out, it will disperse into a less reactive shape than inside the vessel.	No
1.46	What if the fuel salt mixture is below operating temperature?	• Operator error • Mechanical error	• Fuel precipitation and settling • Increased criticality • Potential critical excursion	Credible		Yes Sec 4.3.1.7
	Process Zone 2: Transportation Process					

No.	What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
2.2	What if the transport vessel's volume was smaller?	• Manufacturer error	• Decreased space between walls and storage vessels • More reflection • Potential of increased criticality	Not Credible	• Insignificant reflection. • Transport vessel design limits significant volume change.	No
2.4	What if the pitch between storage vessels was smaller?	• Manufacturer error • Operator error	• Increased interaction with other storage vessels • Decreased reflection from the wall • Overall increased criticality	Credible		Yes Sec 4.3.1.2
2.5	What if the shielding was thicker?	• Manufacturer error	• Increased reflection • Increased criticality	Not Credible	• Insignificant reflection. • Transport vessel design limits significant change in shielding thickness.	No
2.7	What if PUR was more compacted?	• Manufacturer error • Operator error	• Increased moderation • Increased criticality	Credible		Yes Sec 4.3.1.4
2.9	What if the bed of the rail car/trailer was thicker?	• Manufacturer error	• Increased reflection • Potential of increased criticality	Not Credible	• Insignificant reflection. • Neutron re-entry is limited by transport vessel shielding.	No
2.12	What if the transport vessel was shorter?	• Manufacturer error	• Increased reflection from other surfaces • Potential of increased criticality	Not Credible	• Insignificant reflection. • Neutron re-entry is limited by transport vessel shielding.	No
2.13	What if PUR was replaced by water?	• Operator error • Mechanical error	• Increased moderation • Increased criticality	Credible		Yes Sec 4.3.1.4
2.14	What if the transport vessel was submerged in water?	• Transport accident • Natural disaster	• Increased reflection • Potential of increased criticality	Not Credible	• Insignificant reflection. • Neutron re-entry is limited by transport vessel shielding.	No
2.15	What if the transport vessel was on its side (horizontal)?	• Natural disaster • Operator error	• Increased reflection • Potential of increased criticality	Not Credible	• Insignificant reflection. • Neutron re-entry is limited by transport vessel shielding.	No

No.	What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
2.16	What if the transport vessel was encased in a fire?	• Natural disaster • Mechanical error • Electrical error	• Potential plug melt and leak onto transport vessel floor • Potential critical excursion and radiation exposure	Credible		Yes Sec 4.3.1.7
2.18	What if a reflector was added to the transport vessel?	• Operator error	• Increased criticality • Potential of critical excursion	Credible		Yes Sec 4.3.1.6
2.19	What if the storage vessel (cold) was lying horizontal to the floor?	• Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential of critical excursion	Not Credible	• Insignificant reflection. • Neutron re-entry is limited by transport vessel shielding.	No
2.20	What if too much fuel was added to the storage vessels?	See No. 1.1		Credible		Yes Sec 4.3.1.1
2.22	What if the storage vessel plug was shorter?	See No. 1.3		Not Credible	• More likely for an accident to occur during the fuel loading process.	No
2.24	What if the storage vessel plug's diameter was wider?	See No. 1.5		Not Credible	• More likely for an accident to occur during the fuel loading process.	No
2.26	What if the storage vessel's diameter was wider?	See No. 1.7		Not Credible	• Diameter vs k_{eff} was considered in the design of the vessel. Negligible increase in criticality.	No
2.28	What if the storage vessel's baffles were wider?	See No. 1.13		Credible		Yes Sec 4.3.1.1
2.29	What if the storage vessel's baffles were narrower?	See No. 1.14		Credible		Yes Sec 4.3.1.1
2.30	What if the storage vessel head's depth was lower?	See No. 1.15		Credible		Yes Sec 4.3.1.1
2.31	What if the storage vessel head's depth was higher?	See No. 1.16		Credible		Yes Sec 4.3.1.1
2.33	What if the storage vessel thickness was thicker?	See No. 1.18		Not Credible	• Negligible increase in criticality. Would need to be a significant difference.	No
2.34	What if the storage vessel cylinder was taller?	See No. 1.19		Not Credible	• Storage vessel height itself does not lead to increased criticality. Would need an increase in the liquid volume.	No
2.36	What if the volume of the storage vessel was larger?	See No. 1.23		Not Credible	• Storage vessel volume itself would not lead to increased criticality. Would need an increase in the liquid volume.	No
2.38	What if the concentration of the fuel in the salt was larger?	See No. 1.25		Credible		Yes Sec 4.3.1.3

No.	What-If	Causes	Consequences	Screening Results	Justification	Carries Forward?
2.41	What if water was added on top of the cooled fuel salt?	See No. 1.28		Not Credible	• Small surface area and volume of water on top of the salt. Insignificant reflection.	No
2.42	What if the ^{235}U enrichment increased?	See No. 1.31		Credible		Yes Sec 4.3.1.5
2.44	What if the storage vessel was lowered closer to the floor of the transport vessel?	See No. 1.33		Not Credible	• Insignificant reflection.	No
2.45	What if the vessel was brought closer to a wall of the transport vessel?	See No. 1.34		Credible		Yes Sec 4.3.1.6
2.46	What if a group of people surrounds the transport vessel?	See No. 1.35		Not Credible	• Insignificant reflection. • Neutron re-entry is limited by transport vessel shielding.	No
2.47	What if some type of reflective material was brought closer to the transport vessel?	See No. 1.36		Not Credible	• Insignificant reflection. • Neutron re-entry is limited by transport vessel shielding.	No
Process Zone 3: Fuel Salt Unloading Process						
3.1	What if the storage vessel and structure were laid horizontal to the battery?	• Natural disaster • Operator error • Mechanical error	• Increased reflection • Increased criticality • Potential critical excursion	Not Credible	• Insignificant reflection. • Support structure provides space between vessel and floor.	No

Appendix B - Preparation Vessel Process Serpent Codes

```
% --- Final FLiNaK-UF4 Preparation Vessel Design
/************************
 * Material Definitions *
 ************************/
% --- Tank Material (304 SS), rho = 8.000 g/cm3
mat   ss    -8.000000   rgb 255 255 0 % Yellow
 6000.06c   -0.000400   %   Carbon, Natural
14000.06c   -0.005000   %   Silicon, Natural
15031.06c   -0.000230   %   Phosphorus-31
16000.06c   -0.000150   %   Sulfur, Natural
24000.06c   -0.189998   %   Chromium, Natural
25055.06c   -0.010000   %   Manganese-55
26000.06c   -0.701723   %   Iron, Natural
28000.06c   -0.092499   %   Nickel, Natural
% --- Mixer Material (304 SS), rho = 8.000 g/cm3
mat   imp   -8.000000   rgb 255 255 0 % Yellow
 6000.06c   -0.000400   %   Carbon, Natural
14000.06c   -0.005000   %   Silicon, Natural
15031.06c   -0.000230   %   Phosphorus-31
16000.06c   -0.000150   %   Sulfur, Natural
24000.06c   -0.189998   %   Chromium, Natural
25055.06c   -0.010000   %   Manganese-55
26000.06c   -0.701723   %   Iron, Natural
28000.06c   -0.092499   %   Nickel, Natural
% --- Argon
mat   Ar    -0.000547   rgb 233 126 19 % Orange
18036.06c   -0.003365   %   Argon-36
18038.06c   -0.000632   %   Argon-38
18040.06c   -0.996003   %   Argon-40
% --- Air, rho = 0.001205 g/cm3
mat   air   -0.001205   rgb 166 231 255 % Blue
 6000.03c   -0.000124   %   Carbon, Natural
 7014.03c   -0.755268   %   Nitrogen-14
 8016.03c   -0.231781   %   Oxygen-16
18036.03c   -0.000043   %   Argon-36
18038.03c   -0.000008   %   Argon-38
18040.03c   -0.012776   %   Argon-40
% --- FLiNaK-UF4
mat   fsalt -3.64608987 tmp 873.15 rgb 123 173 0 % Green
 3006.06c   -0.00000253 %   Lithium-6
 3007.06c   -0.02951598 %   Lithium-7
 9019.06c   -0.32368899 %   Fluorine-19
11023.06c   -0.02392133 %   Sodium-23
19039.06c   -0.13808856 %   Potassium-39
19041.06c   -0.01047650 %   Potassium-41
92235.06c   -0.09272355 %   Uranium-235
92238.06c   -0.38158256 %   Uranium-238
% --- FLiNaK
mat   salt  -2.03471635 tmp 873.15 rgb 227 255 152 % Light Green
 3006.06c   -0.00000677 %   Lithium-6
 3007.06c   -0.07894025 %   Lithium-7
 9019.06c   -0.45973952 %   Fluorine-19
11023.06c   -0.06397740 %   Sodium-23
19039.06c   -0.36931674 %   Potassium-39
19041.06c   -0.02801932 %   Potassium-41
% --- FLiNaK Salt Plug, rho = 2.53263357 g/cm3
mat   plug  -2.53263357 rgb 227 255 152 % Light Green
 3006.03c   -0.00000677 %   Lithium-6
```

```
 3007.03c   -0.07894025 %   Lithium-7
 9019.03c   -0.45973952 %   Fluorine-19
11023.03c   -0.06397740 %   Sodium-23
19039.03c   -0.36931674 %   Potassium-39
19041.03c   -0.02801932 %   Potassium-41
% --- Regular Concrete, rho = 2.30 g/cm3
mat   Rconc -2.300000   rgb 211 211 211 % Gray
 1001.03c   -0.010000   %   Hydrogen-1
 8016.03c   -0.532000   %   Oxygen-16
11023.03c   -0.029000   %   Sodium-23
13027.03c   -0.034000   %   Aluminum-27
14000.03c   -0.337000   %   Silicon, Natural
20000.03c   -0.044000   %   Calcium, Natural
26000.03c   -0.014000   %   Iron, Natural
% --- Earth, US Average, rho = 1.52 g/cm3
mat   earth -1.520000   rgb 225 169 95 % Earth Yellow
 8016.03c   -0.513713   %   Oxygen-16
11023.03c   -0.006140   %   Sodium-23
12000.03c   -0.013303   %   Magnesium, Natural
13027.03c   -0.068563   %   Aluminum-27
14000.03c   -0.271183   %   Silicon, Natural
19000.03c   -0.014327   %   Potassium, Natural
20000.03c   -0.051167   %   Calcium, Natural
22000.03c   -0.004605   %   Titanium, Natural
25055.03c   -0.000716   %   Manganese-55
26000.03c   -0.056283   %   Iron, Natural
% --- Water, rho = 0.998207 g/cm3
mat   H2O   -0.998207   tmp 300 moder lwtr 1001 rgb 164 244 249 % Pale Blue
 1001.03c   -0.111894   %   Hydrogen-1
 8016.03c   -0.888106   %   Oxygen-16
therm lwtr 300 lwe7.00t lwe7.02t % Thermal Scattering
/************************
 * Geometry definitions *
 ************************/
% --- Impeller
surf   1   cyl       0 0 0.952500  5.803838 120.000000 % Shaft
surf   2   cyl       0 0 2.121320  5.803838  10.046478 % Impeller Mount
surf   3   cyl       0 0 2.121320 67.079312  71.321953 % Impeller Mount
surf   4   px        2.121320                          % Blade Length
surf   5   px       12.500000
surf   6   px       -2.121320
surf   7   px      -12.500000
surf   8   py        2.121320
surf   9   py       12.500000
surf  10   py       -2.121320
surf  11   py      -12.500000
surf  12   plane     1 0  1   7.218051                 % Blade Width n Thick
surf  13   plane     1 0  1   8.632265
surf  14   plane     1 0 -1 -11.460692
surf  15   plane     1 0 -1  -4.389624
surf  16   plane     1 0 -1  -8.632265
surf  17   plane     1 0 -1  -7.218051
surf  18   plane     1 0  1  11.460692
surf  19   plane     1 0  1   4.389624
surf  20   plane     0 1  1   7.218051
surf  21   plane     0 1  1   8.632265
surf  22   plane     0 1 -1 -11.460692
surf  23   plane     0 1 -1  -4.389624
surf  24   plane     0 1 -1  -8.632265
surf  25   plane     0 1 -1  -7.218051
surf  26   plane     0 1  1  11.460692
surf  27   plane     0 1  1   4.389624
surf  28   plane     1 0  1  68.493526
```

```
surf  29   plane     1 0  1  69.907739
surf  30   plane     1 0 -1 -72.736166
surf  31   plane     1 0 -1 -65.665099
surf  32   plane     1 0 -1 -69.907739
surf  33   plane     1 0 -1 -68.493526
surf  34   plane     1 0  1  72.736166
surf  35   plane     1 0  1  65.665099
surf  36   plane     0 1  1  68.493526
surf  37   plane     0 1  1  69.907739
surf  38   plane     0 1 -1 -72.736166
surf  39   plane     0 1 -1 -65.665099
surf  40   plane     0 1 -1 -69.907739
surf  41   plane     0 1 -1 -68.493526
surf  42   plane     0 1  1  72.736166
surf  43   plane     0 1  1  65.665099
cell   1 0 imp      -1:(12 -13  8 -9 14 -15):(16 -17 -10 11 -18 19):
                       (20 -21 -6  7 22 -23):(24 -25   4 -5 -26 27):
                       (1   -2):
                       (28 -29  8 -9 30 -31):(32 -33 -10 11 -34 35):
                       (36 -37 -6  7 38 -39):(40 -41   4 -5 -42 43):
                       (1   -3)
% --- Baffles
surf  44   cuboid   -0.317500   0.317500  20.138889  24.305556 0 120
surf  45   cuboid   -0.317500   0.317500 -24.305556 -20.138889 0 120
surf  46   cuboid   20.138889  24.305556  -0.317500   0.317500 0 120
surf  47   cuboid  -24.305556 -20.138889  -0.317500   0.317500 0 120
cell   2 0 ss      -44
cell   3 0 ss      -45
cell   4 0 ss      -46
cell   5 0 ss      -47
% --- Vessel Inner - FLiNaK-UF4/Argon
surf  48   cyl       0 0 25                            % Inner Cylinder Radius
surf  49   pz        0                                 % Origin
surf  50   pz      120                                 % Inner Cylinder Height
surf  51   quadratic 0.001600 0.001600 0.006400 0 0 0 0 0 0 -1
                                                       % Inner Ellipsoid Radius
surf  52   pz      -20                                 % Salt/Fuel Salt Height
surf  53   pz      -15
surf  54   pz      -10
surf  55   pz       -5
surf  56   pz        5
surf  57   pz       10
surf  58   pz       15
surf  59   pz       20
surf  60   pz       25
surf  61   pz       30
surf  62   pz       35
surf  63   pz       40
surf  64   pz       45
surf  65   pz       50
surf  66   pz       55
surf  67   pz       60
surf  68   pz       65
surf  69   pz       70
surf  70   pz       75
surf  71   pz       80
surf  72   pz       85
surf  73   pz       90
surf  74   pz       95
surf  75   pz      100
surf  76   pz      105
surf  77   pz      110
surf  78   pz      110.051                             % 110.051 Hot Height
```

```
surf  79   pz      115
surf  80   pz      120
cell   6 0 fsalt   -51 -52      #1 #2 #3 #4 #5          % -20 cm
cell   7 0 fsalt   -51  52 -53 #1 #2 #3 #4 #5          % -15 cm
cell   8 0 fsalt   -51  53 -54 #1 #2 #3 #4 #5          % -10 cm
cell   9 0 fsalt   -51  54 -55 #1 #2 #3 #4 #5          %  -5 cm
cell  10 0 fsalt   -51  55 -49 #1 #2 #3 #4 #5          %   0 cm
cell  11 0 fsalt   -48  49 -56 #1 #2 #3 #4 #5          %   5 cm
cell  12 0 fsalt   -48  56 -57 #1 #2 #3 #4 #5          %  10 cm
cell  13 0 fsalt   -48  57 -58 #1 #2 #3 #4 #5          %  15 cm
cell  14 0 fsalt   -48  58 -59 #1 #2 #3 #4 #5          %  20 cm
cell  15 0 fsalt   -48  59 -60 #1 #2 #3 #4 #5          %  25 cm
cell  16 0 fsalt   -48  60 -61 #1 #2 #3 #4 #5          %  30 cm
cell  17 0 fsalt   -48  61 -62 #1 #2 #3 #4 #5          %  35 cm
cell  18 0 fsalt   -48  62 -63 #1 #2 #3 #4 #5          %  40 cm
cell  19 0 fsalt   -48  63 -64 #1 #2 #3 #4 #5          %  45 cm
cell  20 0 fsalt   -48  64 -65 #1 #2 #3 #4 #5          %  50 cm
cell  21 0 fsalt   -48  65 -66 #1 #2 #3 #4 #5          %  55 cm
cell  22 0 fsalt   -48  66 -67 #1 #2 #3 #4 #5          %  60 cm
cell  23 0 fsalt   -48  67 -68 #1 #2 #3 #4 #5          %  65 cm
cell  24 0 fsalt   -48  68 -69 #1 #2 #3 #4 #5          %  70 cm
cell  25 0 fsalt   -48  69 -70 #1 #2 #3 #4 #5          %  75 cm
cell  26 0 fsalt   -48  70 -71 #1 #2 #3 #4 #5          %  80 cm
cell  27 0 fsalt   -48  71 -72 #1 #2 #3 #4 #5          %  85 cm
cell  28 0 fsalt   -48  72 -73 #1 #2 #3 #4 #5          %  90 cm
cell  29 0 fsalt   -48  73 -74 #1 #2 #3 #4 #5          %  95 cm
cell  30 0 fsalt   -48  74 -75 #1 #2 #3 #4 #5          % 100 cm
cell  31 0 fsalt   -48  75 -76 #1 #2 #3 #4 #5          % 105 cm
cell  32 0 fsalt   -48  76 -77 #1 #2 #3 #4 #5          % 110 cm
cell  33 0 fsalt   -48  77 -78 #1 #2 #3 #4 #5          % 110.051 cm
%cell  34 0 fsalt   -48  78 -79 #1 #2 #3 #4 #5          % 115 cm
%cell  35 0 fsalt   -48  79 -80 #1 #2 #3 #4 #5          % 120 cm
% --- Argon
%cell   6 0 Ar      -51 -52      #1 #2 #3 #4 #5          % -20 cm
%cell   7 0 Ar      -51  52 -53 #1 #2 #3 #4 #5          % -15 cm
%cell   8 0 Ar      -51  53 -54 #1 #2 #3 #4 #5          % -10 cm
%cell   9 0 Ar      -51  54 -55 #1 #2 #3 #4 #5          %  -5 cm
%cell  10 0 Ar      -51  55 -49 #1 #2 #3 #4 #5          %   0 cm
%cell  11 0 Ar      -48  49 -56 #1 #2 #3 #4 #5          %   5 cm
%cell  12 0 Ar      -48  56 -57 #1 #2 #3 #4 #5          %  10 cm
%cell  13 0 Ar      -48  57 -58 #1 #2 #3 #4 #5          %  15 cm
%cell  14 0 Ar      -48  58 -59 #1 #2 #3 #4 #5          %  20 cm
%cell  15 0 Ar      -48  59 -60 #1 #2 #3 #4 #5          %  25 cm
%cell  16 0 Ar      -48  60 -61 #1 #2 #3 #4 #5          %  30 cm
%cell  17 0 Ar      -48  61 -62 #1 #2 #3 #4 #5          %  35 cm
%cell  18 0 Ar      -48  62 -63 #1 #2 #3 #4 #5          %  40 cm
%cell  19 0 Ar      -48  63 -64 #1 #2 #3 #4 #5          %  45 cm
%cell  20 0 Ar      -48  64 -65 #1 #2 #3 #4 #5          %  50 cm
%cell  21 0 Ar      -48  65 -66 #1 #2 #3 #4 #5          %  55 cm
%cell  22 0 Ar      -48  66 -67 #1 #2 #3 #4 #5          %  60 cm
%cell  23 0 Ar      -48  67 -68 #1 #2 #3 #4 #5          %  65 cm
%cell  24 0 Ar      -48  68 -69 #1 #2 #3 #4 #5          %  70 cm
%cell  25 0 Ar      -48  69 -70 #1 #2 #3 #4 #5          %  75 cm
%cell  26 0 Ar      -48  70 -71 #1 #2 #3 #4 #5          %  80 cm
%cell  27 0 Ar      -48  71 -72 #1 #2 #3 #4 #5          %  85 cm
%cell  28 0 Ar      -48  72 -73 #1 #2 #3 #4 #5          %  90 cm
%cell  29 0 Ar      -48  73 -74 #1 #2 #3 #4 #5          %  95 cm
%cell  30 0 Ar      -48  74 -75 #1 #2 #3 #4 #5          % 100 cm
%cell  31 0 Ar      -48  75 -76 #1 #2 #3 #4 #5          % 105 cm
%cell  32 0 Ar      -48  76 -77 #1 #2 #3 #4 #5          % 110 cm
%cell  33 0 Ar      -48  77 -78 #1 #2 #3 #4 #5          % 110.051 cm
cell  34 0 Ar      -48  78 -79 #1 #2 #3 #4 #5          % 115 cm
cell  35 0 Ar      -48  79 -80 #1 #2 #3 #4 #5          % 120 cm
```

```
% --- Salt Plug
surf  81   cyl       0 0 2 -37.5     -12.45            % Inner Cylinder Plug
%surf  82   cyl       0 0 2 -20.46875 -12.45
cell  36 0 plug    -81   51
%cell  37 0 salt    -82   51
% --- SS304 Structure
surf  83   cyl       0 0 25.635                        % Outer Cylinder Radius
surf  84   pz      120.635                             % Vessel Upper Thickness
surf  85   quadratic 0.001522 0.001522 0.005796 0 0 0 0 0 0 -1
                                                       % Outer Ellipsoid Radius
surf  86   cyl       0 0 2.635 -37.5 -12.75            % Outer Cylinder Plug
cell  38 0 ss      (50 -83 -84):(49 -50 48 -83):(-49 51 -85 #36):(81 -86)
% --- Support Structure
surf  87   cuboid  -50  50 -50  50 -13     -12         % Lower Support Plate
surf  88   cuboid  -50  50 -50  50  85.135  86.135     % Upper Support Plate
surf  89   cuboid   40  50  40  50 -50      86.135     % Support Legs
surf  90   cuboid   41  49  41  49 -50      86.135
surf  91   cuboid   40  50 -50 -40 -50      86.135
surf  92   cuboid   41  49 -49 -41 -50      86.135
surf  93   cuboid  -50 -40 -50 -40 -50      86.135
surf  94   cuboid  -49 -41 -49 -41 -50      86.135
surf  95   cuboid  -50 -40  40  50 -50      86.135
surf  96   cuboid  -49 -41  41  49 -50      86.135
cell  39 0 ss     (-87 85):(-88 83):(90 -89):(92 -91):(94 -93):(96 -95)
% --- Air around Vessel and Structure
surf  97   cuboid  -50 50 -50 50 -50 120.635
cell  40 0 air      49 -84 83 -97 #39
cell  41 0 air     -49  85 86 -97 #39
% --- Surrounding Air and Concrete
surf  98   pz      -50                                 % Floor Surface
surf  99   pz       250                                % Upper Boundary
surf 100   pz     -250                                 % Lower Boundary
surf 101   px       250                                % Right Boundary
surf 102   px     -250                                 % Left  Boundary
surf 103   py       250                                % Front Boundary
surf 104   py     -250                                 % Back  Boundary
surf 105   pz      -65.24                              % Concrete/Earth Surface
cell  42 0 air      97  98 -99 -101 102 -103 104
cell  43 0 Rconc       -98 105 -101 102 -103 104
cell  44 0 earth      -105 100 -101 102 -103 104
% --- Void
surf 106   cuboid -250 250 -250 250 -250 250
cell  45 0 outside 106
%plot 23 640 320 [0 -25 25 -26.5 -23]
%plot 23 640 640 [0 -2.5 2.5 47.5 52.5]
plot 22 640 640 [0 -251 251 -251 251]
%plot 22  640 1280 [0 -50 50 -50 150]
%plot 13 640 640 [0 -27 27 -27 27]
%plot 23 640 1620 [0 -75 75 -50 330]
%plot 33 640 640 [86.5 -50 50 -50 50]
%plot 33 640 640 [69.723 -27 27 -27 27]
set pop 10000 200 20
%set mcvol 500000000
```

```
% --- Final FLiNaK-UF4 Preparation + Transport Vessels Design
/***********************
 * Material Definitions *
 ***********************/
% --- Tank Material (304 SS), rho = 8.000 g/cm3
mat   ss    -8.000000   rgb 255 255 0 % Yellow
 6000.03c   -0.000400   %   Carbon, Natural
14000.03c   -0.005000   %   Silicon, Natural
15031.03c   -0.000230   %   Phosphorus-31
16000.03c   -0.000150   %   Sulfur, Natural
24000.03c   -0.189998   %   Chromium, Natural
25055.03c   -0.010000   %   Manganese-55
26000.03c   -0.701723   %   Iron, Natural
28000.03c   -0.092499   %   Nickel, Natural
% --- Mixer Material (304 SS), rho = 8.000 g/cm3
mat   imp   -8.000000   rgb 255 255 0 % Yellow
 6000.03c   -0.000400   %   Carbon, Natural
14000.03c   -0.005000   %   Silicon, Natural
15031.03c   -0.000230   %   Phosphorus-31
16000.03c   -0.000150   %   Sulfur, Natural
24000.03c   -0.189998   %   Chromium, Natural
25055.03c   -0.010000   %   Manganese-55
26000.03c   -0.701723   %   Iron, Natural
28000.03c   -0.092499   %   Nickel, Natural
% --- Argon
mat   Ar    -0.001608   rgb 233 126 19 % Orange
18036.03c   -0.003365   %   Argon-36
18038.03c   -0.000632   %   Argon-38
18040.03c   -0.996003   %   Argon-40
% --- Air, rho = 0.001205 g/cm3
mat   air   -0.001205   rgb 166 231 255 % Blue
 6000.03c   -0.000124   %   Carbon, Natural
 7014.03c   -0.755268   %   Nitrogen-14
 8016.03c   -0.231781   %   Oxygen-16
18036.03c   -0.000043   %   Argon-36
18038.03c   -0.000008   %   Argon-38
18040.03c   -0.012776   %   Argon-40
% --- FLiNaK-UF4
mat   fsalt -4.14797777 tmp 300    rgb 123 173 0 % Green
 3006.03c   -0.00000253 %   Lithium-6
 3007.03c   -0.02951598 %   Lithium-7
 9019.03c   -0.32368899 %   Fluorine-19
11023.03c   -0.02392133 %   Sodium-23
19039.03c   -0.13808856 %   Potassium-39
19041.03c   -0.01047650 %   Potassium-41
92235.03c   -0.09272355 %   Uranium-235
92238.03c   -0.38158256 %   Uranium-238
% --- FLiNaK
mat   salt  -2.53263357 tmp 300    rgb 227 255 152 % Light Green
 3006.03c   -0.00000677 %   Lithium-6
 3007.03c   -0.07894025 %   Lithium-7
 9019.03c   -0.45973952 %   Fluorine-19
11023.03c   -0.06397740 %   Sodium-23
19039.03c   -0.36931674 %   Potassium-39
19041.03c   -0.02801932 %   Potassium-41
% --- FLiNaK Salt Plug, rho = 2.53263357 g/cm3
mat   plug  -2.53263357 rgb 227 255 152 % Light Green
 3006.03c   -0.00000677 %   Lithium-6
 3007.03c   -0.07894025 %   Lithium-7
 9019.03c   -0.45973952 %   Fluorine-19
11023.03c   -0.06397740 %   Sodium-23
19039.03c   -0.36931674 %   Potassium-39
19041.03c   -0.02801932 %   Potassium-41
```

```
% --- Regular Concrete, rho = 2.30 g/cm3
mat   Rconc -2.300000   rgb 211 211 211 % Gray
 1001.03c   -0.010000   %   Hydrogen-1
 8016.03c   -0.532000   %   Oxygen-16
11023.03c   -0.029000   %   Sodium-23
13027.03c   -0.034000   %   Aluminum-27
14000.03c   -0.337000   %   Silicon, Natural
20000.03c   -0.044000   %   Calcium, Natural
26000.03c   -0.014000   %   Iron, Natural
% --- Earth, US Average, rho = 1.52 g/cm3
mat   earth -1.520000   rgb 225 169 95 % Earth Yellow
 8016.03c   -0.513713   %   Oxygen-16
11023.03c   -0.006140   %   Sodium-23
12000.03c   -0.013303   %   Magnesium, Natural
13027.03c   -0.068563   %   Aluminum-27
14000.03c   -0.271183   %   Silicon, Natural
19000.03c   -0.014327   %   Potassium, Natural
20000.03c   -0.051167   %   Calcium, Natural
22000.03c   -0.004605   %   Titanium, Natural
25055.03c   -0.000716   %   Manganese-55
26000.03c   -0.056283   %   Iron, Natural
% --- Water, rho = 0.998207 g/cm3
mat   H2O   -0.998207   tmp 300 moder lwtr 1001 rgb 164 244 249 % Pale Blue
 1001.03c   -0.111894   %   Hydrogen-1
 8016.03c   -0.888106   %   Oxygen-16
therm lwtr 300 lwe7.00t lwe7.02t % Thermal Scattering
% --- Steel Shield (SA-516 Gr. 70), rho = 7.82 g/cm3
mat   cs    -7.82000    rgb 70 130 180 %Steel Blue
 6000.03c   -0.00280    %   Carbon, Natural
14000.03c   -0.00290    %   Silicon, Natural
15031.03c   -0.00035    %   Phosphorus-31
16000.03c   -0.00040    %   Sulfur, Natural
25055.03c   -0.01045    %   Manganese-55
26000.03c   -0.98310    %   Iron, Natural
% --- Lead, rho=11.30 g/cm3
mat   lead -11.300000   rgb 47 79 79 %Dark slate gray
26000.03c   -0.000020   %   Iron, Natural
28000.03c   -0.000020   %   Nickel, Natural
29000.03c   -0.000800   %   Copper, Natural
30000.03c   -0.000010   %   Zinc, Natural
33075.03c   -0.000010   %   Arsenic-75
47000.03c   -0.000200   %   Silver, Natural
50000.03c   -0.000010   %   Tin, Natural
51000.03c   -0.000010   %   Antimony, Natural
82000.03c   -0.998670   %   Lead, Natural
83209.03c   -0.000250   %   Bismuth-209
% --- Polyurethane Foam, rho = 0.021000 g/cm3
mat   poly  -0.021000   rgb 248 248 255
 1001.03c   -0.041000   %   Hydrogen-1
 6000.03c   -0.544000   %   Carbon, Natural
 7014.03c   -0.121000   %   Nitrogen-14
 8016.03c   -0.294000   %   Oxygen-16
/************************
 * Geometry definitions *
 ************************/
% --- Impeller
surf   1   cyl       0 0 0.952500  5.803838 120.000000 % Shaft
surf   2   cyl       0 0 2.121320  5.803838  10.046478 % Impeller Mount
surf   3   cyl       0 0 2.121320 67.079312  71.321953 % Impeller Mount
surf   4   px        2.121320                          % Blade Length
surf   5   px       12.500000
surf   6   px       -2.121320
surf   7   px      -12.500000
```

```
surf   8   py        2.121320
surf   9   py       12.500000
surf  10   py       -2.121320
surf  11   py      -12.500000
surf  12   plane     1 0  1   7.218051                 % Blade Width n Thick
surf  13   plane     1 0  1   8.632265
surf  14   plane     1 0 -1 -11.460692
surf  15   plane     1 0 -1  -4.389624
surf  16   plane     1 0 -1  -8.632265
surf  17   plane     1 0 -1  -7.218051
surf  18   plane     1 0  1  11.460692
surf  19   plane     1 0  1   4.389624
surf  20   plane     0 1  1   7.218051
surf  21   plane     0 1  1   8.632265
surf  22   plane     0 1 -1 -11.460692
surf  23   plane     0 1 -1  -4.389624
surf  24   plane     0 1 -1  -8.632265
surf  25   plane     0 1 -1  -7.218051
surf  26   plane     0 1  1  11.460692
surf  27   plane     0 1  1   4.389624
surf  28   plane     1 0  1  68.493526
surf  29   plane     1 0  1  69.907739
surf  30   plane     1 0 -1 -72.736166
surf  31   plane     1 0 -1 -65.665099
surf  32   plane     1 0 -1 -69.907739
surf  33   plane     1 0 -1 -68.493526
surf  34   plane     1 0  1  72.736166
surf  35   plane     1 0  1  65.665099
surf  36   plane     0 1  1  68.493526
surf  37   plane     0 1  1  69.907739
surf  38   plane     0 1 -1 -72.736166
surf  39   plane     0 1 -1 -65.665099
surf  40   plane     0 1 -1 -69.907739
surf  41   plane     0 1 -1 -68.493526
surf  42   plane     0 1  1  72.736166
surf  43   plane     0 1  1  65.665099
cell   1 1 imp      -1:(12 -13  8 -9 14 -15):(16 -17 -10 11 -18 19):
                       (20 -21 -6  7 22 -23):(24 -25   4 -5 -26 27):
                       (1   -2):
                       (28 -29  8 -9 30 -31):(32 -33 -10 11 -34 35):
                       (36 -37 -6  7 38 -39):(40 -41   4 -5 -42 43):
                       (1   -3)
% --- Baffles
surf  44   cuboid   -0.317500   0.317500  20.138889  24.305556 0 120
surf  45   cuboid   -0.317500   0.317500 -24.305556 -20.138889 0 120
surf  46   cuboid   20.138889  24.305556  -0.317500   0.317500 0 120
surf  47   cuboid  -24.305556 -20.138889  -0.317500   0.317500 0 120
cell   2 1 ss      -44
cell   3 1 ss      -45
cell   4 1 ss      -46
cell   5 1 ss      -47
% --- Vessel Inner - FLiNaK-UF4/Argon
surf  48   cyl       0 0 25                            % Inner Cylinder Radius
surf  49   pz        0                                 % Origin
surf  50   pz      120                                 % Inner Cylinder Height
surf  51   quadratic 0.001600 0.001600 0.006400 0 0 0 0 0 0 -1
                                                       % Inner Ellipsoid Radius
surf  52   pz      -20                                 % Salt/Fuel Salt Height
surf  53   pz      -15
surf  54   pz      -10
surf  55   pz       -5
surf  56   pz        5
surf  57   pz       10
```

```
surf  58   pz       15
surf  59   pz       20
surf  60   pz       25
surf  61   pz       30
surf  62   pz       35
surf  63   pz       40
surf  64   pz       45
surf  65   pz       50
surf  66   pz       55
surf  67   pz       60
surf  68   pz       65
surf  69   pz       70
surf  70   pz       75
surf  71   pz       80
surf  72   pz       85
surf  73   pz       90
surf  74   pz       95
surf  75   pz       95.749                             % 95.749 Cold Height
surf  76   pz      100
surf  77   pz      105
surf  78   pz      110
surf  79   pz      115
surf  80   pz      120
cell   6 1 fsalt   -51 -52     #1 #2 #3 #4 #5           % -20 cm
cell   7 1 fsalt   -51  52 -53 #1 #2 #3 #4 #5           % -15 cm
cell   8 1 fsalt   -51  53 -54 #1 #2 #3 #4 #5           % -10 cm
cell   9 1 fsalt   -51  54 -55 #1 #2 #3 #4 #5           %  -5 cm
cell  10 1 fsalt   -51  55 -49 #1 #2 #3 #4 #5           %   0 cm
cell  11 1 fsalt   -48  49 -56 #1 #2 #3 #4 #5           %   5 cm
cell  12 1 fsalt   -48  56 -57 #1 #2 #3 #4 #5           %  10 cm
cell  13 1 fsalt   -48  57 -58 #1 #2 #3 #4 #5           %  15 cm
cell  14 1 fsalt   -48  58 -59 #1 #2 #3 #4 #5           %  20 cm
cell  15 1 fsalt   -48  59 -60 #1 #2 #3 #4 #5           %  25 cm
cell  16 1 fsalt   -48  60 -61 #1 #2 #3 #4 #5           %  30 cm
cell  17 1 fsalt   -48  61 -62 #1 #2 #3 #4 #5           %  35 cm
cell  18 1 fsalt   -48  62 -63 #1 #2 #3 #4 #5           %  40 cm
cell  19 1 fsalt   -48  63 -64 #1 #2 #3 #4 #5           %  45 cm
cell  20 1 fsalt   -48  64 -65 #1 #2 #3 #4 #5           %  50 cm
cell  21 1 fsalt   -48  65 -66 #1 #2 #3 #4 #5           %  55 cm
cell  22 1 fsalt   -48  66 -67 #1 #2 #3 #4 #5           %  60 cm
cell  23 1 fsalt   -48  67 -68 #1 #2 #3 #4 #5           %  65 cm
cell  24 1 fsalt   -48  68 -69 #1 #2 #3 #4 #5           %  70 cm
cell  25 1 fsalt   -48  69 -70 #1 #2 #3 #4 #5           %  75 cm
cell  26 1 fsalt   -48  70 -71 #1 #2 #3 #4 #5           %  80 cm
cell  27 1 fsalt   -48  71 -72 #1 #2 #3 #4 #5           %  85 cm
cell  28 1 fsalt   -48  72 -73 #1 #2 #3 #4 #5           %  90 cm
cell  29 1 fsalt   -48  73 -74 #1 #2 #3 #4 #5           %  95 cm
cell  30 1 fsalt   -48  74 -75 #1 #2 #3 #4 #5           %  95.749 cm
%cell  31 1 fsalt   -48  75 -76 #1 #2 #3 #4 #5           % 100 cm
%cell  32 1 fsalt   -48  76 -77 #1 #2 #3 #4 #5           % 105 cm
%cell  33 1 fsalt   -48  77 -78 #1 #2 #3 #4 #5           % 110 cm
%cell  34 1 fsalt   -48  78 -79 #1 #2 #3 #4 #5           % 115 cm
%cell  35 1 fsalt   -48  79 -80 #1 #2 #3 #4 #5           % 120 cm
% --- Argon
%cell   6 1 Ar      -51 -52     #1 #2 #3 #4 #5           % -20 cm
%cell   7 1 Ar      -51  52 -53 #1 #2 #3 #4 #5           % -15 cm
%cell   8 1 Ar      -51  53 -54 #1 #2 #3 #4 #5           % -10 cm
%cell   9 1 Ar      -51  54 -55 #1 #2 #3 #4 #5           %  -5 cm
%cell  10 1 Ar      -51  55 -49 #1 #2 #3 #4 #5           %   0 cm
%cell  11 1 Ar      -48  49 -56 #1 #2 #3 #4 #5           %   5 cm
%cell  12 1 Ar      -48  56 -57 #1 #2 #3 #4 #5           %  10 cm
%cell  13 1 Ar      -48  57 -58 #1 #2 #3 #4 #5           %  15 cm
%cell  14 1 Ar      -48  58 -59 #1 #2 #3 #4 #5           %  20 cm
```

```
%cell  15 1 Ar      -48  59 -60 #1 #2 #3 #4 #5          %  25 cm
%cell  16 1 Ar      -48  60 -61 #1 #2 #3 #4 #5          %  30 cm
%cell  17 1 Ar      -48  61 -62 #1 #2 #3 #4 #5          %  35 cm
%cell  18 1 Ar      -48  62 -63 #1 #2 #3 #4 #5          %  40 cm
%cell  19 1 Ar      -48  63 -64 #1 #2 #3 #4 #5          %  45 cm
%cell  20 1 Ar      -48  64 -65 #1 #2 #3 #4 #5          %  50 cm
%cell  21 1 Ar      -48  65 -66 #1 #2 #3 #4 #5          %  55 cm
%cell  22 1 Ar      -48  66 -67 #1 #2 #3 #4 #5          %  60 cm
%cell  23 1 Ar      -48  67 -68 #1 #2 #3 #4 #5          %  65 cm
%cell  24 1 Ar      -48  68 -69 #1 #2 #3 #4 #5          %  70 cm
%cell  25 1 Ar      -48  69 -70 #1 #2 #3 #4 #5          %  75 cm
%cell  26 1 Ar      -48  70 -71 #1 #2 #3 #4 #5          %  80 cm
%cell  27 1 Ar      -48  71 -72 #1 #2 #3 #4 #5          %  85 cm
%cell  28 1 Ar      -48  72 -73 #1 #2 #3 #4 #5          %  90 cm
%cell  29 1 Ar      -48  73 -74 #1 #2 #3 #4 #5          %  95 cm
%cell  30 1 Ar      -48  74 -75 #1 #2 #3 #4 #5          %  95.749 cm
cell  31 1 Ar      -48  75 -76 #1 #2 #3 #4 #5          % 100 cm
cell  32 1 Ar      -48  76 -77 #1 #2 #3 #4 #5          % 105 cm
cell  33 1 Ar      -48  77 -78 #1 #2 #3 #4 #5          % 110 cm
cell  34 1 Ar      -48  78 -79 #1 #2 #3 #4 #5          % 115 cm
cell  35 1 Ar      -48  79 -80 #1 #2 #3 #4 #5          % 120 cm
% --- Salt Plug
surf  81   cyl       0 0 2 -37.5     -12.45            % Inner Cylinder Plug
%surf  82   cyl       0 0 2 -20.46875 -12.45
cell  36 1 plug    -81   51
%cell  37 1 salt    -82   51
% --- SS304 Structure
surf  83   cyl       0 0 25.635                        % Outer Cylinder Radius
surf  84   pz      120.635                             % Vessel Upper Thickness
surf  85   quadratic 0.001522 0.001522 0.005796 0 0 0 0 0 0 -1
                                                       % Outer Ellipsoid Radius
surf  86   cyl       0 0 2.635 -37.5 -12.75            % Outer Cylinder Plug
cell  38 1 ss      (50 -83 -84):(49 -50 48 -83):(-49 51 -85 #36):(81 -86)
surf  87   cuboid  -37.5 37.5 -37.5 37.5 -13     -12   % Lower Support Plate
surf  88   cuboid  -37.5 37.5 -37.5 37.5  85.135  86.135
                                                       % Upper Support Plate
cell  39 1 ss     (-87 85):(-88 83)
cell  47 2 ss      -87:-88
% --- Polyurethane Foam around prep vessel
surf  97   sqc       0 0 37.5
cell  46 1 poly     84         -97 #39
cell  40 1 poly     49 -84  83 -97 #39
cell  41 1 poly    -49  85  86 -97 #39
cell  48 2 poly    -97 #47
% --- Vessel Lattice Inside Transport Vessel
lat prep 1 0 0 4 4 75
2 2 2 2
2 1 1 2
2 1 1 2
2 2 2 2
surf 107   cyl       0 0 86.36 -50 145.58
cell  49 0 fill prep [-107]
% --- Transport Vessel
surf 108   cyl       0 0 89.2175 -52.8575 148.4375     % Inner SS304 Cylinder
surf 109   cyl       0 0 93.98   -52.8575 148.4375     % Lead Shield
surf 110   cyl       0 0 99.06   -63.97   158.28       % Outer SS304 Cylinder
cell  50 0 cs      107 -108
cell  51 0 lead    108 -109
cell  52 0 cs      109 -110
% --- Impact Limiters
surf 111   cyl       0 0  99.695  -64.605 -10.63       % Bottom Limiter
surf 112   cyl       0 0  60.325 -117.31  -63.97
surf 113   cyl       0 0  60.96  -116.675 -11.265
```

```
surf 114   cyl       0 0 128.905 -116.675 -11.265
surf 115   cyl       0 0 129.54  -117.31 -10.63
cell  53 0 ss     (112 -113  111):(112 110 -111):(112 114 -115 111)
cell  54 0 poly    112  113 -114   111
surf 116   cyl       0 0  99.695 104.94   158.915      % Top Limiter
surf 117   cyl       0 0  60.325 158.28   211.62
surf 118   cyl       0 0  60.96  105.575  210.985
surf 119   cyl       0 0 128.905 105.575  210.985
surf 120   cyl       0 0 129.54  104.94   211.62
surf 121   cyl       0 0  60.325 211.3533 211.62
cell  55 0 ss     (117 110 -116):(117 -118 116):(117 119 -120 116):(-121)
cell  56 0 poly    117 118 -119    116
surf 122 cuboid -381 381 -129.54 129.54 -147.79 -117.31 %25'x8.5'x1'
cell 57 0 ss      -122
% --- Surrounding Air and Concrete
surf  98   pz     -117.31                              % Floor Surface
surf  99   pz      300                                 % Upper Boundary
surf 100   px     -400                                 % Lower Boundary
surf 101   px      400                                 % Right Boundary
surf 102   py     -300                                 % Left  Boundary
surf 103   py      300                                 % Front Boundary
surf 104   pz     -300                                 % Back  Boundary
cell  42 0 air      98 -99 100 -101 102 -103 110 #53 #54 #55 #56
cell  44 0 earth       -98 100 -101 102 -103 104
% --- Void
surf 106   cuboid -400 400 -300 300 -300 300
cell  45 0 outside 106
%plot 23 640 320 [0 -25 25 -26.5 -23]
%plot 23 640 640 [0 -2.5 2.5 47.5 52.5]
plot 22 1280 960 [37.5 -401 401 -301 301]
%plot 22 640 1493 [25 -37.5 37.5 -35 140]
%plot 13 640 640 [0 -27 27 -27 27]
%plot 23 640 1620 [0 -75 75 -50 330]
%plot 32 640 640  [69.205885 -100 100 -100 100]
%plot 33 640 640  [69.723 -27 27 -27 27]
set pop 10000 200 20
%set mcvol 500000000
```

```
% --- Final FLiNaK-UF4 Preparation Vessel Design + MSnB
/***********************
 * Material Definitions *
 ***********************/
% --- Tank Material (304 SS), rho = 8.000 g/cm3
mat   ss    -8.000000   rgb 255 255 0 % Yellow
 6000.06c   -0.000400   %   Carbon, Natural
14000.06c   -0.005000   %   Silicon, Natural
15031.06c   -0.000230   %   Phosphorus-31
16000.06c   -0.000150   %   Sulfur, Natural
24000.06c   -0.189998   %   Chromium, Natural
25055.06c   -0.010000   %   Manganese-55
26000.06c   -0.701723   %   Iron, Natural
28000.06c   -0.092499   %   Nickel, Natural
% --- Mixer Material (304 SS), rho = 8.000 g/cm3
mat   imp   -8.000000   rgb 255 255 0 % Yellow
 6000.06c   -0.000400   %   Carbon, Natural
14000.06c   -0.005000   %   Silicon, Natural
15031.06c   -0.000230   %   Phosphorus-31
16000.06c   -0.000150   %   Sulfur, Natural
24000.06c   -0.189998   %   Chromium, Natural
25055.06c   -0.010000   %   Manganese-55
26000.06c   -0.701723   %   Iron, Natural
28000.06c   -0.092499   %   Nickel, Natural
% --- Argon
mat   Ar    -0.000547   rgb 233 126 19 % Orange
18036.06c   -0.003365   %   Argon-36
18038.06c   -0.000632   %   Argon-38
18040.06c   -0.996003   %   Argon-40
% --- Air, rho = 0.001205 g/cm3
mat   air   -0.001205   rgb 166 231 255 % Blue
 6000.03c   -0.000124   %   Carbon, Natural
 7014.03c   -0.755268   %   Nitrogen-14
 8016.03c   -0.231781   %   Oxygen-16
18036.03c   -0.000043   %   Argon-36
18038.03c   -0.000008   %   Argon-38
18040.03c   -0.012776   %   Argon-40
% --- FLiNaK-UF4
mat   fsalt -3.64608987 tmp 873.15 rgb 123 173 0 % Green
 3006.06c   -0.00000253 %   Lithium-6
 3007.06c   -0.02951598 %   Lithium-7
 9019.06c   -0.32368899 %   Fluorine-19
11023.06c   -0.02392133 %   Sodium-23
19039.06c   -0.13808856 %   Potassium-39
19041.06c   -0.01047650 %   Potassium-41
92235.06c   -0.09272355 %   Uranium-235
92238.06c   -0.38158256 %   Uranium-238
% --- FLiNaK
mat   salt  -2.03471635 tmp 873.15 rgb 227 255 152 % Light Green
 3006.06c   -0.00000677 %   Lithium-6
 3007.06c   -0.07894025 %   Lithium-7
 9019.06c   -0.45973952 %   Fluorine-19
11023.06c   -0.06397740 %   Sodium-23
19039.06c   -0.36931674 %   Potassium-39
19041.06c   -0.02801932 %   Potassium-41
% --- FLiNaK Salt Plug, rho = 2.53263357 g/cm3
mat   plug  -2.53263357 rgb 227 255 152 % Light Green
 3006.03c   -0.00000677 %   Lithium-6
 3007.03c   -0.07894025 %   Lithium-7
 9019.03c   -0.45973952 %   Fluorine-19
11023.03c   -0.06397740 %   Sodium-23
19039.03c   -0.36931674 %   Potassium-39
19041.03c   -0.02801932 %   Potassium-41
```

```
% --- Regular Concrete, rho = 2.30 g/cm3
mat   Rconc -2.300000   rgb 211 211 211 % Gray
 1001.03c   -0.010000   %   Hydrogen-1
 8016.03c   -0.532000   %   Oxygen-16
11023.03c   -0.029000   %   Sodium-23
13027.03c   -0.034000   %   Aluminum-27
14000.03c   -0.337000   %   Silicon, Natural
20000.03c   -0.044000   %   Calcium, Natural
26000.03c   -0.014000   %   Iron, Natural
% --- Earth, US Average, rho = 1.52 g/cm3
mat   earth -1.520000   rgb 225 169 95 % Earth Yellow
 8016.03c   -0.513713   %   Oxygen-16
11023.03c   -0.006140   %   Sodium-23
12000.03c   -0.013303   %   Magnesium, Natural
13027.03c   -0.068563   %   Aluminum-27
14000.03c   -0.271183   %   Silicon, Natural
19000.03c   -0.014327   %   Potassium, Natural
20000.03c   -0.051167   %   Calcium, Natural
22000.03c   -0.004605   %   Titanium, Natural
25055.03c   -0.000716   %   Manganese-55
26000.03c   -0.056283   %   Iron, Natural
% --- Water, rho = 0.998207 g/cm3
mat   H2O   -0.998207   tmp 300 moder lwtr 1001 rgb 164 244 249 % Pale Blue
 1001.03c   -0.111894   %   Hydrogen-1
 8016.03c   -0.888106   %   Oxygen-16
therm lwtr 300 lwe7.00t lwe7.02t % Thermal Scattering
/************************
 * Geometry definitions *
 ************************/
% --- Impeller
surf   1   cyl       0 0 0.952500  5.803838 120.000000 % Shaft
surf   2   cyl       0 0 2.121320  5.803838  10.046478 % Impeller Mount
surf   3   cyl       0 0 2.121320 67.079312  71.321953 % Impeller Mount
surf   4   px        2.121320                          % Blade Length
surf   5   px       12.500000
surf   6   px       -2.121320
surf   7   px      -12.500000
surf   8   py        2.121320
surf   9   py       12.500000
surf  10   py       -2.121320
surf  11   py      -12.500000
surf  12   plane     1 0  1   7.218051                 % Blade Width n Thick
surf  13   plane     1 0  1   8.632265
surf  14   plane     1 0 -1 -11.460692
surf  15   plane     1 0 -1  -4.389624
surf  16   plane     1 0 -1  -8.632265
surf  17   plane     1 0 -1  -7.218051
surf  18   plane     1 0  1  11.460692
surf  19   plane     1 0  1   4.389624
surf  20   plane     0 1  1   7.218051
surf  21   plane     0 1  1   8.632265
surf  22   plane     0 1 -1 -11.460692
surf  23   plane     0 1 -1  -4.389624
surf  24   plane     0 1 -1  -8.632265
surf  25   plane     0 1 -1  -7.218051
surf  26   plane     0 1  1  11.460692
surf  27   plane     0 1  1   4.389624
surf  28   plane     1 0  1  68.493526
surf  29   plane     1 0  1  69.907739
surf  30   plane     1 0 -1 -72.736166
surf  31   plane     1 0 -1 -65.665099
surf  32   plane     1 0 -1 -69.907739
surf  33   plane     1 0 -1 -68.493526
```

```
surf  34   plane     1 0  1  72.736166
surf  35   plane     1 0  1  65.665099
surf  36   plane     0 1  1  68.493526
surf  37   plane     0 1  1  69.907739
surf  38   plane     0 1 -1 -72.736166
surf  39   plane     0 1 -1 -65.665099
surf  40   plane     0 1 -1 -69.907739
surf  41   plane     0 1 -1 -68.493526
surf  42   plane     0 1  1  72.736166
surf  43   plane     0 1  1  65.665099
cell   1 0 imp      -1:(12 -13  8 -9 14 -15):(16 -17 -10 11 -18 19):
                       (20 -21 -6  7 22 -23):(24 -25   4 -5 -26 27):
                       (1   -2):
                       (28 -29  8 -9 30 -31):(32 -33 -10 11 -34 35):
                       (36 -37 -6  7 38 -39):(40 -41   4 -5 -42 43):
                       (1   -3)
% --- Baffles
surf  44   cuboid   -0.317500   0.317500  20.138889  24.305556 0 120
surf  45   cuboid   -0.317500   0.317500 -24.305556 -20.138889 0 120
surf  46   cuboid   20.138889  24.305556  -0.317500   0.317500 0 120
surf  47   cuboid  -24.305556 -20.138889  -0.317500   0.317500 0 120
cell   2 0 ss      -44
cell   3 0 ss      -45
cell   4 0 ss      -46
cell   5 0 ss      -47
% --- Vessel Inner - FLiNaK-UF4/Argon
surf  48   cyl       0 0 25                           % Inner Cylinder Radius
surf  49   pz        0                                % Origin
surf  50   pz      120                                % Inner Cylinder Height
surf  51   quadratic 0.001600 0.001600 0.006400 0 0 0 0 0 0 -1
                                                      % Inner Ellipsoid Radius
surf  52   pz      -20                                % Salt/Fuel Salt Height
surf  53   pz      -15
surf  54   pz      -10
surf  55   pz       -5
surf  56   pz        5
surf  57   pz       10
surf  58   pz       15
surf  59   pz       20
surf  60   pz       25
surf  61   pz       30
surf  62   pz       35
surf  63   pz       40
surf  64   pz       45
surf  65   pz       50
surf  66   pz       55
surf  67   pz       60
surf  68   pz       65
surf  69   pz       70
surf  70   pz       75
surf  71   pz       80
surf  72   pz       85
surf  73   pz       90
surf  74   pz       95
surf  75   pz      100
surf  76   pz      105
surf  77   pz      110
surf  78   pz      110.051                            % 110.051 Hot Height
surf  79   pz      115
surf  80   pz      120
cell   6 0 fsalt   -51 -52     #1 #2 #3 #4 #5         % -20 cm
cell   7 0 fsalt   -51  52 -53 #1 #2 #3 #4 #5         % -15 cm
cell   8 0 fsalt   -51  53 -54 #1 #2 #3 #4 #5         % -10 cm
```

```
cell   9 0 fsalt   -51  54 -55 #1 #2 #3 #4 #5         %  -5 cm
cell  10 0 fsalt   -51  55 -49 #1 #2 #3 #4 #5         %   0 cm
cell  11 0 fsalt   -48  49 -56 #1 #2 #3 #4 #5         %   5 cm
cell  12 0 fsalt   -48  56 -57 #1 #2 #3 #4 #5         %  10 cm
cell  13 0 fsalt   -48  57 -58 #1 #2 #3 #4 #5         %  15 cm
cell  14 0 fsalt   -48  58 -59 #1 #2 #3 #4 #5         %  20 cm
cell  15 0 fsalt   -48  59 -60 #1 #2 #3 #4 #5         %  25 cm
cell  16 0 fsalt   -48  60 -61 #1 #2 #3 #4 #5         %  30 cm
cell  17 0 fsalt   -48  61 -62 #1 #2 #3 #4 #5         %  35 cm
cell  18 0 fsalt   -48  62 -63 #1 #2 #3 #4 #5         %  40 cm
cell  19 0 fsalt   -48  63 -64 #1 #2 #3 #4 #5         %  45 cm
cell  20 0 fsalt   -48  64 -65 #1 #2 #3 #4 #5         %  50 cm
cell  21 0 fsalt   -48  65 -66 #1 #2 #3 #4 #5         %  55 cm
cell  22 0 fsalt   -48  66 -67 #1 #2 #3 #4 #5         %  60 cm
cell  23 0 fsalt   -48  67 -68 #1 #2 #3 #4 #5         %  65 cm
cell  24 0 fsalt   -48  68 -69 #1 #2 #3 #4 #5         %  70 cm
cell  25 0 fsalt   -48  69 -70 #1 #2 #3 #4 #5         %  75 cm
cell  26 0 fsalt   -48  70 -71 #1 #2 #3 #4 #5         %  80 cm
cell  27 0 fsalt   -48  71 -72 #1 #2 #3 #4 #5         %  85 cm
cell  28 0 fsalt   -48  72 -73 #1 #2 #3 #4 #5         %  90 cm
cell  29 0 fsalt   -48  73 -74 #1 #2 #3 #4 #5         %  95 cm
cell  30 0 fsalt   -48  74 -75 #1 #2 #3 #4 #5         % 100 cm
cell  31 0 fsalt   -48  75 -76 #1 #2 #3 #4 #5         % 105 cm
cell  32 0 fsalt   -48  76 -77 #1 #2 #3 #4 #5         % 110 cm
cell  33 0 fsalt   -48  77 -78 #1 #2 #3 #4 #5         % 110.051 cm
%cell  34 0 fsalt   -48  78 -79 #1 #2 #3 #4 #5         % 115 cm
%cell  35 0 fsalt   -48  79 -80 #1 #2 #3 #4 #5         % 120 cm
% --- Argon
%cell   6 0 Ar      -51 -52     #1 #2 #3 #4 #5         % -20 cm
%cell   7 0 Ar      -51  52 -53 #1 #2 #3 #4 #5         % -15 cm
%cell   8 0 Ar      -51  53 -54 #1 #2 #3 #4 #5         % -10 cm
%cell   9 0 Ar      -51  54 -55 #1 #2 #3 #4 #5         %  -5 cm
%cell  10 0 Ar      -51  55 -49 #1 #2 #3 #4 #5         %   0 cm
%cell  11 0 Ar      -48  49 -56 #1 #2 #3 #4 #5         %   5 cm
%cell  12 0 Ar      -48  56 -57 #1 #2 #3 #4 #5         %  10 cm
%cell  13 0 Ar      -48  57 -58 #1 #2 #3 #4 #5         %  15 cm
%cell  14 0 Ar      -48  58 -59 #1 #2 #3 #4 #5         %  20 cm
%cell  15 0 Ar      -48  59 -60 #1 #2 #3 #4 #5         %  25 cm
%cell  16 0 Ar      -48  60 -61 #1 #2 #3 #4 #5         %  30 cm
%cell  17 0 Ar      -48  61 -62 #1 #2 #3 #4 #5         %  35 cm
%cell  18 0 Ar      -48  62 -63 #1 #2 #3 #4 #5         %  40 cm
%cell  19 0 Ar      -48  63 -64 #1 #2 #3 #4 #5         %  45 cm
%cell  20 0 Ar      -48  64 -65 #1 #2 #3 #4 #5         %  50 cm
%cell  21 0 Ar      -48  65 -66 #1 #2 #3 #4 #5         %  55 cm
%cell  22 0 Ar      -48  66 -67 #1 #2 #3 #4 #5         %  60 cm
%cell  23 0 Ar      -48  67 -68 #1 #2 #3 #4 #5         %  65 cm
%cell  24 0 Ar      -48  68 -69 #1 #2 #3 #4 #5         %  70 cm
%cell  25 0 Ar      -48  69 -70 #1 #2 #3 #4 #5         %  75 cm
%cell  26 0 Ar      -48  70 -71 #1 #2 #3 #4 #5         %  80 cm
%cell  27 0 Ar      -48  71 -72 #1 #2 #3 #4 #5         %  85 cm
%cell  28 0 Ar      -48  72 -73 #1 #2 #3 #4 #5         %  90 cm
%cell  29 0 Ar      -48  73 -74 #1 #2 #3 #4 #5         %  95 cm
%cell  30 0 Ar      -48  74 -75 #1 #2 #3 #4 #5         % 100 cm
%cell  31 0 Ar      -48  75 -76 #1 #2 #3 #4 #5         % 105 cm
%cell  32 0 Ar      -48  76 -77 #1 #2 #3 #4 #5         % 110 cm
%cell  33 0 Ar      -48  77 -78 #1 #2 #3 #4 #5         % 110.051 cm
cell  34 0 Ar      -48  78 -79 #1 #2 #3 #4 #5         % 115 cm
cell  35 0 Ar      -48  79 -80 #1 #2 #3 #4 #5         % 120 cm
% --- Salt Plug
surf  81   cyl       0 0 2 -37.5     -12.45            % Inner Cylinder Plug
%surf  82   cyl       0 0 2 -20.46875 -12.45
cell  36 0 plug    -81   51
%cell  37 0 salt    -82   51
```

```
% --- SS304 Structure
surf  83   cyl       0 0 25.635                        % Outer Cylinder Radius
surf  84   pz      120.635                             % Vessel Upper Thickness
surf  85   quadratic 0.001522 0.001522 0.005796 0 0 0 0 0 0 -1
                                                       % Outer Ellipsoid Radius
surf  86   cyl       0 0 2.635 -37.5 -12.75            % Outer Cylinder Plug
cell  38 0 ss      (50 -83 -84):(49 -50 48 -83):(-49 51 -85 #36):(81 -86)
% --- Support Structure
surf  87   cuboid  -50  50 -50  50 -13     -12         % Lower Support Plate
surf  88   cuboid  -50  50 -50  50  85.135  86.135     % Upper Support Plate
surf  89   cuboid   40  50  40  50 -50      86.135     % Support Legs
surf  90   cuboid   41  49  41  49 -50      86.135
surf  91   cuboid   40  50 -50 -40 -50      86.135
surf  92   cuboid   41  49 -49 -41 -50      86.135
surf  93   cuboid  -50 -40 -50 -40 -50      86.135
surf  94   cuboid  -49 -41 -49 -41 -50      86.135
surf  95   cuboid  -50 -40  40  50 -50      86.135
surf  96   cuboid  -49 -41  41  49 -50      86.135
cell  39 0 ss     (-87 85):(-88 83):(90 -89):(92 -91):(94 -93):(96 -95)
% --- Air around Vessel and Structure
surf  97   cuboid  -50 50 -50 50 -37.5 120.635
cell  40 0 air      49 -84 83 -97 #39
cell  41 0 air     -49  85 86 -97 #39
% --- Surrounding Air and Concrete
surf  98   pz      -37.5                               % Floor Surface
surf  99   pz      250                                 % Upper Boundary
surf 100   pz     -300                                 % Lower Boundary
surf 101   px      250                                 % Right Boundary
surf 102   px     -250                                 % Left  Boundary
surf 103   py      250                                 % Front Boundary
surf 104   py     -250                                 % Back  Boundary
surf 105   pz      -65.24                              % Concrete/Earth Surface
cell  42 0 air      97  98 -99 -101 102 -103 104
/********
 * MSnB *
 *******/
% --- Fuel/Archimedes Screw Blades
cell 111 0 Ar      125  -132 -141  150               % NaF-RbF in core- slice 1
cell 112 0 ASgr    132  -133 -141  150               % AS Blade#1
cell 113 0 Ar      133  -134 -141  150               % NaF-RbF in core- slice 3
cell 114 0 ASgr    134  -135 -141  150               % AS Blade#2
cell 115 0 Ar      135  -136 -141  150               % NaF-RbF in core- slice 5
cell 116 0 ASgr    136  -137 -141  150               % AS Blade#3
cell 117 0 Ar      137  -138 -141  150               % NaF-RbF in core- slice 7
cell 118 0 ASgr    138 -1112 -141  150               % AS Blade#4
                                                     % Graphite lower half
cell 130 0 ASBe   1112  -139 -141  150               % AS Blade#4
                                                     % Be Refl upper half
cell 119 0 Ar      139  -126 -141  150               % NaF-RbF in core- slice 9
cell 120 0 ASBe    126 -1111 -141  150               % AS BeO Blade#1
cell 121 0 Ar     1111  -211 -141  150               % NaF-RbF in chimney
cell 122 0 ASBe    211  -212 -141  150               % AS BeO Blade#2
cell 127 0 Ar      212  -217 -141  150
cell 128 0 Ar      217  -130 -141  150
cell 102 0 Ar      123  -124  142 -147 152 153       % NaF-RbF in lower plenum
cell 103 0 Ar      124  -127  146 -147 152 153       % NaF-RbF around core
cell 104 0 Ar      129  -130 -147  142 152 153
                   171   172  173  174 175 176
                   177   178  181  182 183 184
                   185   186  187  188                % Fuel in upper plenum
cell 105 0 Ar      127  -129  144 -147 152 153
                   171   172  173  174 175 176
                   177   178  181  182 183 184
```

```
                   185   186  187  188               % Fuel around chimney
cell 106 0 Ar      123  -124 -142                    % Fuel in center
                                                     % of lower plenum
cell 107 0 ASgr    125  -126 -150                    % AS center stem
                                                     % in core - Graphite
cell 108 0 ASB4C   126  -130 -150                    % AS center stem in
                                                     % chimney - Boron Carbide
% --- Structure
cell 200 0 m2      122 -123 -147                     % base
cell 201 0 m2      124 -125 -146                     % core reflector lower
                                                     % clad / orifice plate
cell 202 0 m2      125 -130  141 -142                % core vessel
cell 203 0 m2      125 -126  145 -146                % core reflector
                                                     % outer clad
cell 204 0 m2      140 -127  143 -146 171 172
                   173  174  175  176 177 178
                   181  182  183  184 185 186
                   187 188                           % chimney step
cell 205 0 m2      128 -129  142 -144 171 172
                   173  174  175  176 177 178
                   181  182  183  184 185 186
                   187  188                          % chimney top clad
cell 206 0 m2      127 -128  143 -144 171 172
                   173  174  175  176 177 178
                   181  182  183  184 185 186
                   187  188                          % chimney absorber clad
cell 207 0 m2      121 -130  147 -148                % RV cylinder
cell 208 0 m2      130 -131 -148  171 172 173
                   174  175  176  177 178 181
                   182  183  184  185 186 187
                   188                               % RV lid
% --- Reflector / Absorber
cell 300 0 Be      121 -122 -147                     % reflector below core
cell 301 0 Be      125 -126  142 -149 171 172
                   173  174  175  176 177 178
                   181  182  183  184 185 186
                   187  188  191  192 193 194
                   195  196  197  198 201 202
                   203  204  205  206 207 208        % reflector around core
cell 302 0 m4      140 -128 -143  142 171 172
                   173  174  175  176 177 178
                   181  182  183  184 185 186
                   187  188                          % absorber around chimney
cell 303 0 m3      125 -126  149 -145                % safety reflector around
                                                     % core reflector
cell 304 0 m4      126 -140  142 -145 171 172
                   173  174  175  176 177 178
                   181  182  183  184 185 186
                   187  188                          % upper drumless absorber
% --- Control Drum Reflectors
cell 400 0 Be      125 -126 -201 171                 % drum 1
cell 401 0 Be      125 -126 -202 172                 % drum 2
cell 402 0 Be      125 -126 -203 173                 % drum 3
cell 403 0 Be      125 -126 -204 174                 % drum 4
cell 404 0 Be      125 -126 -205 175                 % drum 5
cell 405 0 Be      125 -126 -206 176                 % drum 6
cell 406 0 Be      125 -126 -207 177                 % drum 7
cell 407 0 Be      125 -126 -208 178                 % drum 8
% --- Control Drum Absorbers
cell 500 0 m4      125 -126 -191 171                 % drum 1
cell 501 0 m4      125 -126 -192 172                 % drum 2
cell 502 0 m4      125 -126 -193 173                 % drum 3
cell 503 0 m4      125 -126 -194 174                 % drum 4
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cell 504 0 m4      125 -126 -195 175                 % drum 5
cell 505 0 m4      125 -126 -196 176                 % drum 6
cell 506 0 m4      125 -126 -197 177                 % drum 7
cell 507 0 m4      125 -126 -198 178                 % drum 8
% --- Control Rod Driveshafts
cell 600 0 m2     -171 181 125 -131                  % driveshaft tube 1
cell 601 0 m2     -172 182 125 -131                  % driveshaft tube 2
cell 602 0 m2     -173 183 125 -131                  % driveshaft tube 3
cell 603 0 m2     -174 184 125 -131                  % driveshaft tube 4
cell 604 0 m2     -175 185 125 -131                  % driveshaft tube 5
cell 605 0 m2     -176 186 125 -131                  % driveshaft tube 6
cell 606 0 m2     -177 187 125 -131                  % driveshaft tube 7
cell 607 0 m2     -178 188 125 -131                  % driveshaft tube 8
cell 700 0 m20    -181     125 -131                  % driveshaft tube 1 fill
cell 701 0 m20    -182     125 -131                  % driveshaft tube 2 fill
cell 702 0 m20    -183     125 -131                  % driveshaft tube 3 fill
cell 703 0 m20    -184     125 -131                  % driveshaft tube 4 fill
cell 704 0 m20    -185     125 -131                  % driveshaft tube 5 fill
cell 705 0 m20    -186     125 -131                  % driveshaft tube 6 fill
cell 706 0 m20    -187     125 -131                  % driveshaft tube 7 fill
cell 707 0 m20    -188     125 -131                  % driveshaft tube 8 fill
% --- Flow separators
cell 800 0 m2     -152 123 -124 142 -147 #102        % lower plenum dividers 1
cell 801 0 m2     -152 124 -127 146 -147             % core surround dividers 1
cell 802 0 m2     -152 127 -129 144 -147             % chimney surround-RbFd
                                                     % dividers 1
cell 803 0 m2     -152 129 -130 142 -147 #104        % upper plenum dividers 1
cell 804 0 m2     -153 123 -124 142 -147 #102        % lower plenum dividers 2
cell 805 0 m2     -153 124 -127 146 -147             % core surround-RbFd
                                                     % dividers 2
cell 806 0 m2     -153 127 -129 144 -147             % chimney surround-RbFd
                                                     % dividers 2
cell 807 0 m2     -153 129 -130 142 -147 #104        % upper plenum dividers 2
% --- Earth
cell 900 0 earth  -121 100 -101  102 -103  104       % earth below
cell 901 0 earth   121 148 -131 -101  102 -103 104   % earth around vessel
% _________________Surface cards_______________________________________________
% --- Reactor Planes
surf  121  pz     -279.5                         % lower reflector base
surf  122  pz     -269.5                         % ground
surf  123  pz     -268.5                         % RV base inner (floor)  (FIX)
surf  124  pz     -256.5                         % reflector clad outer  (FIX)
surf  125  pz     -255.5                         % reflector clad inner
surf  126  pz      -89.5                         % core / chimney divider
surf  127  pz      -88.5                         % step clad upper  (FIX)
surf  128  pz      -53.5                         % chimney clad inner
surf  129  pz      -52.5                         % chimney clad outer  (FIX)
surf  130  pz      -40.5                         % top plate (RV) inner (FIX)
surf  131  pz      -37.5                         % top plate outer (ceiling)
surf  140  pz      -89.5                         % step clad lower
surf 1111  pz      -80.72223
% --- Fuel Stratification
surf  132  pz     -237.0556                      %top of slice 1
surf  133  pz     -218.6111                      %top of slice 2
surf  134  pz     -200.1667                      %top of slice 3
surf  135  pz     -181.7222                      %top of slice 4
surf  136  pz     -163.2778                      %top of slice 5
surf  137  pz     -144.8333                      %top of slice 6
surf  138  pz     -126.3889                      %top of slice 7
surf 1112  pz     -117.1666                      %divider in refl/abs blade
surf  139  pz     -107.9444                      %top of slice 8
surf  211  pz      -62.27778                     %top of 1st Chimney Blade
surf  212  pz      -53.50                        %top of 2nd BeO chimney blad
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surf  217  pz      -52.50                        %chimney clad upper
% --- Reactor Cylinders
surf  141  cyl       0.0 0.0 25.0                % core vessel inner (FIX)
surf  142  cyl       0.0 0.0 25.1                % core vessel liner
surf  143  cyl       0.0 0.0 47.55               % chimney reflector outer
surf  144  cyl       0.0 0.0 48.55               % absorber liner (FIX)
surf  145  cyl       0.0 0.0 66.0                % safety absorber outer
surf  146  cyl       0.0 0.0 67.0                % reflector liner (FIX)
surf  147  cyl       0.0 0.0 69.5                % RV inner (FIX)
surf  148  cyl       0.0 0.0 72.5                % RV outer
surf  149  cyl       0.0 0.0 63.5                % reflector outer
surf  150  cyl       0.0 0.0  2.0                % AS center stem
% --- Control drum absorber pads, numbered clockwise from 9 o'clock
surf  191  pad     -45.05 0 2.5 17 240 120                % drum 1
surf  192  pad     -31.8551605 31.8551605 2.5 17 285 165  % drum 2
surf  193  pad       0 45.05 2.5 17 330 210               % drum 3
surf  194  pad      31.8551605 31.8551605 2.5 17 15 255   % drum 4
surf  195  pad      45.05 0 2.5 17 60 300                 % drum 5
surf  196  pad      31.8551605 -31.8551605 2.5 17 105 345 % drum 6
surf  197  pad       0 -45.05 2.5 17 150 30               % drum 7
surf  198  pad     -31.8551605 -31.8551605 2.5 17 195 75  % drum 8
% --- Control drum reflector pads, likewise
surf  201  pad     -45.05 0 2.5 17 120 240                % drum 1
surf  202  pad     -31.8551605 31.8551605 2.5 17 165 285  % drum 2
surf  203  pad       0 45.05 2.5 17 210 330               % drum 3
surf  204  pad      31.8551605 31.8551605 2.5 17 255 15   % drum 4
surf  205  pad      45.05 0 2.5 17 300 60                 % drum 5
surf  206  pad      31.8551605 -31.8551605 2.5 17 345 105 % drum 6
surf  207  pad       0 -45.05 2.5 17 30 150               % drum 7
surf  208  pad     -31.8551605 -31.8551605 2.5 17 75 195  % drum 8
% --- Control drum driveshafts
surf  171  cyl     -45.05        0.0       2.5        % drum drive tube outer 1
surf  172  cyl     -31.8551605  31.8551605 2.5        % drum drive tube outer 2
surf  173  cyl       0.0        45.05      2.5        % drum drive tube outer 3
surf  174  cyl      31.8551605  31.8551605 2.5        % drum drive tube outer 4
surf  175  cyl      45.05        0.0       2.5        % drum drive tube outer 5
surf  176  cyl      31.8551605 -31.8551605 2.5        % drum drive tube outer 6
surf  177  cyl       0.0       -45.05      2.5        % drum drive tube outer 7
surf  178  cyl     -31.8551605 -31.8551605 2.5        % drum drive tube outer 8
surf  181  cyl     -45.05        0.0       2.0        % drum drive tube inner 1
surf  182  cyl     -31.8551605  31.8551605 2.0        % drum drive tube inner 2
surf  183  cyl       0.0        45.05      2.0        % drum drive tube inner 3
surf  184  cyl      31.8551605  31.8551605 2.0        % drum drive tube inner 4
surf  185  cyl      45.05        0.0       2.0        % drum drive tube inner 5
surf  186  cyl      31.8551605 -31.8551605 2.0        % drum drive tube inner 6
surf  187  cyl       0.0       -45.05      2.0        % drum drive tube inner 7
surf  188  cyl     -31.8551605 -31.8551605 2.0        % drum drive tube inner 8
% --- Flow separators
surf 152   cross 0 0 75.5 3
strans 152 0 0 1 0 0 22.5
surf 153   cross 0 0 75.5 3
strans 153 0 0 1 0 0 -22.5
% _________________Material cards______________________________________________
% --- 304 Stainless Steel
mat   m2    -7.5983     rgb 255 20 147 % Red tmp 923
26054.03c   -0.037589   %54-Fe
26056.03c   -0.611384   %56-Fe
26057.03c   -0.014379   %57-Fe
26058.03c   -0.001932   %58-Fe
 7014.03c   -0.000995   %14-N
 7015.03c   -0.000004   %15-N
28058.03c   -0.070485   %58-Ni
28060.03c   -0.028087   %60-Ni
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28061.03c   -0.001241   %61-Ni
28062.03c   -0.004025   %62-Ni
28064.03c   -0.001058   %64-Ni
24050.03c   -0.008338   %50-Cr
24052.03c   -0.167231   %52-Cr
24053.03c   -0.019327   %53-Cr
24054.03c   -0.004902   %54-Cr
14028.03c   -0.006881   %28-Si
14029.03c   -0.000363   %29-Si
14030.03c   -0.000248   %30-Si
16032.03c   -0.000284   %32-S
16033.03c   -0.000002   %33-S
16034.03c   -0.000014   %34-S
15031.03c   -0.000020   %31-P
25055.03c   -0.019980   %55-Mn
 6000.03c   -0.000799   %(Carbon)
% --- Graphite
mat   m3    -1.8650     tmp 300 moder grph 6000 rgb 160 160 160 % Gray
 6000.03c   -1          %(Carbon)
therm grph 300 gre7.00t gre7.04t
mat   ASgr  -1.8650     tmp 300 moder grph 6000 rgb 160 160 160 % Gray
 6000.03c   -1          %(Carbon)
% --- Boron Carbide (10-B enriched)
mat   m4    -2.52       rgb 48 48 48 % Black
 5010.03c   -0.782610   %10-B
 6000.03c   -0.217390   %(Carbon)
mat ASB4C   -2.52       rgb 48 48 48 % Black
 5010.03c   -0.782610   %10-B
 6000.03c   -0.217390   %(Carbon)
% --- "Air"
mat   m5    -0.001608   rgb 233 126 19 % Orange
18036.03c   -0.003365
18038.03c   -0.000632
18040.03c   -0.996003
% --- Beryllium Oxide Reflector
mat   Be    -3.01       rgb 255 255 0 % Yellow
 4009.03c   -0.360320
 8016.03c   -0.639680
mat   ASBe  -3.01       rgb 255 255 0 % Yellow
 4009.03c   -0.360320
 8016.03c   -0.639680
% --- Blue Hastelloy Chimney Reflector
mat   m20   -8.89       rgb 13 102 239
28058.03c   -0.48
24052.03c   -0.07
26056.03c   -0.05
14028.03c   -0.01
28060.03c   -0.23
42092.03c   -0.02344
42094.03c   -0.014704
42095.03c   -0.025392
42096.03c   -0.026672
42097.03c   -0.015328
42098.03c   -0.038864
42100.03c   -0.0156
% --- Void
surf 106 cuboid   -250 250 -250 250 -300 250
cell 45 0 outside 106
%plot 23 640 320 [0 -25 25 -26.5 -23]
%plot 23 640 640 [0 -2.5 2.5 47.5 52.5]
plot 22 640 640 [0 -251 251 -251 251]
%plot 23 320 987 [0 -25.635 25.635 -37.5 120.635]
%plot 13 640 640 [0 -27 27 -27 27]
```

```
%plot 23 640 1620 [0 -75 75 -50 330]
%plot 33 640 640 [-150 -100 100 -100 100]
%plot 33 640 640 [69.723 -27 27 -27 27]
set pop 10000 200 20
%set mcvol 500000000
```