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Improvement of Spent Fuel Storage with Advanced Mechanical Shielding Placement

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Senior Design Project

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Abstract

Recent events at the Fukushima Daiichi Nuclear Power Plant have introduced several concerns about the spent fuel pool of power plants, as well as the safety and stability of the current storage of spent nuclear fuel. This report looks into alterations to current dry cask storage conditions to attempt to cut down on costs and to cut down on storage space required. Increasing the boiling point of the spent fuel pool in an accident situation is also looked into, with ethylene glycol chosen as a possible cheap solution. The design developed involves removing fuel rods from used fuel assemblies via a lifting device and placing them into individual stainless steel tubes. Once placed into these tubes, a machine seals the tubes with threaded caps. Each tube has a thickness of 0.07 cm and has an air gap of 0.01 cm between the inner wall of the tube and the fuel cladding. By removing the fuel rods from the fuel assemblies, the number of fuel rods that can be acceptably placed into a single dry cask goes up significantly, which would cut down on the number of dry casks required for storage of spent fuel and cut down on overall cost of dry cask storage in the long term. A thermal analysis where the fuel rods were transported to the stainless steel tubes after only 3 years showed a centerline temperature of just under 1140 K (867℃), and a criticality analysis showed that k_{eff} would be roughly 0.61, indicating that neither of these would be a major safety concern with this design. The design was modeled in SolidWorks, the thermal analysis was performed using COMSOL Multiphysics, and the criticality analysis was performed using SCALE 6.1.

1. Background

On March 11, 2011, an earthquake and subsequent tsunami struck Japan in an area including the Fukushima Daiichi Nuclear Power System. A loss of power and leaks in the containment boundary led to a decrease in water level and uncovered fuel in the reactor pressure vessels in Units 1, 2, and 3 [1]. This resulted in the zirconium fuel cladding reacting with water, producing hydrogen gas, as shown by equation 1 [1]. To prevent a hydrogen explosion, attempts were made to inject fresh and salt water into the reactor pressure vessels. Unfortunately, due to the leakage and the amount of time the fuel was exposed, hydrogen explosions occurred in Units 1, 2, and 3. However, no hydrogen production occurred in the spent fuel pools, as Unit 4 spent fuel pools were used to successfully restore the water level in Unit 1 before any spent fuel was exposed and damaged [1]. These events have raised concerns over spent fuel pools and their boiling points, leading to an exploration of the possibility of increasing the boiling point in accident situations.

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 \quad \text{(Eq. 1)}$$

Fuel rods in a typical commercial nuclear reactor consist of uranium oxide pellets surrounded by a zirconium cladding. Every 12 to 18 months, roughly one-fourth to one-third of the total fuel load in a reactor is unloaded and replaced with fresh fuel [2]. When nuclear fuel is discharged from a nuclear power plant reactor, it is still highly radioactive and is designated as "spent" or "used" fuel [3]. The spent fuel is then stored under water in spent fuel pools up to 40 feet deep, with the rods being at least 20 feet deep to provide adequate shielding [2]. Generally, the spent fuel pools hold approximately 400,000 gallons (1.51 million liters) of water [4]. The walls of the spent fuel pools are constructed of reinforced concrete, which has a thickness ranging from 4 to 8 feet (1.2 to 2.4 meters), and they contain a stainless-steel liner that is ¼ to ½ inches thick (6 to 13 millimeters thick) [4]. A typical spent fuel pool can be seen in Figure 1. These pools provide radiation shielding, provide cooling, and prevent criticality accidents.

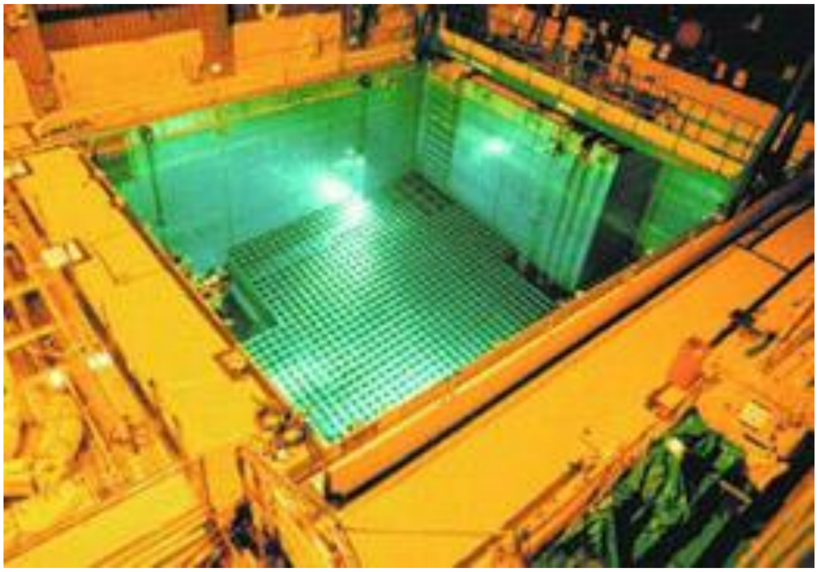

Figure 1: A typical spent fuel pool design [2]

With one-fourth to one-third of a reactor's fuel being unloaded into a spent fuel pool every 12 to 18 months, the available space in a pool can quickly disappear. Fortunately with how deep the pools are, fuel assembly consolidation and re-racking of the spent fuel pool grid can usually be performed to increase the amount of spent fuel that can be stored in the pool, without running the risk of exposing workers to the radiation [2]. Even with these methods, a spent fuel pool is only so large, meaning that it will eventually reach its capacity for storage. Before a spent fuel pool reaches this limit, older fuel can be moved to a dry storage system, so that the plant can continue operating. Current U.S. regulations allow transfer to dry storage only after the spent fuel has been in the pool for at least five years [3]. Dry storage systems are designed to provide radiation shielding, dissipate heat, and prevent degradation or damage to the fuel.

In the United States, there are two main types of storage systems: bare-fuel casks and canister-based storage systems [3]. In bare-fuel cask storage systems, used fuel assemblies are placed directly into a basket within a thick-walled cask and sealed with two bolted lids. In canister-based storage, used fuel assemblies are placed into a basket within a thin-walled stainless steel canister and sealed with two welded lids. The canister is then stored in a cylindrical overpack system, usually made up of concrete. The thick exterior canisters provide radiation shielding, a thermal barrier, and protection against natural and man-made events [3]. The storage system is then placed as a free-standing structure on a reinforced concrete pad. All bare-fuel dry-storage systems and most canister-based systems in the United States store the used fuel vertically; however, some used fuel is also stored horizontally in a concrete module [3]. Figures 2 and 5 below show vertical dry casks, while Figures 3 and 4 show a sketch of a dry cask and its components.

Figure 2: Spent fuel storage site at Connecticut Yankee Nuclear Power Plant [3]

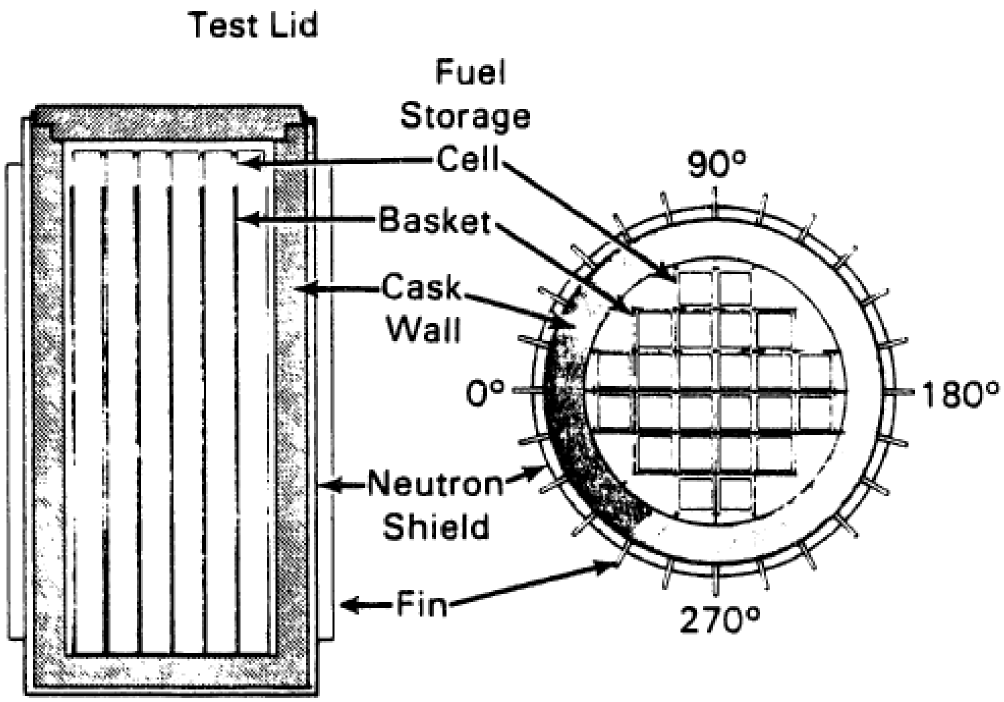

Figure 3: Aerial view of dry cask with basket design [3]

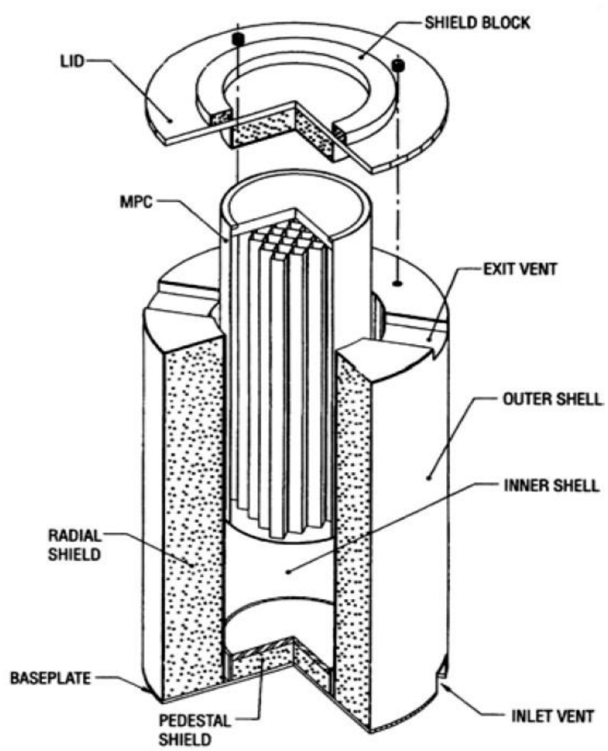

Figure 4: Dry cask storage system [3]

Dry-storage systems are loaded by placing them directly into the spent fuel pool. After the assemblies are loaded into the basket, the canister is removed from the pool and decontaminated, with moisture then removed from the system by vacuum drying [3]. The canister is backfilled with helium to protect the integrity of the fuel cladding. Due to all of these steps and the necessary precautions, the loading of a single system can take up to one week.

Figure 5: Vertical storage casks [3]

Although the conditions found within a dry cask are not as severe as those found inside of a reactor, some degradation processes will occur during extended dry storage [3]. The properties of the fuel, cladding, and storage cask components may change due to radiation, elevated temperatures, and the presence of moisture. Oxidation is the most significant fuel degradation mechanism, as irradiated UO_2 will eventually oxidize to U_3O_8 when exposed to an oxidizing atmosphere [3]. Maintaining a helium environment that surrounds the cladding is therefore important to prevent air or water from coming into contact with the fuel pellet. Once fuel rods are removed from a reactor, cladding temperature, pressure, and stress decrease significantly [3]. During the drying process, temperatures and stresses increase sharply. Fracture of the cladding while vacuum drying is one of the most likely failure mechanisms for used fuel rods, as they are no longer in water, allowing for an increase in their temperature. Unlike used fuel and cladding, certain dry storage cask components can be accessed for inspection and maintenance [3]. Certain components such as bolts, welded areas, and seals are more susceptible to corrosion due to high stresses, loads, or dripping water. However, many aging problems can be corrected before significant damage occurs.

2. Purpose

With the recent Fukushima Daiichi accident, concerns over accident response times and general safety conditions have been raised for nuclear power plants. The tsunami caused minimal damage to the plant's structure; however, the electricity supplied to the plant was cut off, with the backup diesel generators to be used in such situations damaged by the tsunami [1]. Emergency batteries were able to power the coolant pumps, but this was only for around 8 hours [1]. While the Fukushima accident was a combination of an unusually large natural disaster and some bad luck, it did shed some light on issues that should be addressed for nuclear power plants, especially with spent fuel pools and dry cask storage. Specifically, the spent fuel pool at Fukushima started to boil during the accident. Fortunately, the fuel was not uncovered; however, it very easily could have been exposed to the air. As a result of this disaster and the fallout from it, a few possible improvements to spent fuel pools and dry cask storage are examined in this paper, with simulated results presented and discussed. COMSOL Multiphysics[1], SCALE 6.1[2], and SolidWorks[3] were all used in this project to model and simulate various aspects of the design chosen.

3. Boiling Point of Spent Fuel Pool

Fukushima's spent fuel pool water started to boil during the accident, which could have led to an even bigger problem than already present. With this in mind, an improvement to the boiling point of the pool water has been considered. Because spent fuel pool water is connected to the coolant water, it would be difficult to change the chemistry of the water, as the coolant water cannot have any type of contaminant in it. As such, the proposed improvement to the boiling point of the water should only be considered in an accident situation, where safety is of top concern. In addition to this, any type of reaction needs to be avoided, even in an accident situation, so a substance that is already known to mix well with water is ideal. Ethylene glycol, which is used in conjunction with water in car radiators, is one such substance.

By itself, ethylene glycol has an extremely high boiling point of 197.3℃, but it has poor heat transfer properties, meaning that it cannot be used by itself [5]. Mixing ethylene glycol with water will increase its boiling point beyond the normal 100℃; however, it will also make water's heat transfer properties worse [5]. As a result of this, a solution of 50% ethylene glycol by volume is a nice medium between the increasing boiling point and the decreasing heat transfer capabilities. Increasing the boiling point of the spent fuel water in an accident situation would

[1] COMSOL, Inc., Burlington, Massachusetts
[2] Oak Ridge National Laboratory, Oak Ridge, Tennessee
[3] Dassault Systèmes SolidWorks Corp., Waltham, Massachusetts

then be possible by just dumping ethylene glycol into the pool, with the volume being roughly 50% of the water volume. By placing the aforementioned amount of ethylene glycol into the pool, the boiling point of the water could be increased by approximately 7.2℃ [5]. This increase is not a tremendous amount, but it could be enough to buy the personnel on-site enough time to come up with another solution in an accident situation.

By utilizing the volume of water in a spent fuel pool mentioned earlier, along with some assumptions, the amount of time this would provide can be estimated. Equation 2, shown below, was used to estimate the extra time that adding ethylene glycol in this manner would provide. In order for Equation 2 to be used, the following assumptions were made: the total volume of water in the spent fuel pool is 1.51 million liters, the specific heat of the water is 4,186 J/kg-℃, the initial temperature is 50℃, the final temperature is 107℃ , and there are a total of 1,000 assemblies in the spent fuel pool, each with a decay heat of 3,986 W, making the total decay heat being generated by the fuel 3.986 MW. Substituting these values into Equation 2 gives a result of approximately 1 day before the water would reach its new boiling point when starting at 50℃. When using pure water, it would take just 0.92 days for the water to reach its boiling point of 100℃. As a result of adding the ethylene glycol to the spent fuel pool, it appears that it would take the pool approximately 3.2 hours longer to reach a boiling state. Because ethylene glycol would only raise water's boiling point by 7.2℃, this seems reasonable and could very well be enough time for personnel to find an alternative solution. In addition to this, ethylene glycol is relatively inexpensive, making for a fairly cheap solution to raising the water boiling point without risking neutron activation or an adverse reaction when mixed with the water.

$$t = \frac{m * c_p * (T_f - T_s)}{Q} \quad \text{(Eq. 2)}$$

Where:
- t = Time
- m = Mass
- c_p = Specific Heat
- T_f = Final Temperature
- T_s = Initial Temperature
- Q = Heat Generation

4. Design Details

Coating a fuel rod, or an entire fuel assembly, in a neutron poison alloy could lead to increased survivability for individual fuel rods in both pool storage and dry cask storage for decades. Initially, several different cadmium alloys were considered for coating the fuel rods, including In-25Cd, Pb-17Cd, and Sn-32Cd. Unfortunately the more this idea was explored, the more it seemed like it simply would not produce viable results. In the case of all three of these alloys, the melting point is actually lower than what typical fuel rods are at when transported to dry storage. This means that even if the rods were successfully coated, the coating would likely melt off quickly, making the coating process not worthwhile. Even if the melting point was not a problem, consistently coating the rods evenly and getting an appropriate thickness would be very difficult. Due to these shortcomings of coating the fuel rods via dipping, several other ideas were considered. Such considerations include the following: electroplating and using a boron nitride foam. Neither of these methods seemed promising after more investigation, as electroplating would not practically provide a good coating and would take too long to get an appropriate thickness and the boron nitride foam has very poor heat transfer properties. After looking into the previously mentioned ideas and deciding they were not the best methods to pursue, the idea of removing fuel rods from fuel assemblies and placing them inside of premade tubes was selected.

The reasons for this design choice and the feasibility of such a design will be discussed in sections 4.1 and 4.2.

4.1 Reason for Selection

After seeing that initial ideas did not seem to have much value, a final, somewhat different idea was considered. If the fuel rods need to be coated in some sort of neutron poison, why not bypass the need to dip the rods and avoid the possibility of an uneven coating? This type of thinking is what led to the idea of using premade tubes for containing the fuel rods individually. Initially, Inconel was considered for the tubing material. This was because of the melting point of Inconel and its availability. However, after looking into the price of Inconel, it was decided that it would not be the most economical choice. Due to cost effectiveness, stainless steel was selected as the tubing material. Specifically, type 304 stainless steel was selected, which actually has a higher melting point than Inconel by around 200℃, making it better than Inconel in that respect as well. As for the design itself, it was selected because the tubing would eliminate the idea of the fuel's melting point being the limiting factor, as the tubing has a much higher melting point. In addition to this, taking the fuel rods out of the fuel assemblies could lead to more fuel rods in individual dry casks, decreasing the total number of dry casks needed for storage, and it could increase the longevity of the casks if the tubing can reduce the number of interactions between the concrete and neutrons.

4.2 Mechanical Feasibility

In order for this tube design to properly work, a mechanical device needs to be created for removing the fuel rods from the fuel assembly and placing them into the prefabricated tubes. A model of a proposed design to accomplish this task was created using SolidWorks and the various aspects of this design can be seen in Figures 6-20. A lifting device consisting of a lifting bracket and 289 driving rods is submerged into the spent fuel pool and attached to the entire fuel assembly. As a safety measure for workers, the lifting device will have a shield surrounding itself and the fuel rods during the drying and moving process. Once the lifting device is securely attached, it moves the rods out of the water, allowing for the water residue to be evaporated off of the fuel rods via their own decay heat. The device then moves the fuel assembly to where it is on top of a stainless steel tube assembly that is relatively similar to the existing assembly. This stainless steel tube assembly contains 289 empty tubes, each with a capped bottom and a UNC-2B threaded inner rim on the top. Once the fuel assembly is placed above the stainless steel assembly, the brackets that hold and space the fuel rods are cut in such a way that they can now freely slide up the length of the fuel rods. The fuel assembly is then lowered onto the stainless steel assembly, such that each fuel rod fits into a single, individual stainless steel tube. Although the possibility of fuel rods being slightly bent exists, this should not be a concern for placing them into the stainless steel tubes, as they would bend less than a centimeter. As the fuel assembly is lowered, the spacing brackets slide up the fuel assembly and collect at the top of the fuel assembly.

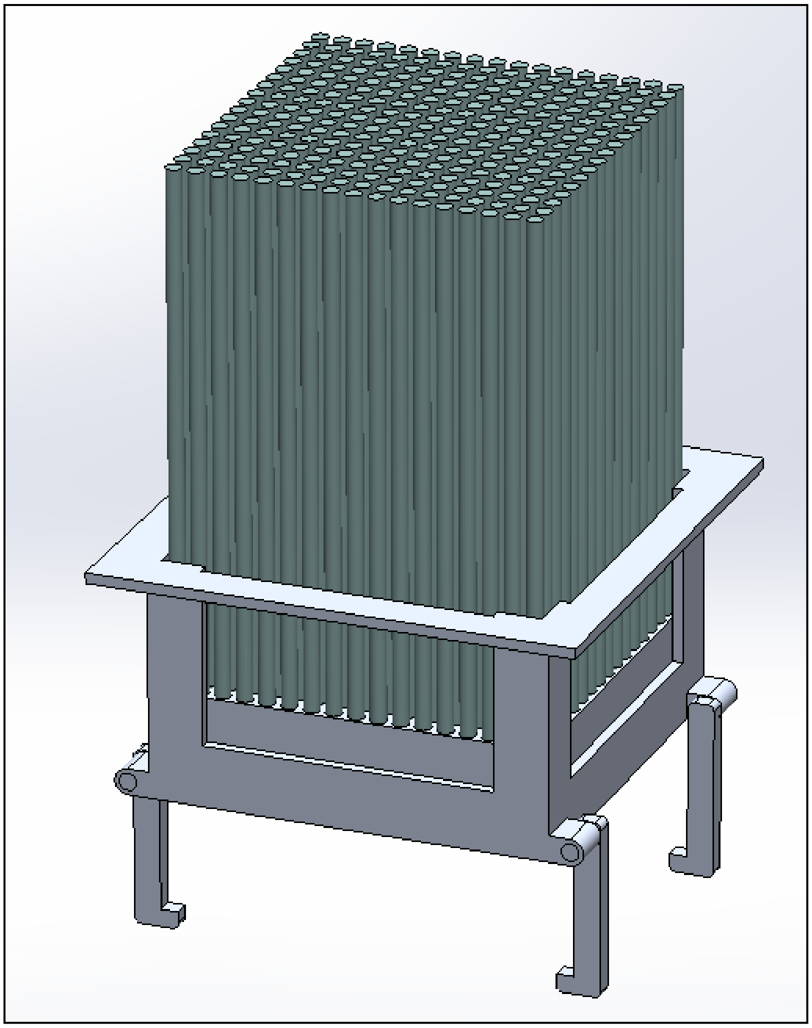

Figure 6: Lifting device used for picking up the fuel assembly, with 289 driving rods for removing the fuel rods

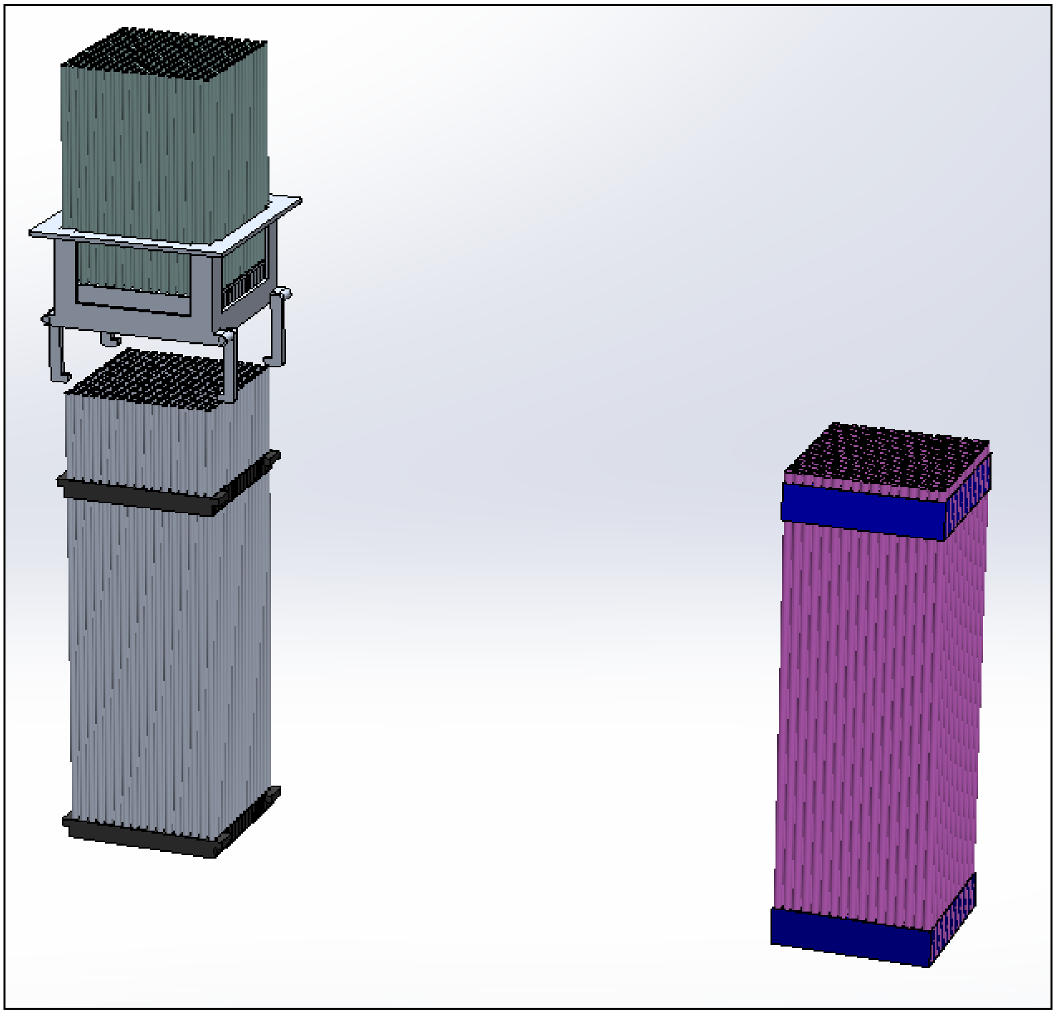

Figure 7: The lifting device about to pick up the fuel assembly, with the stainless steel tubes on the right side

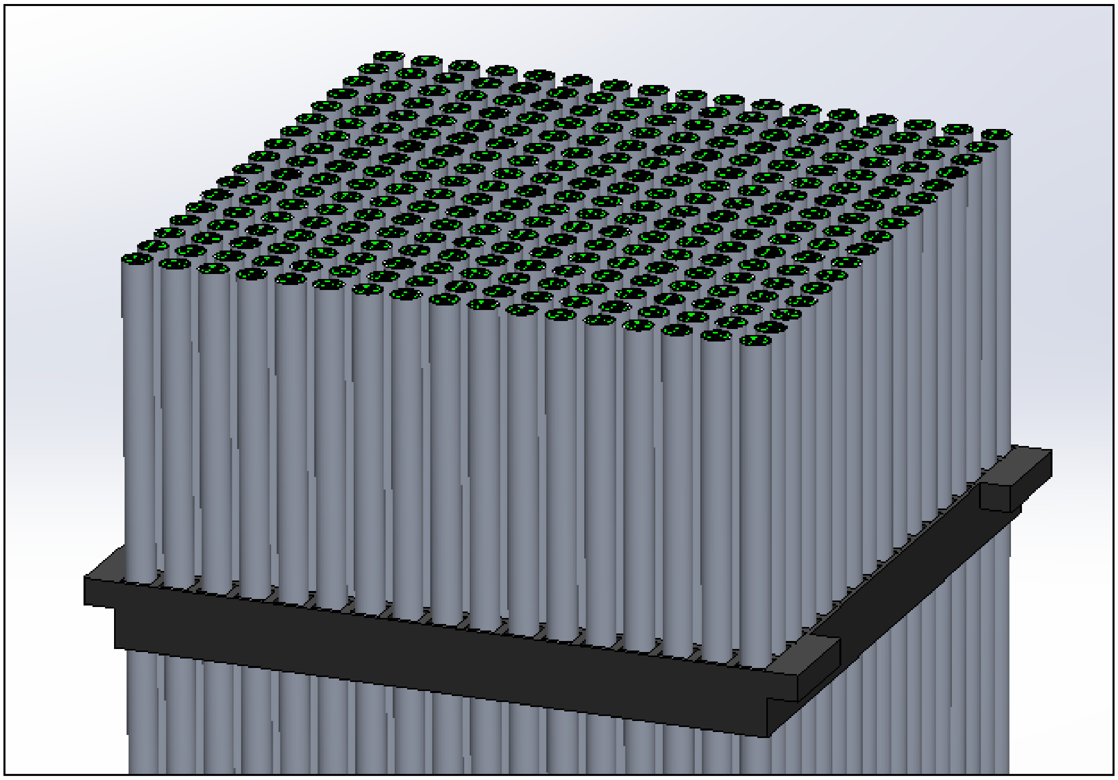

Figure 8: Close up of the fuel assembly

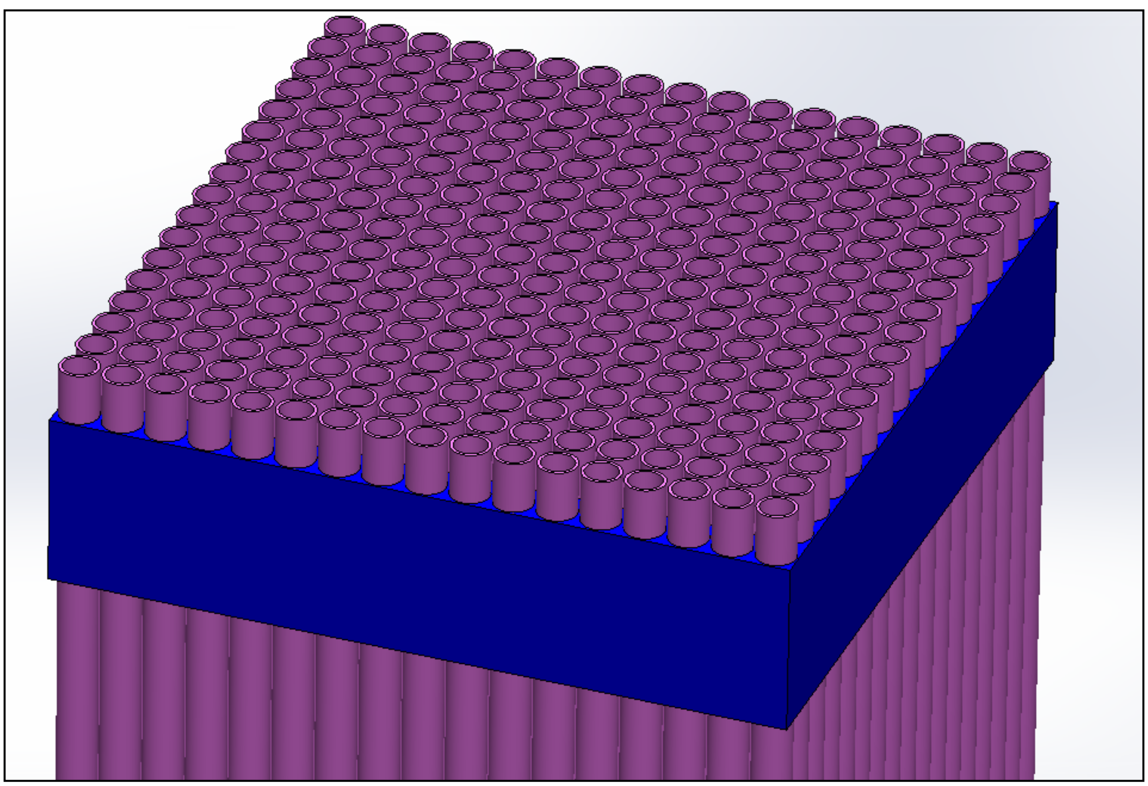

Figure 9: Close up of the stainless steel tubes that will contain the individual fuel rods

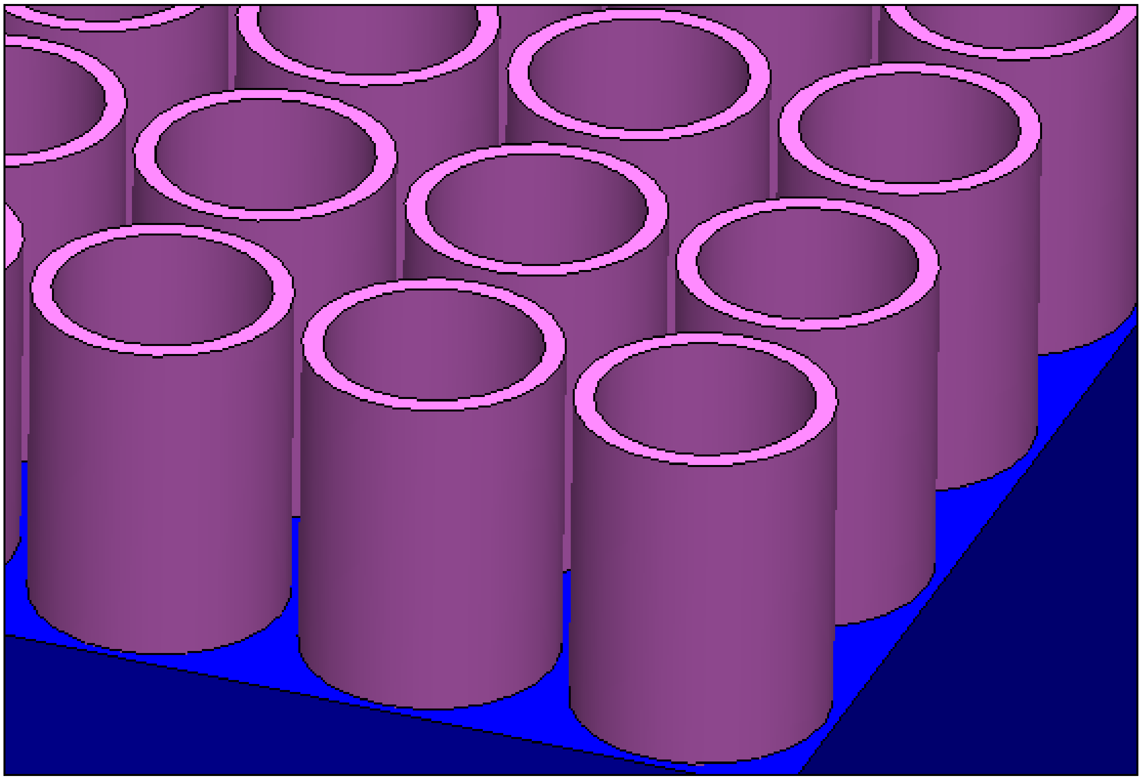

Figure 10: Another close up of the stainless steel tubes that will house the individual fuel rods

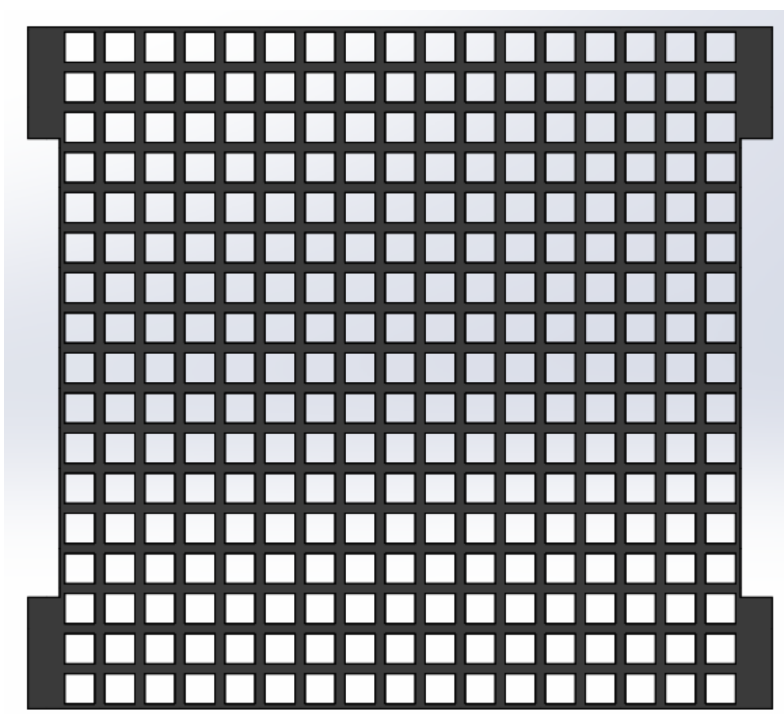

Figure 11: Top view of the bracket that holds the stainless steel tubes in place while the fuel rods are placed into the tubes

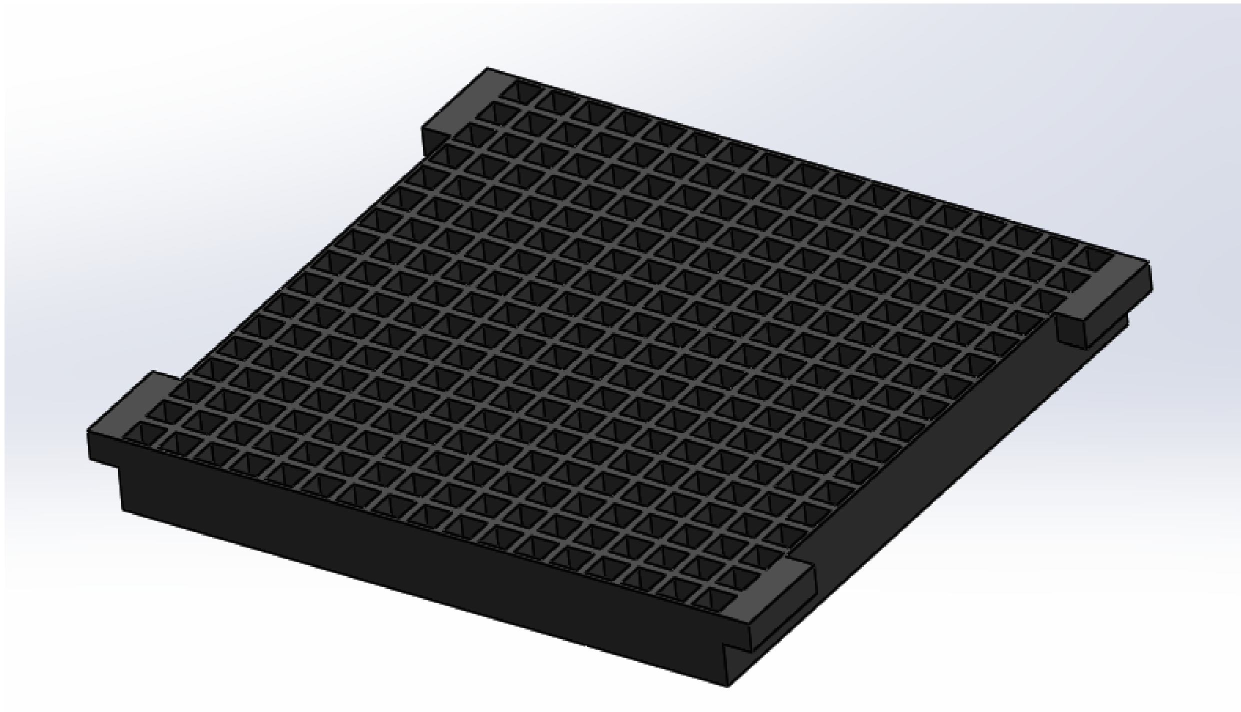

Figure 12: Angled view of the bracket that holds the stainless steel tubes in place while the fuel rods are placed into the tubes

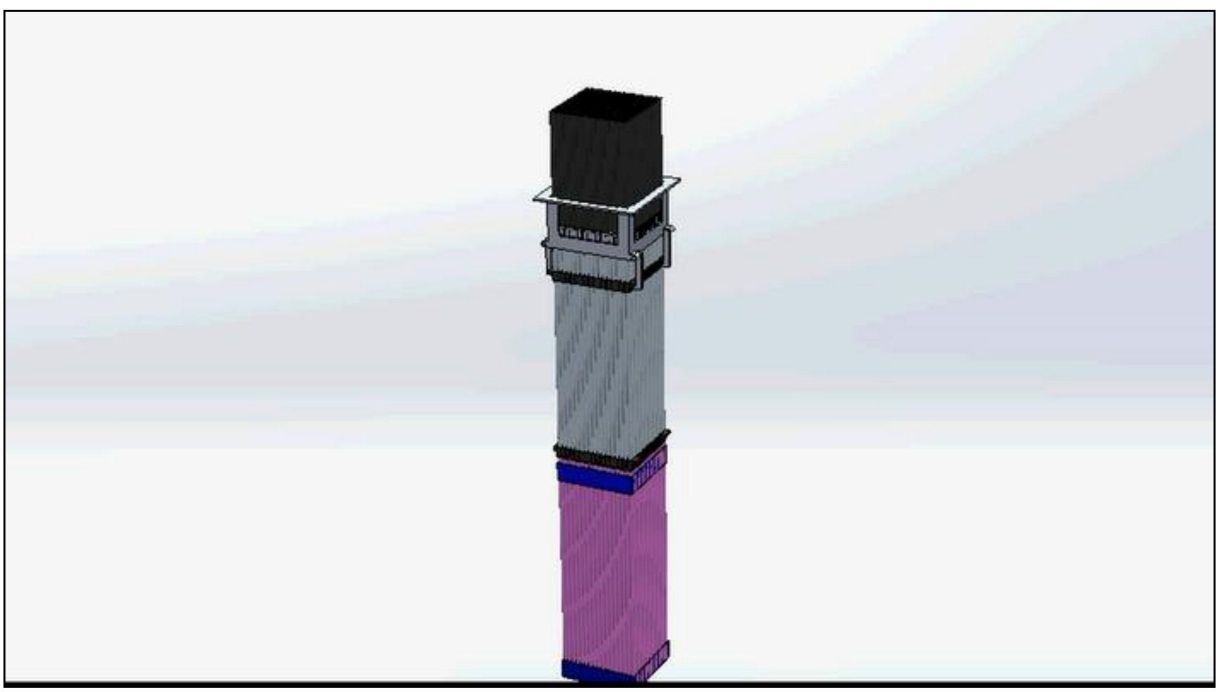

Figure 13: The lifting device placing the fuel assembly above the stainless steel tube assembly, with the driving rods preparing for the fuel rods to be pushed into the tubes

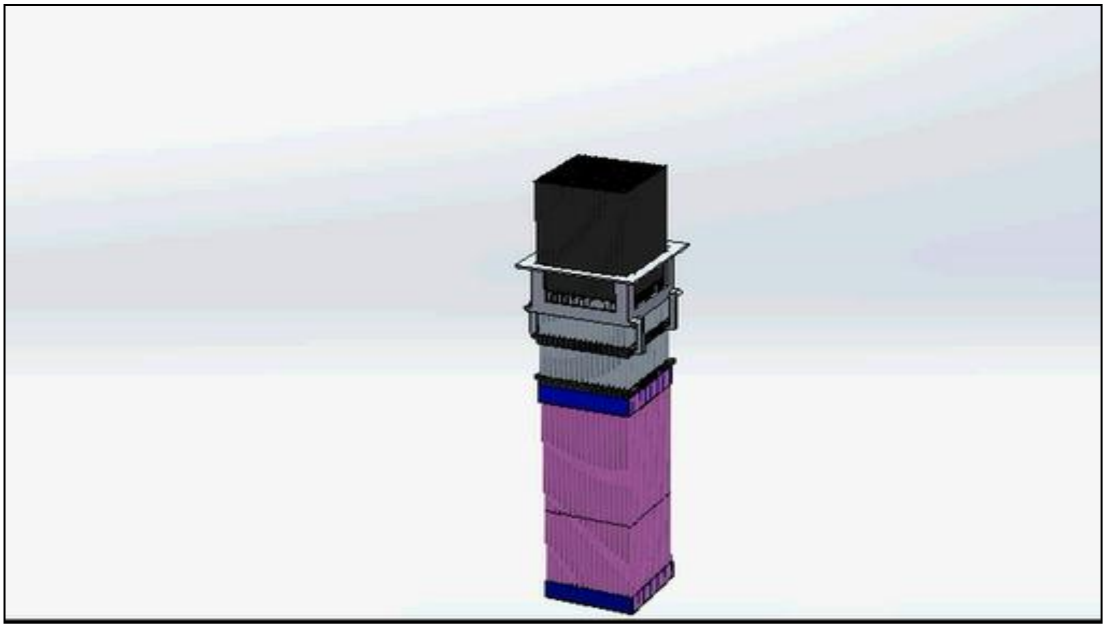

Figure 14: The fuel rods being pushed into the tube assembly via the driving rods

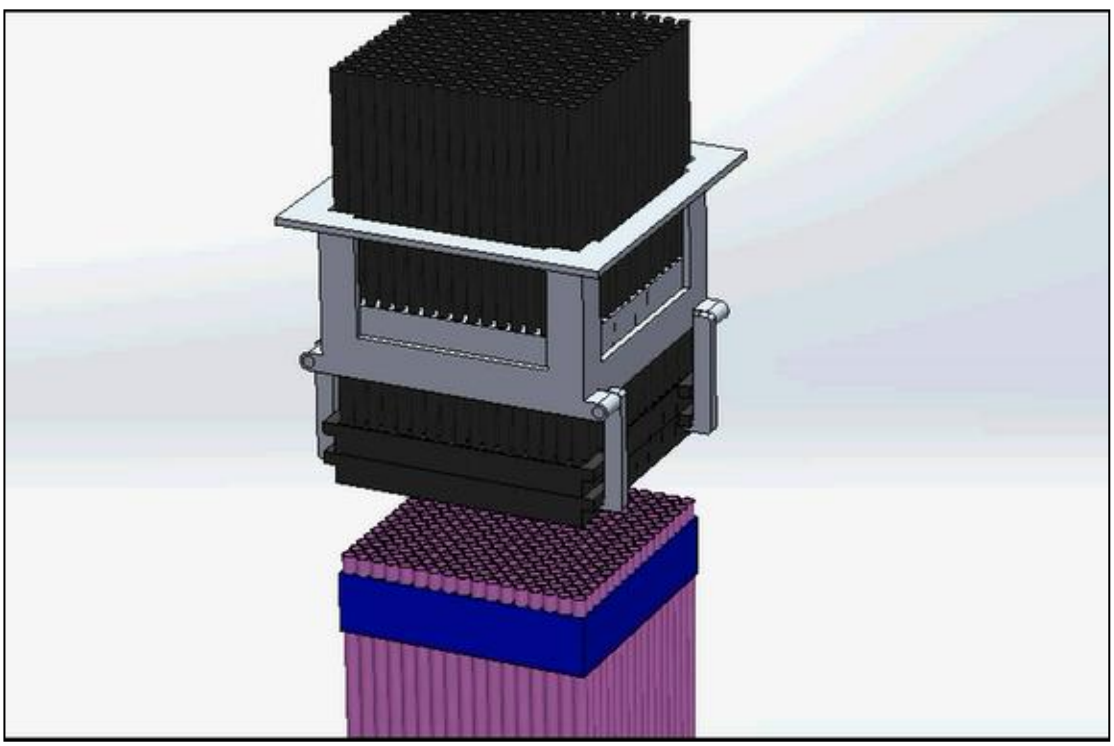

Figure 15: The brackets remaining in the lifting device after the fuel rods have been pushed into the tubes

After the fuel rods have been successfully placed inside of the stainless steel assembly, a device with the 289 corresponding UNC-2A threaded caps is placed on top of the stainless steel assembly, with the caps then mechanically screwed in place. These caps can later be tightened individually if needed. The dry casks used for this storage uses an “egg crate” design, with 32 individual spaces that are usually in place for storing fuel assemblies. With the fuel rods enclosed in the type 304 stainless steel tubes, they can be placed into the individual holders of the dry cask, providing for more tubes in each space than a typical fuel assembly, with this concept shown in Figures 18, 19, and 20. These will either be bundled within another shielded box (as shown in Figure 18) or bound with metal bands around the bundle.

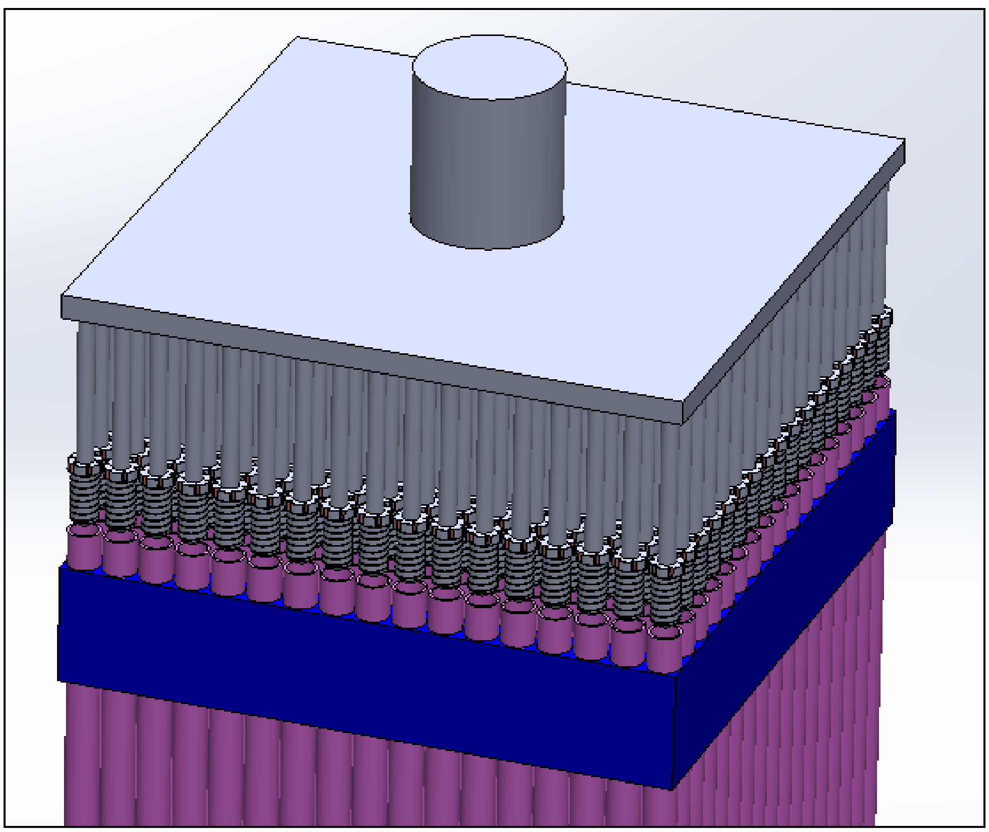

Figure 16: Device used to mechanically cap all of the stainless steel tubes with threaded ends

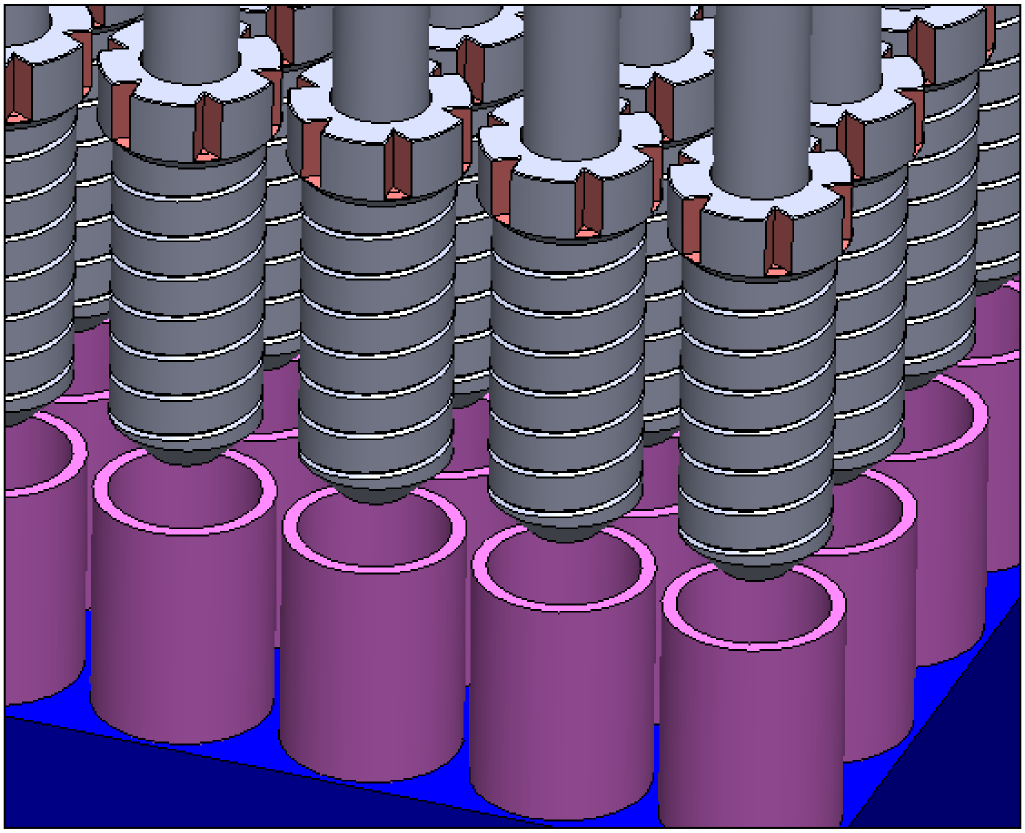

Figure 17: Close up of the threaded caps

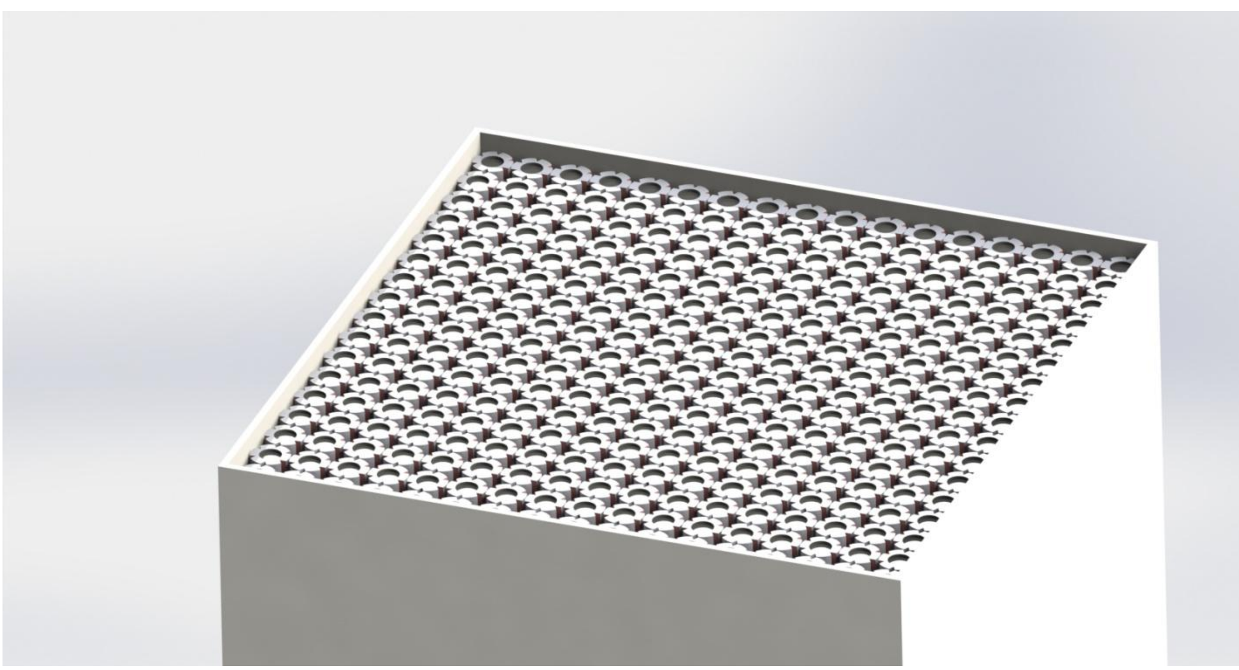

Figure 18: Model showing possible layout for stainless steel tubes in one of the baskets of the dry cask

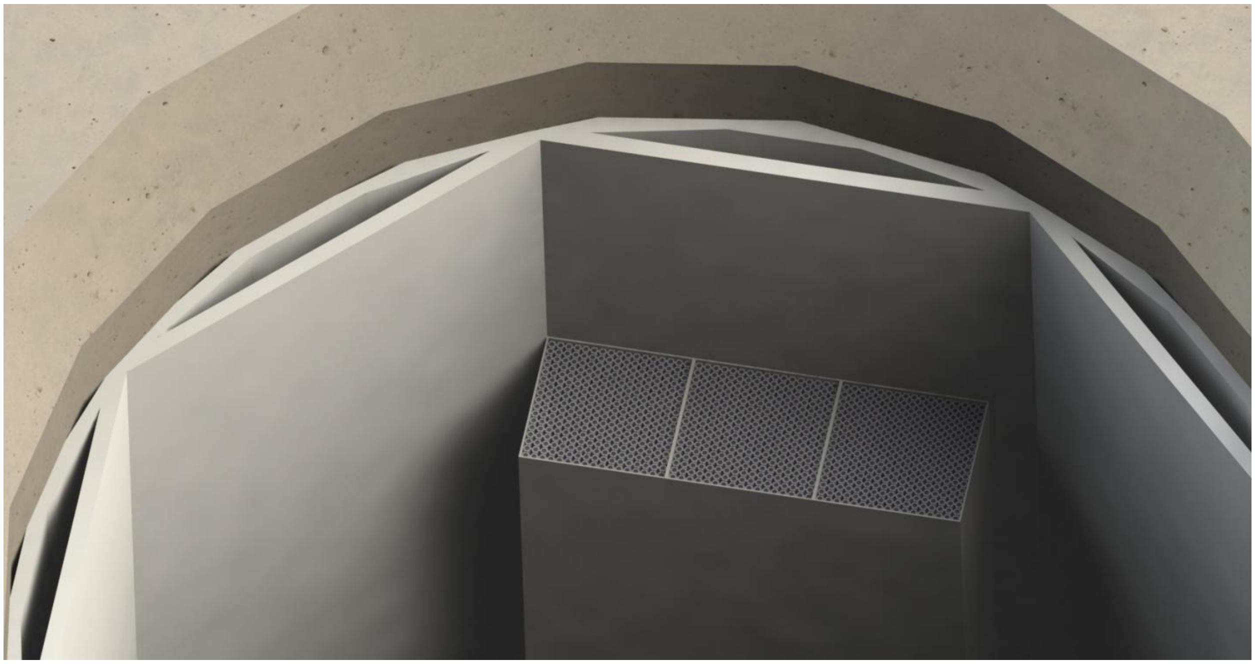

Figure 19: A close-up showing three baskets with stainless steel tubes placed inside of a dry cask

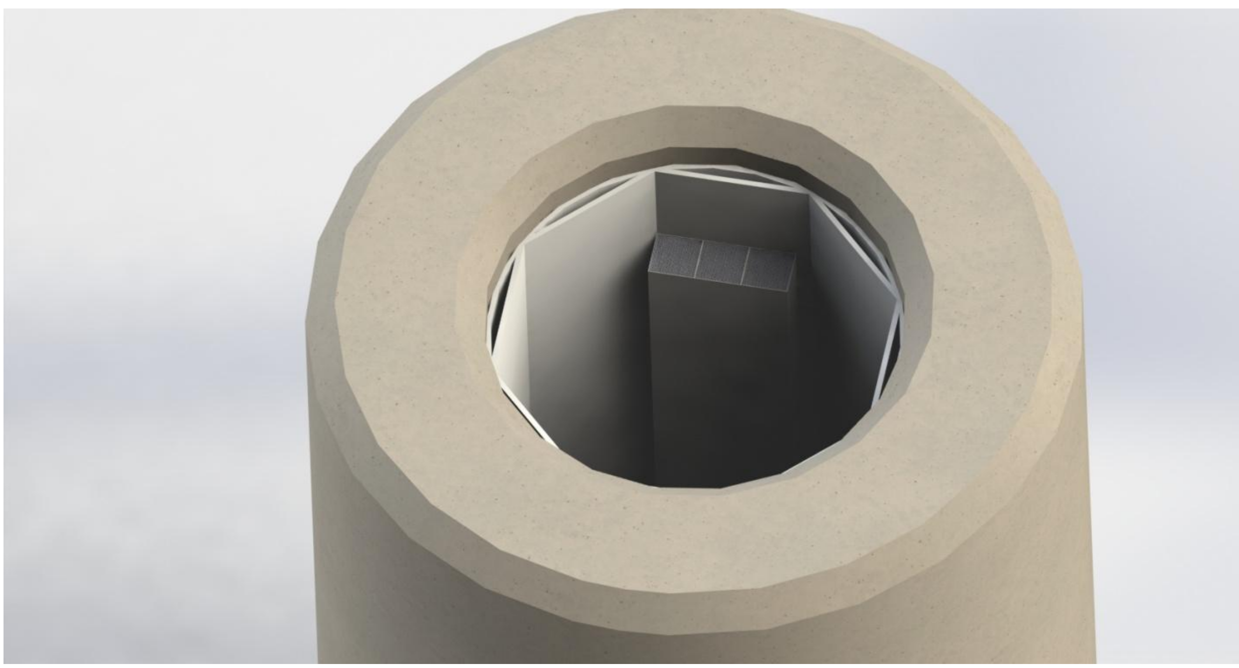

Figure 20: Three baskets with stainless steel tubes placed inside of a modeled dry cask

5. Thermal Analysis

In order to perform a realistic heat transfer analysis for this design, COMSOL Multiphysics was used, as it has the capability to do finite element calculations that can solve for the temperature of the fuel rods. COMSOL is an application-based program that allows users to make geometries and specify the type of physics model that should be used. In the fuel rod bundle described previously, a 2D conduction model is used in place of a 3D model. This is done for two reasons: the 2D model can be used to approximate the 3D design because of the similar temperatures in the height and to cut down on computational requirements. Because most heat transfer is radial, this 2D approximation should provide satisfactory results. Although the center of the fuel will be at a higher temperature, a higher heat flux for each individual rod was used in the model to accommodate for a worst-case scenario. The dimensions used in this design for the fuel rod and stainless steel tubing can be seen in Table 1. Figure 21 shows each finite element used in the simulation. Each element uses a different equation based on the results generated from the surrounding elements. The equation used to approximate conduction through a solid is given in Equation 3.

Table 1: Dimensions used for the fuel rod modeling and analysis

Element:	Radius or Thickness (cm):
Fuel	0.41
Gap between Fuel and Cladding	0.01
Zircaloy Cladding	0.05
Gap between Rod and Tube Wall	0.01
Stainless Steel Tube Thickness	0.07

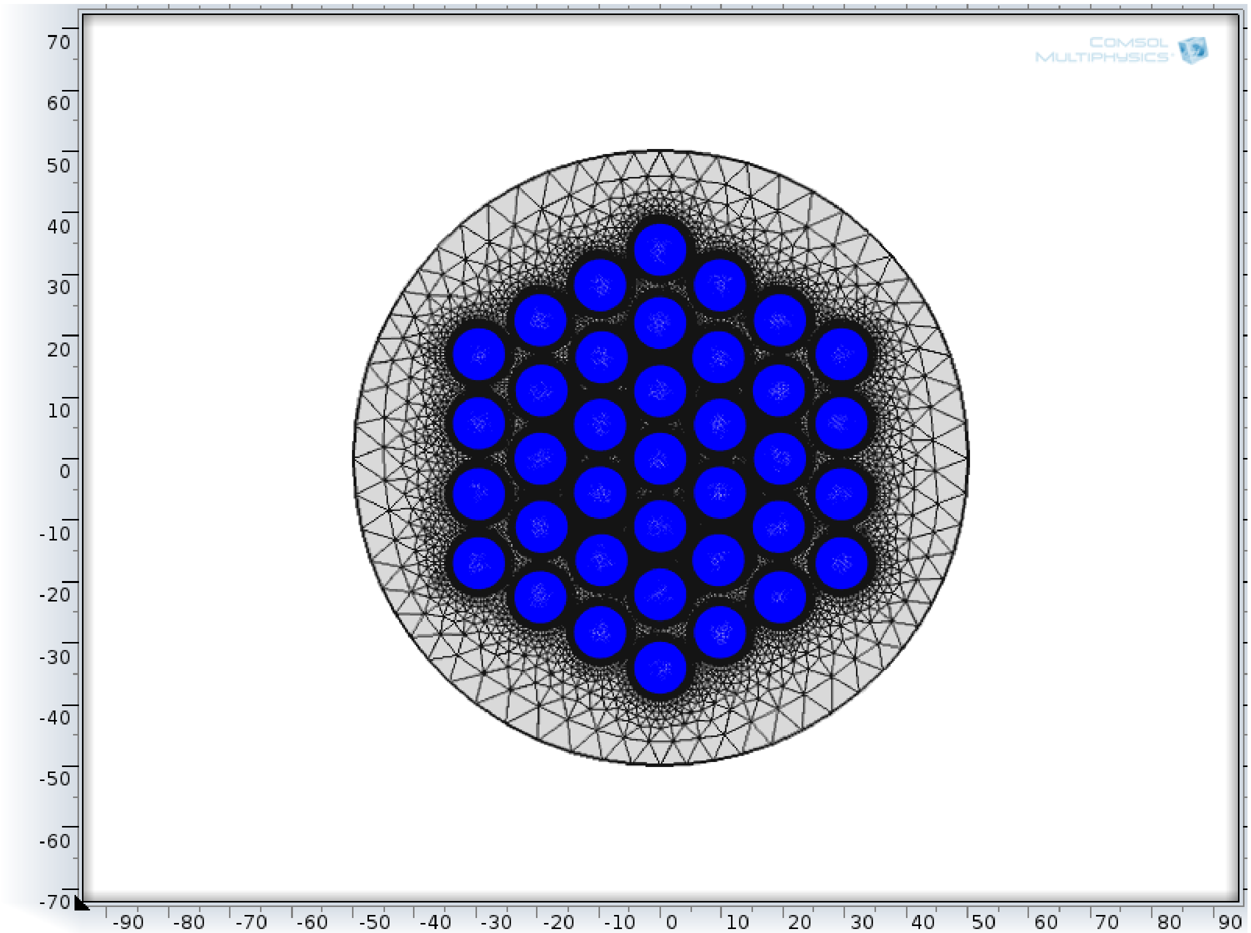

Figure 21: Visualization of finite element analysis and the heat generation used in the simulation

$$\rho c_p u_{trans} \nabla T = \nabla \bullet (k \nabla T) + Q \quad \text{(Eq. 3)}$$

Where: ρ = Density
c_p = Specific Heat
u_{trans} = Translational Motion Vector
∇T = Temperature Gradient
k = Thermal Conductivity
Q = Heat Generation

The change in temperature depends on the thermal conductivity (k) and the heat generation (Q) of each fuel rod. The heat generation from each fuel rod was found using ORIGEN in SCALE. In this particular example, the watts per assembly after being removed from a reactor for 3 years was just over 3,986 W, which was determined with an executable in

SCALE 6.1 known as ORIGEN-ARP. This must be transformed to find the heat generation in each rod that is modeled. Because there are only 41 fuel rods modeled compared to approximately 19,000 actual fuel rods, the heat generation per rod differs from the modeled heat generation. In order to simulate the heat generated for the 41-rod temperature profile, decay heat was taken from ORIGEN-ARP. This decay heat was outputted in heat generated per fuel assembly, which was converted to watts per fuel rod. Because the model only has 41 rods, the next step required that one simulated rod be equivalent to nearly 500 actual rods in terms of heat output. Since the model is a 2D approximation, the total watts were divided by the height of each fuel rod. After these calculations were completed, the heat generated per simulated rod was 2,325 W.

The heat generation is approximated to a much smaller area because fewer equal-sized fuel rods are used in the model. Since the center fuel rod will have the highest temperature, it is the limiting factor. The radius of the modeled cask is far less than an actual cask radius, so the temperature on the outside of the fuel model has no real value. In addition, the model assumed that the fuel burnup was 40 GWd/t and that the fuel rods were to be moved to dry storage after only 3 years. The inner temperature in this model is just under 1140 K (867°C). This result represents a worst-case scenario in a sense, as conduction was the only method of heat transfer modeled in this simulation. Although type 304 stainless steel has a melting point of 1450°C, the limiting temperature for the fuel rods is around 1200°C, as the cladding would begin to exothermically react at that point, causing the temperature to quickly rise above the melting point of the tubing. A temperature flux model and a contour figure modeling heat flow are shown in Figures 22 and 23.

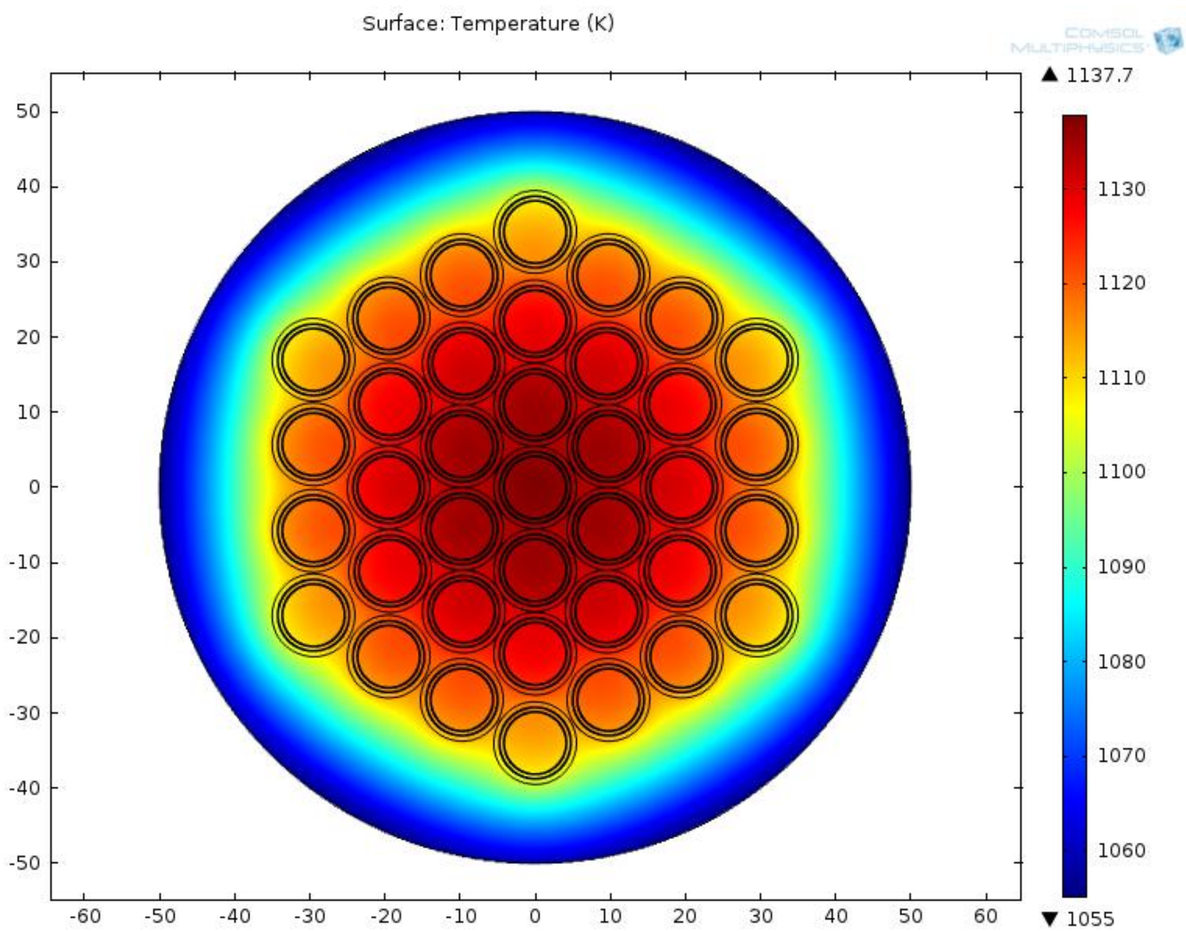

Figure 22: Plot of surface temperature in 41-rod model

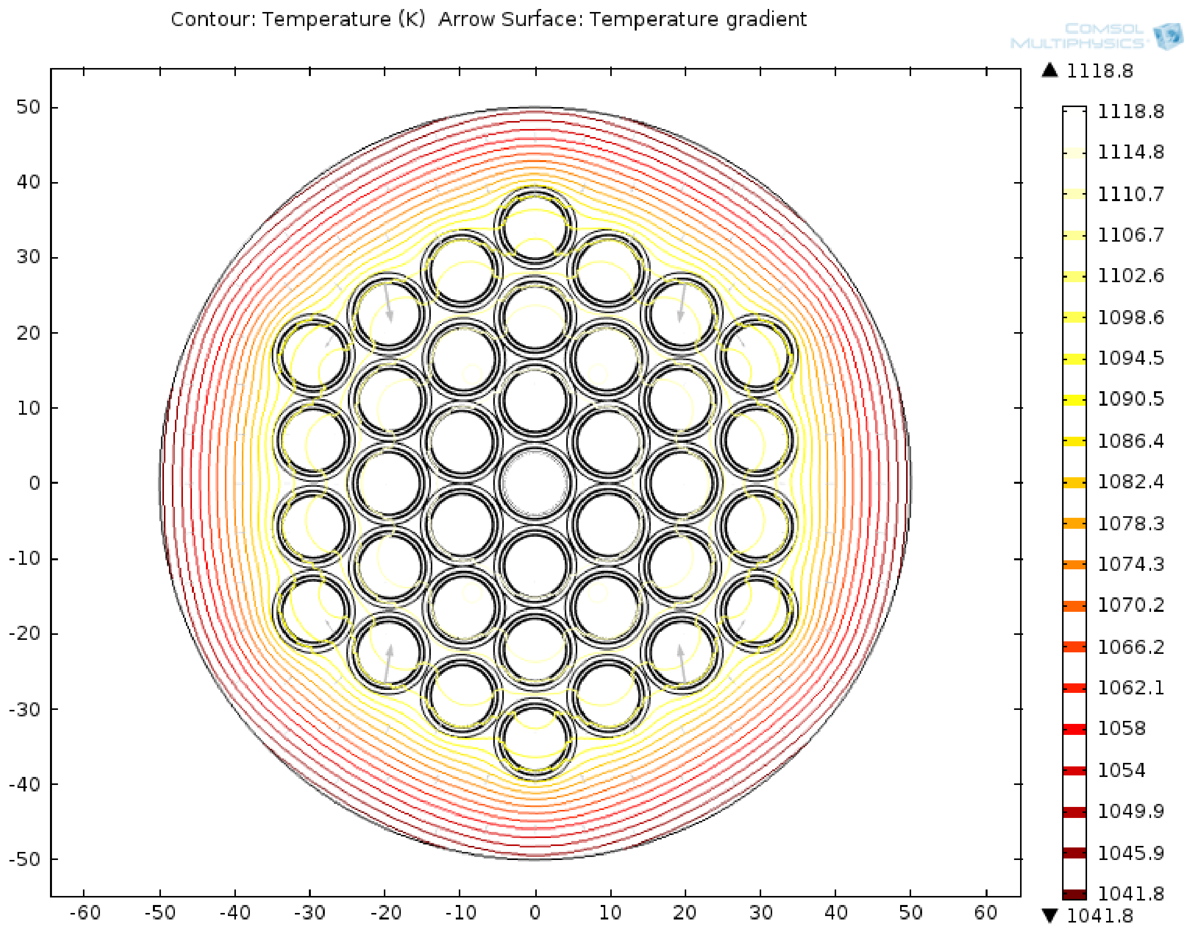

Figure 23: Temperature gradient of the 41-rod model

The blue signifies a lower temperature, while the dark red is the hottest temperature in Figure 22. As previously stated, the radius of the cask is very small at only 50 mm. This small radius is the reason that the temperature difference is not very high, and the surrounding temperature is still very hot. If the computational model was big enough, it would show that the temperature at the edge of the cask would be near 150°C.

Figures 24 and 25 show a simulation of the 41-rod model where the rods were transported to the stainless steel tubes at different times. This was accomplished by using appropriate decay heats at the specific times. In Figure 24, the rods were transported to the tubes after only 36 days, showing an extremely high temperature of nearly 11,000 K (10,727°C) for the center rod. This gives very good justification for why the spent fuel rods should not be removed from a spent fuel pool shortly after they are unloaded from a nuclear reactor. In contrast to the extremely high temperatures found in Figure 24, Figure 25 shows that transporting the rods after 10 years would leave the center rod at only 590 K (317°C), a much more reasonable temperature for the rods. Figure 26 shows a comparison of the temperature of the center rod when transported to the stainless steel tubes, ranging from less than 1 year after being unloaded all the way to 50 years after being unloaded. A steep drop off in temperature can be seen within the first 5 years, but it appears to asymptotically approach approximately 600 K (327°C), with diminishing returns being apparent from 10 years to 50 years.

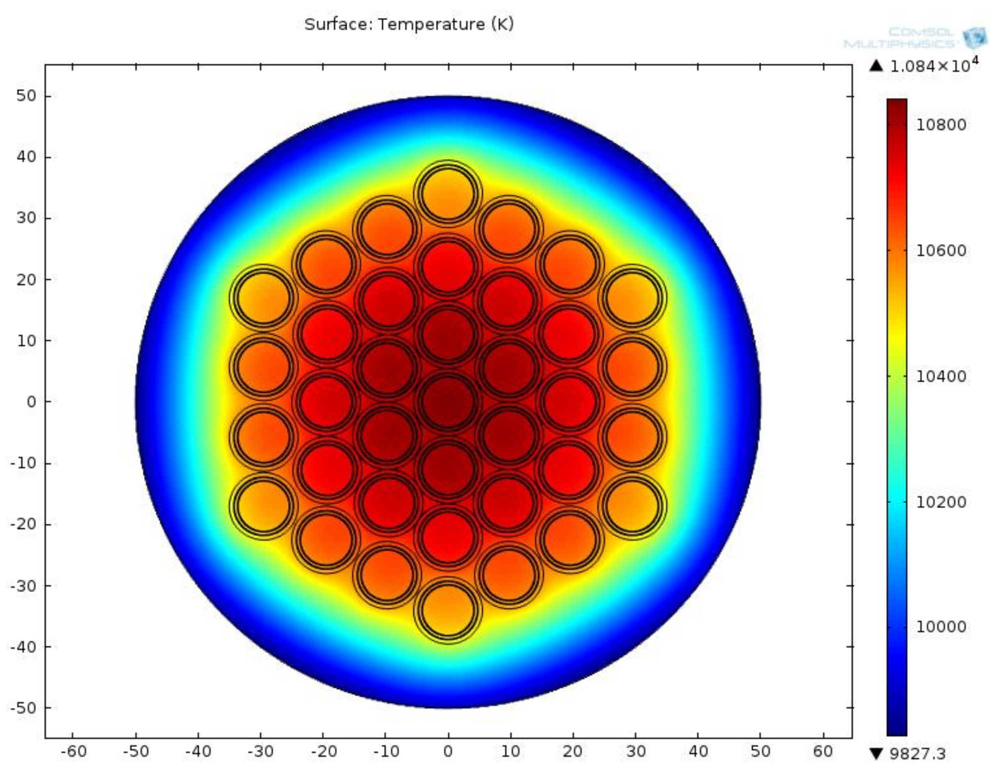

Figure 24: Temperature of 41-rod model assuming rods are placed in the stainless steel tubes after only 36 days

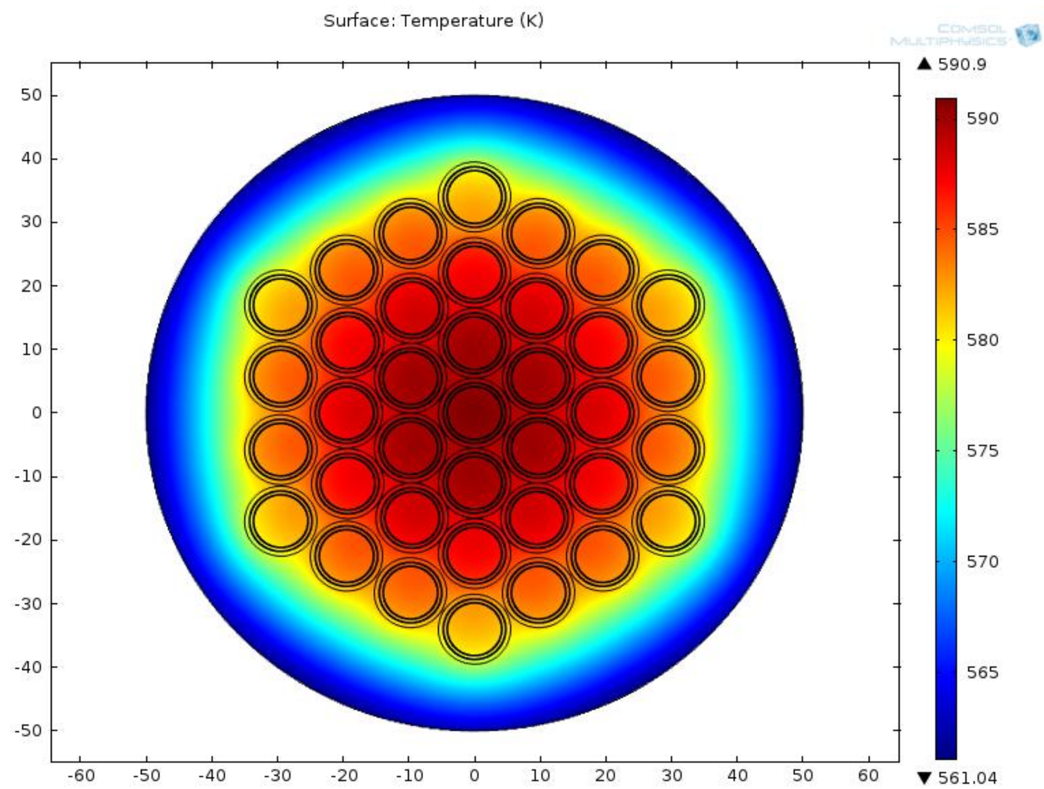

Figure 25: Temperature of 41-rod model assuming rods are placed in the stainless steel tubes after 10 years

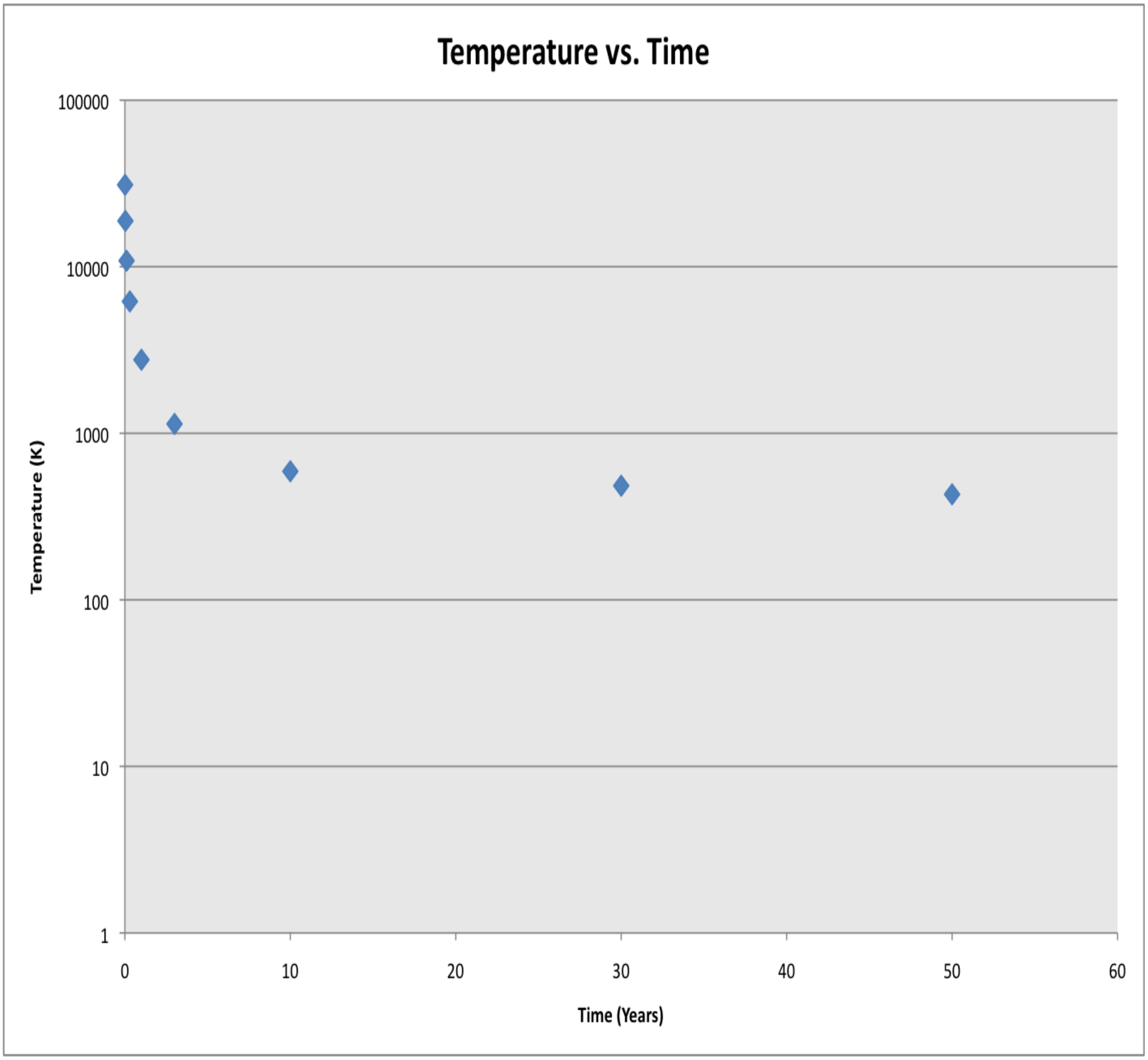

Figure 26: Plot of temperature vs. time for when the rods are placed into the stainless steel tubes, from less than 1 year to 50 years

6. Criticality Analysis

A criticality calculation was performed on the proposed technique of bundling individual fuel pins with a shield tube completely surrounding the fuel pin. This technique would allow for more fuel pins to be placed per basket in current dry casks storage equipment. Using the dimensions of current dry cask technology, it was calculated that approximately 450 fuel pins could be placed per basket. From this calculation, it was determined that a 21x21 array of fuel pins should be modeled to best represent the newly proposed storing technique to ensure that criticality would stay below the upper subcritical limit.

For this criticality model, the GeeWiz (Graphically Enhanced Editing Wizard) of SCALE 6.1 was utilized to construct the desired array. To begin, a 2D model of an individual fuel pin was constructed with a proposed shield in place. This model is shown in Figure 27.

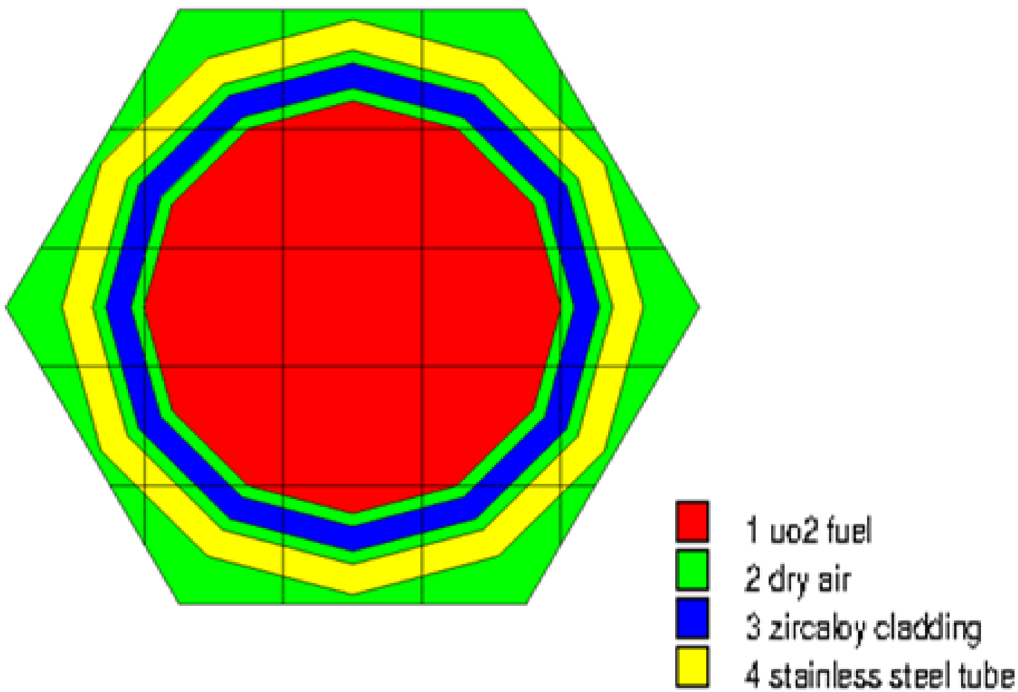

Figure 27: Image showing the basic SCALE model of fuel with cladding and stainless steel tubing

The dimensions of the fuel, air gap, cladding, and gap between tube and cladding were consistent with those used for the heat transfer model (Table 1). The shield thickness is a parameter that can be varied to optimize the heat transfer and criticality characteristics. With this base model in place, a 21x21 test array was generated and the effect of $k_{effective}$ was recorded. This model is shown in Figure 28.

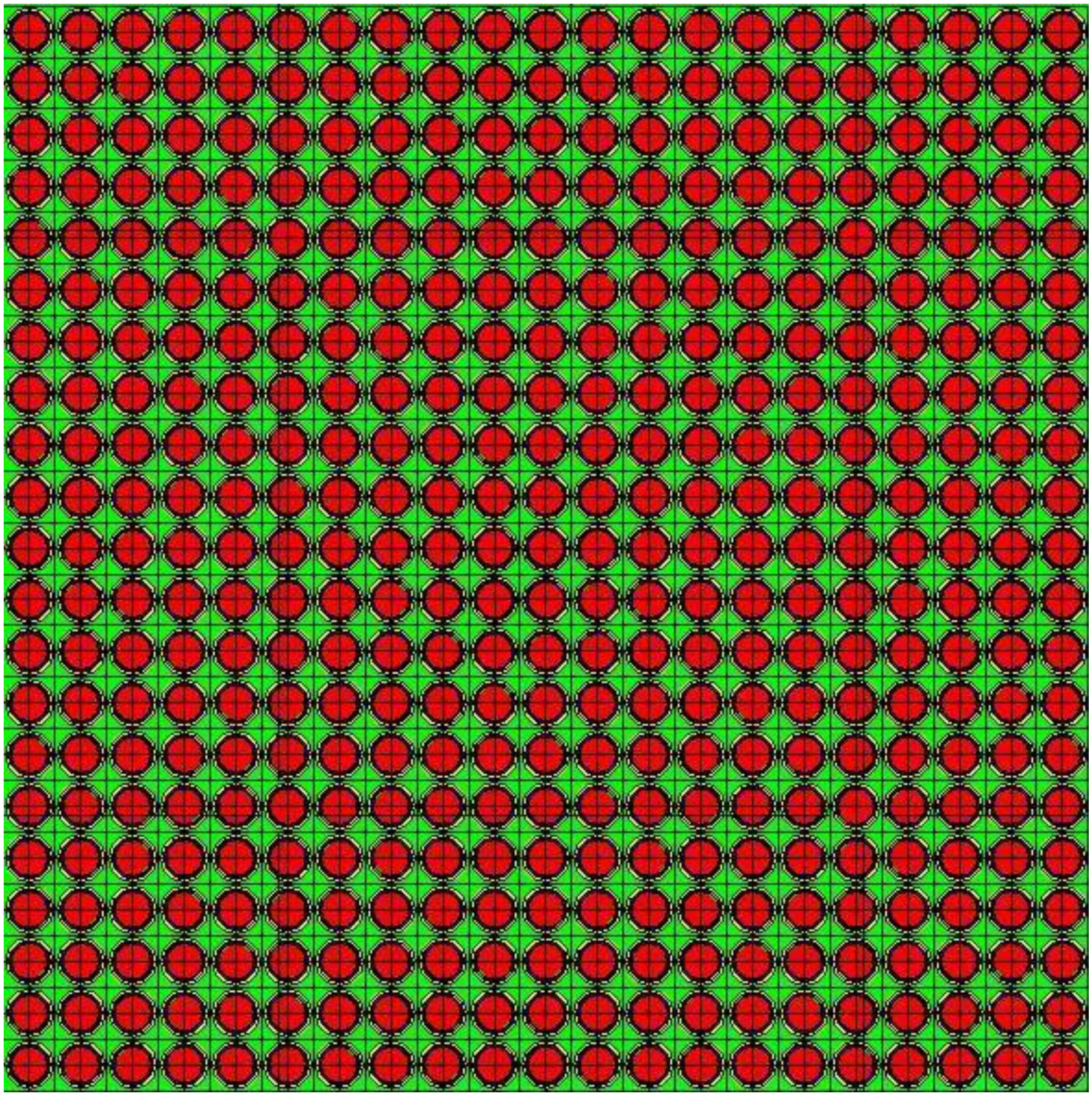

Figure 28: SCALE model of 21x21 array of fuel pins with tubing shield

Through this study, it was determined that the proposed model with a tube thickness of 0.07 cm has a k_{eff} of around 0.61, much lower than the standard for an allowable operation of 0.90 for dry storage [6].

Because the 21x21 model took so long to actually simulate, a 5x5 model was created to allow for comparisons when varying parameters of the model. Before any parameters were altered, this 5x5 array was simulated in the same manner as the 21x21 array, with k_{eff} again being

0.61, indicating that the results from the 5x5 simulations should be comparable to the 21x21 model. Figure 29 shows the 5x5 model that was created in SCALE, with it having the same dimensions for the fuel rods and stainless steel tubing as the model shown in Figure 28. Once this 5x5 model was created, simulations comparing the k_{eff} for a varying tube thickness were performed, with some of these models seen in Figure 30. Simulations were performed varying from no tube on the fuel rods, to a tube thickness of 0.5 cm. The resulting k_{eff} for each case can be seen in Figure 31. Even with no stainless steel tubes, the k_{eff} came out to be only 0.68, indicating that a criticality problem is not likely. In order to optimize the amount of fuel rods that can fit into each basket of a dry cask, a tube thickness of 0.07 cm was selected, with k_{eff} coming out to be around 0.61 for this thickness, indicating that the upper limit of 0.90 should not be a concern.

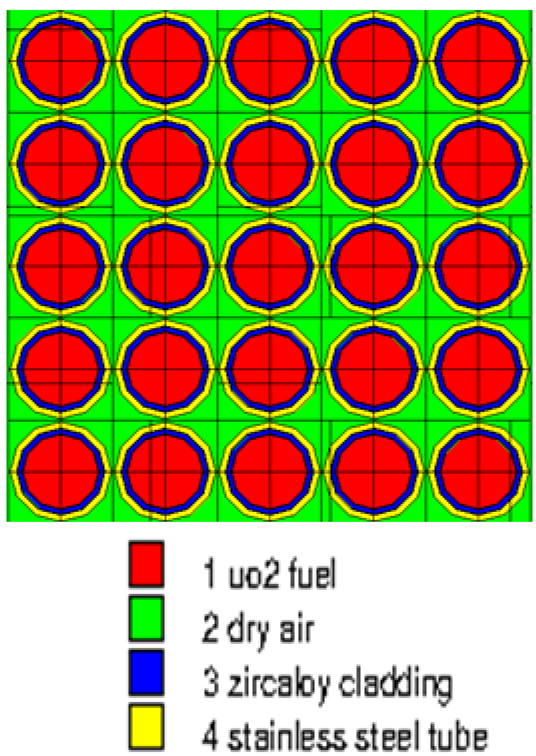

Figure 29: Original 5x5 model that was used in SCALE for differing parameters

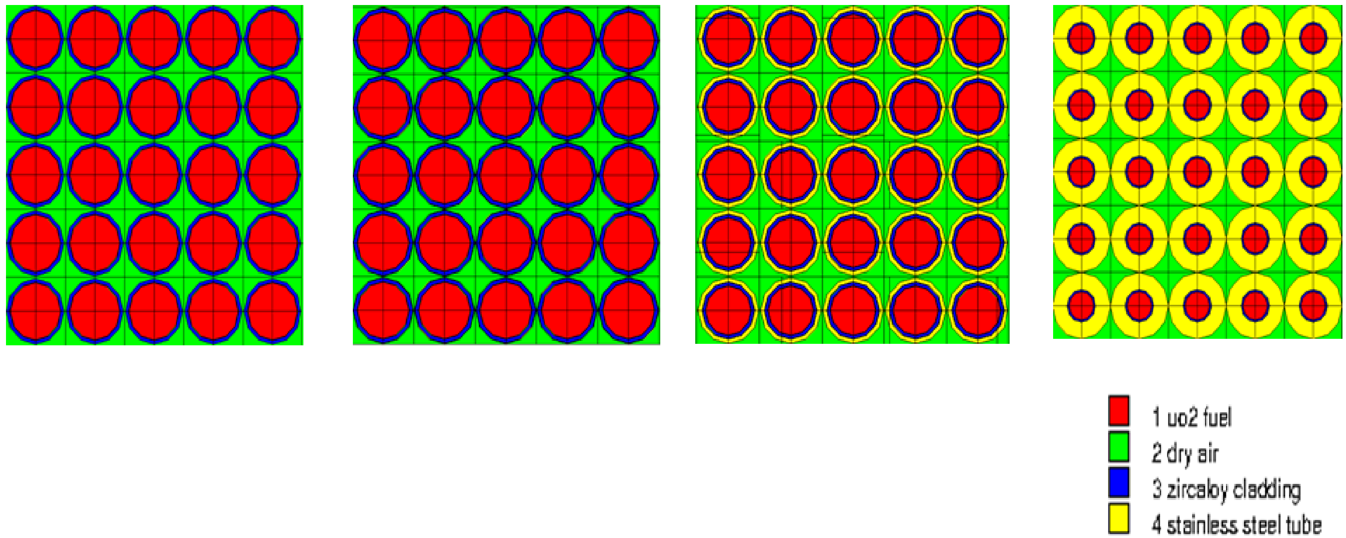

Figure 30: Four separate 5x5 models, each with varying tube thickness

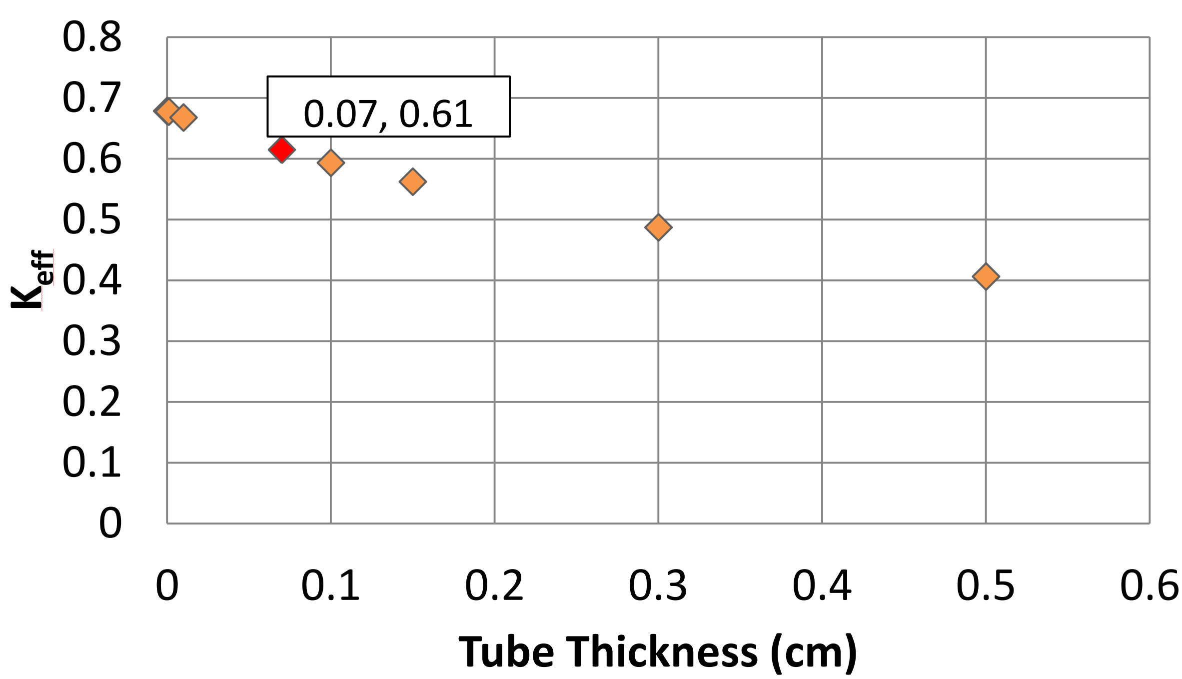

Figure 31: Graphical representation of the k_{eff} for each of the tube thicknesses shown in Figure 30, with the thickness that was eventually selected highlighted in red

In addition to varying the tube thickness, different fuel enrichments were used to see the effect it had on k_{eff}. Because 0.07 cm was selected as the optimal tube thickness, this thickness was used for each test case, and the results can be seen in Figure 32. An enrichment of 7% showed a k_{eff} just under the operational limit of 0.9 for dry storage; however, US reactors are currently restricted to no more than 5% enrichment, which had a k_{eff} of 0.74, showing that even the maximum allowable enrichment should not pose criticality problems with the stainless steel tubes at a thickness of 0.07 cm. In the previous SCALE simulations, an enrichment of 3.5% was assumed, with this enrichment producing a k_{eff} of 0.62.

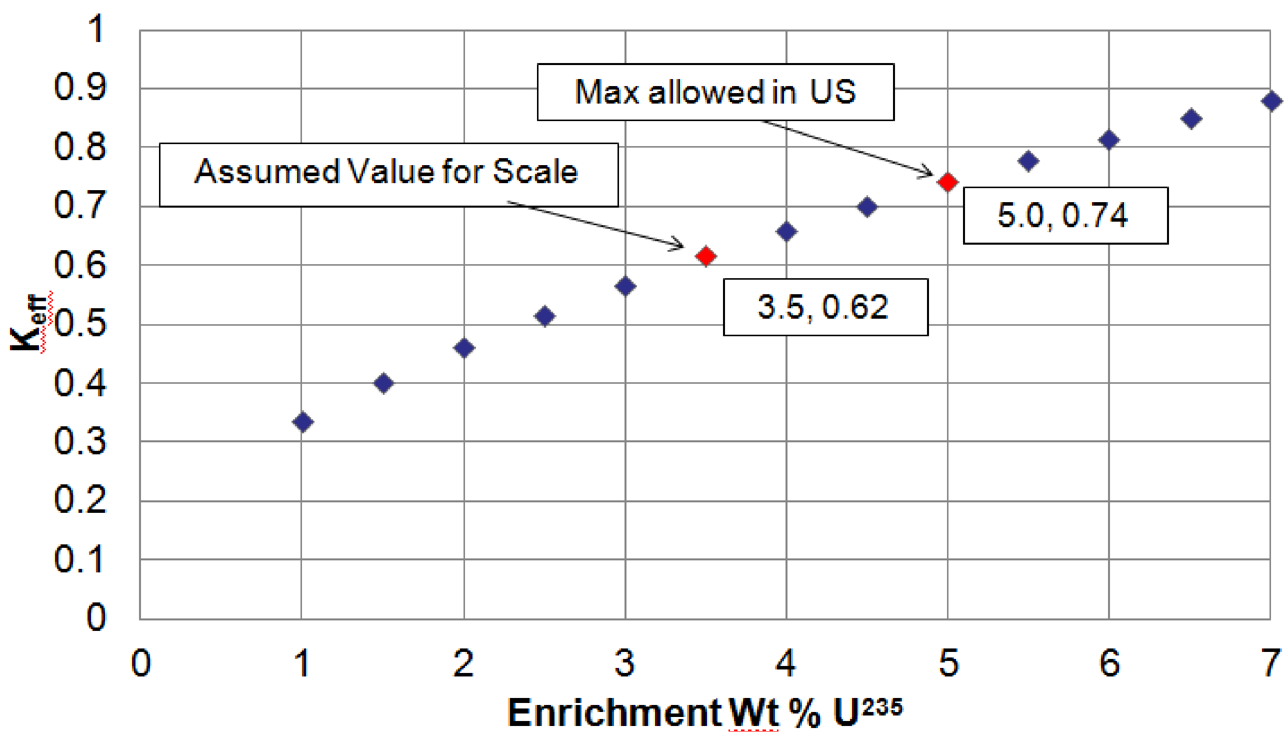

Figure 32: Representation of the k_{eff} for varying enrichment values

An additional contingency analysis was performed to see the effect on k_{eff} if the spent fuel water residue was not completely burned off before enclosing the fuel rods in the stainless steel tubes. For the SCALE model, it was assumed that the gap between the cladding and inner tube wall was now completely water, instead of air. Figure 33 below shows a pictorial representation of this worst-case analysis. This geometry was then placed in a 5x5 array, and a test was performed. Even if this situation occurred, the k_{eff} only rises to 0.69. This means that even in this worst case, the system would remain subcritical and well below the acceptable operational limit of 0.90 for dry storage.

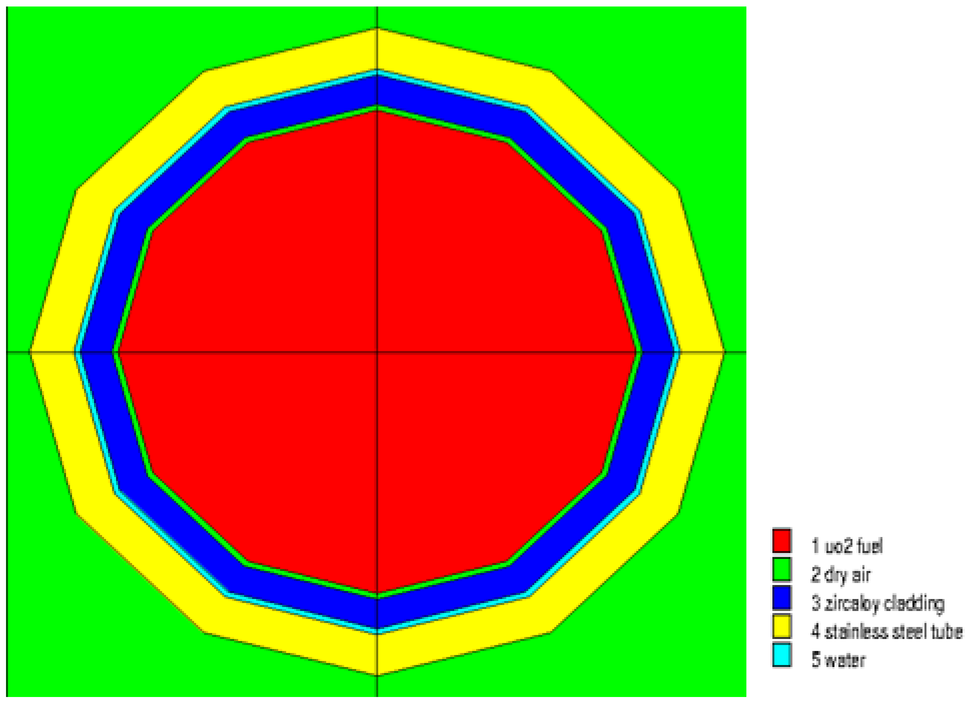

Figure 33: Representation of a worst-case scenario where water is still on the fuel rods before going into the stainless steel tubes

7. Economics Analysis

No design will ever work out if it is not economically viable. A preliminary cost analysis has been performed to select the best possible tubing material to still have satisfactory results. Type 304 stainless steel, type 316 stainless steel, and Inconel 600 were all looked at as possible materials. Type 304 and type 316 stainless steel are comparable in cost, with 304 costing approximately $50.00 per tube and 316 costing approximately $70.00 per tube at appropriate dimensions. Alternatively, an Inconel 600 tube only 6 feet in length of otherwise appropriate dimensions would cost approximately $100.00; therefore, type 304 stainless steel would be the best economical option, while still producing satisfactory thermal and criticality conditions.

By using type 304 stainless steel tubing at a conservative price of $50.00 a tube and assuming no cost reduction for buying in bulk, a total of $14,450 would be spent for an individual fuel assembly. Assuming that each dry cask used for these calculations can hold up to 32 fuel assemblies, using only the fuel rods from 32 fuel assemblies would cost around $462,400. Rather than doing this, though, it would be more viable to put as many fuel rods that will fit inside of each cask, leading to a reduction in the number of dry casks used. By assuming a thickness of 0.07 cm for each tube, along with the set dimensions of the fuel rod (Table 1), approximately 15,360 tubes could be placed into a single cask; however, only 14,112 tubes were considered for a single cask for overall space concerns. This would mean that the tubing cost for each fuel cask would actually be $705,600. By placing this many tubes, each cask would hold 4,864 extra rods. As a result of this increase, the total number of casks needed would approximately become 2 for every 3 when comparing the new design and the current design. Since dry casks cost approximately $1,000,000 just to make—along with another $500,000 to load the fuel—this could help cut down on the overall cost of dry cask storage [7]. By utilizing a 21x21 bundle in each dry cask basket and assuming a site that normally has 100 dry casks, a total of approximately $4,760,000 could be saved and 34 fewer casks could be used, as Figure 34 and Table 2 show. This was found by assuming that the only costs were making the dry casks, loading the fuel, and buying the material for the stainless steel tubing. The more advantageous aspect of this method, though, is the fact that it could cut down on the amount of space required for storing spent fuel, as storage space is quickly becoming a very big concern for spent fuel storage. Although these numbers show the possibility of cost reductions from fewer dry casks needed, it does not take into account the cost of developing the machines required to remove the fuel rods from the fuel assemblies and to place them into the stainless steel tubes, and it does not take into account operation costs of the equipment. These would likely make the cost savings more apparent in the long term, rather than in the short term.

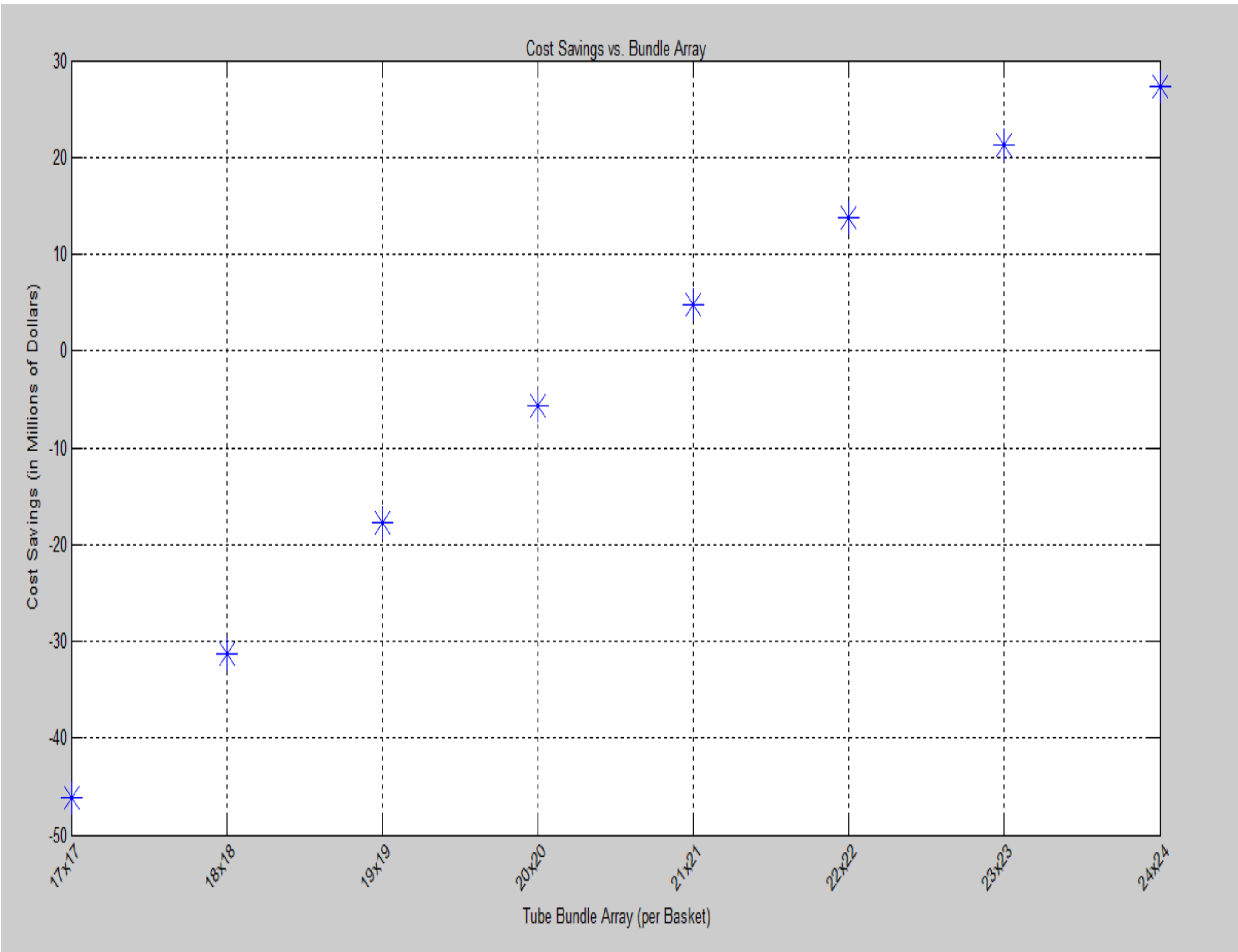

Figure 34: Plot showing the cost savings vs. the tube bundle array per basket, with it costing money until the 21x21 bundle array (assuming an original site size of 100 casks)

Table 2: Total Casks Needed and Savings for Varying Bundle Array Sizes

Rod Bundle Array	Total Casks Needed	Total Cost (in Millions of Dollars)	Savings (in Millions of Dollars)
17x17	100	196.24	-46.24
18x18	90	181.24	-31.24
19x19	81	167.74	-17.74
20x20	73	155.74	-5.74
21x21	66	145.24	4.76
22x22	60	136.24	13.76
23x23	55	128.74	21.26
24x24	51	122.74	27.26

8. Conclusion

The recent events that occurred at the Fukushima Daiichi site brought about several concerns for current spent fuel storage. Two alternative designs were discussed in this report: raising the boiling point of the spent fuel pool in accident situations and altering the way that spent fuel is stored in dry casks. By adding ethylene glycol to the spent fuel pool during an accident situation, the boiling point of the water could be increased by approximately 7.2℃, while maintaining adequate heat transfer properties. This could buy personnel enough time to consider other options. Ethylene glycol is also relatively inexpensive and should not cause any adverse reactions when put into the pool. Current dry cask storage is quite expensive to maintain, with a single dry cask possibly costing $1,500,000 alone, and there are currently serious concerns about how much space dry cask storage takes up. By removing used fuel rods from fuel assemblies and placing them into stainless steel tubes of 0.07 cm thickness, the total number of casks needed for storage could be reduced, saving on both storage space and total cost.

Stainless steel tubes of this thickness seemed to give satisfactory results from a thermal analysis and criticality analysis standpoint. The thermal analysis showed the fuel centerline temperature would not be above 1200℃, meaning that the fuel rods should be able to be moved to dry storage after 3 years without concern of the cladding exothermally reacting. The criticality analysis showed a k_{eff} of around 0.61, indicating that there would not be a criticality issue. The dry casks should last longer than they do currently, as there will be fewer interactions between the neutrons and the concrete of the dry casks. Overall, assuming mechanical feasibility, this design seems like it would help cut down on total costs of dry cask storage and help free up some much-needed storage space.

9. Future Work

Moving forward with this idea of placing the fuel rods into stainless steel tubes would require looking further into the mechanical concepts and the feasibility of a design such as the one presented in this report. A mechanical design would need to be refined, with actual models built and tested. A method to consistently keep the fuel rods from becoming misaligned with the stainless steel tubes would need to be developed, and a tested method for bundling the stainless steel tubes into the individual baskets of the dry casks would be needed as well. The mechanics displayed in this report are simply for proofs of concept. Should this idea be pursued, machines would be designed with the actual capabilities of the models proposed here.

In order to verify that the design would be effective, a more thorough heat transfer analysis would need to be performed. Due to time constraints and limited exposure to COMSOL, it was difficult to perform an extensive heat transfer analysis of fuel rods once placed in the stainless steel tubes. Gaining more experience with COMSOL would allow for the model to include convective and radiative heat transfer to make for a more accurate heat transfer simulation, with these results indicating whether a design like this would actually be feasible.

10. References

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