

The Use of a Fluidized Bed in a Spent Fuel Pool

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Abstract

The Fukushima earthquake and subsequent tsunami shed light on potential safety hazards with the current spent fuel pool design, the main hazard being a total station blackout where the pool loses all cooling capabilities and the water boils out of the pool. Uncovering of the fuel greatly reduces the heat transfer away from the assemblies and could lead to fuel melting along with very serious radiation hazards. Also, there is a risk of hydrogen explosions due to the oxidation of zirconium when steam is present. To avoid total reliance on the water for cooling and shielding, a pool design using a fluidized bed is proposed. The bed medium of choice is aluminum due to its availability, low cost, and heat transfer properties. The bed would retain a very similar geometry to current spent fuel design. However, a fluidized bed would cover the fuel, and a layer of water would cover the fluidized bed. The bed would only be fluidized in the case of arranging or placing new fuel into the pool and would remain in a “solid” form during the normal operation. It is demonstrated in this report and model that a fluidized bed used in a spent fuel pool could be a potential design improvement for spent fuel pools. The use of a Comsol multiphysics heat transfer model demonstrated that there would be sufficient heat transfer in the aluminum beads to prevent the melting of the bed media and/or the fuel. Criticality safety analysis was done using a SCALE6.1 code on the proposed aluminum-water mixture. It concluded that there are no criticality-related issues with the design. Finally, the minimum fluidizing velocities and recommended bead sizes were calculated. The fluidized bed design could potentially increase the margin of safety of the spent fuel pool.

Introduction

On March 11, 2011 at 2:46 pm, a magnitude 9.0 earthquake occurred off the coast of Japan, producing a tsunami with wave heights of up to 39 meters. The tsunami waves at the Fukushima Daiichi Nuclear Power Plant were 13 meters high [1]. Though the plant survived the initial earthquake, the resulting tsunami caused devastation to much of the plant's equipment, including the emergency diesel generators.

At the time the earthquake struck Japan, units 1, 2, and 3 were in operation. In all units, reactors scrammed due to the earthquake. The control rods were inserted, and the reactors shut down. Steam produced from the decay heat in the reactors was dumped into the condenser. The first off-normal condition was the loss of off-site power due to the destruction of power lines and the grid due to earthquake. Initially, the emergency diesel generators supplied power to the plant's emergency systems. The reactor core isolation cooling system (RCIC) took over the cooling using power-driven pumps. However, the tsunami produced by the earthquake disabled the diesel generators which powered the RCIC pumps, thus introducing the second off-normal condition. The backup batteries supplied electrical power for the emergency systems until they ran out.

The third failure was a complete station blackout in which all safety systems were disabled. This accident was beyond the design basis of the plant. The water level inside the reactor core dropped, and pressure levels in the containment building rose. In response to the increase in pressure, operators opened pressure relief valves. These valves vented steam which

contained hydrogen; the hydrogen then ignited and caused explosions. Figure I.1 shows the damage caused in the hydrogen explosion.



Figure I.1. Building damage caused by hydrogen explosion at Fukushima. Source: Air Photo Service Co. Ltd., Japan

The hydrogen in the explosions was formed by the oxidation of zirconium in the presence of steam in the reactor. Due to the hydrogen explosions, the spent fuel pools became exposed to the outside environment. The water level in the fuel pools dropped due to boiling, but the fuel was never uncovered or damaged. Radiation levels rose due to the reduced shielding from the lower water level in the spent fuel pool.

The boiling of water in the spent fuel pool confirmed the fact that water can be lost from the pool. Thus, a design in which water is not relied-upon for cooling and shielding purposes would be more suited for an accident of this type.

Fluidized Bed Physics

A fluidized bed works in such a way that a packed bed of particles is given adequate upward flow of liquid or gas to cause it to act as a fluidized material. A fluidized material acts very similar to a fluid. An increase in the velocity of the fluidizing material (i.e. the gas or liquid being shot up into the particle bed) will result in uniform mixing. "As a result, fluidized beds are widely used for conducting gas solid reactions (coal combustion), gas solid catalytic reactions (catalytic cracking of petroleum), etc." [2]. In this design, a fluidized bed will be used for storage of spent fuel assemblies from nuclear reactors. In the figure 1, below, a the THOR[®] Fluidized Bed Steam Reformer is shown.

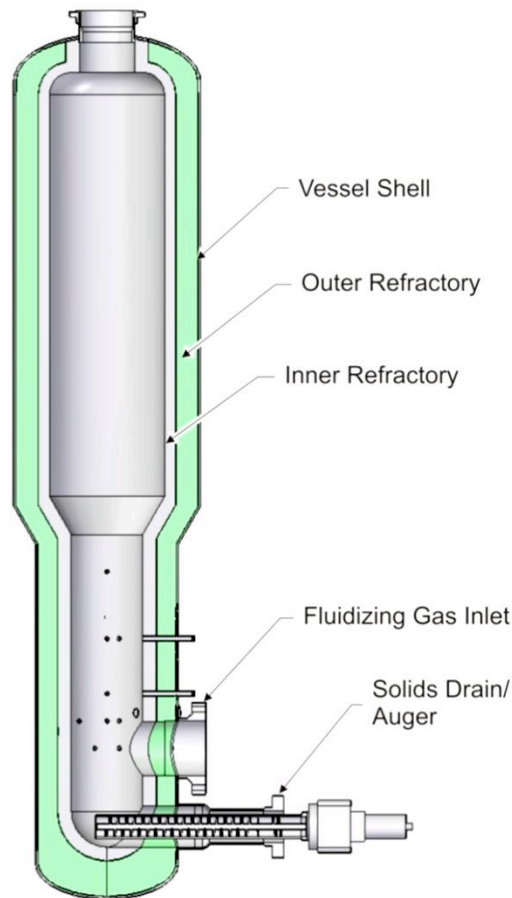


Figure 1: THOR® Fluidized Bed Steam Reformer. W.E. McCabe, J.C.S., and P.Harriot, ed. Unit Operations of Chemical Engineering. 2001, McGraw Hill: New York.

One advantage of fluidized beds include complete and uniform mixing as a result of the fluid behavior of the materials. Another advantage is that they can be used for large volumes, and high heat transfer rates. Heat transfer is an important consideration for the design of spent fuel pools. There are, however, disadvantages to consider as well. For example, the movement of particles around the spent fuel rods could cause attrition of the rods. In addition, particles can become lodged inside the fuel assemblies, which would prevent the assemblies from being transferred back into the reactor.

The basis of the physics behind minimum fluidizing velocity is the change in pressure of the system must be equal to the effective weight per unit area of the particles at the time of initial fluidization. This can be seen in the following equation where ρ_p is the particle density, ρ_g is the gas density, ε_M is the porosity at minimum fluidization (i.e void fraction), g is the acceleration due to gravity, L is the height, and ΔP is the change in pressure.

$$\Delta P = (\rho_p - \rho_g)(1 - \varepsilon_M)gL \quad (\text{Equation 1})$$

In order to calculate the pressure drop in a packed bed, the Ergun equation (Equation 2) is used. In the following equation: μ is the viscosity, D_p is the diameter of the particle, and V_0 is the superficial velocity (volume flow rate per cross-sectional area). D_p can be said to be the "equivalent spherical diameter of the particle defines by $D_p = 6(\text{Volume of the particle} / \text{Surface area of the particle})$ "[2].

$$\frac{\Delta P}{L} = \frac{150\mu V_0}{D_p^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} - \frac{1.75\rho_g V_0^2}{D_p} \frac{(1-\varepsilon)}{\varepsilon^3} \quad (\text{Equation 2})$$

The Reynold's number is also considered in the design of fluidized beds. It is an important factor which is used to determine whether the flow is laminar, turbulent, or in a transient state.

$$Re_p = \frac{D_p V_s \rho}{(1-\varepsilon)\mu} \quad (\text{Equation 3})$$

Fluidization falls into two separate categories. The first is particulate fluidization, which occurs in liquids. "As the velocity of the liquid is increased past the minimum fluidization

velocity, the bed expands uniformly, and uniform conditions prevail in the liquid solid mixture"[2]. The second is bubbling fluidization. This occurs in gas-fluidized beds. For this type of fluidization, when the bed is fluidized pockets of gas without particles intermixed ascend through the bed.. "Where there are particles, the bed void fraction is approximately at the value that prevails at the point of incipient fluidizations. The bubbles grow until they fill the cross-section, and then successive bubbles move up the column, a condition known as slugging"[2].

Along with consideration of the pressure in the system, Harmonic Mean Particle Distribution (HMPD) must be considered. This is used to determine the minimum fluidizing velocity of the fluidizing medium (liquid or gas) with respect to particle size. The HMPD is given by Equation 4.

$$HMPD = \frac{1}{\sum_{i=1}^n \frac{x_i}{d_i}} \quad (\text{Equation 4})$$

In this equation, i is the material number, x_i is the fraction of material in i , and d_i is the average diameter particle of i .

Another equation that must be examined is the Mass Mean Particle Distribution (MMPD). This considers average diameter of the particles of the fluidized bed by mass.

$$MMPD = \sum_{i=1}^n x_i d_i \quad (\text{Equation 5})$$

For the equation above, x_i and d_i are the fraction of material in i and the average diameter of particles in i .

One of the most important things that must be considered when attempting to fluidize a bed of material is the minimum velocity, u_{mf} , that must be applied to the fluidizing medium in order to fluidize the bed. For smaller particles:

$$u_{mf} = Re_{mf} \frac{\mu}{HMPD \times \rho_g} \quad (\text{Equation 6})$$

where ρ_g is the gas density in kilogram per cubic meter, μ is the gas viscosity in Pascal-second, and Re_{mf} is the particle Reynolds number at minimum fluidizing velocity.

$$Re_{mf} = \sqrt{33.7^2 - 0.0408Ar} - 33.7 \quad (\text{Equation 7})$$

where:

$$Ar = \frac{gHMPD^3 \rho_g (\rho_p - \rho_g)}{\mu^2} \quad (\text{Equation 8})$$

In the above equation, g is the acceleration due to gravity (9.807 m/s^2), ρ_p is the particle density in kilograms per cubic meter, and μ is the gas viscosity.

when looking at fluidizing a bed, the "terminal velocity at which a particle falls through a fluid" [2] is an important equation to consider. The equation is as follows:

$$u_t = u_t^* \left[\frac{\mu(\rho_p - \rho_g)g}{\rho_g^2} \right], \text{ units are } \frac{m}{s} \quad (0.5 < \phi_s < 1) \quad (\text{Equation 9})$$

where

$$u_t^* = \left[\frac{18}{(HMPD^*)^2} + \frac{2.335 - 1.744\phi_s}{(HMPD^*)^{0.5}} \right]^{-1}, \text{ dimensionless} \quad (\text{Equation 10})$$

where

$$HMPD^* = HMPD \left[\frac{\rho_g(\rho_p - \rho_g)g}{\mu^2} \right]^{\frac{1}{3}}, \text{ dimensionless} \quad (\text{Equation 11})$$

In the equations above, ϕ_s is the sphericity, a dimensionless property, u_0 is the actual gas velocity through the bed. If $u_0 > u_{mf}$ the bed is fluidized. If $u_{mf} < u_0 < u_t$ the bed has no elutriation, essentially. In other words, heavier particles do not separate from lighter particles in this flow regime. If $u_0 > u_t$ then the particles elutriate.

Fluidization has other considerations such as fluid regime and bed media. The first flow regime to be considered is that of minimum fluidization ($u_0 \geq u_{mf}$). This is also considered smooth fluidization. In this regime, it is hard to establish the most favorable value for gas velocity due to particle size distribution, also known as volume or weight mean distribution. For this to occur, fine, light particles with a dense gas at a high pressure are needed. This condition is found more frequently when using a liquid fluidizing agent through a solid particle bed. The next fluid regime is bubbling fluidization ($u_0 > u_{mf}$). This is the most widespread variety of gas-solid fluidized beds and is ideal for chemical procedures.

Another type of fluidization occurs when the fluidizing velocity is greater than the turbulent velocity. It is called turbulent fluidization ($u_0 > u_t$). In turbulent fluidization, particle elutriation arises and particles size distribution, also known as weight mean distribution or volume mean distribution, becomes complicated. The next fluidization regime is said to make a fast fluidized bed ($u_0 \gg u_t$). In this type of flow, the bed inflates and there is a density deviation between the bottom and the top of the fluidized bed. The final type of fluidization regime is called "lean phase fluidization with Pneumatic transport. In this type of flow, solid particles

become completely entrained in gas flow. This is used in dense pneumatic solids handling systems"[2]. Figure 2 below depicts various forms of flow distributions.

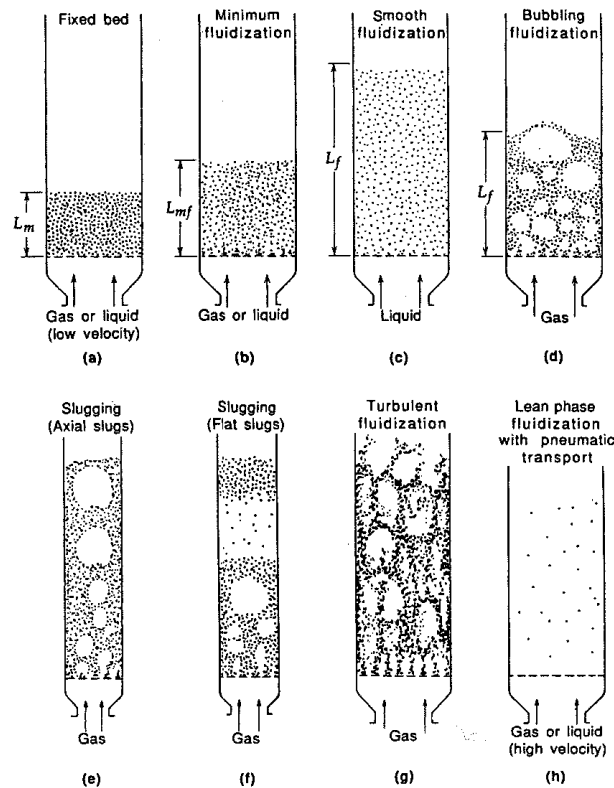


Figure 2: Depictions of various flow regimes. W.E. McCabe, J.C.S., and P. Harriot, ed. Unit Operations of Chemical Engineering. 2001, McGraw Hill: New York.

Another consideration taken into account for fluidized beds is bed media. What is the bed made out of? There are a few categories, one of which is ceramics and minerals. Some examples of these types of media include Alumina, Bauxite, Zeolite, and sand. These are very durable with densities in the area of 2 g/cc. They hold heat making them good insulators. This type of medium is relatively inexpensive

Heat Transfer Mechanisms and Properties

When using a fluidized bed in a spent fuel pool, heat transfer is an important component of the design. One of the great characteristics of a fluidized bed is the heat transfer qualities while in a fluidized state. Therein also lies a problem: a system that is constantly fluidized requires power. For the fluidized bed to be viable as a spent fuel pool solution, the bed medium must give sufficient heat transfer while not fluidized to keep the assemblies and fluidizing medium from exceeding the desired temperature. To properly model heat transfer in the spent fuel pool, all applicable heat transfer mechanisms must be taken into account.

Conduction involves the transfer of heat through a solid material by the interactions of individual atoms. The driving force behind conductive heat transfer is the energy transfer because of the temperature difference between materials. Heat transfer problems are typically done in solid media and take into account the geometry of the object, the physical properties of the material, and the temperature difference between the objects being studied. This corresponds to the steady state slab equation for heat transfer given by Equation 12. [3]

$$Q = kA \left(\frac{\Delta T}{\Delta r} \right) \quad (\text{Equation 12})$$

Where:

Q = rate of heat transfer

A = cross sectional area of heat transfer

Δr = change in direction

ΔT = change in temperature

k = thermal conductivity of the material

Conduction is a mode of heat transfer in the use of a fluidized bed in a spent fuel pool because the bed material is in physical contact with the assemblies and also the rest of the pool. The maximum packing factor, the ratio of the volume of a substance to the total volume in the system, that sphere-shaped beads can have is 0.74 [4]. In other words, this would be the effective heat transfer surface area of the beads. The fraction 0.74 is based on the greatest fraction of space that can be occupied by spheres in a regular lattice arrangement and is given by the value:

$$\frac{\pi}{3\sqrt{2}} \simeq 0.74048.$$

Convective heat transfer is the transfer of heat from one place to another by the movement of fluids. This form of heat transfer is dominant in liquids and gases and is the most efficient form of heat transfer. It is normally discussed as a separate form of heat transfer but it is really the combination of conduction and fluid flow. Convective heating can be split into two different categories, natural and forced. Natural convection gets its fluid motion from density differences in the liquid due to temperature gradients. In natural convection, the fluid around the heat source is heated, becomes less dense and rises. Cooler fluid in the surrounding area then moves to replace it. The other is forced convection, which involves pumps or fans to give the fluid motion. The thermodynamics behind it is the same as natural convection. The basic equation for convection is what is known as Newton's law of cooling which can be seen below. [3]

$$\dot{Q} = hA\Delta T \quad \text{(Equation 13)}$$

Where:

$\dot{Q}$ = the magnitude of the rate of energy transfer by convection

h = heat transfer coefficient

A = surface area

ΔT = temperature difference

Natural convection gives rise to the term natural circulation, which involves the same processes as do forced and natural circulation; however, natural circulation relies on the work of gravity on the fluid. Natural circulation is the ability of a system to circulate continuously.

Radiation heat transfer is an important physical phenomenon that needs to be taken into account in the heat transfer model. Radiation heat transfer is a mechanism which is caused by the thermal movement of atoms. This thermal motion of atoms creates electromagnetic waves, predominantly in the infrared spectrum. [3] Radiation heat transfer is given by the equation:

$$Q = \sigma A \Delta T^4 \quad (\text{Equation 14})$$

Where Q is the amount of heat transferred in watts, σ is the Stefan-Boltzmann constant ($5.6703 \times 10^{-8} \text{ W}/(\text{m}^2\text{K})$), A is the area of the emitting body, and ΔT is change in temperature across the two bodies. An important note to make about radiation heat transfer is that the temperature difference is raised to the fourth power. Thus, the amount of heat transferred through radiation is very high when the temperature difference is high. This also means that radiation heat transfer contributes very little to the overall heat transfer when the temperature difference is very low. To gain a full understanding of how heat will dissipate from the fuel assemblies, radiation heat transfer must be considered. [3]

To combine all of these heat transfer modes, an advanced heat transfer simulation software is required. Comsol Multiphysics¹ is a program that is relatively user-friendly and very versatile for engineering design. Comsol is a finite element analysis and simulation software that

¹ Software package available from COMSOL, Inc. Burlington, MA.

has various packages for physics and engineering applications. Comsol is special in its ability to couple different physical phenomena in one code. The software has an ergonomic user interface for inputting geometries. However, for very intricate or complicated design, Comsol can also import designs from CAD software like Autodesk's Inventor or AutoCAD. Comsol offers an extensive interface to MATLAB and toolboxes for a long list of other programming software. As with most advanced design software, it requires a very large amount of computing space for multivariable engineering problems. Finite Element Analysis (FEA) is a technique for finding approximate solutions to partial differential equations (PDE's) as well as integral solutions. It is normally completed by eliminating the PDE's by putting it into a steady state problem or rendering the PDE into an ODE and solving using a numerical method like Euler's Method or Runge-Kutta. Comsol's heat transfer package has the ability to physically display how heat is dissipated in a system. As in the example below, the user can actually see how the heat moves through objects or systems.

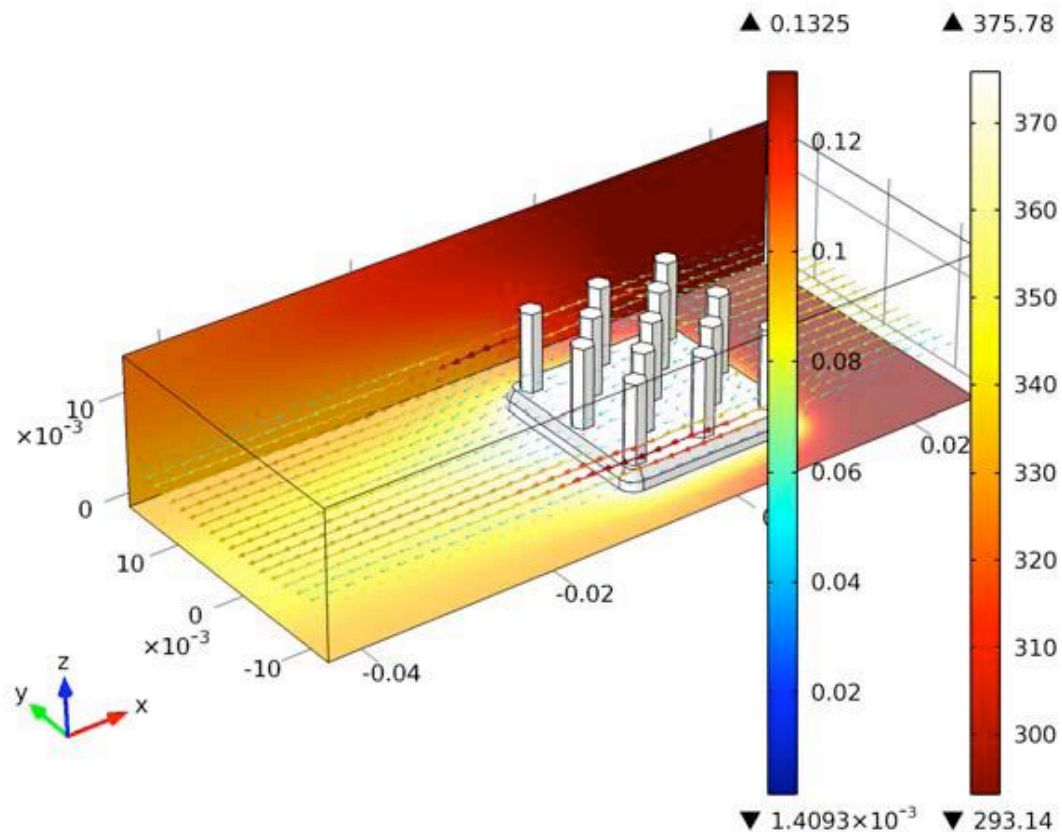


Figure 3. Example Comsol model demonstrating the capabilities of the Comsol heat transfer package.

Nuclear Criticality Safety: Terminology, Regulations, and Codes

Nuclear criticality safety is important to consider in nuclear design. Nuclear criticality safety is the “art of avoiding a nuclear excursion” [5]. In addition to defining criticality safety, it is important to understand what is meant by a criticality accident. A criticality accident is “uncontrolled and unshielded” [5]. An uncontrolled fission chain reaction can result in harmful radiation, which can cause illness in personnel and may damage equipment.

The most important quantity in criticality safety is k-effective. In storing fuel in the spent fuel pool, the system must remain subcritical. According to NRC Regulation 10 CFR 50.68, a system is adequately subcritical if k-effective is less than 0.95. The use of different materials in

the spent fuel pool can cause an increase or a decrease in the k-effective value of the system. Materials which are better reflectors may increase k-effective, while materials which are better absorbers may serve to decrease this value. Therefore, it is important to study the effects of various materials on the criticality of the system before implementing changes.

The software used to analyze the criticality of a system is SCALE². The scale package is “a comprehensive modeling and simulation suite for nuclear safety analysis and design” [6]. Scale is a verified and validated computer code used for criticality safety and reactor physics, and radiation shielding. The Scale package includes nuclear data libraries and can perform multigroup neutronics and decay calculations. In addition to performing calculations and determining the k-effective value for the system, Scale can perform depletion, decay, and radioactive source term analysis. Depletion is important in the analysis of a spent fuel pool since the fuel is depleted before being stored as spent fuel; performing the depletion in Scale allows the code to more accurately model the nuclides present in the fuel pins during the calculation.

Scale uses the Oak Ridge Isotope Generation in Scale (ORIGEN-S) code to apply “a matrix exponential expansion model to calculate time-dependent concentrations, activities, and radiation source terms for a large number of isotopes simultaneously generated or depleted by neutron transmutation, fission, and radioactive decay” [6]. The ORIGEN-S code is used for depletion calculations. Alongside ORIGEN-S, the Transport Rigor Implemented with Time-dependent Operation for Neutronic depletion (TRITON) module provides pin-cell depletion using two-dimensional lattice physics and three-dimensional Monte Carlo depletion.

² Distributed by the Radiation Safety Information Computational Center (ORNL: Oak Ridge, TN)

Assumptions

In modeling the heat transfer in the fluidized bed, several assumptions were made. In the Comsol design, the fluidized bed material was modeled as aluminum beads only; no water was homogenized between the beads. Also, the bead size was assumed to be 0.0625 mm in diameter, a value falling within the range of optimum particle sizes for fluidization. no variation in bead size was accounted for. The heat transfer was modeled as heat transfer through a solid. Conservative values of material properties were used to account for this assumption. It was also assumed that 74 percent of the volume of the fluidized material is taken up by aluminum beads and contributes to conductive heat transfer. This value was chosen because it is the maximum packing fraction for spheres of uniform size. Radiative and convective heat transfer were disregarded on the grounds that the majority of heat transfer is conductive. The assumption was also made that if a small-scale model does not exceed design criteria for the pool (i.e. uncovering of assemblies or melting of fluidizing material) then a working full-scale system is probable. A heat load of 5000 W/assembly was assumed [7]. This corresponds to an average heat load of an assembly after one year of its removal from the core. The heat transfer model was assumed to be non-fluidized. This is due to the fact that the non-fluidized state is the worst-case scenario.

Design

Design of the Heat Transfer Model

To model the heat transfer in the spent fuel pool, the multiphysics package Comsol was used to model conductive heat transfer. The major objective in modeling the heat transfer within the spent fuel pool is to ensure that the temperature of the fuel does not increase. To model the system, a 5x5x7 meter slab of aluminum was modeled in Comsol. Aluminum was chosen because it is relatively inexpensive and has good conductive heat transfer properties. Next, a

typical pressurized water reactor (PWR) fuel assembly was modeled. Due to time constraints and a limited knowledge of the use of the Comsol package, the fuel assembly was modeled as a block with dimensions 0.21x0.21x4.1 meters. The fuel assembly material was modeled as solid zirconium. A five-by-five array of assemblies was then modeled in Comsol; adequate computing memory was not available to handle a larger array.

After creating the geometry for the heat transfer model, initial temperatures of the bulk and for the fuel assemblies were entered into the Comsol software. The initial temperatures for the slab were 300 Kelvin and for the assemblies 400 Kelvin. Comsol then was able to display results regarding the temperatures of the fuel assemblies and the pool material.

Design of Criticality Model

In modeling the fuel in the spent fuel pool for nuclear criticality safety analysis, it was first necessary to conduct a depletion calculation to model the fuel correctly. A depletion of the fuel pins was conducted in the TRITON package of Scale6.1. This depletion calculation provided the isotopes present in the spent nuclear fuel.

Once the depletion was performed to simulate a typical twice-burned assembly, the composition of the spent fuel was determined and saved. A single fuel assembly was then modeled in the Keno-V.a package within SCALE using the compositions determined by the depletion. The 17x17 fuel assembly was modeled as one-quarter of the assembly with reflected boundary conditions to model the entire assembly, as shown in Figure 4. The shaded region represents the section of the assembly which was modeled in the calculation. The unshaded region corresponds to the part of the assembly which was modeled by the reflected conditions.

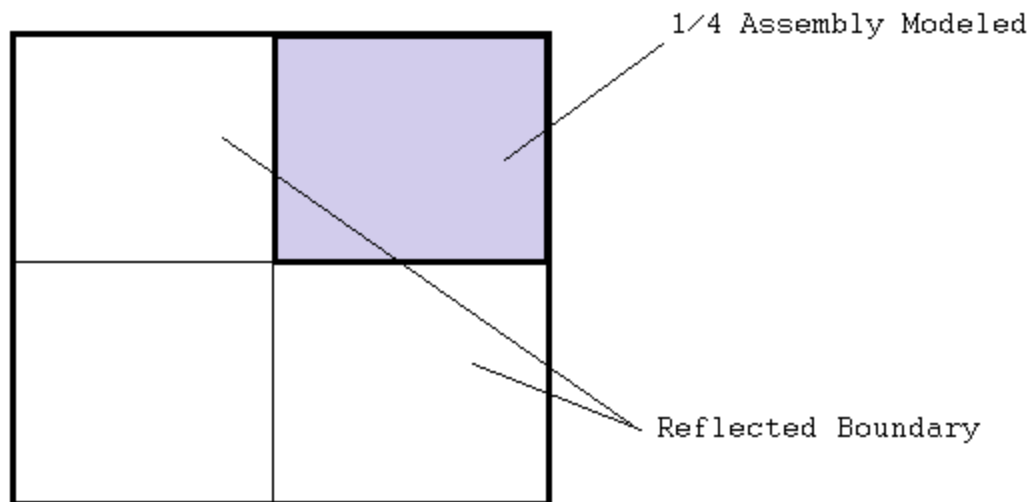


Figure 4. Model of Fuel Assembly in Spent Fuel Pool

The individual fuel pins in the spent fuel assembly were arranged in KENO-V.a using a matrix. The matrix contains the unit number corresponding to each pin, and uses these numbers to place each fuel pin in the fuel assembly. The full input deck is included in Appendix A. The fuel assembly model that was used for both the TRITON depletion calculation and then the KENO-V.a criticality calculation is shown in Figure 5. Each fuel pin was modeled using separate material specifications, so in the TRITON depletion calculation, each pin depleted uniquely, as to better simulate a spent PWR assembly. The assembly was depleted to simulate a “twice-burned” assembly, which would be the most reactive type of assembly to enter the storage pool for long-term storage. The average burn-up for a twice-burned assembly is 40,000 MWD/MTU (megawatt-days per metric ton of uranium). The specific power for a typical PWR varies depending on the operation, but a specific power of 37.37 MW/MTU was chosen. Dividing the average burn-up of a twice-burned assembly by the specific power yielded a time (in days) for which the assembly must be depleted. The PWR assembly was depleted to 1070 days.

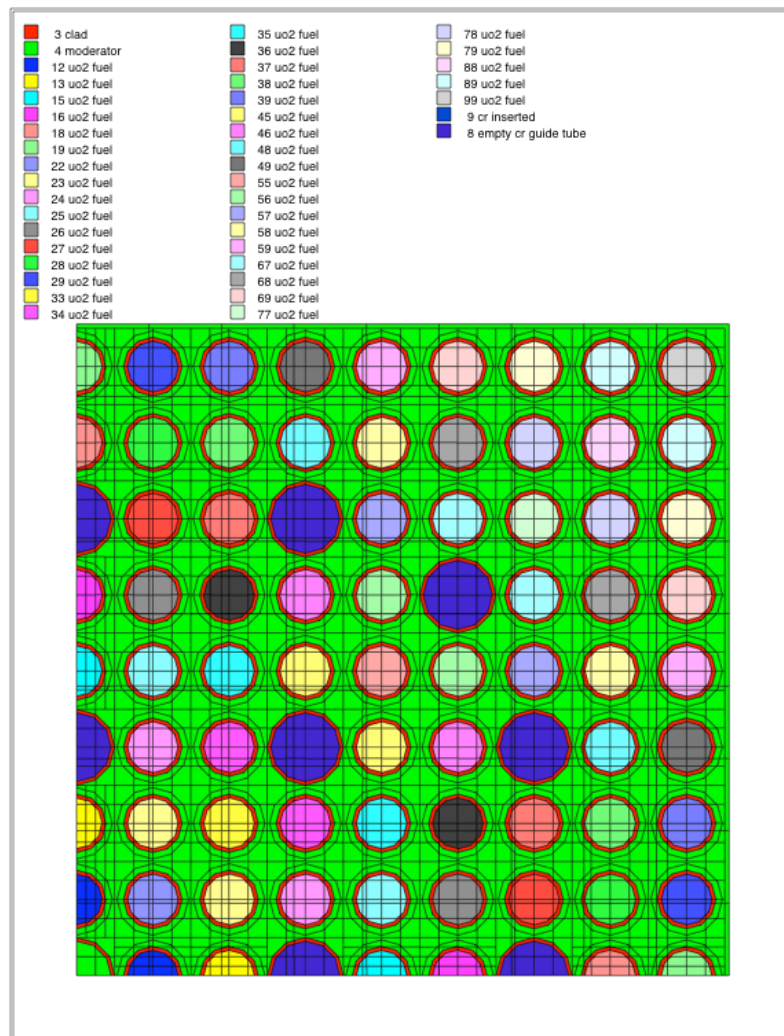


Figure 5. TRITON/KENO Model of a Typical 17x17 PWR Fuel Assembly

The resulting material specifications from the TRITON calculation were saved for use in the KENO-V.a model, with the major difference being that TRITON modeled a 2-D slice of an assembly and the KENO-V.a modeled a 3-D representation of an entire assembly. KENO-V.a was used to calculate the k-effective value for four different variations of moderator: water only, aluminum only, homogenized water and aluminum, and homogenized air and aluminum. The water case was used as a benchmark or reference when comparing the aluminum type moderators. Since the Comsol model used a slab of solid aluminum, a SCALE case was done

using solid aluminum as moderator to compare with Comsol model. The homogenized water and aluminum case simulated the moderator under normal operation (i.e. a fuel assembly sitting in a stagnant bed of aluminum beads in water). The homogenized air and aluminum case simulated the pool under a severe accident scenario where all water has boiled out leaving only aluminum beads. In Figure 5, the moderator is labeled as ‘mod’ and was assigned a material number four (4) by the user and a green color by SCALE. The moderator fills the space between the fuel pins. When the moderator was changed in these four cases, it is replacing all of material number 4 (the green colored ‘mod’) with the respective new materials. The k-effective values can be found Table 1 in the Results section.

Results

The results of the heat transfer model are shown in Figure 6, which shows the data for the first time step of the Comsol simulation.

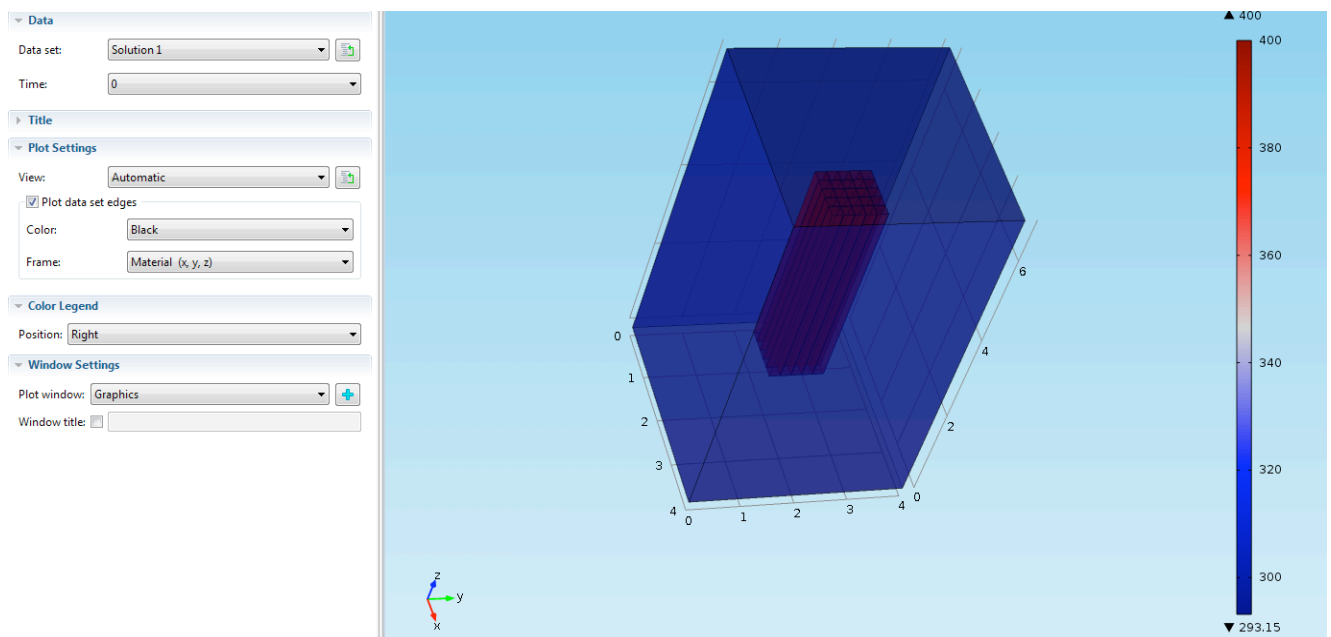


Figure 6. First time step data for the fuel assembly heat transfer calculation using the Comsol model.

Figure 6 shows the five-by-five array of assemblies surrounded by a slab of aluminum. The initial temperatures can be seen with the assemblies at 400 Kelvin and the bulk aluminum at 300 Kelvin. As the simulation progressed, the temperature of the bulk aluminum began to increase, but the temperature of the fuel assemblies never rose above 400 Kelvin. This validates that the aluminum is able to direct heat away from the fuel assemblies, and this is clearly seen in the last time step, which is shown in Figure 7.

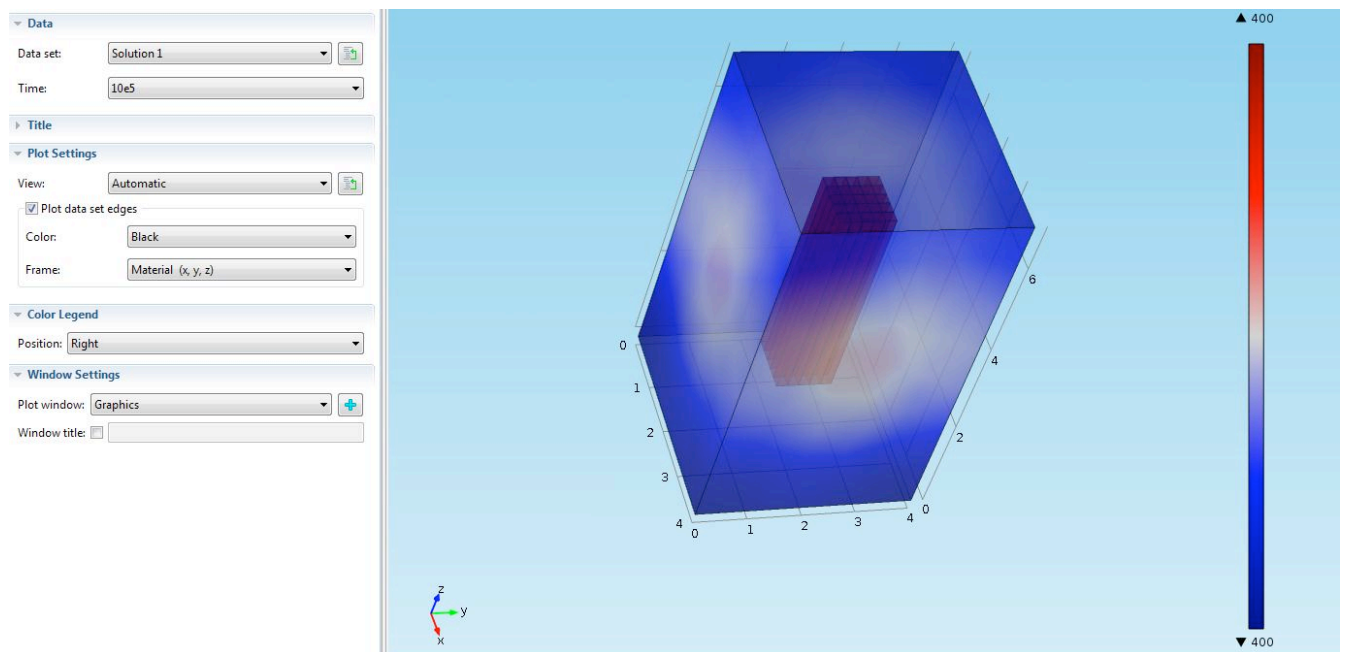


Figure 7. Time step 1,000,000 (corresponding to 12 days) for the fuel assembly heat transfer calculation using the Comsol model.

From Figure 7, it is apparent that the temperature of the system has risen to 400 Kelvin, but the system has not exceeded 400 Kelvin. The white areas within the aluminum bulk show that the heat has dissipated from the fuel assembly. The results of the heat transfer model show that aluminum has the ability to effectively transfer heat from the fuel assembly. However, aluminum beads would have different heat transfer properties than would a slab of aluminum. An assumption that was made to account for the fact that the beads will have a lower thermal

conductivity was to use a much lower thermal conductivity for aluminum in the heat transfer model. Thus, a fluidized bed composed of aluminum beads may be a practical design choice for the spent fuel pool if the thermal conductivity of the beads is comparable to that of the aluminum slab.

Table 1 shows the resulting k-effective values for the four variations of moderators modeled in the criticality safety analysis.

Table 1: Results for k-effective from KENO-V.a Model

	k-eff	Error ($\pm$)
Water Only	0.342954	0.000056
Aluminum Only	0.083574	0.000014
Water and Aluminum	0.107589	0.000019
Air and Aluminum	0.084151	0.000015

These k-effectives were calculated for a single fuel assembly with leakage allowed at the boundaries. Thus, the k-effective is very low since the model is for a single assembly. The k-effective would be expected to increase as more assemblies are put next to each other in the pool. However, the k-effective for any variation on the moderator with aluminum is one third of the value compared to plain water moderator. Since the spent fuel pools which currently use plain water moderators are within margin, it is reasonable to expect that the pool will remain subcritical using a moderator containing aluminum. The k-effective value for a single assembly surrounded by a moderator containing aluminum is less than the k-effective for a single, water-moderated assembly. For this reason, it is not necessary to calculate k-effective for the entire spent fuel pool; the comparison based on a single assembly is sufficient.

In order for a fluidized bed to work for a spent fuel pool, the bed must be able to be fluidized enough to get the fuel assembly into position. As shown in Figure 8, the minimum fluidizing velocity is plotted, showing a comparison of particle size and density.

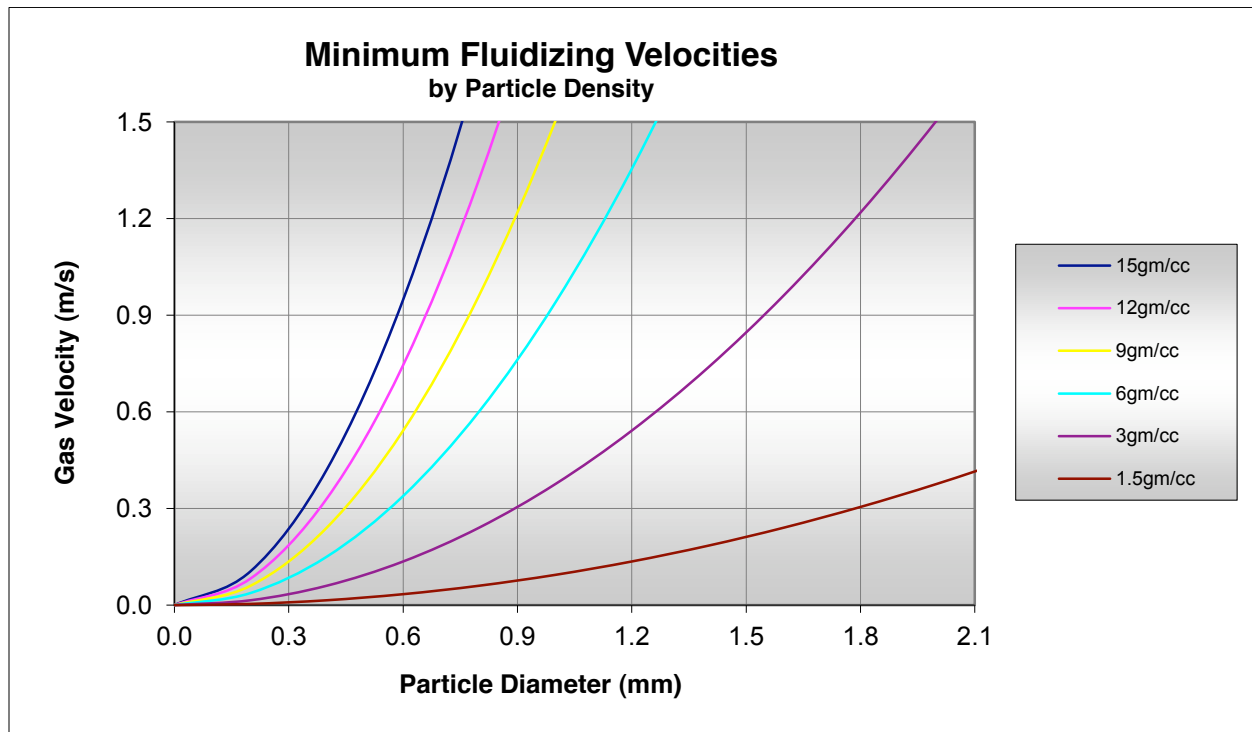


Figure 8. Minimum Fluidizing Velocity vs. Particle Diameter

As shown in the above figure, the larger the particle diameter, the larger the required gas velocity to fluidize the material. Thus, it is advantageous to use small particle diameters. The following figure shows an expanded scale in the region below 0.01 mm for the plot of fluidizing velocity vs. particle diameter, focusing on the area most applicable to the design.

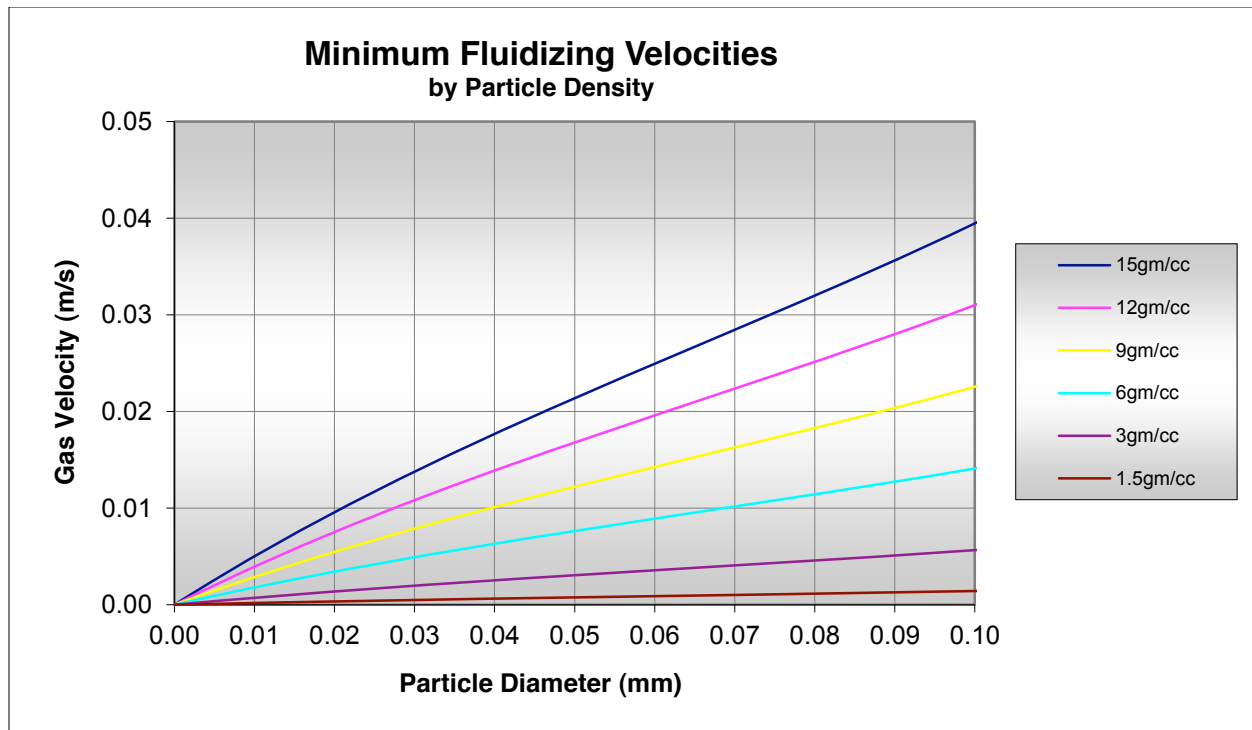


Figure 9. Gas Velocity vs. Particle Diameter (Concentrated Area of Interest)

For low-density materials with small particle diameters, the minimum gas velocity required to fluidize the bed of material is fairly low. For aluminum particles ($\rho = 2.7 \text{ g/cc}$) with diameters of less than 0.1 mm, the minimum gas velocity is less than or equal to 0.006 m/s. Therefore, the minimum required velocity can be achieved with pumps that are available today.

Image (c) in Figure 10 below shows the result that would be ideal for a spent fuel pool when fluidized.

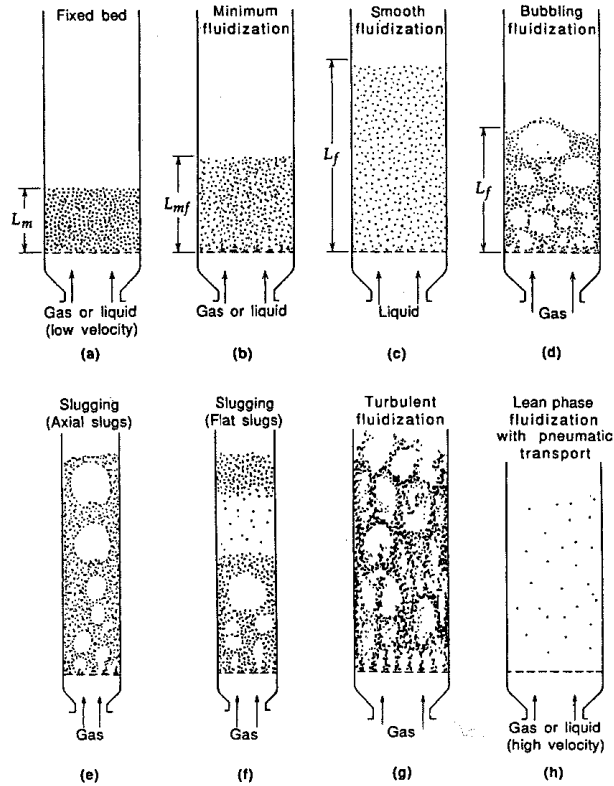


Figure 10. Stages of fluidizing a bed of material as fluid velocity increase. W.E. McCabe, J.C.S., and P. Harriot, ed. Unit Operations of Chemical Engineering. 2001, McGraw Hill: New York.

Thus, using aluminum in the fluidized bed with water as the fluidizing medium, the minimum fluidizing velocity is easily achievable with many water jets that are available. The minimum fluidization stage is shown in Figure 10(b). The particle size based on thermal properties as well as fluidized bed properties needs to be fine. The size of a grain of sand, 0.0625 mm, was the size chosen for the particles based on these needs as well as the need to maintain the integrity of the particles to prevent having to change them out frequently.

Conclusions

A fluidized bed made of aluminum beads with particle diameters of less than one millimeter requires a minimum fluidizing velocity of less than one meter per second. The density of aluminum is fairly low, and requires a low fluidizing velocity. For these reasons, a fluidized bed design is achievable in a spent fuel pool design.

The heat transfer models show that aluminum has a high enough thermal conductivity to efficiently remove heat from the fuel assemblies in the spent fuel pool. The conductive heat transfer through the aluminum would suffice for keeping the fuel pins from melting or becoming damaged in the storage process. An experiment using aluminum beads, rather than an aluminum slab, would determine whether aluminum beads would efficiently conduct heat.

From a nuclear criticality safety standpoint, the aluminum and water mixture results in a k-effective value of less than one. Thus, the system remains subcritical with the introduction of the aluminum beads. Also, the system remains subcritical in the event of a total loss of all water in the spent fuel pool.

Considering the required fluidizing velocity, the required amount of heat transfer, and nuclear criticality safety, the use of a fluidized bed in place of water in a spent fuel pool is achievable. This design could be effectively implemented and safely used in nuclear power plants.

Recommendations for Future Work

In order to better study the application and implementation of a fluidized bed as a coolant in the spent fuel pool of a nuclear reactor, more work must be done. In regards to the heat transfer study, multiple spent fuel assemblies should be modeled in order to more accurately study the heat transfer from the assemblies into the fluidized bed. In addition, a more intricate modeling of a fuel assembly would yield more accurate results.

In regards to the fluidized bed modeling and calculations, a study of the available pump technology would determine whether it is feasible to fluidize a bed of material with a volume as large as an entire spent fuel pool. Furthermore, a recommendation for future studies would be to investigate the availability of small-diameter aluminum spheres for use as the beads in the fluidized bed.

The criticality safety analysis could be improved by modeling multiple spent fuel assemblies. The k-effective values would then be more accurate depictions of the actual values if the spent fuel pool were filled with assemblies. However, the aluminum moderator would still exhibit a lower k-effective value than a water moderator would. The current water-moderated spent fuel pools are already designed for a k-effective of less than 0.95. The fuel assemblies also contain boron plates, which further reduce the k-effective value. Thus, the criticality analysis would indicate a subcritical system even when modeling multiple spent fuel assemblies.

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