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ALTERNATIVE DESIGNS OF MOLTEN SALT STORAGE SHELLS FOR USE IN SOLAR ENERGY STORAGE

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Molten salt (MS) storage systems in the 565°C range can store green solar energy from thermal solar power station, such as the Crescent Dunes solar plant in Nevada. Large containers can be used to store energy and generate electricity for eight hours or more to be used at night or during peak demand hours, depending on the container size. Energy storage can reduce the fluctuation due to weather conditions experienced at thermal solar power stations because stable diurnal energy supply is made available by MS energy storage. Supported by the Office of Naval Research (ONR), the research presented discusses the considerations for designing molten salt storage tanks. An alternate molten salt storage cylindrical tank design layout is presented, including an improved roof design concept. A preliminary heat transfer analysis is presented and discussed for the alternate cylindrical tank design. This preliminary analysis was used to determine the thickness of insulating material in and around the cylindrical tank to reduce heat flux. These insulating materials include the use of firebrick and ceramic insulation to complement the structural carbon steel and the stainless steel that is used for corrosion resistance. This paper also introduces the alternate designs of a semi-buried spherical tank and drop shell tank that can be used storing molten salts.

Keywords: Commercial electric station, Energy production, Solar salts, Thermal solar power.

1 INTRODUCTION

Molten solar salts are known for their capacities for heat storage, which can be effective for storing excess energy. Large insulted tanks are used to provide a closed system to contain these salts for future use. This paper highlights the layout of an optimal tank design. In addition, an alternative shell design based on this information is presented along with a preliminary heat transfer analysis, which is used to size insulating materials.

2 IDEAL CYLINDRICAL STORAGE TANK DESIGN

Gabrielli and Zamparelli (2009) present an optimal design for molten salt storage tanks. Based on their process, determining the height and diameter of the tank is the first step, and then that is followed the determination of the thicknesses of all shell layers that best limit heat loss. Once this information has been determined, the structural design is checked against a finite element model (FEM) analysis, which is then followed by a cost analysis to determine if the design is economical.

Using this procedure, they determined that the optimal design is a cylindrical storage tank with a SA-516 Grade 70 carbon steel shell, used for both the cylindrical shell and the roof shell, as shown in Figure 1. Outside the carbon steel shell is a layer of ceramic insulation. Inside the cylindrical carbon steel shell, there is a layer of firebrick insulation. Directly above the firebrick insulation is a plate of ceramic insulation supported from the tank roof that prevents heat from reaching the roof shell. Lastly, there is a flexible layer of AISI 321H stainless steel inside of the firebrick insulation and the top ceramic insulation which is used to provide corrosion resistance. Based on their design process, the height of the tank should not exceed 12 meters (39.37 feet) because that is the maximum length of piping that the pumps allow based on what is commercially available. This paper presents an alternative design based on this information with the modification using firebrick only at the bottom of the tank.

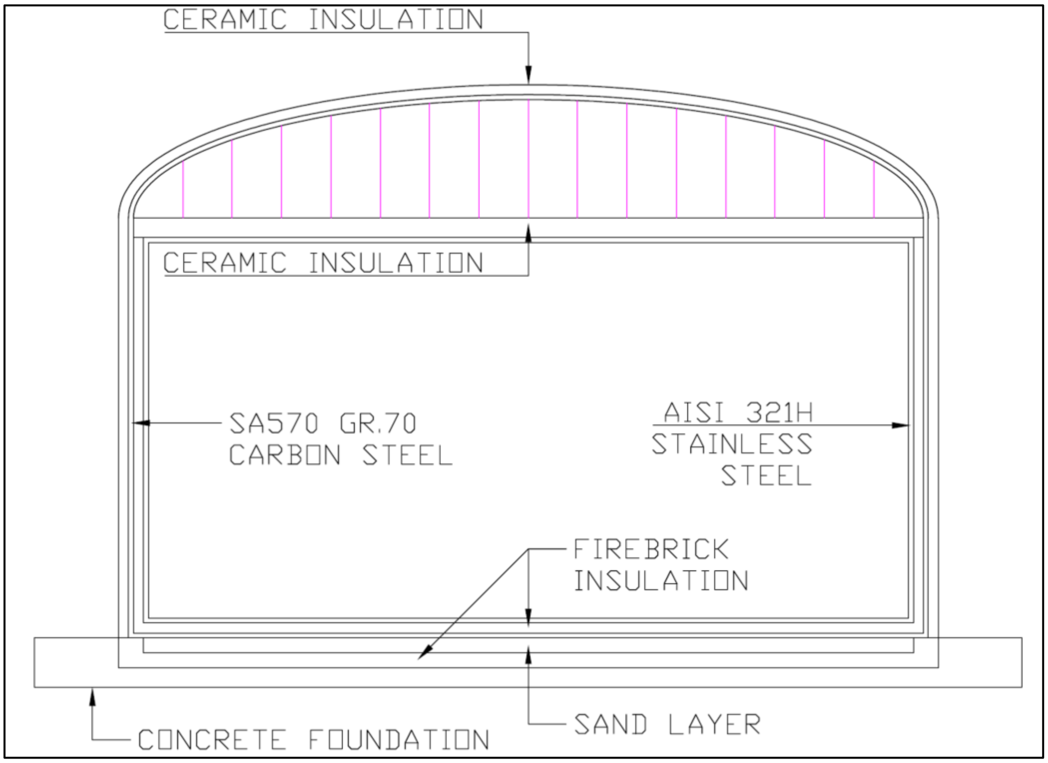


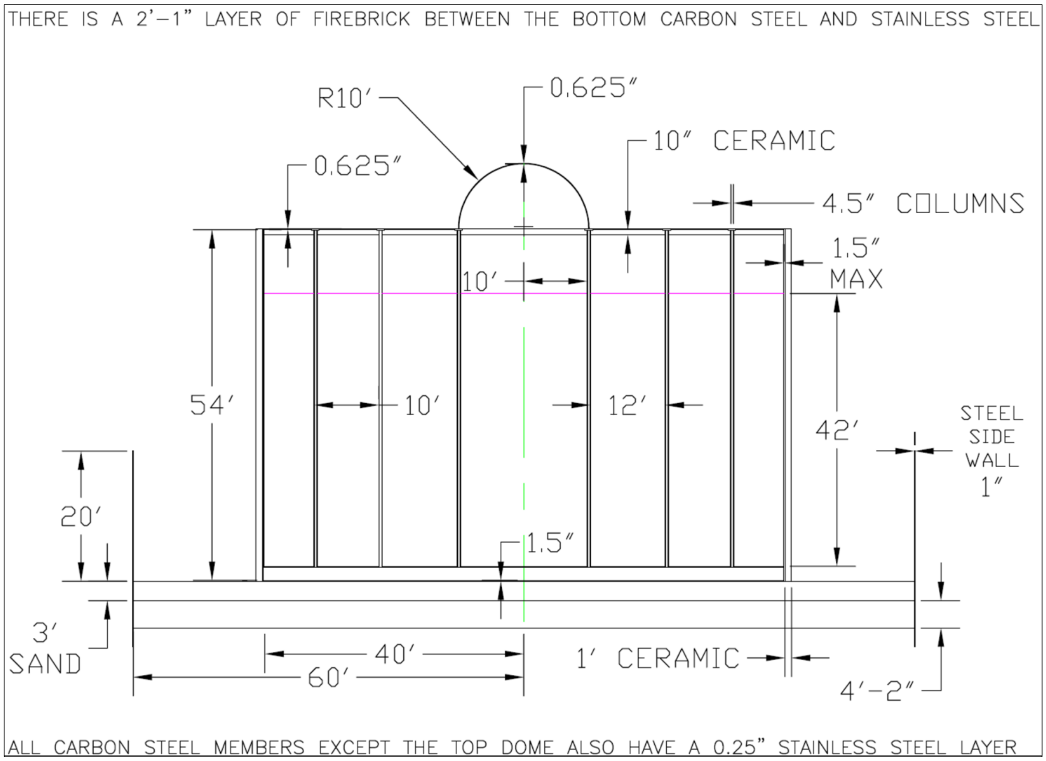
Figure 1. An example of an optimal tank design layout (Gabrielli and Zamparelli 2009).

3 ALTERNATIVE CYLINDRICAL TANK STRUCTURAL DESIGN

The structural design of the cylindrical storage tank is similar to a design presented in "Design of Molten Salt Shells for Use in Energy Storage at Solar Power Plants" by Ladkany *et al.* (2016) with some modifications. As shown in Figure 3, the new structural design has some changes compared to the original design as shown in Figure 2, with thicknesses shown in both figures. The main changes in Figure 3 to the structural design include the removal of steel columns and the flat plate roof, which is instead replaced with either elliptical roof. Other roof shapes previously considered include spherical and parabolic shells (Ladkany *et al.* 2018).

Like the original design, the alternate tank has the same shell wall design. The bottom nine feet (2.734 meters) of the shell requires a structural steel thickness of 1.5 inches (38.1 mm). The section of the shell wall that is between 9 and 15 feet (2.734 and 4.572 meters) above the ground requires a structural steel thickness of 0.625 inches (15.9 mm). The section of the shell wall that is between 15 and 22 feet (4.572 and 6.706 meters) above the ground requires a structural steel thickness of 0.5 inches (12.7 mm). The section of the shell wall that is between 22 and 29 feet (6.706 and 8.839 meters) above the ground requires a structural steel thickness of 0.375 inches (9.5 mm). The section of the shell wall that is between 29 and 36 feet (8.839 and 10.973 meters) above the ground requires a structural steel thickness of 0.25 inches (6.4 mm). All sections of the shell wall above 36 feet (10.973 m) will require a structural steel thickness of 0.125 inches (3.2 mm). Lastly, in order to combat corrosion effects, a 316 Stainless Steel liner of 0.25 inch (6.35 mm) thickness will line the inside of the shell wall (Loyd 2016, Ladkany *et al.* 2016).

For an alternative roof design as shown in Figure 3, an elliptical carbon steel shell roof with a thickness of 1.5 inches (38.1 mm) is used instead of a flat roof presented in the traditional design. In this design, the elliptical roof has a height of 12 feet (3.658 meters). An important design consideration is that an extra factor of safety had to be included due to the high temperatures associated with molten salts, which will reach temperatures as high as 565°C. At this temperature, the yield strength of the steel is approximately 60% of its nominal yield strength (Salmon *et al.* 2009). In addition, the tank uses insulating materials to control heat loss, which is discussed in the following section. These elements, which are shown in Figure 3, include insulating firebrick at the bottom of the tank as well as Kaowool ceramic insulation (Ladkany *et al.* 2018).


THERE IS A 2'–1" LAYER OF FIREBRICK BETWEEN THE BOTTOM CARBON STEEL AND STAINLESS STEEL

ALL CARBON STEEL MEMBERS EXCEPT THE TOP DOME ALSO HAVE A 0.25" STAINLESS STEEL LAYER

Figure 2. Steel cylindrical shell model design including top dome, supporting rows of columns, sand layer, 50" posttension slab, and safety steel walls at the edge (Loyd 2016).

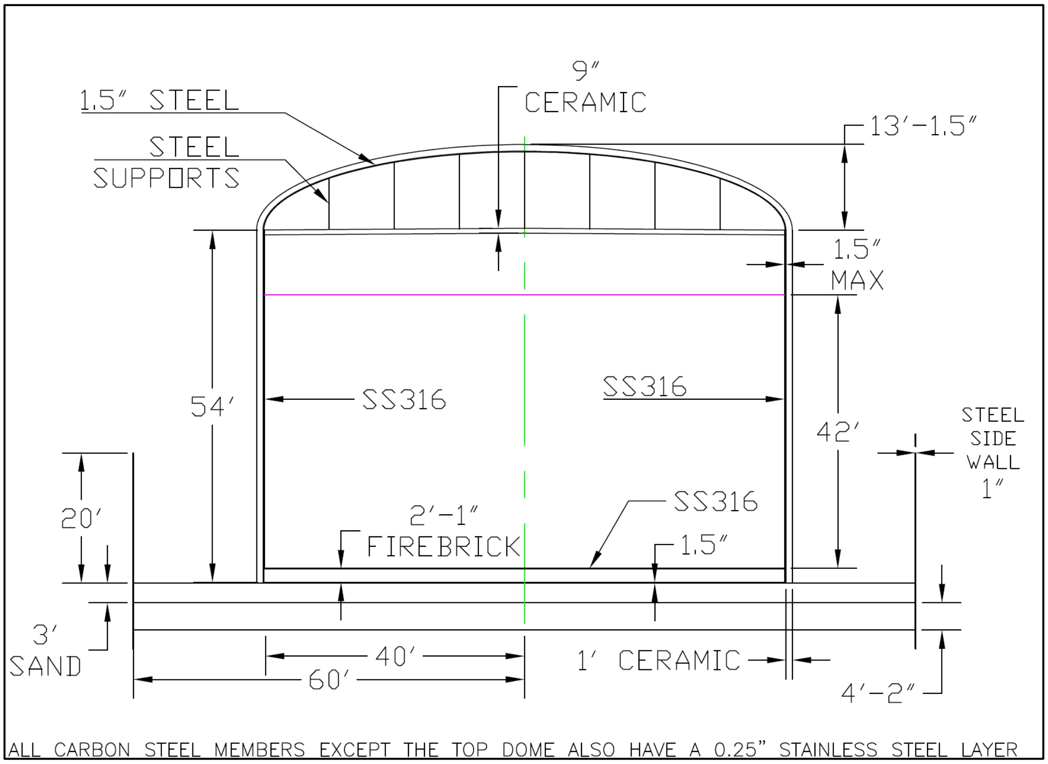


Figure 3. Steel cylindrical shell model design including alternative elliptical top dome designs, sand layer, 50" posttension supporting slab, and safety steel walls at the edge (Ladkany *et al.* 2018).

4 INITIAL HEAT TRANSFER ANALYSIS

This section discusses the initial considerations used for the heat transfer analysis used in designing the molten salt tank structure, particularly sizing the insulating materials (Ladkany *et al.* 2018). Halotechnics designed a small-scale test tank for the National Renewable Energy Laboratory for experimentation in which their maximum heat flux was capped at 300 Watts per square meter (W/m^2) (Jonemann 2013). Using this information, our design tank, which is of a much larger scale, uses an initial maximum heat flux of 250 W/m^2. Steady state analysis was used to calculate the heat losses since the design life of the tank is 50 years. Further in-depth finite element analysis will be performed to verify the heat losses of the design and presented in a future publication.

Table 1. Thermal conductivity values of insulation and structural material used in tank design (Bauman and Zunft 2011, Jonemann 2013, Engineering ToolBox 2003).

Material	**Thermal conductivity (W/m^2)**
Kaowool	0.12
Granular Sand	0.40
Carbon Steel	16.00
Stainless Steel	43.00
G-23 Firebrick	0.33

As shown in Figure 3, surrounding the outside steel tank is Kaowool, which is commercially available on Amazon (CM Ceramics 2020). In addition, Kaowool insulation is hangs from the elliptical roof directly above the shell walls. In addition, the bottom of the tank will contain G-23 firebrick insulation, which is grouted with hot well concrete and placed between the stainless-steel layer and the carbon steel layer. Thermal conductivities values for these materials are shown in Table 1.

The first step in performing a heat transfer analysis is to determine the thermal conductivity through the bottom of the tank using traditional linear thermal conductivity as shown in Eq. (1) (Holman 1986). The insulating firebrick at the bottom of the tank is incased with 0.25 inches (6.35 mm) of stainless steel and 1.5 inches (38.1 mm) of carbon steel. The ground below the tank can be treated as a semi-infinite medium, using Eq. (2) to describe its behavior over time, with erf referring to the Gaussian Error Function as shown in Eq. (3) (Holman 1986).

$$q = kA\frac{dT}{dx} \tag{1}$$

$$\frac{T(x,t)-T_0}{T_S-T_0} = \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right) \tag{2}$$

$$\operatorname{erf}(w) = \frac{2}{\sqrt{\pi}}\int_0^w e^{-v^2}\,dv \tag{3}$$

In determining this behavior, the temperature of the salt (T_S) is set to 565°C and the temperature of the ground (T_0) is set to 15°C. The tank life span of 50 years is used as the time (t) in Eq. (2). Lastly, the depth of the sand layer (x) between the tank and the supporting concrete slab is 36 inches (914 mm). In addition, the maximum temperature the concrete slab is expected to experience during its lifespan is set at 90°C. This is done to prevent cracking due to evaporation of the water of hydration inside the concrete given the long life of the tank. The required thickness of firebrick insulation based on these equations is 25 inches (635 mm) (Ladkany *et al.* 2018).

The next step in performing a heat transfer analysis is to determine how heat dissipates through the side walls, which exhibits radial heat conduction as detailed in Eq. (4) (Holman 1986).

$$q = 2\pi krL\frac{dT}{dr} \tag{4}$$

An insulation design for the side of steel shell tank using the structural shell thicknesses as stated earlier. The required thickness of Kaowool insulation along the outside of the tank to maintain maximum heat flux is 12 inches (305 mm).

$$q = h\,\Delta T \tag{5}$$

$$h = 1.52\sqrt[3]{\Delta T} \tag{6}$$

$$h = 1.31\sqrt[3]{\Delta T} \tag{7}$$

The last step in the heat transfer analysis is determining the heat dissipation through the top of the tank. Eqs. (1) and (5) through (7) are used to describe this behavior (Holman 1986). Eq. (1) is used to determine the flux due conduction through the hanging insulation. Eq. (5) is used to calculate the flux under free convection both immediately below and above the hanging ceramic insulation. Eq. (6) is used in calculating the coefficient of convection for the convection pocket below the hanging insulation while Eq. (7) is used for the coefficient of convection for the convection pocket above the hanging insulation. Using the maximum allowed flux of 250 W/m^2, the required thickness of hanging Kaowool insulation is nine inches (229 mm).

5 CONCLUSION

In designing molten salt storage tanks, the structural design and insulation design are the most important elements to consider. Proper attention must be paid to the structural design due to the temperatures of these molten salts and the weight of these salts. In addition, a proper insulation design is important to limit heat losses and improve system efficiency. With these considerations, an optimal molten salt storage tank design can be achieved with a carbon steel shell, stainless steel liner, and insulation (firebrick and ceramic).

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