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DESIGN OF MOLTEN SALT SHELLS FOR USE IN ENERGY STORAGE AT SOLAR POWER PLANTS

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Design of a steel tank for the storage of excess energy from thermal solar power plants using molten salts (MS) at 580°C is presented. Energy can be stored up to a week in large containers to generate eight hours of electricity for use at night or to reduce weather related fluctuation at solar thermal energy plants. Our research supported by Office of Naval Research (ONR) presents a detailed design of a cylindrical shell for the storage of high temperature molten salts. The storage shell consists of an inner stainless steel layer designed to resist corrosion and an external steel structural layer to contain the large pressures resulting from the molten salt. The cylindrical tank is 54 feet (16.459 meters) high and has an 80 feet (48.768 meters) diameter, with the salt level at a height of 42 feet (12.802 meters). Given the heat of the molten salt and the size of the tank, the design includes a flat shell cover supported on stainless steel columns and a semispherical utility access dome at the center. Considerations are made for the reduction of strength of steel at elevated temperatures. Layers of external insulation materials are used to reduce heat loss in the storage shell. The design presents a posttensioned concrete foundation analysis for the storage tank, which sits on a layer of sand to allow for thermal expansion.

Keywords: Commercial electric station, Energy production, Molten salt tanks, Post tensioned concrete slabs, Solar salts, Steel cylindrical shells.

1 INTRODUCTION

Molten solar salts are a great and effective way to store excess solar energy for future use due to the vast heat storage capacities of solar salts. These solar salts are contained in large insulated tanks in order to keep the molten salts in a closed system. This project examines the current method of using insulated hybrid steel cylindrical shells to store molten salt and presents a preliminary design of real life examples.

2 DESIGN METHODS FOR MS STORAGE TANKS

Currently, molten salt (MS) storage shells are usually cylindrical tanks made of stainless steel. The MS steel tanks has a hybrid design of A588 Carbon Steel and an inner layer of 316 Stainless Steel to protect against corrosion, varying in thickness from one inch (25 mm) for a fifty year plant life span to 0.6 in (15 mm) for a thirty year plant life span.

3 TANK REQUIREMENTS

For this stage of the project research, the tanks need to store enough molten solar salt, which is a 60:40 sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3) mix, to provide power for a 300 megawatt power plant for eight hours each night. Calculations determined that in order to satisfy these requirements, the two tanks need to be able to store 12,048 cubic meters of salt or 425.5 x 10^3 cubic feet.

In order to determine the total mass of salt required to operate the power plant, one must start with the basic energy equation, which is shown in Equation 1 (Holman 1986).

$$E = P_{thermal} * \Delta t_{storage} = m * c_p * \Delta T \tag{1}$$

In Equation 1 above, E represents the total energy in the system. The power generated by the power plant is $P_{thermal}$, which as stated earlier is 300 megawatts. The required time of storage is $\Delta t_{storage}$, which is 8 hours or 28,800 seconds. The required amount of solar salt needed for the power plant is represented by m. The specific heat capacity of the salt is c_p, which is 1540 joules per kilogram of salt per degree Kelvin. The temperature range of the salt in the system is ΔT, which is calculated using Equation 2 below.

$$\Delta\mathrm{T} = \mathrm{T}_{\mathrm{salt,max}} - (\mathrm{T}_{\mathrm{sat}} - 20\ \mathrm{K}) \tag{2}$$

In Equation 2 above, the maximum temperature of salt in the system, or $T_{salt,max}$, is 853.15 degrees Kelvin. The temperature of the Rankine cycle, or T_{sat}, is 620.55 degrees Kelvin. Equation 2 determined that the temperature range for the salt is 252.6 degrees Kelvin.

In order to determine the required mass of salt, Equation 1 is rearranged into Equation 3 as shown.

$$\mathrm{m} = \frac{\mathrm{P}_{\mathrm{thermal}} * \Delta \mathrm{t}_{\mathrm{storage}}}{\mathrm{c}_{\mathrm{p}} * \Delta\mathrm{T}} \tag{3}$$

This determined that the power plant requires 22.88 x 10^6 kilograms of salt, or 50.44 x 10^6 pounds (25,220 tons).

Equation 4 is used to determine the volume of solid salt required.

$$\mathrm{V}_{\mathrm{salt}} = \frac{\mathrm{m}}{\rho_{\mathrm{salt}}} \tag{4}$$

Equation 4 determined that the volume of solid salt required is 12,048 cubic meters of salt, or 425.5 x 10^6 cubic feet (12,048 cubic meters). This volume will be divided over two tanks, requiring 212.7 x 10^6 cubic feet (6,024 cubic meters) for each tank. However, a third and fourth tanks, all of carbon steel, are recommended for the storage of cooled MS after power generation and for safety and continued operations during maintenance of the other tanks.

All structural steel used is A588 Grade 50 steel. The cylindrical tank designed with a 40 feet (12.192 meters) radius at the base. This results in a height of salt of 42 feet (12.802 meters) and a salt height for the cylindrical tank.

4 STEEL CYLINDRICAL TANKS

The steel structural design was divided into five elements for individual analysis and design, which are the shell wall, the top cover with a central 10 feet (3.048 meters) diameter steel access dome, support columns, a steel bottom, and the concrete slab below a layer of sand. All of these structural elements are made of structural and stainless steel except the concrete slab. Shell theory was used to perform the structural analysis of the cylindrical tank and central access dome.

The first design performed was for the shell wall. Based on shell theory, axial bending in a cylindrical shell occurs mainly at the base of the wall, at the junction with the ring and base plate, before dissipating further up the wall (Urugal 2009). Further analysis determined that axial bending dissipates nine feet above ground. The first step was to determine the bending in the shell wall. The maximum positive axial bending moment is 4.085 kip-foot/foot, at the bottom of the shell and the maximum negative bending moment is 1.225 kip-foot/foot at a height 2.7 feet above the bottom of the shell. Circumferential moments are equal to the Poisson ratio multiplied by the axial moments. The bottom of the wall contains the maximum circumferential tensile force, which is 153.05 kips per linear foot (klf), which is 2234 kN/m. Tensile membrane force is determined by Equation 5b (Urugal 2009). While maximum axial compressive force, N_x, in the wall at the bottom of the shell is equal to the total dead weight of the shell, top slab, live load and service dome, which is the total weight (W), divided by the circumference of the shell. Equations 5c through 5h are used to determine the bending in the shell wall (Urugal 2009).

$$p = \gamma z \tag{5a}$$

$$N_\theta = pr \tag{5b}$$

$$D = \frac{Et}{12(1-\nu)} \tag{5c}$$

$$\beta = \sqrt{\frac{\sqrt{1-\nu^2}}{rt}} \tag{5d}$$

$$C_1 = \frac{\gamma h r^2}{Et} \tag{5e}$$

$$C_2 = \frac{\gamma r^2}{Et}\left(h - \frac{1}{\beta}\right) \tag{5f}$$

$$w = e^{-\beta x}(C_1 \cos \beta x + C_2 \sin \beta x) + \frac{\gamma(h-x)r^2}{Et} \tag{5g}$$

$$M_x = D\frac{d^2 w}{dx^2} \tag{5h}$$

$$M_\theta = \nu M_x \tag{5i}$$

$$N_x = \frac{W_x}{C} \tag{5j}$$

In determining the applied pressure on the tank from Equation 5a, it is the product of the salt unit weight (γ) and the depth of salt (z) at the specified point. In Equation 5b, p is the applied pressure on the wall and r is the radius of the wall (Urugal 2009).

In Equations 5c through 5h, D, β, C_1, and C_2 are coefficients, E is the Young's Modulus of the shell material, t is thickness of the shell wall, ν is the Poisson's ratio of the shell material, h is the total height of molten salt, w is shell wall deflection at a height of x above ground, and the second derivative of w is used to determine the moment at that point (Urugal 2009). M_x is the axial moment at a height of x above ground, W_x is the weight of the shell including dead and live loads on its top at level above x (Urugal 2009). Figure 1 details the design of the cylindrical shell and the top dome.

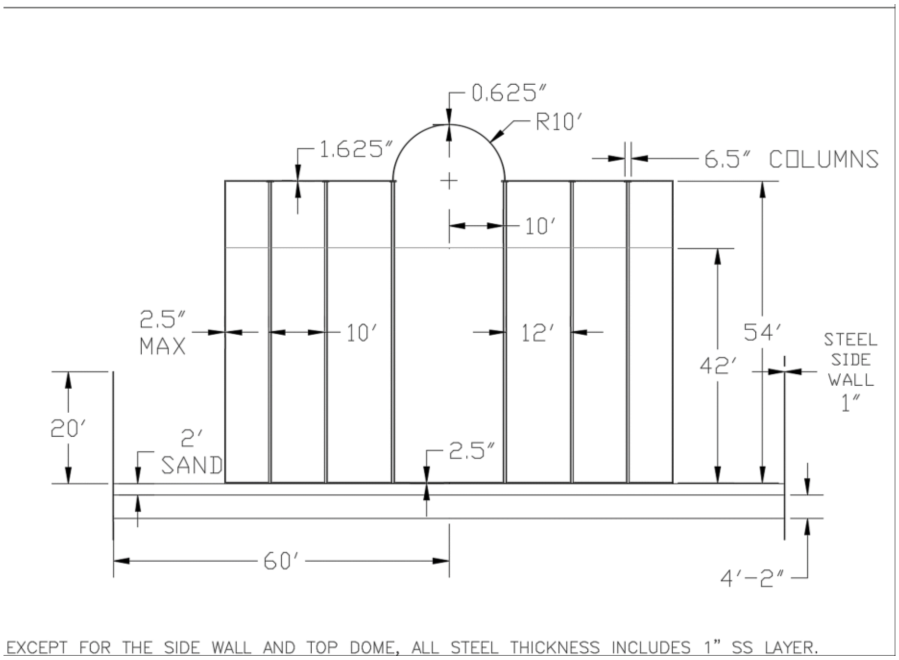

Figure 1. Steel cylindrical shell model including top dome, supporting rows of columns, 2' sand layer, 50" posttension slab, and safety steel walls at the edge.

The shell was designed in sections of varying thickness based on the loading. The bottom nine feet of the shell wall was designed to accommodate excess bending, require 1.5 inches of structural steel thickness due to the combined axial membrane and bending stresses. The next section of the wall, from 9 to 15 feet (2.734 to 4.572 meters) above ground, requires 0.625 inches (15.9 mm) of steel thickness. Starting from 15 feet above ground, the thickness of the shell wall is decreased by 0.125 inches (3.2 mm) every seven feet until a thickness of 0.125 inches (3.2 mm) remain. This results in the wall being 0.5 inches (12.7 mm) thick between 15 and 22 feet (4.572 to 6.706 meters), 0.375 inches (9.5 mm) between 22 and 29 feet (6.706 to 8.839 meters), 0.25 inches (6.4 mm) between 29 and 36 feet (8.839 to 10.973 meters) above ground, and 0.125 inches (3.2 mm) for the remaining portion of the wall above 36 feet (10.973 meters). Due to corrosion effects, a one inch liner of 316 Stainless Steel covers the steel wall.

The next design was for both the top steel plate and the columns supporting it in the cylindrical tank. The top plate is 0.625 inches (15.9 mm) thick and is supported by three circular rows of columns. One row of columns is located ten feet (3.048 meters) away from the center of the tank, at the tip of the opening and the 0.625 inches (15.9) thick service dome. It contains eight equally spaced columns. The second row of columns is located 22 feet (6.706 meters) away from the center of the tank and contains eight equally spaced columns. Lastly, the third row of columns is located 32 feet (9.754 meters) away from center and contains 16 equally spaced columns. These columns are made of carbon steel covered with a layer of stainless steel because of the heat and corrosion from MS. When designing the columns and shell walls, an extra factor of safety is used due to the expected heat of the molten salt. At 580 degrees Celsius, steel is expected to only maintain 60% of its nominal yield strength (Salmon 2009). As a result, the final design load for the first row of columns is 6.5 kips (28.9 kN), 19.6 kips (87.2 kN) for the second row, and 11.7 kips (52.0 kN) for the third row. Ultimately, it is determined that the first row of columns be designed as HSS 4½ x 4½ x 1/8" columns, the second row as HSS 4½ x 4½ x ¼" columns, and the third row as HSS 4½ x 4½ x 1/8" columns (AISC 2012). Due to corrosion effects, a one inch (25.4 mm) liner of 316 Stainless Steel covers the steel column. In addition, the column will be connected to the top steel shell with a 14 inch by 14 inch (356 mm) plate that is two inches thick (50.8 mm).

In order to design for bending in the top steel flat slab, Timoshenko's method was used to design the top plate as a continuous simply supported plate over the edge of the shell and supported by rows of columns as discussed earlier. Moments at the supporting columns are found from the column pattern of annular arrays normalized as rectangular arrays. Based on Timoshenko's (1959) theory, the maximum negative bending moment in each direction is located at the column. With the maximum positive moments, being the radial moments occurring at the center of the normalized annulus, and the maximum circumferential moment, occurring directly halfway between columns. For this shell, the maximum negative moment is 1.785 kip-foot/foot and the maximum positive radial moment is 1.040 kip-foot/foot.

In addition, an opening with a 10 feet (3.048 meters) radius is carved out of the top shell so that a removable steel dome with the same radius can be placed on top of the steel plate. This opening is to allow pipes into the shell and service access into the tank.

5 FOUNDATION DESIGN

A complete design was performed on the concrete slab sitting over dense sand. Included in the foundation design is a 2 feet (610 mm) layer of sand between the tank and the concrete slab as shown in Figure 1 to allow for thermal expansion of the shell. Figure 2 details the radial posttensioning cable layout, the steel ring, and circumferential reinforcement in the concrete slab. The steel ring is necessary because the posttensioning cables cannot intersect with each at the center of the 50 inch concrete slab.

For the slab, 96 radial posttensioning 55/0.5 WG cables that connect to the inner steel ring are required as shown in Figure 2. In addition, six #14 circumferential bars per foot are required under the MS tank, with number of bars decreasing toward the free edge. In addition, the minimum radial posttensioning cables depth is 12.75 inches (324 mm), the maximum radial posttensioning cables depth is 38.75 inches (984 mm), and the circumferential reinforcement depth is 44.125 inches (1.121 meters). This requires a slab thickness of 50 inches (1.270 meters) as shown in Figure 1.

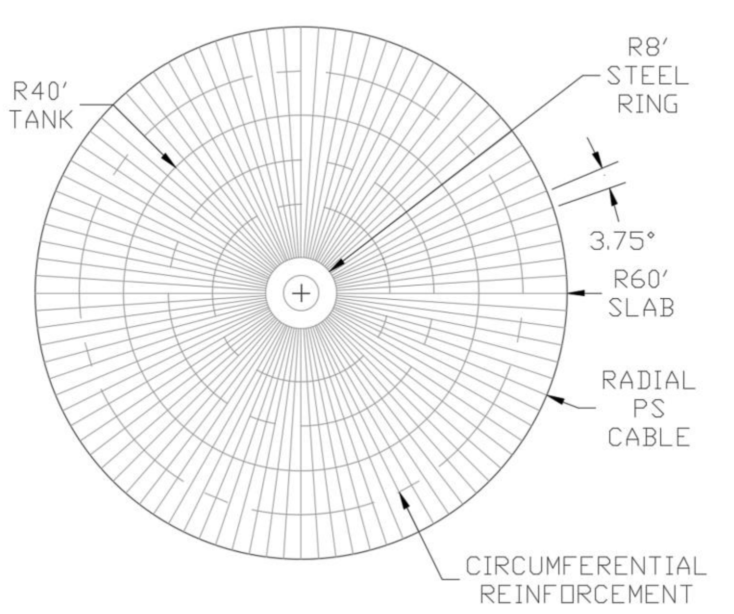

Figure 2. Posttensioning cable and circumferential reinforcement layout for concrete slab including inner steel ring.

6 CONCLUSION

The design of a cylindrical A588 Grade 50 steel shell, having a diameter of 80 feet (24.384 meters), for the storage of molten salts is presented. The shell is 54 feet (16.459 meters) high, has a height of salt of 42 feet (12.802 meters), and has a top access dome with a radius of 10 feet (3.048 meters). The two tank system is designed to store enough molten salt to provide 300 megawatts of power for eight hours. The shell has a one inch (25.4 mm) stainless steel liner to protect against corrosion for a 50 year design life. Also shown is a 120 feet (36.576 meters) diameter concrete foundation with posttensioning, which has a 50 inch (1.270 meters) thickness and steel side walls that are 20 feet (6.048 meters) high for safety in case of an accident.

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