Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 69 (2015) 340 – 349

Energy Procedia

International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014

# System design of a 1 MW north-facing, solid particle receiver

J. Christian[a], C. Ho[a]

[a]Sandia National Laboratories, Albuquerque, NM, jmchris@sandia.gov

**Abstract**

Falling solid particle receivers (SPR) utilize small particles as a heat collecting medium within a cavity receiver structure. The components required to operate an SPR include the receiver (to heat the particles), bottom hopper (to catch the falling particles), particle lift elevator (to lift particles back to the top of the receiver), top hopper (to store particles before being dropped through the receiver), and ducting. In addition to the required components, there are additional features needed for an experimental system. These features include: a support structure to house all components, calibration panel to measure incident radiation, cooling loops, and sensors (flux gages, thermocouples, pressure gages). Each of these components had to be designed to withstand temperatures ranging from ambient to 700°C. Thermal stresses from thermal expansion become a key factor in these types of high temperature systems. The SPR will be housing ~3000 kg of solid particles. The final system will be tested at the National Solar Thermal Test Facility in Albuquerque, NM.


Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG

*Keywords:* Solid Particle Receiver, high temperature receiver, falling particles

## 1. Introduction

The falling particle receiver is an enabling technology that can increase the operating temperature of concentrating solar power (CSP) processes, improving efficiency and lowering the costs of energy storage [1]. Conventional central receiver technologies are limited to temperatures of around 600°C. At higher temperatures, nitrate salt fluids become chemically unstable. In contrast, direct absorption receivers using solid particles that fall through a beam of concentrated solar radiation for direct heat absorption and storage have the potential to increase the maximum temperature of the heat-transfer media to over 1,000°C. Once heated, the particles may be stored in an insulated tank and/or used to heat a secondary working fluid (e.g., steam, CO2, air) for the power cycle. Thermal energy storage costs can be significantly reduced by directly storing heat at higher temperatures in a relatively


Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.03.038

inexpensive medium (i.e., sand-like particles). Because the solar energy is directly absorbed in the sand-like working fluid, the flux limitations associated with tubular central receivers (high stresses resulting from the containment of high temperature, high pressure fluids) are significantly relaxed. The falling particle receiver appears well-suited for scalability ranging from 10 – 100 MWe power-tower systems [1].

Although a number of analytical and laboratory studies have been performed on the falling particle receiver since its inception in the 1980's [2-11], only one set of on-sun tests of a simple falling particle receiver has been performed [11]. Those tests only achieved 50% thermal efficiency, and the maximum particle temperature increase was only ~250°C. Hruby [12] introduced the concept of using ceramic objects or plates in the particle flow stream to decelerate the particles for increased heating, but no studies were conducted.

## 2. Background

A complete SPR requires four main components: top hopper, receiver, bottom hopper, and particle elevation. Most evaluations of SPR systems focus on the receiver itself. Siegel et al. [11] performed on-sun tests for a simple representation of a falling particle receiver. These tests focused on the behavior of the particles as they fell through the receiver. Particle behavior is critical to system performance as high particle curtain opacity is needed to absorb as much incident power as possible from the heliostat field. Kim et al. [8] studied the effects of wind on particle curtain stability and found that it can have severe effects on particle curtain stability with an incoming oblique attack angle. Additional receiver studies involved computational fluid dynamics (CFD) to analyze heat transfer within the receiver cavity and the interaction of the particles and air [13-16]. These CFD results gave great insight into particle curtain placement as well as receiver shape.

Studies involving the entire system required to operate an SPR plant has not been thoroughly evaluated and demonstrated. As part of the on-going effort to design a complete system, an experimental SPR system is being built at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories in Albuquerque, NM. This work describes the design of each of the main components required for a complete SPR. On-sun tests will be performed on this system to demonstrate if it will work and be a viable option for central power towers. Initial testing will bring the particles up to 700°C and maintain them at that temperature while the system is running.

## 3. Engineering design

There are four main components of an SPR: top hopper, receiver, bottom hopper, and particle elevation. However, there are additional features such as the supporting structure and flux characterization needed for a successful system. Fig 1 shows a schematic of what the experimental system will look like. Particles fall from the top hopper through the receiver. The particles are heated in the receiver and fall into the bottom hopper. The hot particles will be transported from the bottom hopper to the particle elevator (Olds elevator). The particles are lifted vertically in the elevator to back into the top hopper. Two particle drop locations are possible, especially during the phase of experimental studies where two simultaneous particle drops are studied.

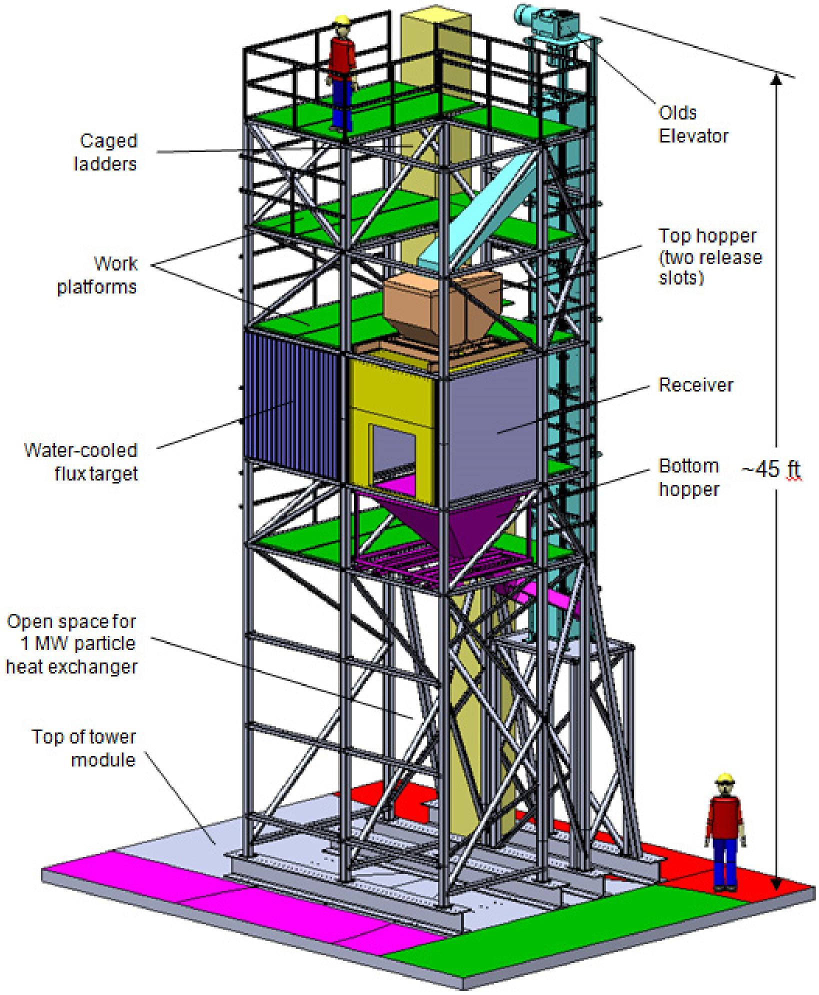


Fig 1. Prototype structure including work platforms and ladders (green and light yellow), bottom hopper (purple), top hopper (light brown), OLDS elevator (light blue), NSTTF module (multi-colored platform at the base; see Figure 1 for color codes). Heat shielding around the receiver and flux target is not shown. This system will be lifted on the module to the top of the 200 ft tower at Sandia's NSTTF.

### *3.1. Receiver*

The receiver of the system is a cavity structure. Slots in the top of the receiver allow particles to fall through the cavity into the bottom hopper of the system. The receiver needs to withstand high flux conditions (1000 suns), high temperatures, and be durable. The scale of the receiver was determined from possible prototypical testing conditions at the NSTTF which required the entire receiver to be less than 2 m. Christian et al. [17] goes into detail on the actual design of the receiver system. CFD was used to evaluate flux patterns, temperatures, particle mass flow rates, and particle behavior in differently shaped receivers. The rigid insulation board RSLE-57 was chosen as the internal wall material for this cavity receiver due to its high flux capabilities and high durability. This insulation is limited to 1200°C which was an important design constraint.

A smaller cubical cavity (1.3 m) was compared to a larger cavity (2 m) to determine which size was suitable for this experimental prototype. The incident fluxes on the cavity had to be below 2000 suns and the temperatures of the walls had to be below 1200°C due to material limitations. An incident flux condition of uniform flux on a 1 m square aperture was applied with beam directionality from the heliostat field at the NSTTF. A 2 m cavity height increased the incident flux penetration depth into the cavity before striking the top of the cavity. This cavity height allowed the particles to absorb the incident radiation before it directly hit the top of the cavity. This greatly reduced the peak flux on the top of the receiver compared to a smaller 1.3 m cavity size. The increase in overall cavity size reduced the flux concentrations on the cavity walls resulting in lower wall temperatures. For these reasons, the 2 m x 2 m x 2 m cavity size was chosen as our prototype size. Fig 2 displays characteristic temperature and flux profiles in the 2 m cubical cavity.

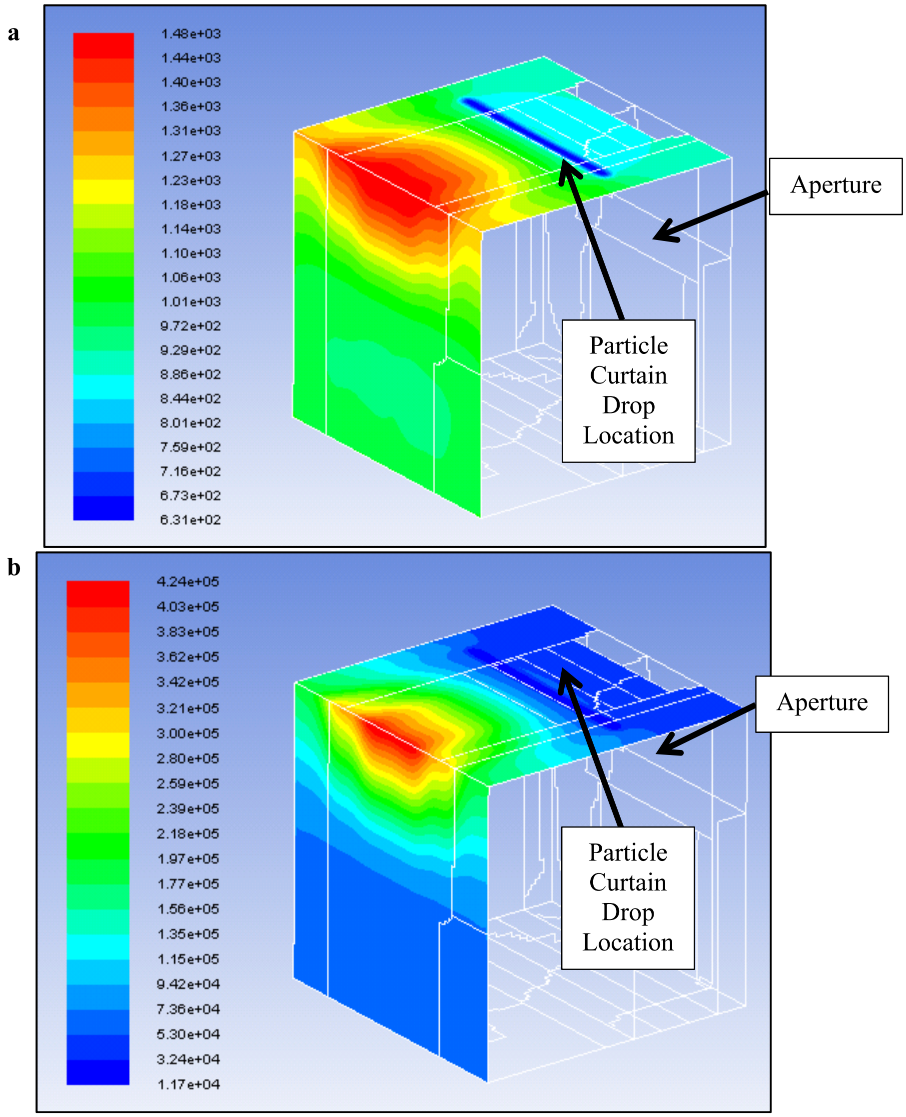


Fig 2. 2 m x 2 m x 2 m, 4 kg/s total particle mass flow rate, (a) Cavity wall temperatures (K) of top and back wall showing high temperature at the joint of the back and top walls; (b) Surface incident radiation (W/m$^2$) on top and back wall showing the high flux concentration on the same joint with high temperatures

The experimental design of the cavity walls has to survive the 1200°C internal cavity temperatures and have a maximum external wall temperature of <100°C to protect the supporting steel structure. To avoid any temperature rise of the structure, the receiver walls are to be built as a “sandwich” structure. Each wall is composed of stainless steel all thread bolts, a layer of Duraboard HD board, a layer of Zircar RSLE board, a layer of Microtherm insulation board and an air gap between the Microtherm insulation and Duraboard insulation. The insulation materials come in rigid boards which will have overlapping joints to prevent direct thermal conductive paths. Analytical and corresponding thermal analysis show that this structure will provide the temperatures that are required (see Fig 3 for structure and thermal analysis figure).

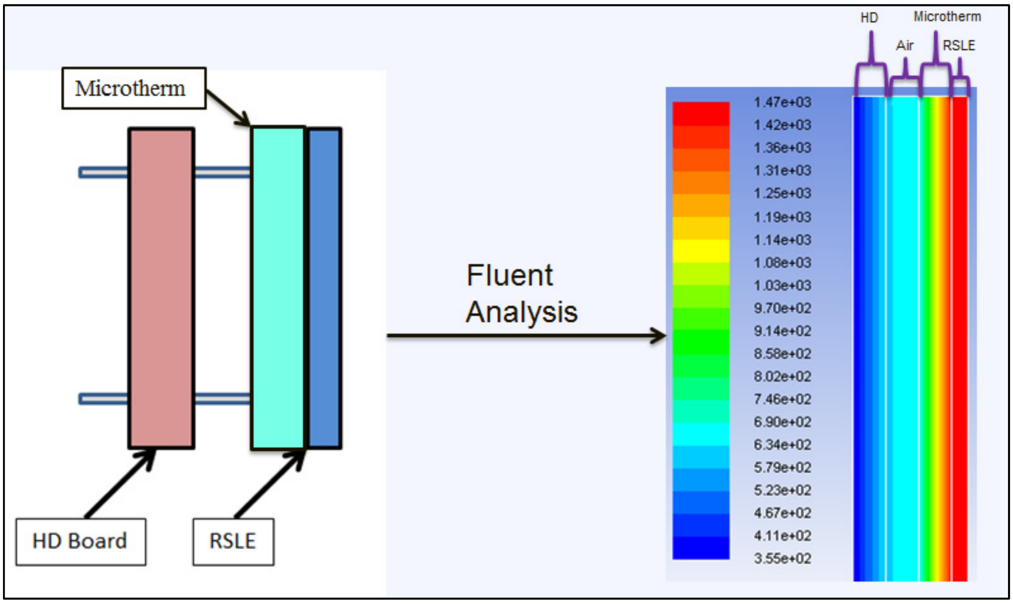


Fig 3. Cavity wall structure composition and thermal analysis (K)

### *3.2. Top hopper*

The top hopper needs to house the particles before they fall through the receiver. In anticipation of future studies this hopper had to have two particle drop locations. A “front” drop location and a “back” drop location. The hopper has to withstand particle temperatures up to 700°C and up to ~3000 kg of particle weight. The hopper needed to be weather resistant and closed to the environment for good thermal efficiency. The hopper needed to be removable and accessible for maintenance. This hopper will control the mass flow rate of the particles. The structure can be seen in Fig 4 which shows two isometric views of a half-symmetric geometry. The hopper walls is 316 stainless steel while the support members are 304 stainless steel.

Several iterations of physical design of the hopper were generated and then subjected to finite element analysis to analyze the combination of thermal loading and dead loading (half-symmetry was used during analysis). Dead loads include the particle weight (internal hydrostatic load with particle density of 2000 kg/m$^3$) and structural weight (~900 kg). SolidWorks Simulation was used to first study the thermal loading. The internal walls were set to be a constant temperature of 105°C. This is the calculated external wall temperature when the inside of the hopper is lined with 76.2 mm of insulation. The outside of the hopper needs to be less than 150°C to reduce the heating of the supporting structure. This thermal loading of the structure was imported into the static loading analysis which included all the dead loads. A grid-independence study was performed to verify that the solution was independent of the mesh. The FEA resulted in acceptable stresses for 316 and 304 stainless steel at elevated temperatures according to the ASME Boiler and Pressure Vessel code. During the FEA, stress singularities were determined at contact locations at certain members which was not unexpected due to the sharp features in the geometry. These locations were analyzed further with analytical beam loading calculations to verify that the stresses at the supports were under the yield strength for the materials and supporting welds. The stress and displacement plots can be seen in Fig 5.

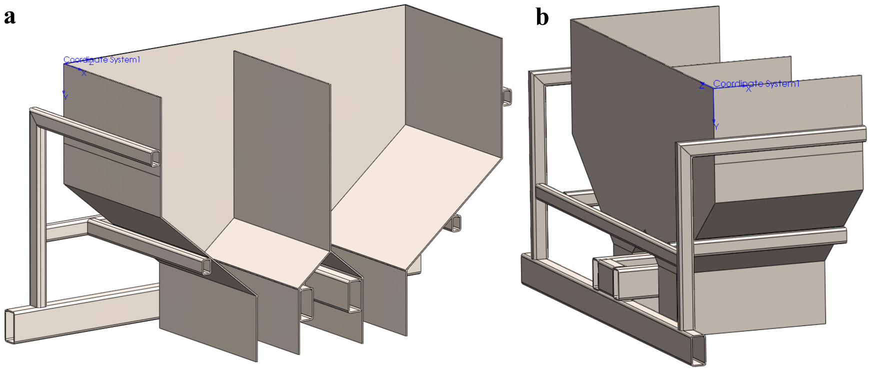


Fig 4. Top Hopper geometry, Isometric views showing inside (a) and outside (b) of symmetrical geometry

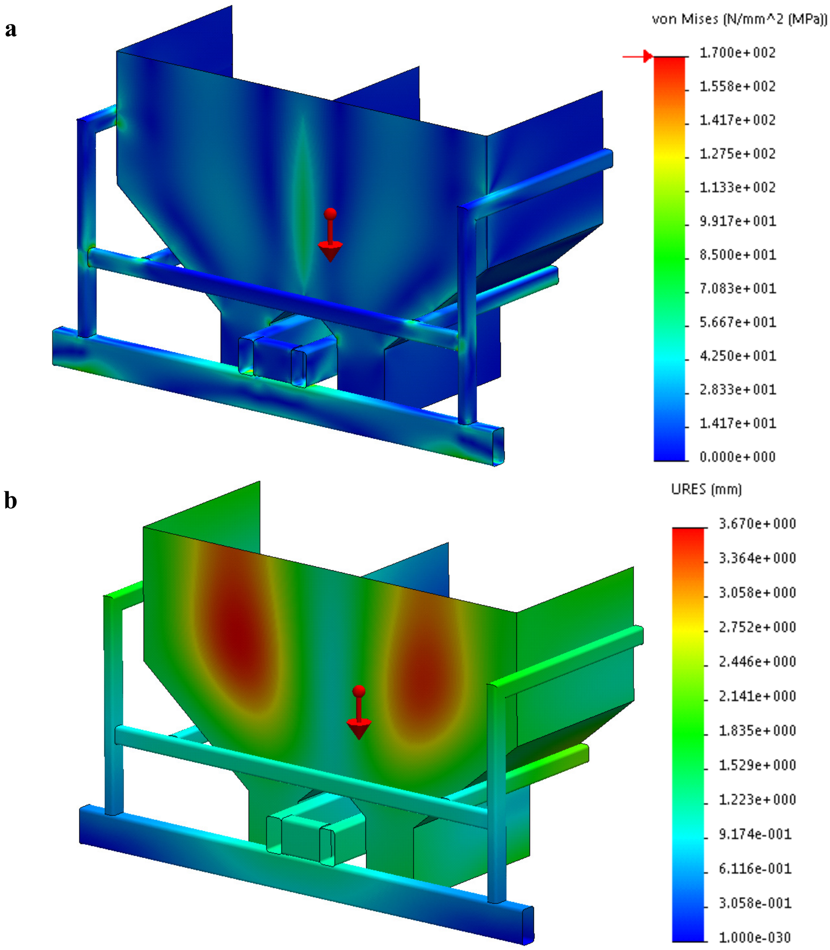


Fig 5. (a) Thermal and dead loading stresses (MPa) in top hopper; (b) Displacements (mm) in bottom hopper due to loading

### *3.3. Bottom hopper*

The bottom hopper component catches the particles as they fall from the cavity receiver. The hopper then stores the particles until they are transported from the hopper back into the particle elevator. The bottom hopper had very similar design constraints as the top hopper. It had to hold 700°C particles and withstand the ~3000 kg particle weight. The hopper needed to be weather resistant. The hopper needed to be removable and accessible for maintenance. There will be a lid that can be slide over the top of the hopper when not running to keep water and dirt out of the hopper.

FEA boundary conditions were very similar to the top hopper analysis. However, only two inches of internal insulation will be used here (because of volume/shape limitations) so the temperature on the external walls of the hopper was set to 150°C. The FEA resulted in acceptable stresses for 316 and 304 stainless steel at elevated temperatures according to the ASME Boiler and Pressure Vessel code. Fig 6 displays the bottom hopper geometry, stress contours and displacement contours from the FEA analysis.

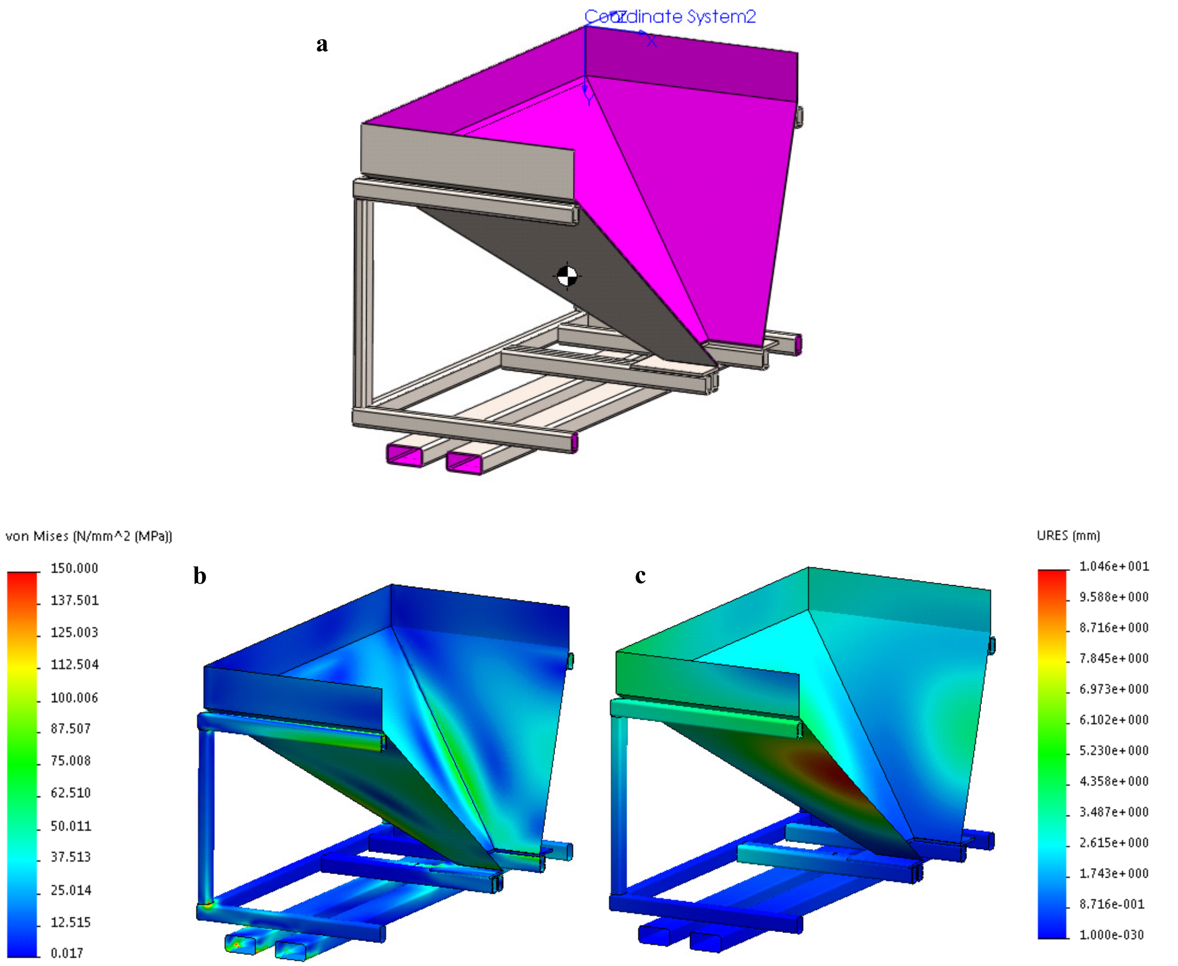


Fig 6. (a) Half-symmetric bottom hopper geometry, purple surfaces designating inside of hopper; (b) Stress (MPa) contours with thermal and dead loading; (c) Displacement (mm) contours with thermal and dead loading

### *3.4. Olds elevator*

For elevating the particles from the bottom hopper back to the top hopper, a high temperature particle lift was needed. To perform this duty, an Olds elevator was purchased. This elevator can withstand temperatures up to 800°C and handle particle mass flow rates up to 8 kg/s. The Olds elevator is a stationary screw with a casing that rotates about the screw. The frictional forces of the casing and particles cause the particles to rise up the elevator in a uniform fashion. The screw/casing volume gets flooded with particles so a uniform flow of particles from the outlet is expected at all ranges of mass flow rates. This phase of experimental tests will require the elevator to transport particles up to 700°C at the maximum mass flow rate of 8 kg/s. The elevator utilizes a 25 HP motor and a variable frequency drive (VFD) such that different desired flow rates can be achieved. The variable flow speed is an advantage of this particle elevator over a bucket lift as well as the high temperature operation.

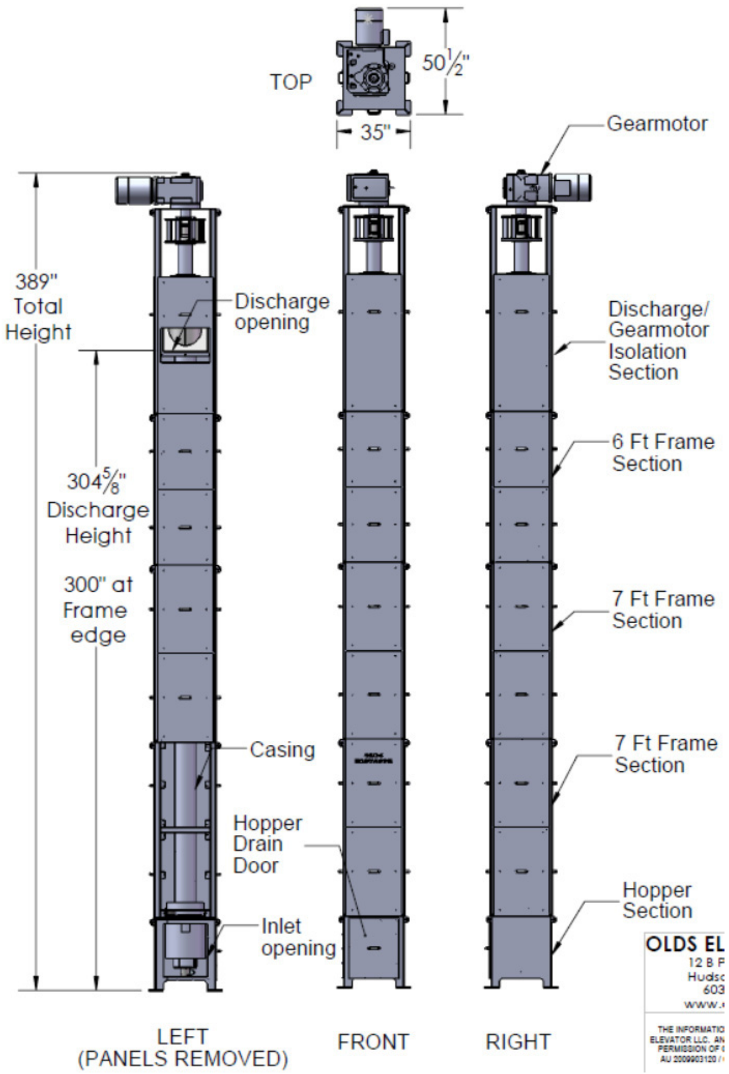


Fig 7. Design of the Olds particle elevator (dimension in inches)

*3.5. Ducting*

There needed to be ductwork which connects the bottom hopper to the Olds elevator inlet and ductwork connecting the Olds elevator outlet to the top hopper. The ducts need to withstand particle flow as well as temperatures up to 700°C. This ductwork was determined to be 321 stainless steel tubing with hydroformed bellows included in the duct to account for any thermal expansion. 321 stainless steel is used for high temperature operation and is similar to 304 stainless steel except it has titanium included to stabilize the material at the high temperatures required for this test.

The ductwork connecting the bottom hopper to the Olds elevator is two ducts. The Olds elevator needed to be fed from two sides opposite of one another. Two individual 127 mm tubes are connected to the bottom hopper that are curved to enter the elevator on opposite sides. Bellows are connected in the middle of these tubes to account for thermal expansion.

The ductwork connecting the top hopper to the Olds elevator outlet is composed of a single 203 mm tube with a single double bellows to account for thermal expansion.

Each of the bellows is a hydroformed bellows with an internal liner to prevent particles from being trapped within the bellows themselves. Any particles that get into the bellows could bind the bellows causing failure.

*3.6. Support structure*

The support structure houses all of the system components. It is composed of A36 structural steel and is a brace frame structure. The structure was analyzed using RISA 3D to evaluate all possible loading conditions on the structure including dead loads (component weights), live loads (particle loading and people), wind loading (specified up to 96 mph winds according to ASCE 7-05), earthquake loading for Albuquerque, NM, and snow loads. The structure was fabricated and installed within the Solar Tower at the NSTTF.

*3.7. Beam characterization panel (BCS)*

A BCS panel is being included on the structure in order to measure the incident flux that will be on the aperture of the cavity. This will allow measurement of the thermal efficiency of the system. The BCS panel is composed of a series of rectangular tubes connected by 180° tubing to flow an ethylene-glycol fluid through the tube. The heliostats will aim at this panel; the beam will then be characterized using a kindle radiometer and photographic images. The flow through the panel will keep the panel from melting during this characterization process.

*3.8. Instrumentation*

A large number of sensors are present in the system on different components in order to measure the temperatures, fluxes, and pressures (in the cooling flow lines). Temperatures will be recorded in the receiver, hoppers, elevator, and ductwork. These temperatures will have alarms installed in case any component gets heated above the acceptable levels. Flux gages will be included in the receiver to measure the flux distribution within the receiver. Pressure switches have been installed in the NSTTF cooling lines to detect if the flow gets interrupted during testing. If the pressure switches are triggered the test will be immediately stopped. The fluxes and temperatures recorded during testing will be compared to CFD and analytical calculations.

## 4. Conclusion

A complete SPR system has been designed and in the process of being fabricated at the NSTTF. The receiver, hoppers, elevator, support structure, and measurement devices have all been engineered to withstand the loads of this test. The receiver was designed to withstand 1200°C and 2000 suns during testing operations. The hoppers and ductwork were studied using analytical and FEA calculations to verify that they will support holding 700°C particles. The particle elevator was purchased from Olds elevator and can transport up to 800°C particles at a maximum flow rate of 8 kg/s. The support structure was designed to withstand all loading conditions including dead and live loads, wind loads, earthquake, and snow loads according to structural building codes. The entire system will be instrumented to verify that temperatures and fluxes in the system match those predicted with CFD codes.

## Acknowledgements

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The authors would like to thank John Kelton, Daniel Ray, David Gill, William Kolb, Nate Siegel and Lars Amsbeck during this design process for their valuable insight.

## References

[1] Kolb, G. J., Diver, R. B., and Siegel, N., 2007, "Central-station solar hydrogen power plant," J Sol Energ-T Asme, 129(2), pp. 179-183.
[2] Evans, G., Houf, W., Greif, R., and Crowe, C., 1987, "Gas-Particle Flow within a High-Temperature Solar Cavity Receiver IncludingRadiation Heat-Transfer," J Sol Energ-T Asme, 109(2), pp. 134-142.
[3] Falcone, P. K., Noring, J. E., and Hruby, J. M., 1985, "Assessment of a Solid Particle Receiver for a High Temperature Solar Central Receiver System," SAND85-8208, Sandia National Laboratories, Livermore, CA.
[4] Hellmann, J. R., Eatough, M. O., Hlava, P. F., and Mahoney, A. R., 1987, "Evaluation of Spherical Ceramic Particles for Solar Thermal Transfer Media," No. SAND86-0981Sandia National Laboratories, Albuquerque, NM.
[5] Hellmann, J. R., and McConnell, V. S., 1986, "Characterization of Spherical Ceramic Particles for Solar Thermal Transfer Media: A Market Survey," No. SAND86-1873Sandia National Laboratories, Albuquerque, NM.
[6] Hruby, J. M., and Steele, B. R., 1986, "A Solid Particle Central Receiver for Solar-Energy," Chem Eng Prog, 82(2), pp. 44-47.
[7] Hruby, J. M., Steele, B. R., and Burolla, V. P., 1984, "Solid Particle Receiver Experiments: Radiant Heat Test," No. SAND84-8251Sandia National Laboratories, Albuquerque, NM.
[8] Kim, K., Moujaes, S. F., and Kolb, G. J., 2010, "Experimental and simulation study on wind affecting particle flow in a solar receiver," Solar Energy, 84(2), pp. 263-270.
[9] Meier, A., 1999, "A predictive CFD model for a falling particle receiver reactor exposed to concentrated sunlight," Chem Eng Sci, 54(13-14), pp. 2899-2905.
[10] Roger, M., Amsbeck, L., Gobereit, B., and Buck, R., 2011, "Face-Down Solid Particle Receiver Using Recirculation," J Sol Energ-T Asme.
[11] Siegel, N., Kolb, G., Kim, K., Rangaswamy, V., and Moujaes, S., 2007, "Solid particle receiver flow characterization studies," Proceedings of the Energy Sustainability Conference 2007, pp. 877-883.
[12] Hruby, J. M., 1986, "A Technical Feasibility Study of a Solid Particle Solar Central Receiver for High Temperature Applications., "SAND87-8005, Sandia National Laboratories, Albuquerque, NM.
[13] Christian, J., and Ho, C., 2013, "Alternative Designs of a High Efficiency, North-Facing, Solid Particle Receiver," SolarPACESLas Vegas, Nevada.
[14] Gobereit, B., Amsbeck, L., Buck, R., Pitz-Paal, R., and Muller-Steinhagen, H., 2012, "Assessment of a Falling Solid Particle Receiver with Numerical Simulation," SolarPACES2012.
[15] Ho, C., and Christian, J., 2013, "Evaluation of Air Recirculation for Falling Particle Receivers," ASME, ES2013-18236 Minneapolis, MN.
[16] Khalsa, S. S. S., Christian, J. M., Kolb, G. J., Röger, M., Amsbeck, L., Ho, C. K., Siegel, N. P., and Moya, A. C., 2011, "CFD Simulation and Performance Analaysis of Alternative Designs for High-Temperature Solid Particle Receivers," ASME International Conference on Energy Sustainability, Washington, DC, USA.
[17] Christian, J., Ho, C., Kolb, W., Kelton, J., and Ray, D., 2013, "Design and evaluation of an on-sun prototype falling-particle cavity receiver," ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference Boston, MA.