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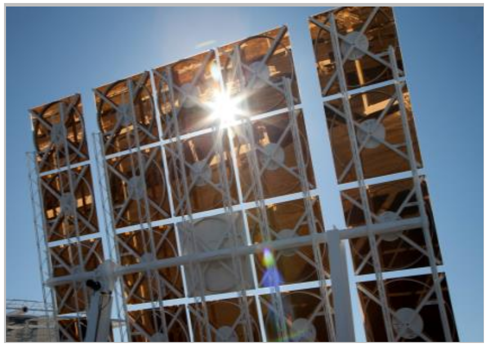


Coupled Optical-Thermal-Fluid and Structural Analyses of Novel Light-Trapping Tubular Panels for CSP Receivers

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U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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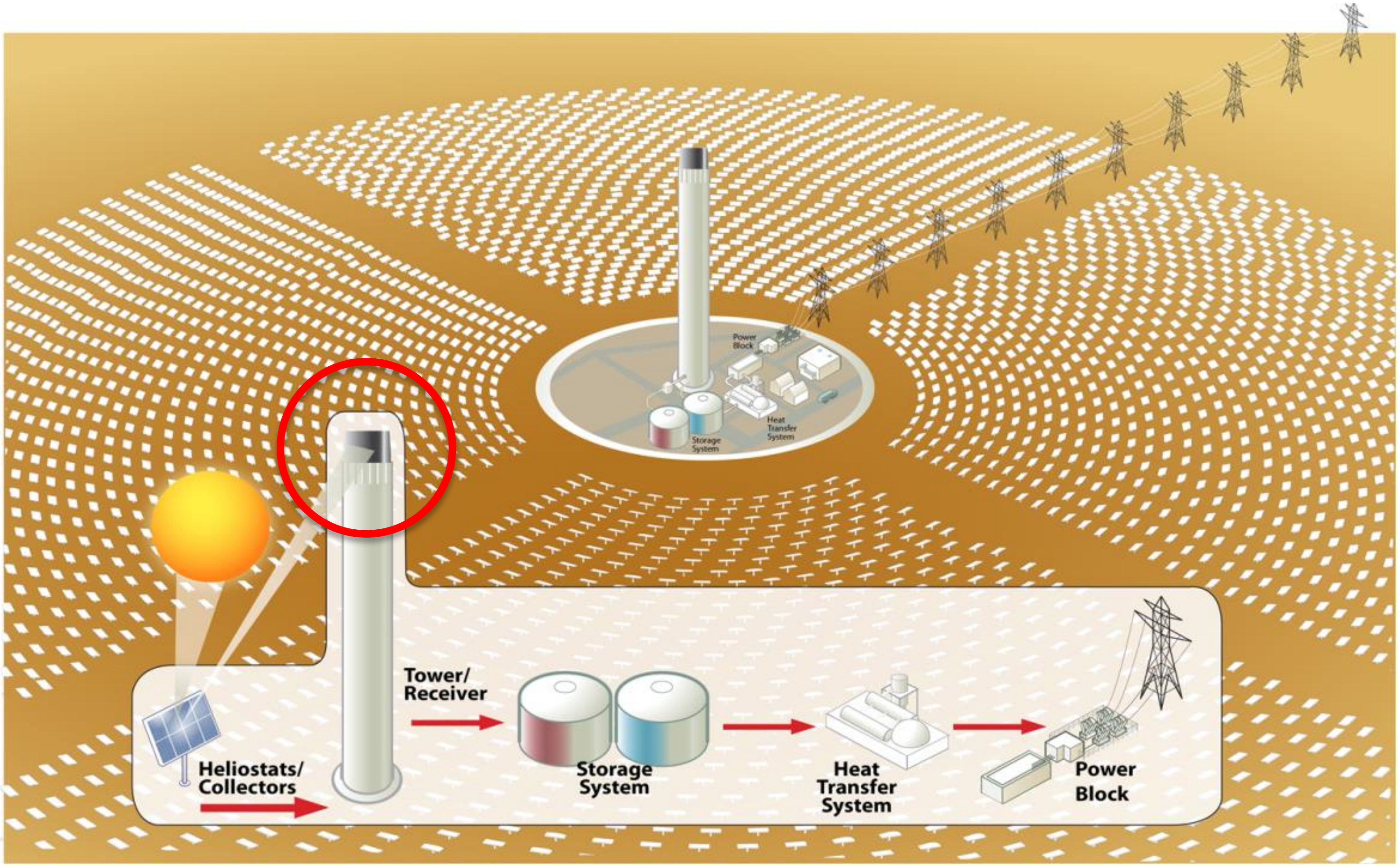
Outline

- Background and Motivation
- CFD Methodology
- Optical-Thermo-Fluid Coupling
- FEA Methodology
- Results
- Conclusions

What are Receivers?



Typical CSP Receiver

Motivation

- Current CSP receivers use coatings or paints to enhance absorption of sunlight
  - Degradation of coatings/paints require re-coats, which increases O&M costs
  - Current geometries have view factors = 1
  - Low thermal efficiencies (high absorb, high emissivity)
- We propose alternative tube geometries that exhibit light-trapping behavior which will enhance solar absorptance and emittance
  - Goal is to achieve ≥90% absorptance and >85% thermal efficiencies without coatings and paints
  - Need tools to simulate coupled optical/thermal/fluid behavior and mechanical stresses for complex receiver geometries
  - Couple ray-tracing tool (SolTrace) with computational fluid dynamics code (ANSYS Fluent) was developed

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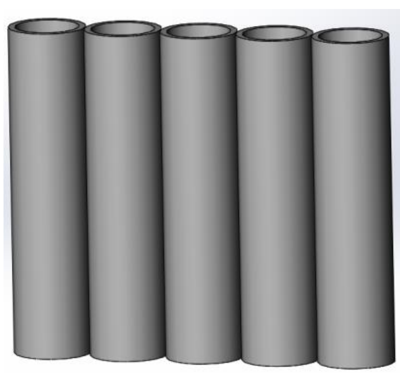
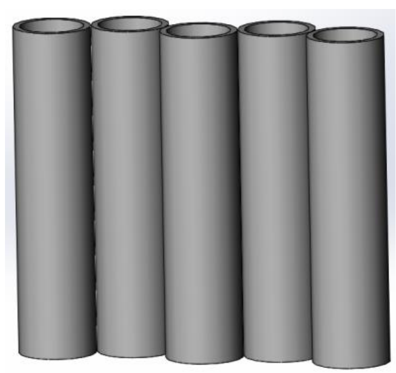
CFD Methodology (1/3)

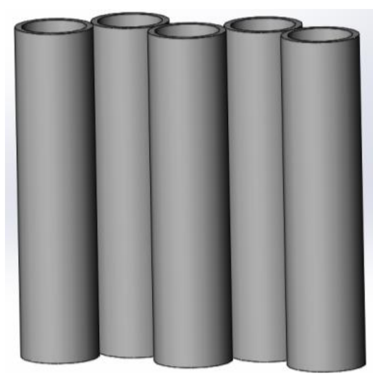
- To evaluate the light-trapping behavior of tubular panels, multiple geometries were evaluated
  - Effective solar absorptance and overall absorbing efficiency of tubes that are staggered or offset by 3 different angles



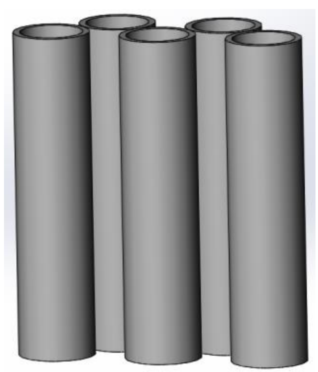
0° Offset Tubes



15° Offset Tubes



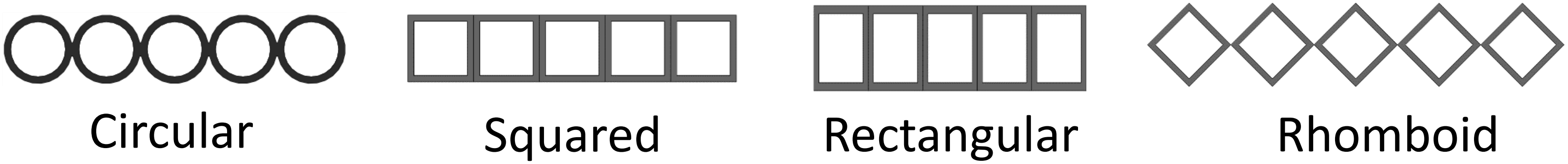
30° Offset Tubes



45° Offset Tubes

CFD Methodology (2/3)

- In addition to cylindrical tubes, three different tube shapes were analyzed
- The tubes were offset by varying degrees
- The goal of this study is to systematically find an optimum solution that meets the effective solar absorptance and thermal efficiency requirements

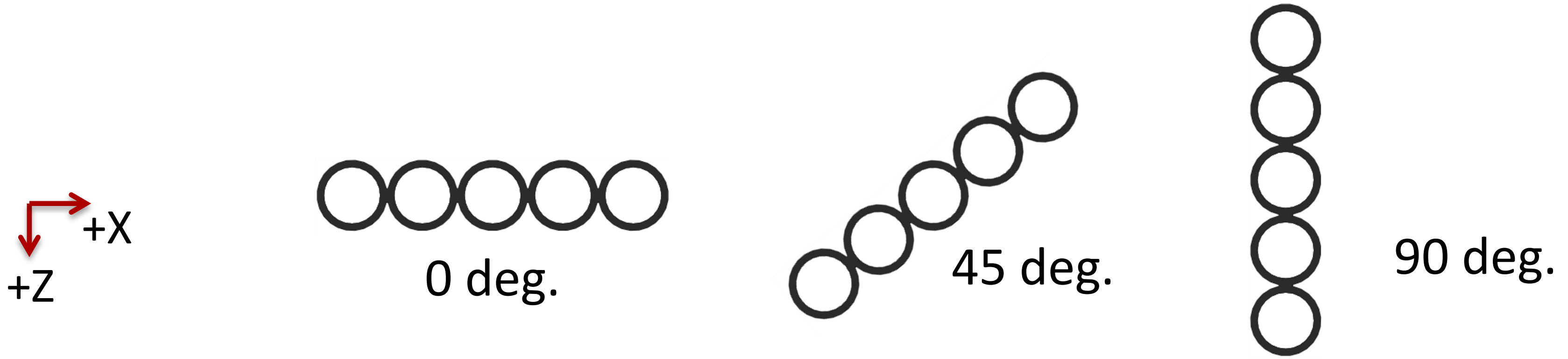


CFD Methodology (3/3)

- Elaborating on the work proposed by Ho, et al., STAR designs will require tubular panels to be aligned in different configurations which have not been analyzed

Clifford K. Ho, et al., "Reduction of radiative heat losses for solar thermal receivers", Proceedings of SPIE Vol. 9175, 917506. (2014)

- Fluid flow patterns can be established taking into account different incidence angles with respect to the collector field

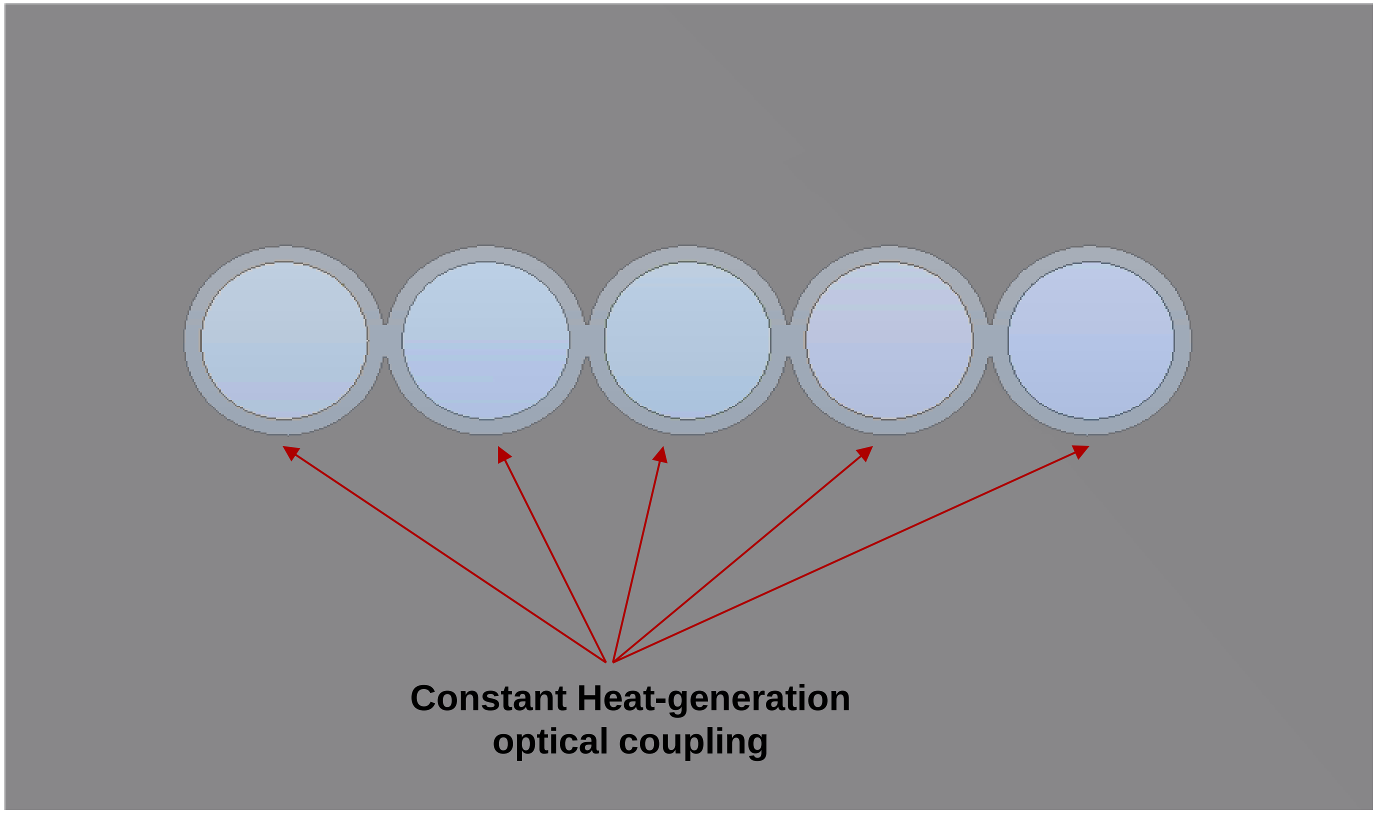


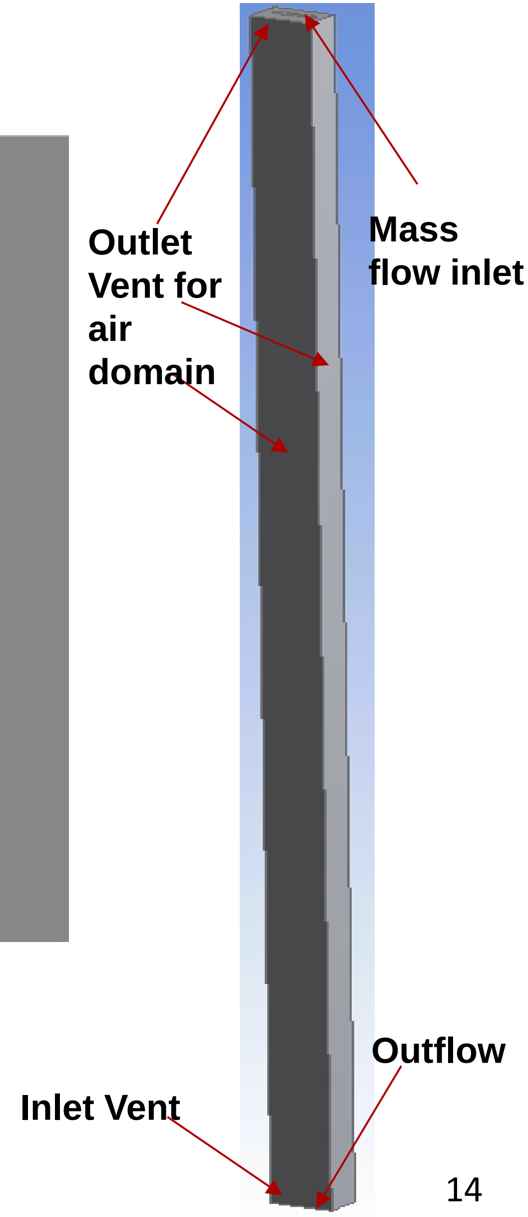
Boundary Conditions

- Twelve different cases were analyzed per cross-section type
- Inconel 718 properties for the tubes were obtained from the vendor
- Supercritical carbon dioxide (s-CO_2) properties were obtained from the NIST database

Heat-flux (kW/m^2)	Mass Flow Per Tube (kg/s)	Inlet Temperature (°C)	Number of Tubes Required
~300	0.0345	490	290

Boundary Conditions





Numerical Models

- Solver: Steady State
  - Gravity enabled Y:-9.81 m/s^2
- Optical Coupling
  - Constant heat generation boundary condition
- Radiation Model
  - Discrete Ordinates Radiation Model
- Turbulence Model
  - Standard K-omega
  - Shear Stress Transport (SST)

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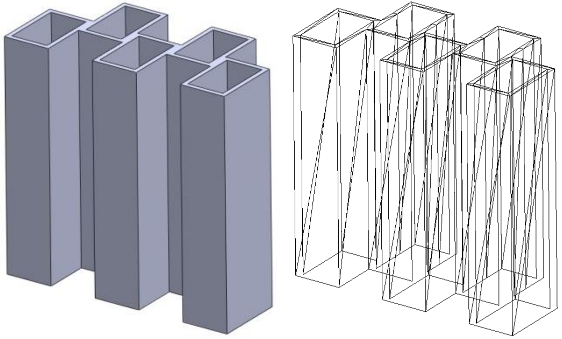
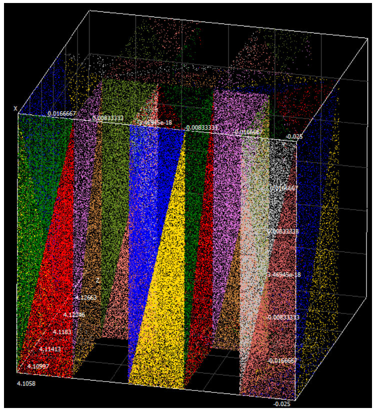
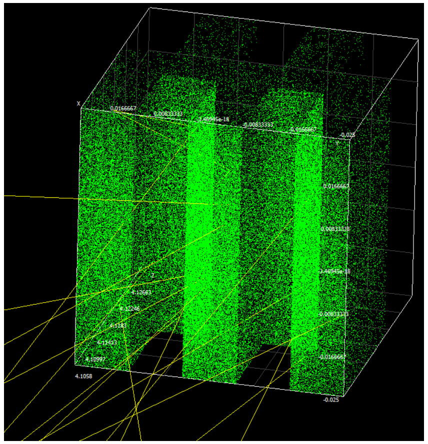


Save CAD geometry as an STL file.

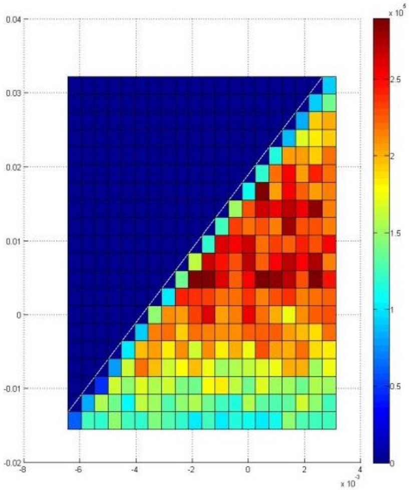
MATLAB: Pre-process STL file into a Stage file for SolTrace.

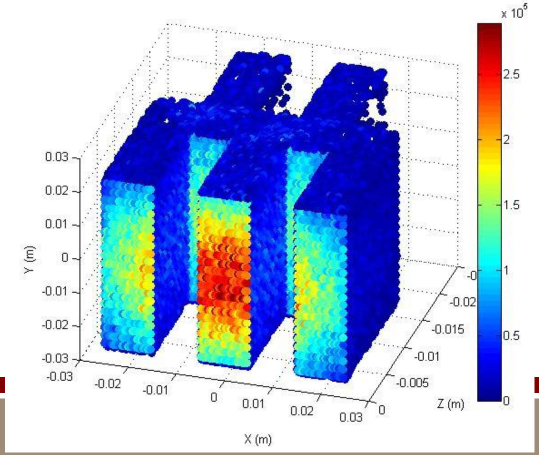




SolTrace: Perform ray tracing using the heliostat field or solar furnace ideal models from NSTTF.

MATLAB: Post-process ray data file to create 2-D heat flux maps.

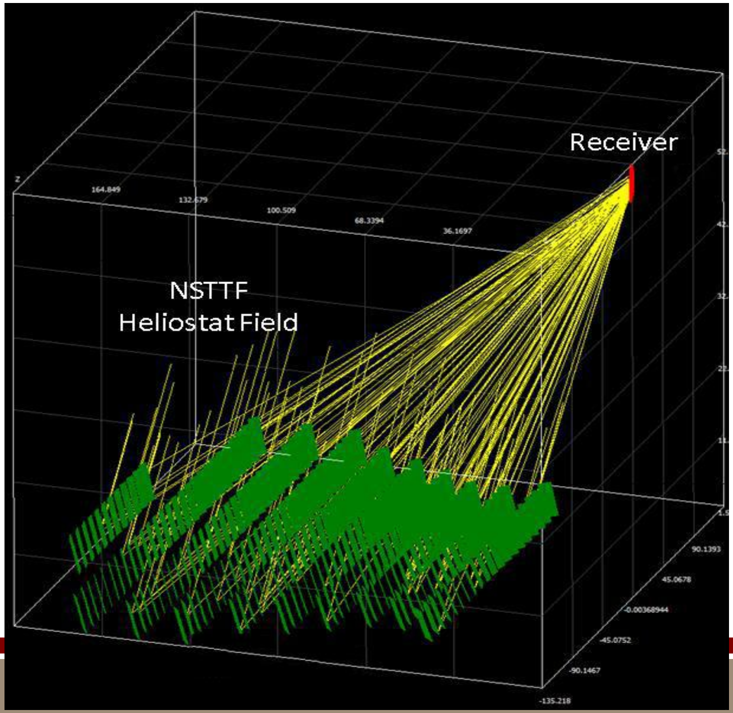


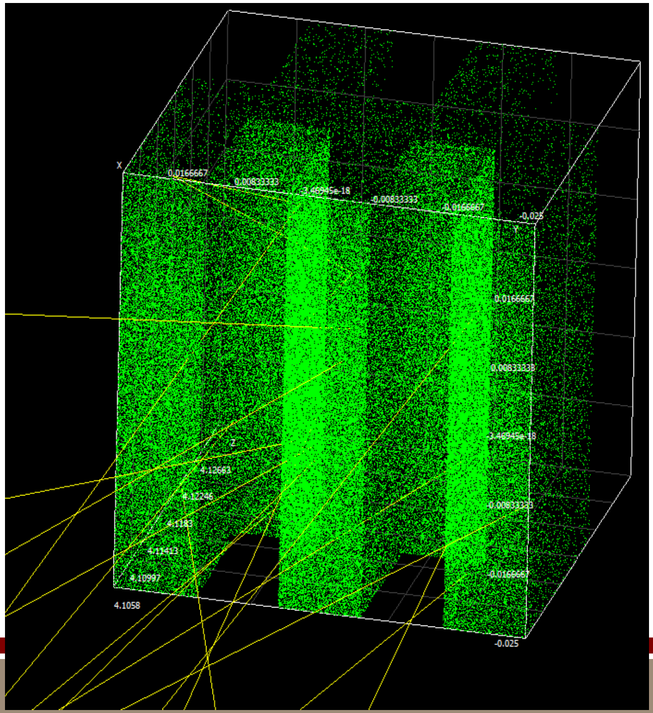


FLUENT: Heat flux profiles can be imported to be used as boundary conditions.

SolTrace: Perform Ray Tracing

- SolTrace was used to perform the optical analyses and generate the flux distributions on the receivers
  - Receiver geometries and NSTTF heliostat field were modeled
- 10M rays were typically traced





FLUENT: Heat Flux Profiles Used as Boundary Conditions

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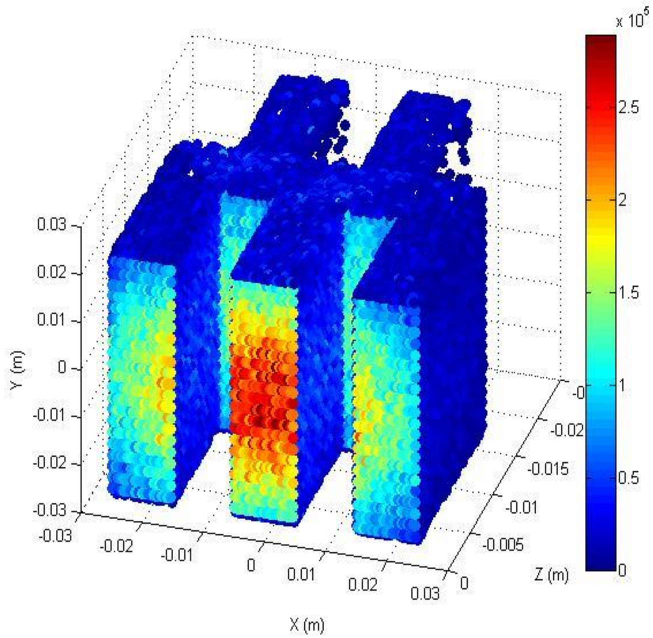
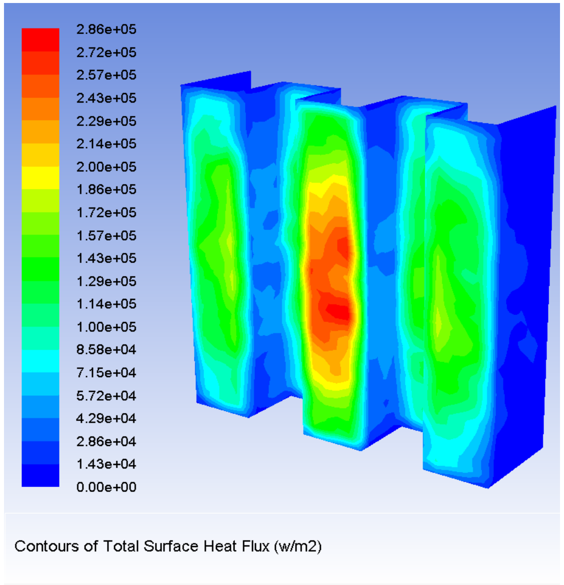
- Once the global heat flux profile is generated, it is written in to a profile format that FLUENT can use as a boundary condition
- FLUENT will read the heat flux points and interpolate between them through out the geometry grid





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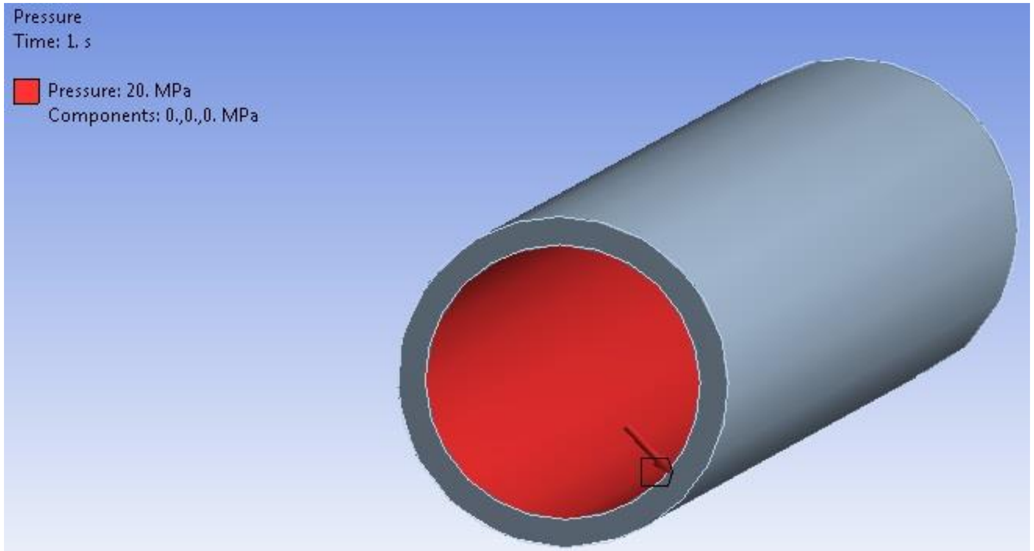
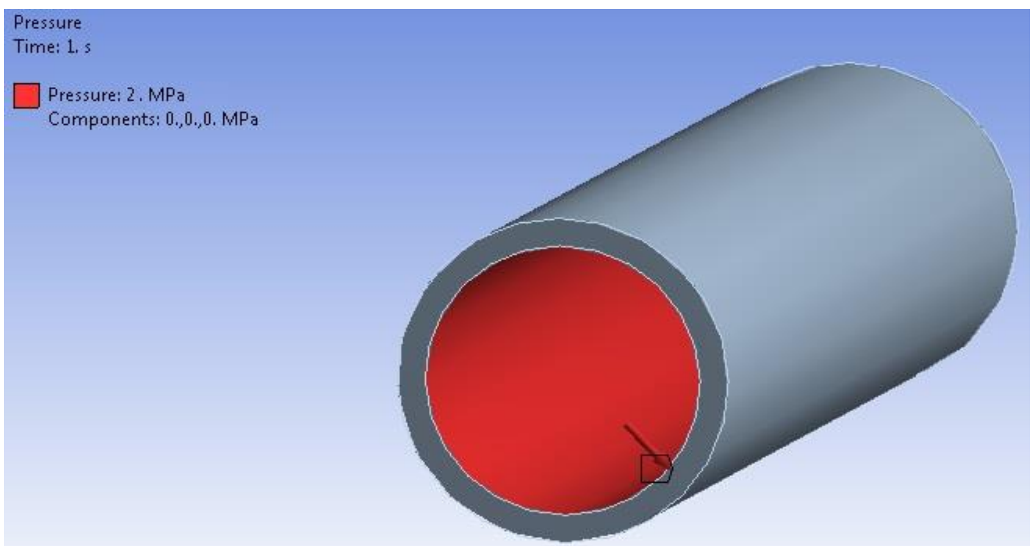
FEA Methodology

- An isothermal static structural stress analysis was performed in order to understand the resulting stress distributions across the tube using an internal load of s-CO_2 and molten salt pressures
  - Case 1: approximating s-CO_2 conditions, will have a constant internal pressure of 20 MPa and isothermal temperature of 800°C
  - Case 2: approximating molten salt conditions, will have a constant internal pressure of 2 MPa and isothermal temperature of 600°C

Boundary Conditions





- Case 1: Internal pressure of 20 MPa at isothermal 800°C for sCO_2 conditions
- Case 2: Internal pressure of 2 MPa at isothermal 600°C for molten salt conditions

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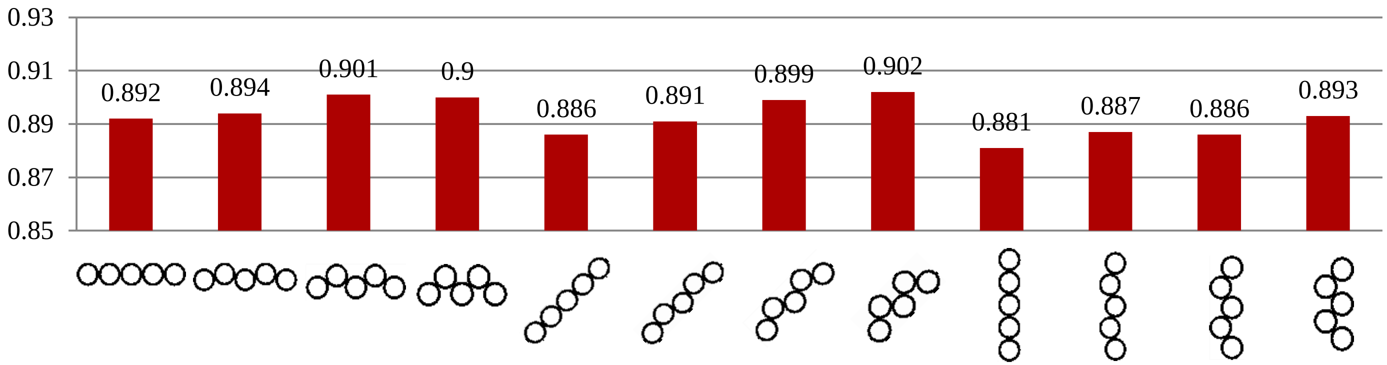
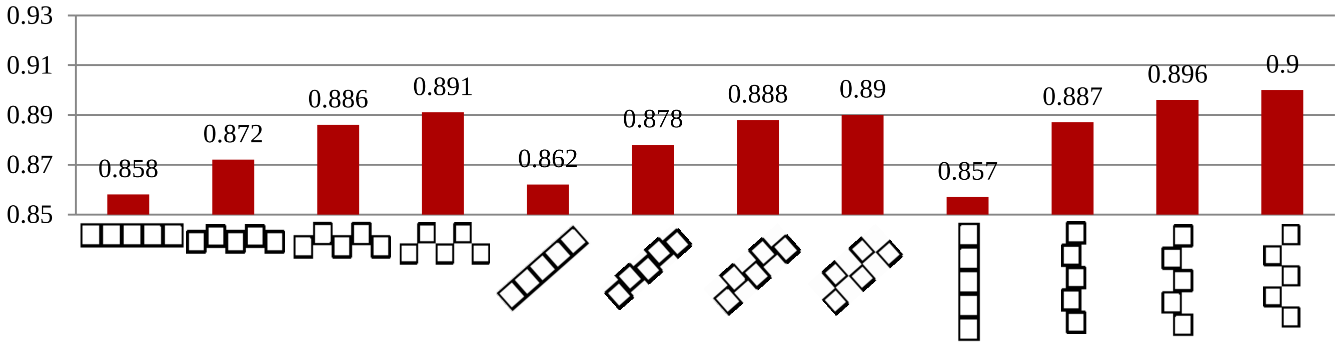
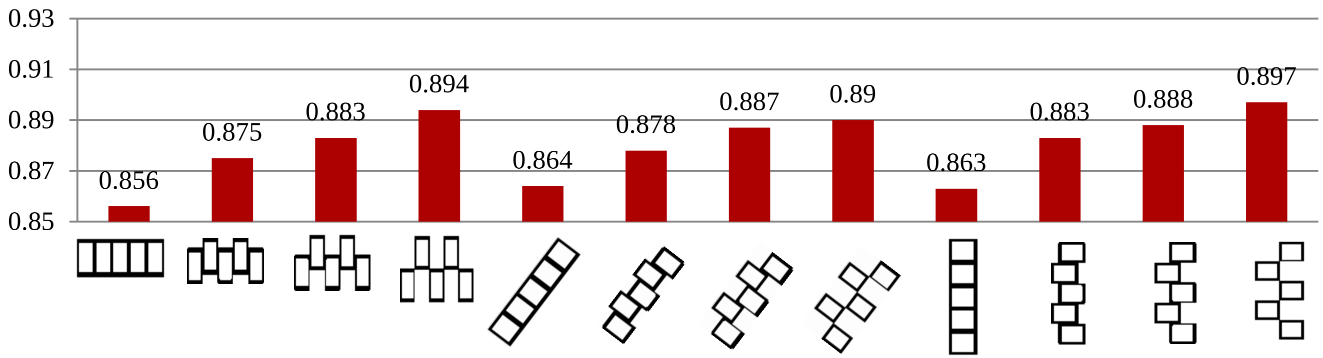
Results of Optical Analysis (1/2)

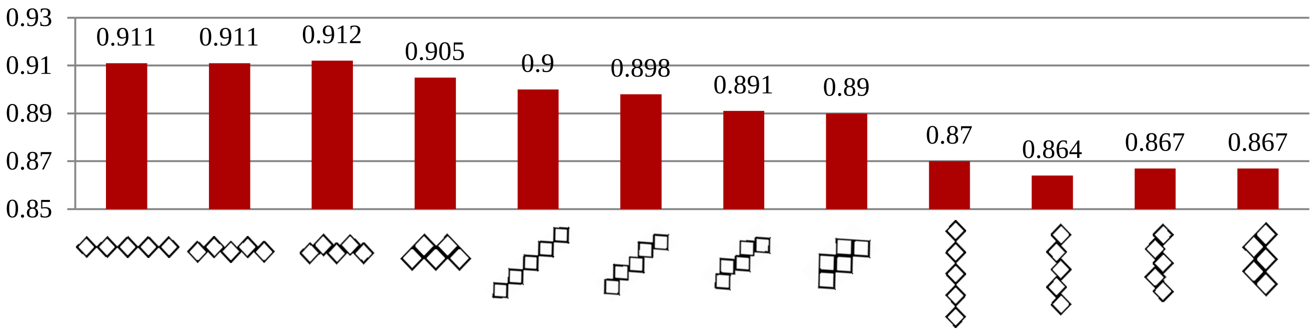
- The circular, square and rectangular tubes show similar trends where the effective solar absorptivity is increasing as the offset angle increases
- The optical intercept areas affect the absorptivity



Results of Optical Analysis (2/2)

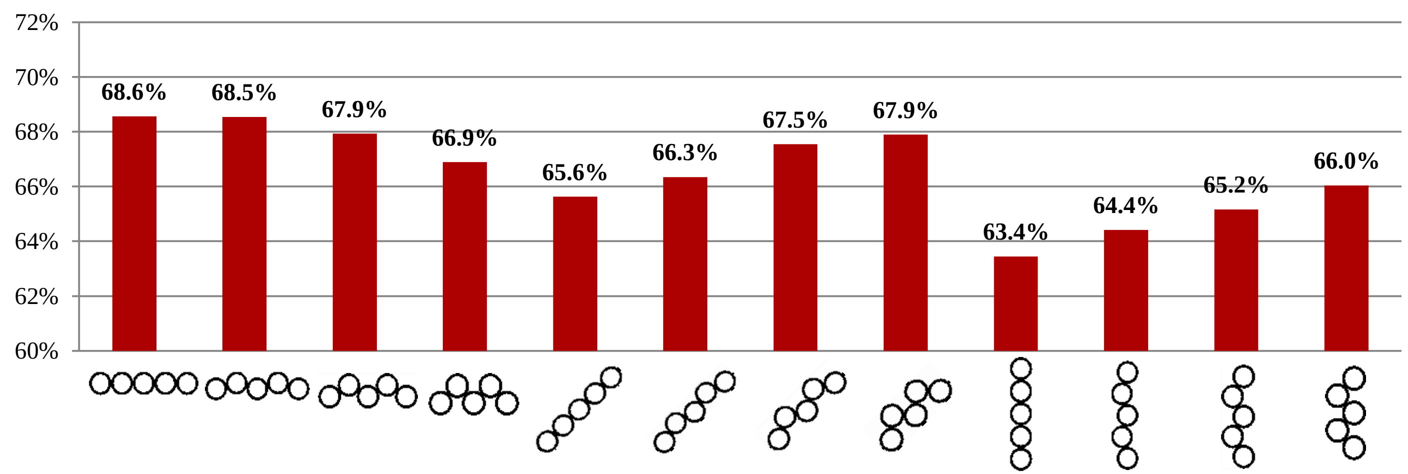




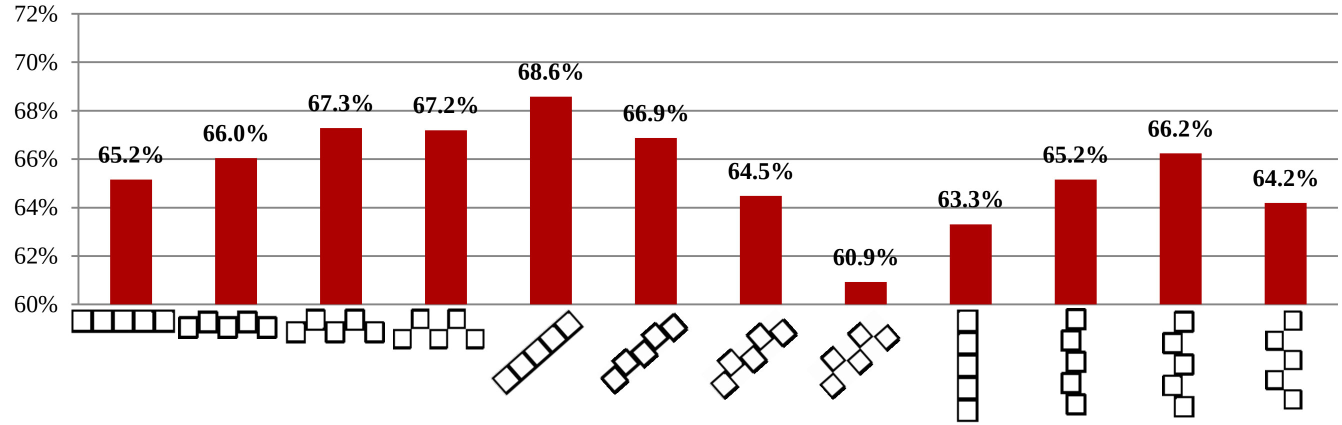


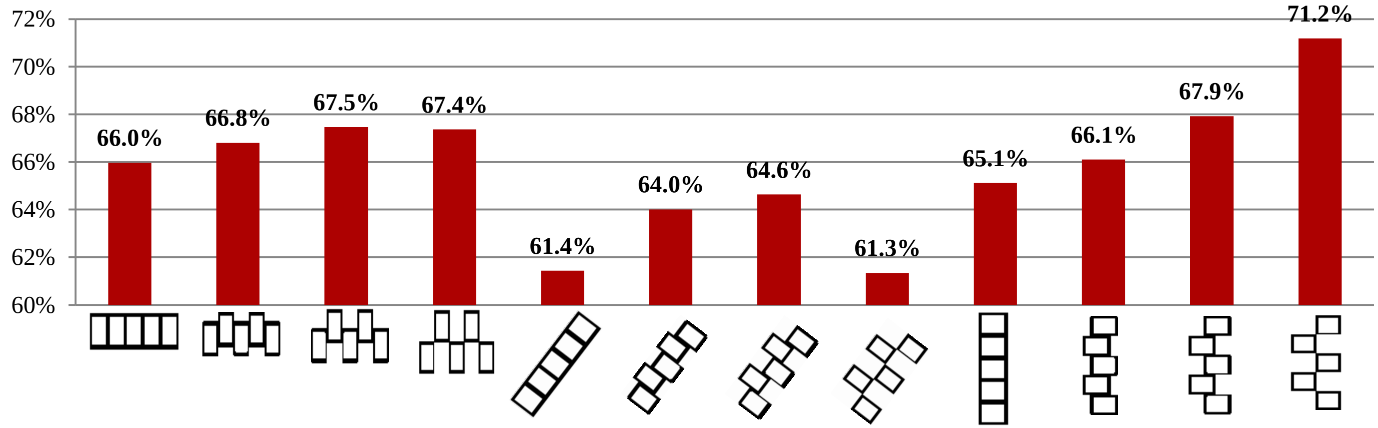
CFD Results: Thermal Efficiency (1/2)

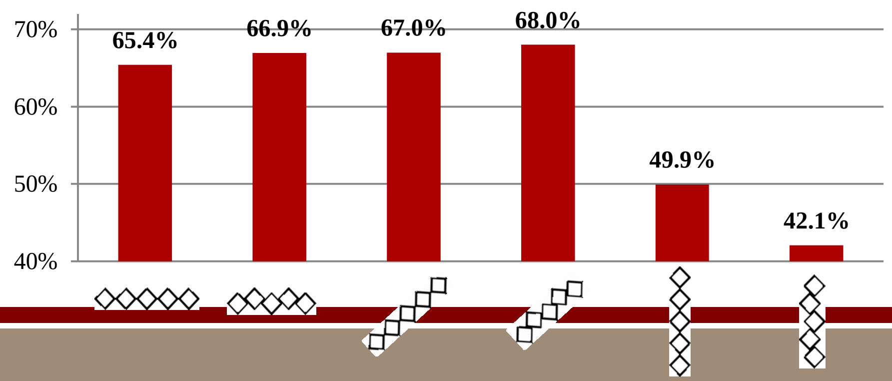
- Thermal efficiencies did not reach our goal, however these results will serve as a baseline for future optimizations
- Optimizations on the outside tube diameter and wall thickness will determine an optimal inner diameter, which will provide the desired heat transfer coefficient



CFD Results: Thermal Efficiency (2/2)

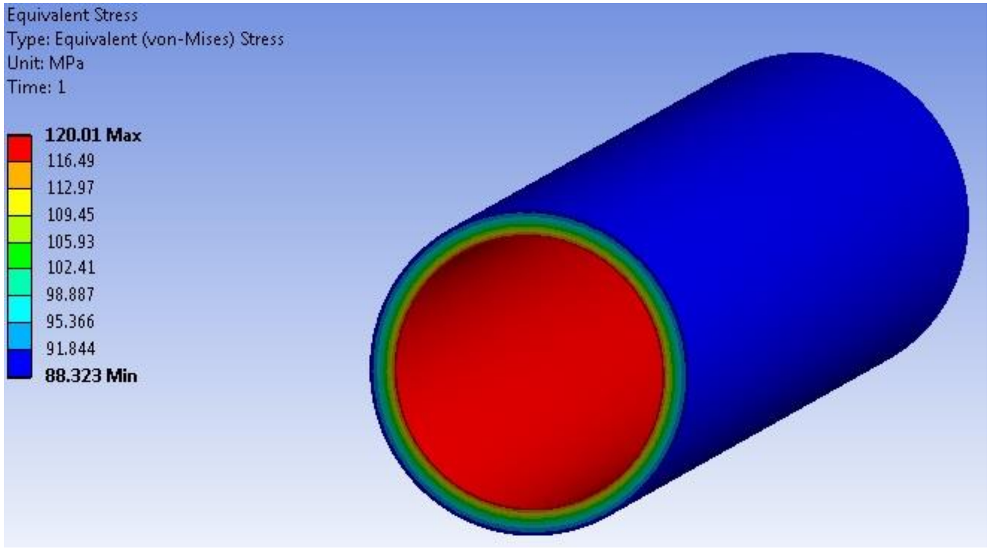


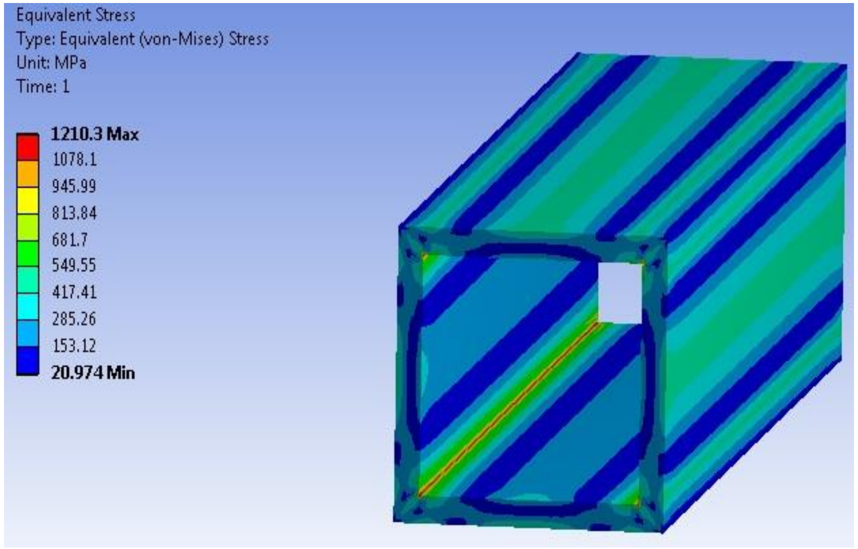




FEA Results (1/3)

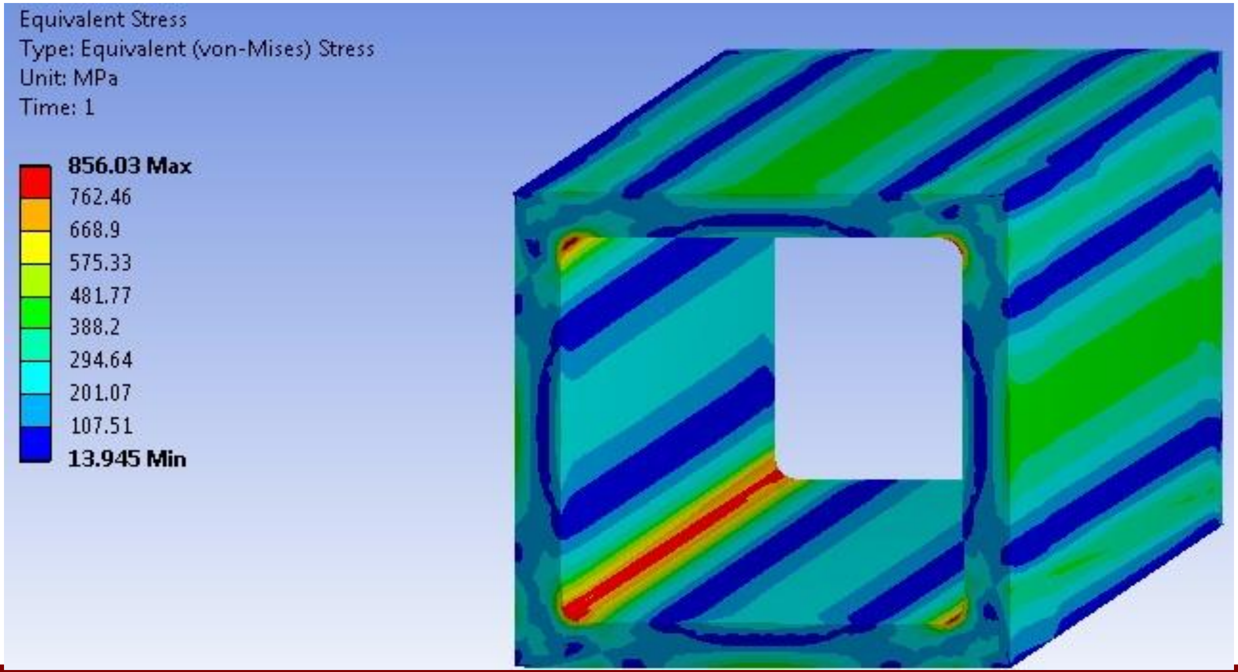
- As anticipated, mechanical stresses on the square and rectangular tubes were higher than the circular tubes





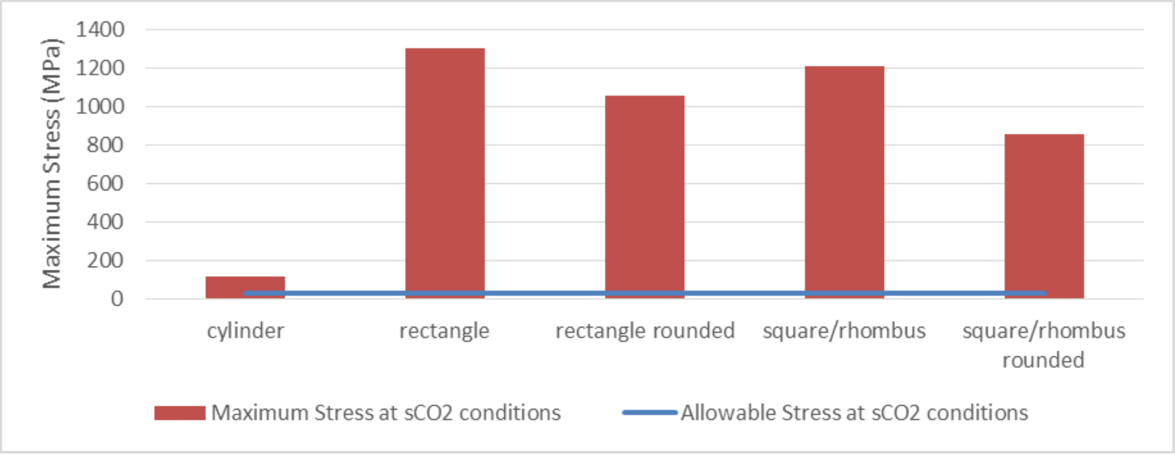
FEA Results (2/3)

- Rounding the internal corners can alleviate the mechanical stresses
- Increasing the thickness of the tubes can also reduce the stresses

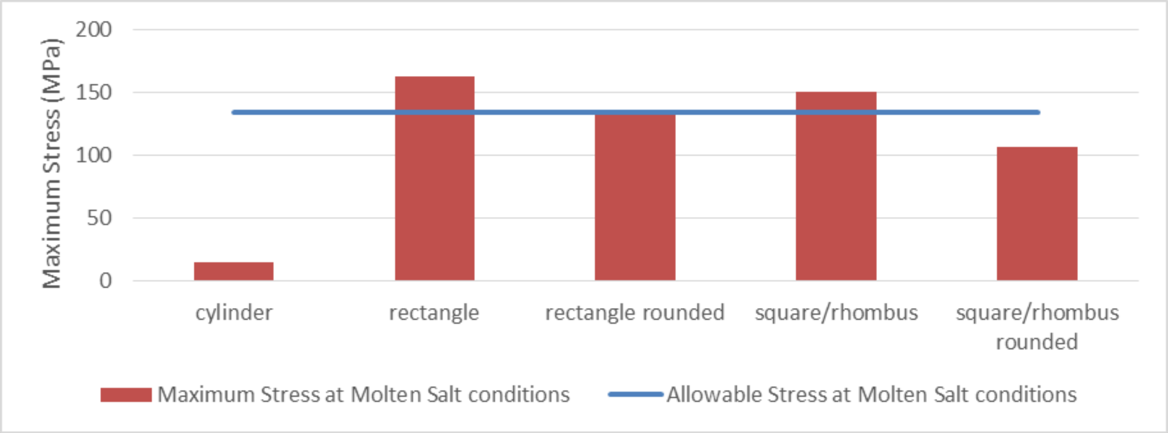


FEA Results (3/3)

- Mechanical stresses are high at sCO_2 conditions – increasing the wall thickness can alleviate stresses



- For molten salt, the lower temperature and internal pressures can allow other geometries to be used



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Summary

- Proposed alternative receiver geometries to enhance solar absorptance and thermal efficiencies with coatings and paints
- Developed a coupled optical-fluid-thermal tool to model and analyze coupled processes for complex receiver geometries
- Evaluated different tube geometries and configurations on their effectiveness for light-trapping
- Performed initial analysis on mechanical stresses

Conclusions

- The optical efficiency was improved from the intrinsic absorptivity of 0.86, showing evidence of light-trapping
- Tube geometries and configurations specified did reach our thermal efficiency goal – further optimizations are required
  - Variables such as diameter, wall thickness, tube length, offset angles, and/or flow patterns must be optimized.
- Trends observed in the optical efficiency are not correlated to the thermal efficiency. Several effects are hypothesized.
  - Increasing offset angles causes blockage of the back tubes
    - Less power is collected by the back tubes and temperature increase is less
    - Irradiance on the front tubes receive is high, which leads to higher surface temperatures and heat losses, if the flow rate is not sufficient
- Preliminary static structural results show stresses are high for s-CO_2 internal pressures at isothermal temperatures.
  - Tube diameters and wall thickness require optimizations

Future Work

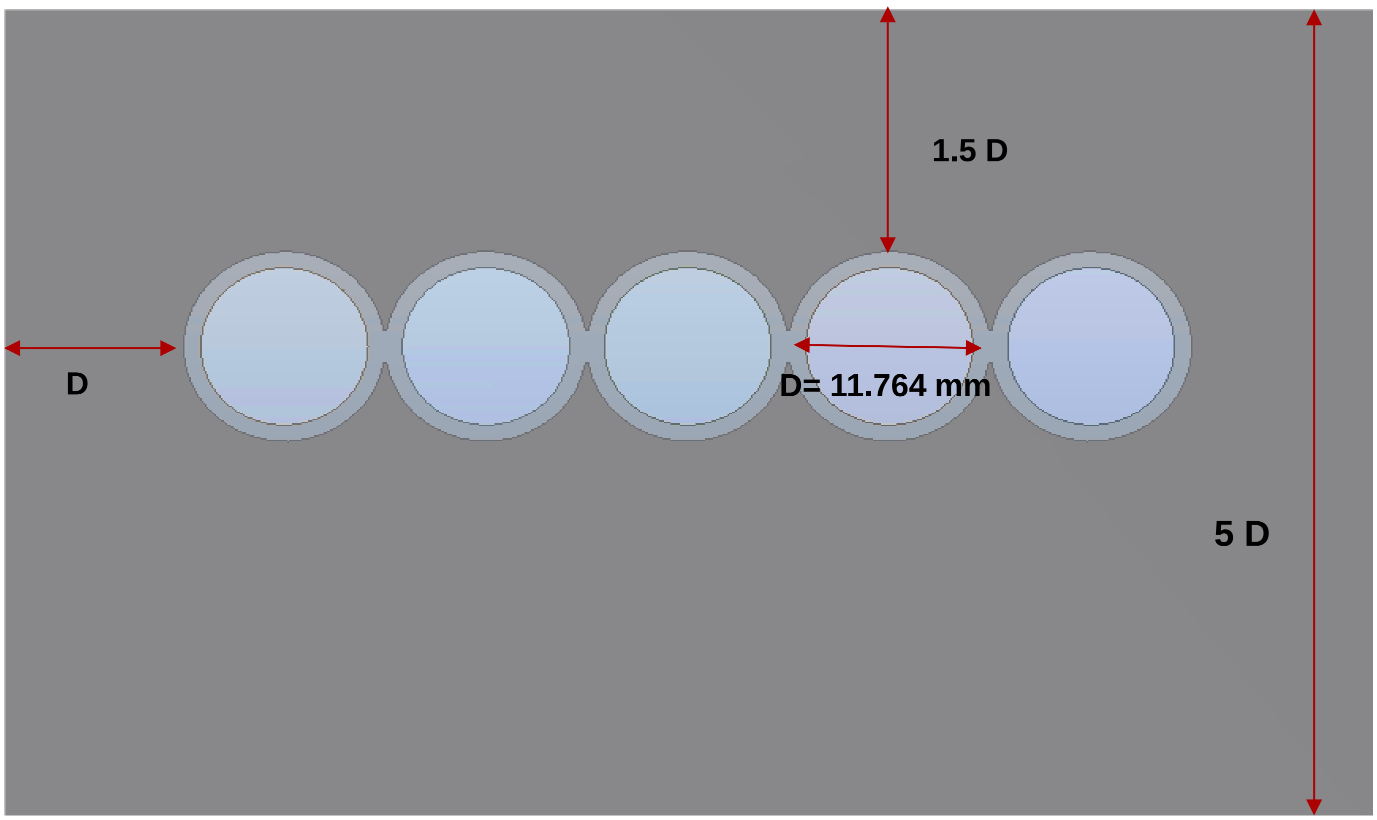
- Future work includes optimization of tube diameters and wall thicknesses to withstand the load conditions as well as the optimization of the internal diameter to achieve the desired heat transfer coefficients
- The structural analyses presented were only considering a load at an isothermal temperature. More complex structural analyses will be performed to include thermal non-uniform loads. This thermal distributions will be more realistic, given that the fluxes are modeled using the coupled optical-fluid-thermal model

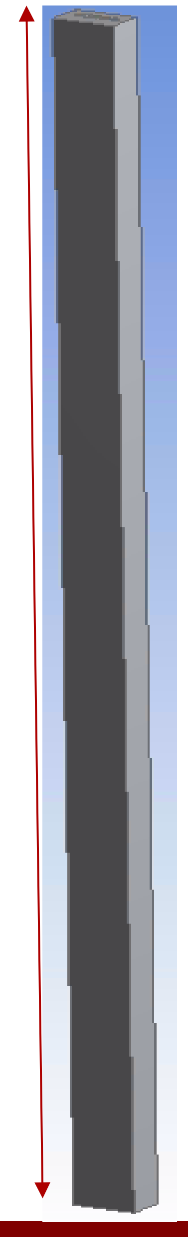
EXTRA SLIDES

Analyzed Cases

- Four different offset angles and three rotation angles were analyzed for each cross-section type.
- In theory, by increasing the heat applied, $Q_{applied}$, and maintain the receiver temperature, T_r, as low as possible, the efficiency of the receiver tends to approach the value of the effective solar absorptivity α.
- Therefore if the effective solar absorptivity α increases, the efficiency increases.
- $\eta_{th} = \frac{\alpha Q_{applied} - Q_{losses}}{Q_{applied}} = \alpha - \frac{Q(T_r)_{rad} + Q(T_r)_{conv}}{Q_{applied}}$

Geometry with Air Domain





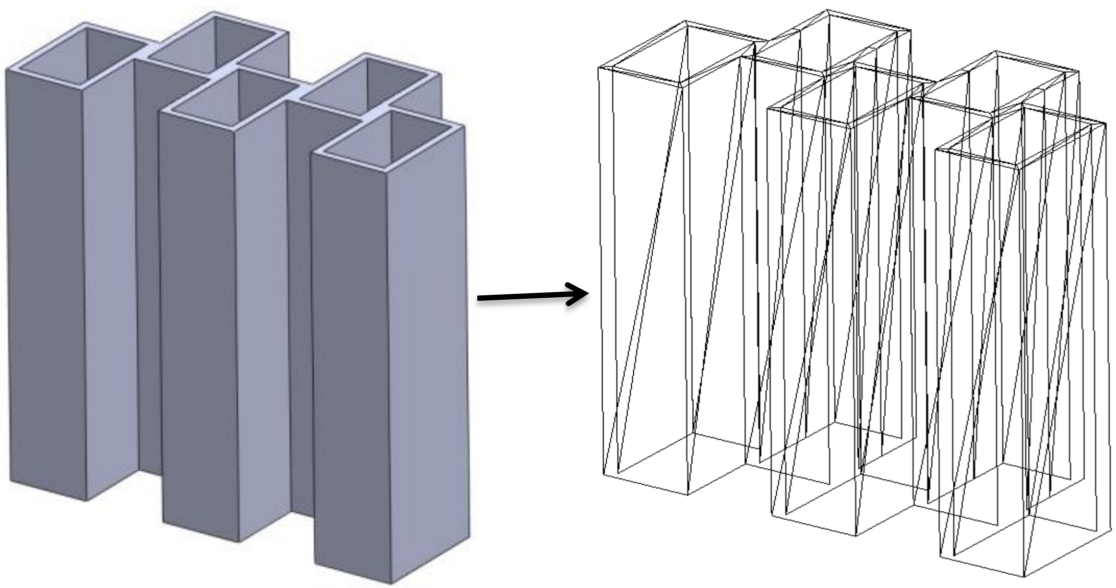
Optical-Thermal-Fluid Coupling

- SolTrace is used to perform the ray tracing analysis on the part by using the NSTTF heliostat field model. Using the procedure developed by Yellowhair et al., the SolTrace model was developed to analyzed the geometry from the previous step.
- The results obtained in SolTrace were coupled using a MATLAB code developed that will output a file which can be used as a boundary condition in ANSYS Fluent.

Saving CAD Geometry as an STL File

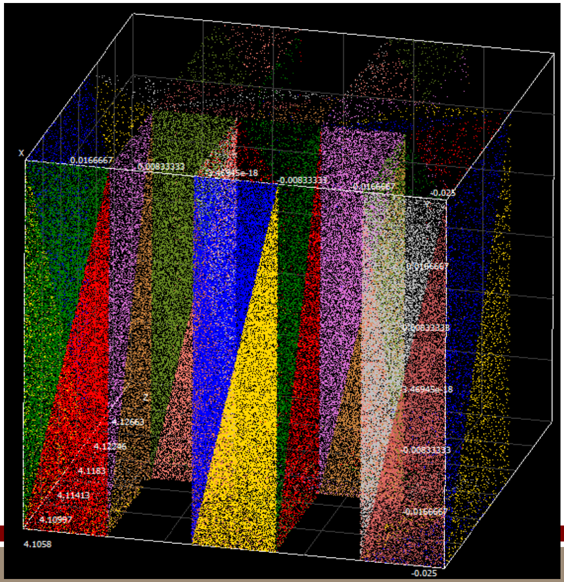
- The STL geometry file contains information of every triangular facet in the geometry.
- XYZ-Coordinates of the vertices and normal vector values are used.

(Move to back???)



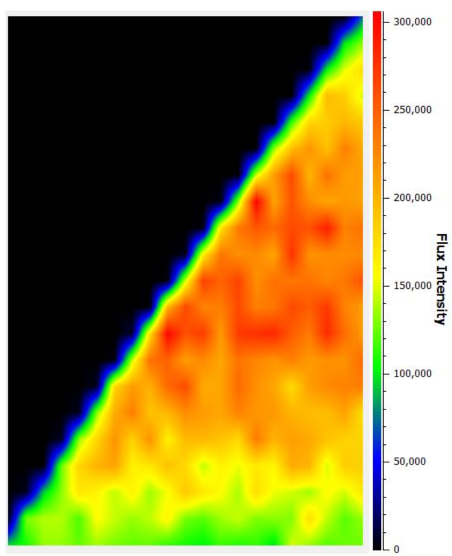
MATLAB: Pre-Process STL File into a STAGE File for SolTrace

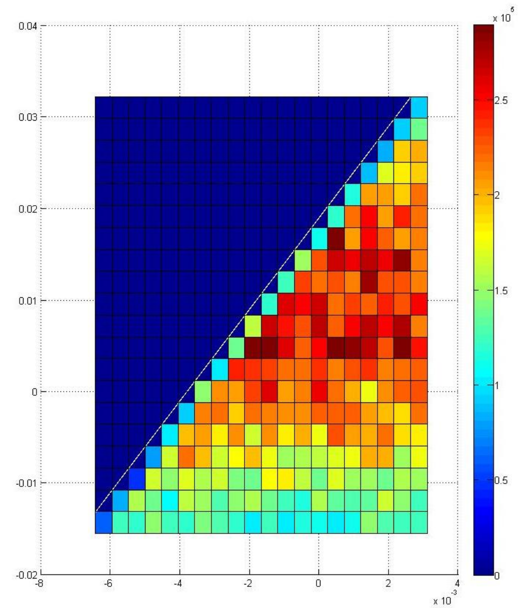
- The first half of the MATLAB script will read the information from the STL file and translate every facet to the XY-plane with the centroid at the origin and facet normal on +Z axis.
- The information is then written to a STAGE file which is used in SolTrace to define the geometry.



MATLAB: Post-Process Ray Data File to Create 2-D Heat Flux Maps

- The ray data of the element and target/receiver is saved from SolTrace.
- The rays are binned in every facet to generate local heat flux maps.
- The local heat flux maps are translated to their global original position.





Output Example of Tools That Analyze Coupled Processes