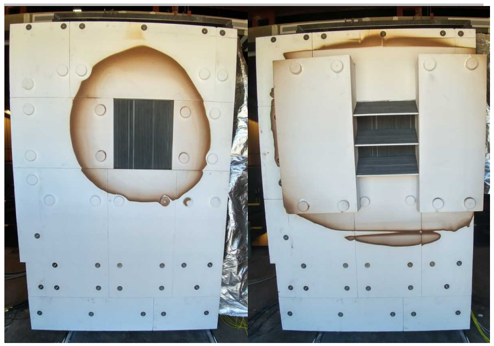
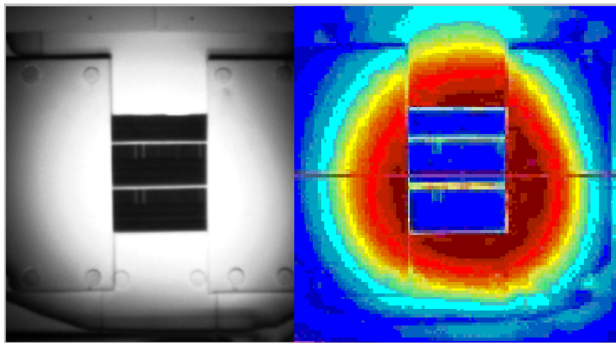
ASME 2017 11th International Conference on Energy Sustainability
SAND2017-6615C
June 27th, 2017

DESIGN AND TESTING OF A NOVEL BLADED RECEIVER

(PowerEnergy2017-3524)

Jesus D. Ortega, Joshua M. Christian, and Clifford K. Ho

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Outline

- Background
- Panel design and fabrication
- Bladed receiver testing
- Results
- Conclusion & Future Work

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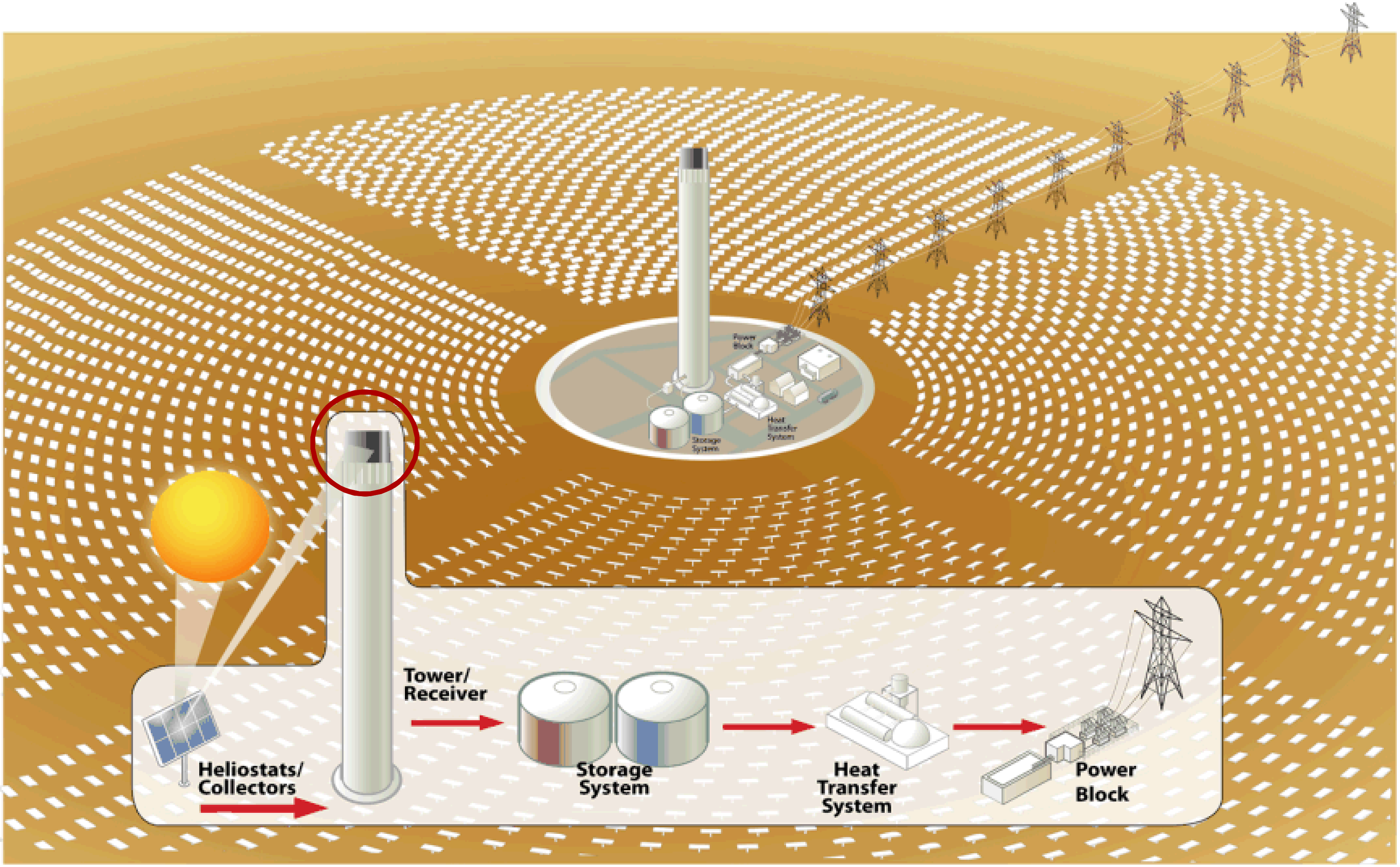
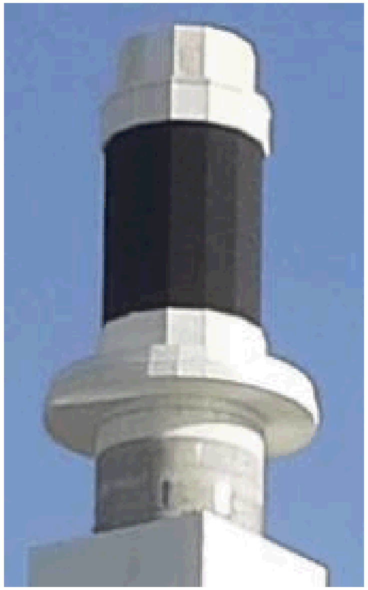
Background


Tower/
Receiver
Heliostats/
Collectors
Storage
System
Heat
Transfer
System
Power
Block

Motivation

- Concentrating solar receivers typically use coatings to enhance solar absorptance
- Coatings degrade and need to be re-applied periodically, which affects performance and increases O&M cost
- Conventional solar receivers are cylindrical or cubic

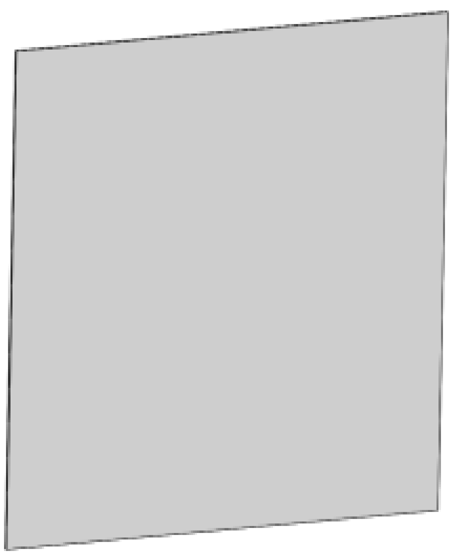


Crescent Dunes Receiver

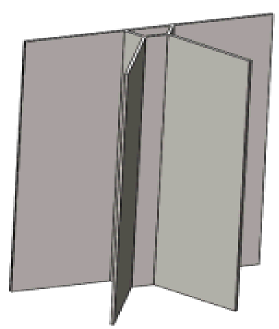
Ivanpah Receiver

Motivation

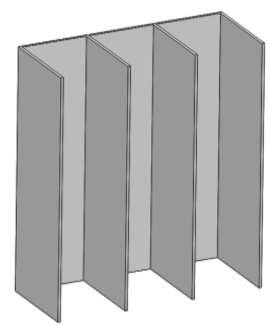
- Sandia proposed fractal-like geometries (FLGs) at multiple scales to enhance solar absorptance – no need to coat receivers
- Need to understand what geometries work best for absorbing and retaining solar energy



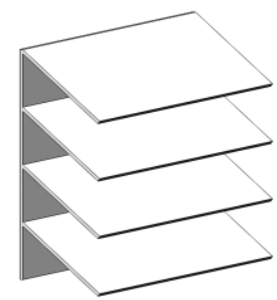
Conventional receiver



Radial fin receiver



Vertical fin receiver



Horizontal fin receiver

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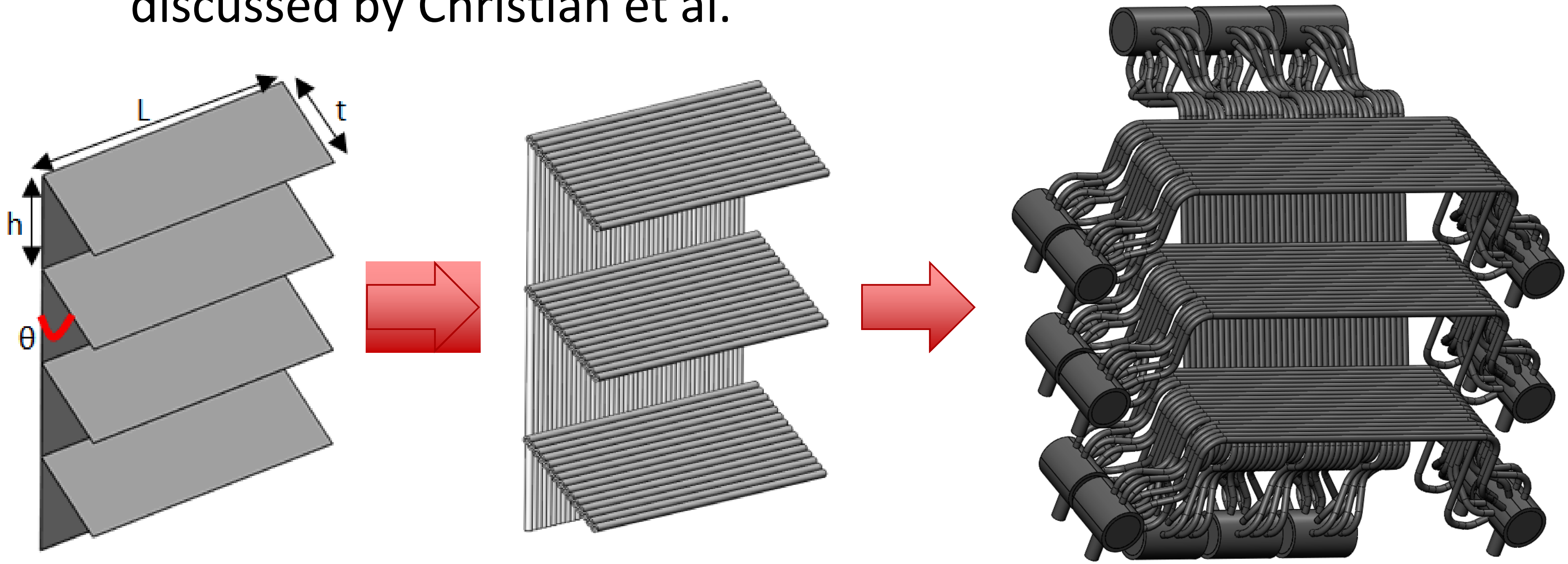
Previous Work

- The horizontal fin (bladed) receiver has many options in terms of number of fins, number of tubes in the fin and back panels, the spacing between the fins, and the angle of the fins
- The parametric study results of a tubular bladed receiver are discussed by Christian et al.



Bladed receiver configuration after parametric study

Panel Design

- The design of the bladed receiver followed the requirements specified for a pressure vessel in the *ASME Boiler and Pressure Vessel Code*
- The design pressure and temperatures for Inconel 625 were initially assumed to be close to the operating conditions that supercritical carbon dioxide (sCO_2) used by Ortega et al.
  - Design Pressure: 20 MPa
  - Design Temperature: 700 C
  - Design Life: 100,000 hours of operation

Panel Design

- Even though suppliers’ stock is typically limited to schedule 40 and 80 in these alloys even a schedule 160 would not be sufficient to meet the *Section VIII* requirements
- The headers are considered our weakest component in the design and the design temperatures and pressures were adjusted accordingly
- These conditions are used to continue the rest of the design:
  - Design Pressure: 15 MPa
  - Design Temperature: 650 C
  - Design Life: 100,000 hours of operation

Panel Design

- Knowing the size requirements, the minimum wall thickness required and maximum allowable working pressures were determined using the UG-27 equations for longitudinal stress:

$$MAWPpipe = \frac{SEt}{R + (.6t)} \qquad t = \frac{PR}{SE - 0.6P}$$

and UG-34 equation for bending stress:

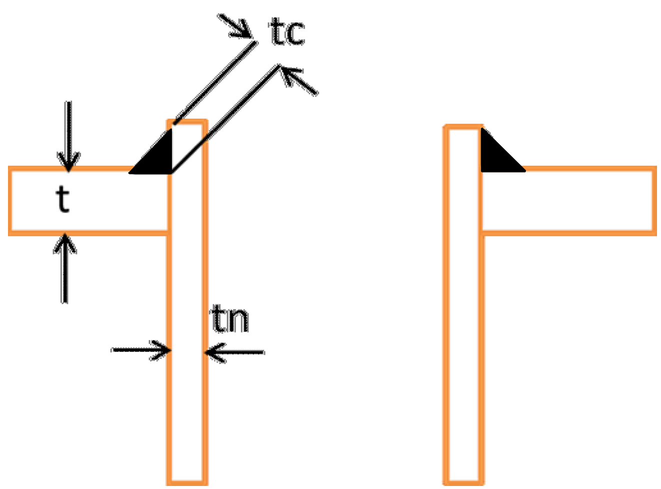
$$MAWP = \frac{(t/R)^2 * SE}{C} \qquad t = d\sqrt{CP / SE}$$

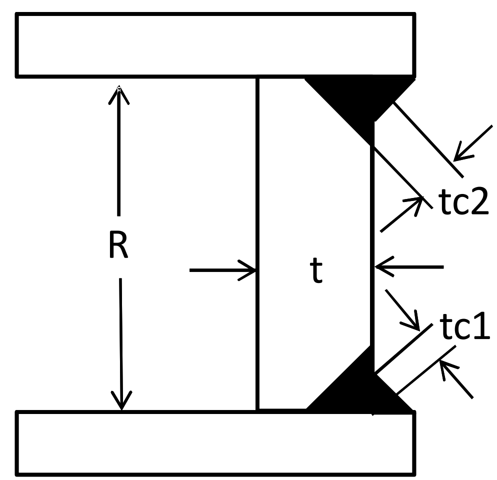
Component	Dimensions
Header Shell	3” sch. 80
Receiver Tubes	½” g.16
Inlet/Outlet Pipe	¾” sch. 40
Header Cap	¾” plate

Final dimensions of the components

Welds

- The header pipes were cut into two longitudinal halves to perform the tube welds internally
- The weld design requirements for the area of reinforcement can be found in UG-37 while the weld strength analysis is located in UG-41 of *Section VIII*
- The joint efficiency of a full-penetration weld is 85% (UW-12)





Manufacturing


Internal welds of tubes


Caps tacked in place before closing header


Full penetration seam weld


Header tacked in place

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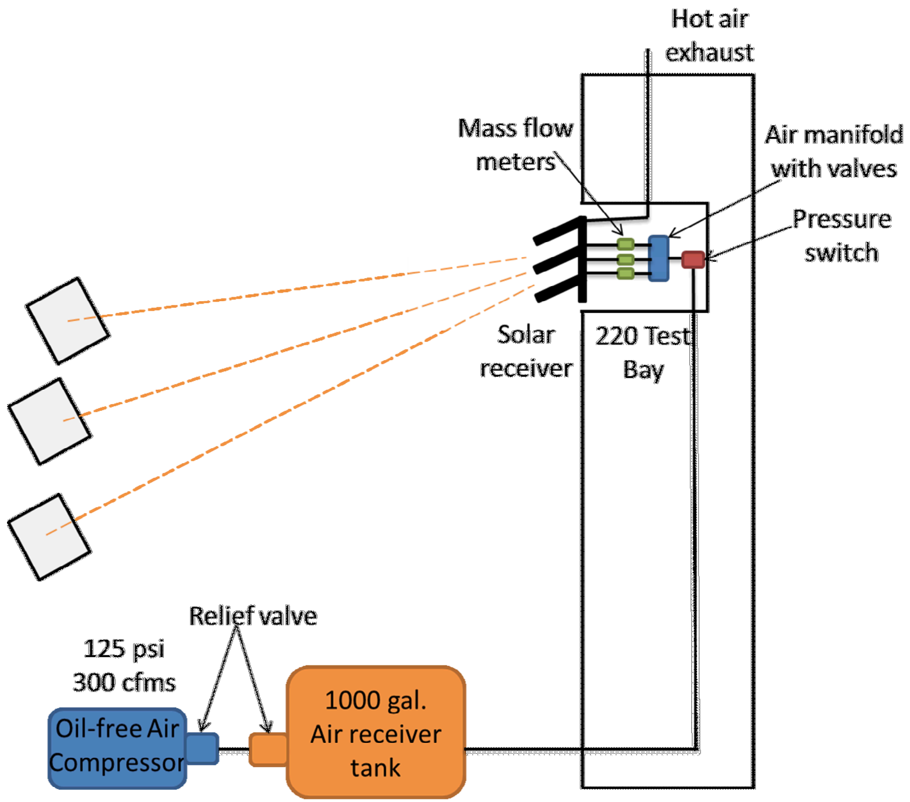
Receiver Test-loop

- The test loop designed provided air to the receivers at 800 kPa and ~0.11 kg/s with associated sensors to measure temperature, mass flow rate, and pressure.



Simple schematic of the test loop for the flat panel and bladed receiver tests

Receiver Test-loop

- The system used air as a heat transfer medium that was provided by an oil-free compressor at the ground level of the Solar Tower.
- The air flow is then separated in three sections each had a temperature, mass flow rate, and pressure at the inlet.

Air compressor and 1000 gallon air receiver tank

Alicat mass flow rate sensors attached to the three outlet manifold tank

Receiver Panel Oxidation

- Inconel 625 sample coupons were oxidized and their reflectivity was measured.
- The oxidation was done at 800 C for different times

Sample Oxidation			
Sample	Temperature (°C)	Time (hrs.)	Reflectivity
1	-	-	0.519 ± 0.007
2	800	1	0.208 ± 0.006
3	800	5	0.18 ± 0.001
4	800	24	0.151 ± 0.001
Panel	800	30	0.124 ± 0.004

Sample 1 and Sample 4 from table

Fin Panel Oxidation

- The leading edge/tube of the bladed receiver panels is subject to very high solar fluxes (up to 3.5 times higher) relative to the rest of the tubes due to higher view factors

Bladed receiver panels with front tube painted white with VHT Flame Proof Header Paint.

Bladed Receiver Support and Insulation

- The structure holds the weight of the panels, the spillage board required for on-sun testing, and thermal insulation The insulation covered the inlet and outlet headers as well as the back of the receiver tubes to reduce heat loss

Spillage board and insulation of the receiver mounted on the structure

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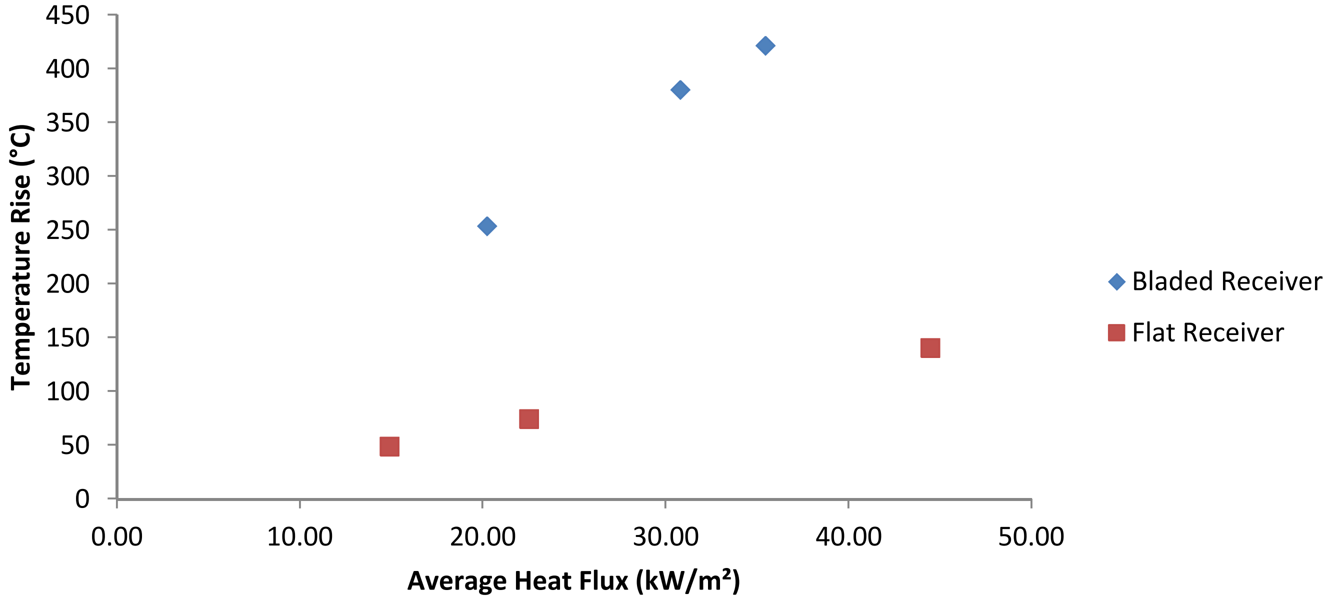
Results

- The temperature increase was recorded throughout all the tests and the average of the temperatures and standard deviations were used to estimate the overall error propagation
- The impact on the mass flow rate fluctuation and the heat flux positioning were also included in the error propagation analysis

Results: Temperature Rise

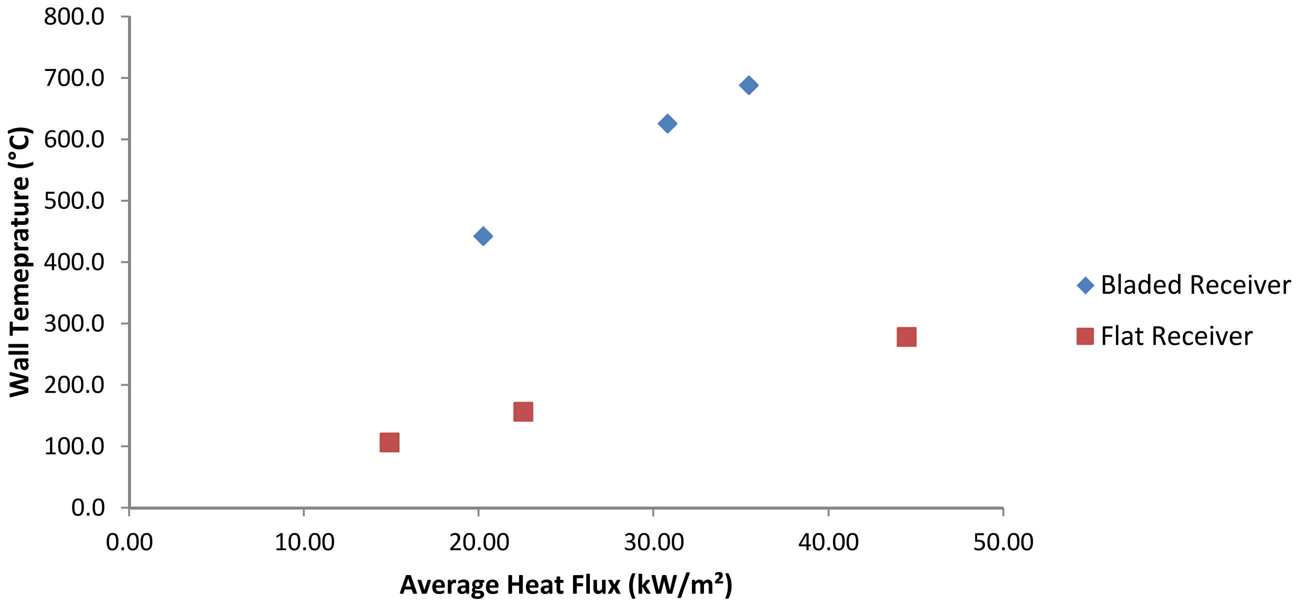
- Inlet, outlet, and back wall temperatures were recorded during the tests
- Comparison of the temperature rise in the air flowing through the receivers as function of average irradiance



Temperature rise of pressurized air through receivers as a function of the incident average irradiance

Results: Wall Temperature

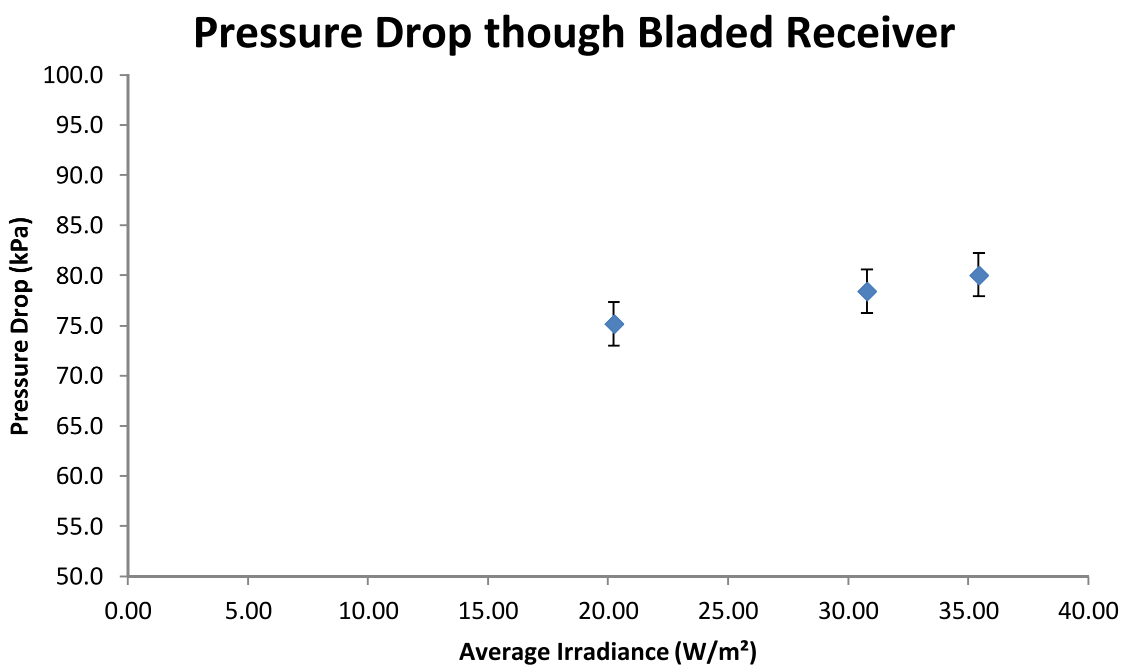
- The thermocouple in the back of the receiver is 20 cm from the top from the exposed tube length
  - This was used to track the peak temperatures



Surface temperature of pressurized air through receivers as a function of the incident average irradiance

Results: Pressure Drop

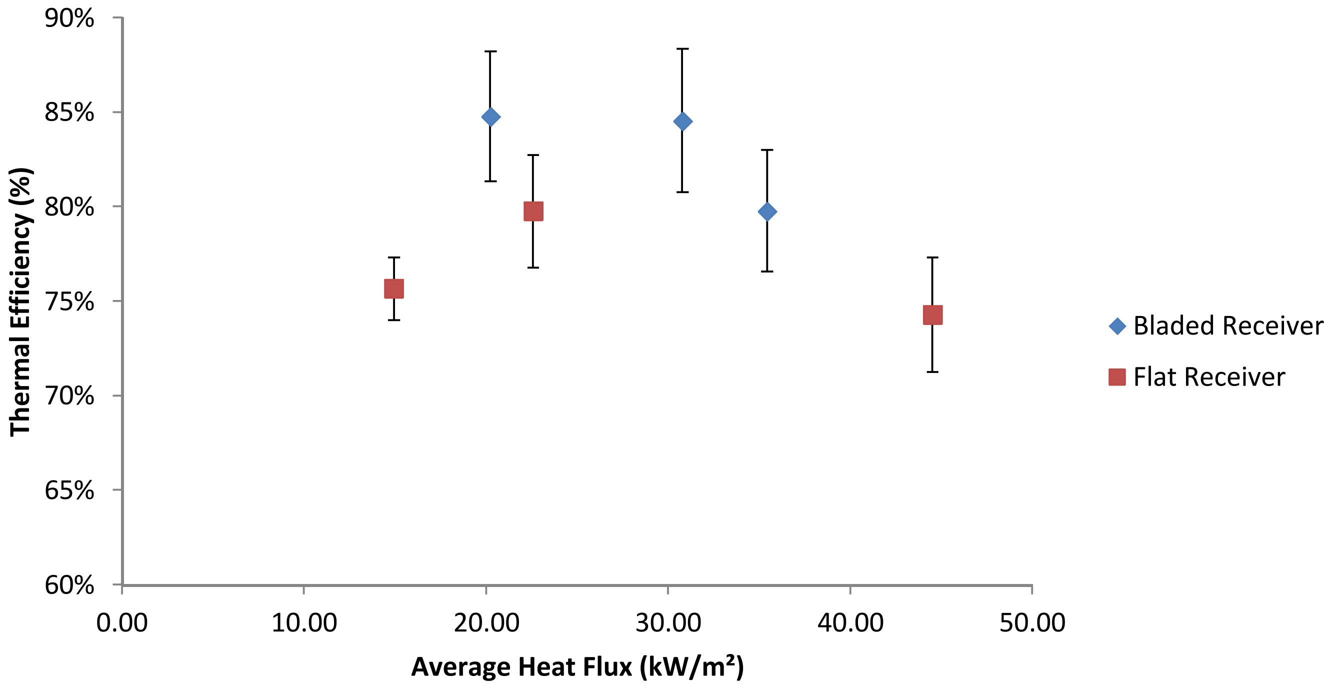
- Pressure drops across the receiver is below 10% of the inlet
- As it is expected, the pressure drop increases as the viscosity increases due to the temperature rise



Pressure drop of pressurized air through Bladed receiver as a function of the incident average irradiance

Results: Thermal Efficiency

- The data collected in the steady-state region was used to compute the thermal efficiencies as a function of the power incident on each receiver



Thermal efficiency of pressurized air through Bladed receiver as a function of the incident average irradiance

Outline

- Background
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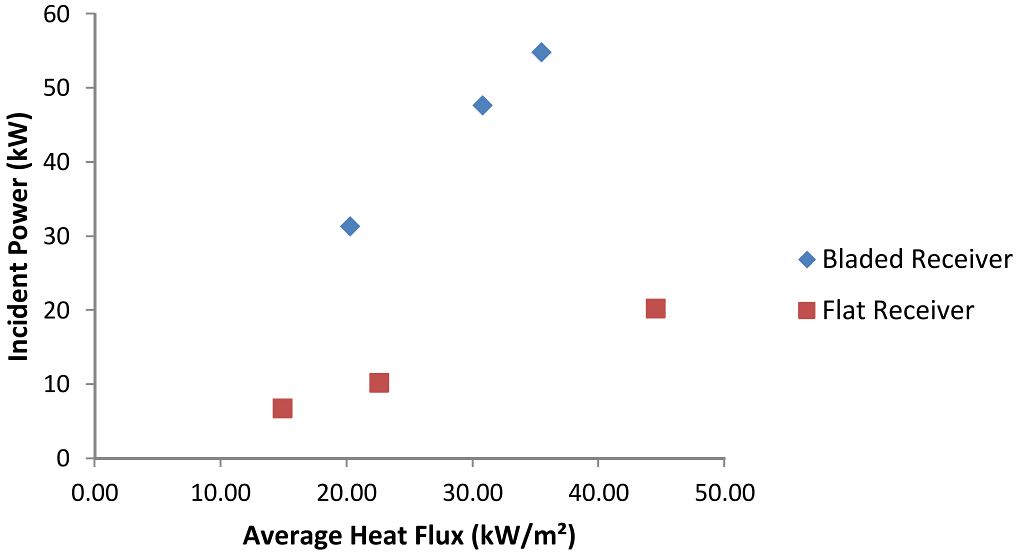
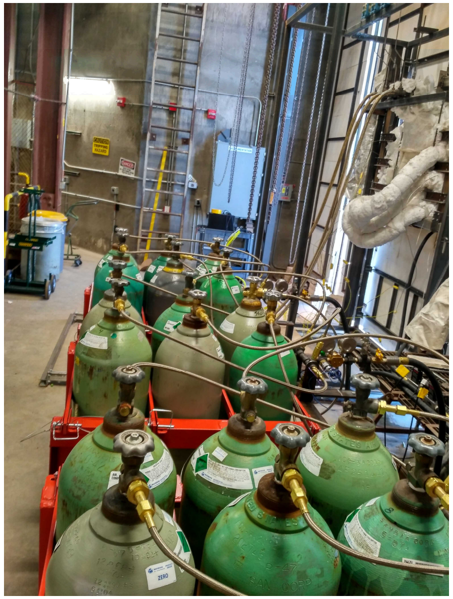
Conclusions

- Fractal-like receiver designs with novel light-trapping geometries and features have been developed and tested
- The peak flux on the aperture of the bladed receiver panel was over 200 kW/m^2
- Fractal-like designs, the ability to accommodate higher concentration ratios with on similar optical apertures



Future Work

- Currently, the plan for the near future is to develop a test-loop using pressurized gas bottles to test the receiver performance at high pressure and temperature while investigating the effectiveness of different gases and mixtures as heat transfer media



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- Ortega, J., Khivsara, S., Christian, J., Ho, C., Yellowhair, J., Dutta, P., “Coupled Modeling of a Directly Heated Tubular Solar Receiver for Supercritical Carbon Dioxide Brayton Cycle: Optical and Thermal-Fluid Evaluation”, Applied Thermal Engineering, Volume 109, Part B, 25 October 2016, Pages 970–978
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- ASME Boiler and Pressure Vessel Code. New York, NY: American Society of Mechanical Engineers, 2013
- Ho, C., Ortega, J., Christian, J., Yellowhair, J., 2016, "Fractal-Like Materials Design with Optimized Radiative Properties for High-Efficiency Solar Energy Conversion," SAND2016-9526, Sandia National Laboratories.

Acknowledgments

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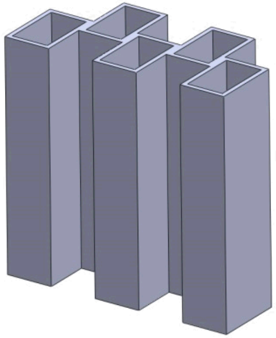
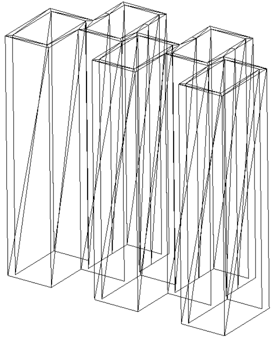
Jesus Ortega
jdorte@sandia.gov

Questions?

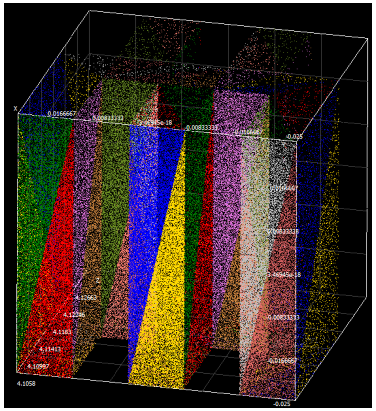
Back-up slides



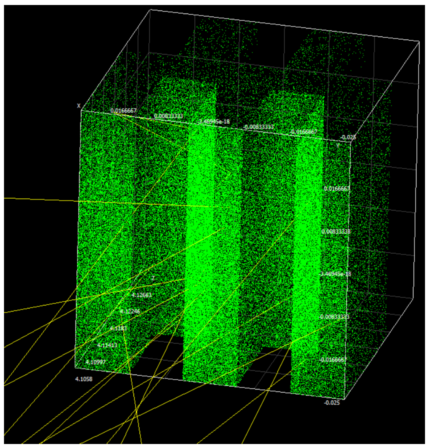


Save CAD geometry as an STL file.

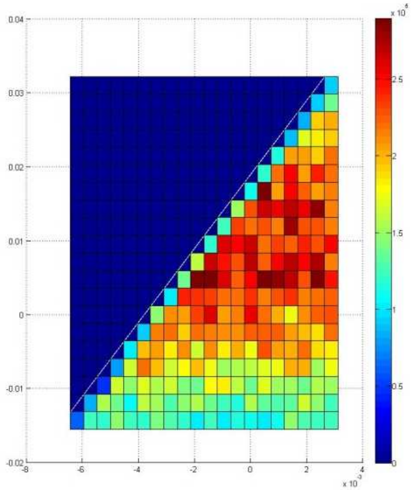
MATLAB: Pre-process STL file into a Stage file for SolTrace.



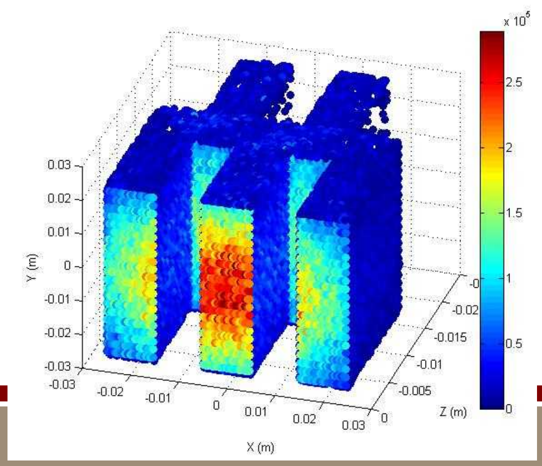
SolTrace: Perform ray tracing using the heliostat field or solar furnace ideal models from NSTTF.



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



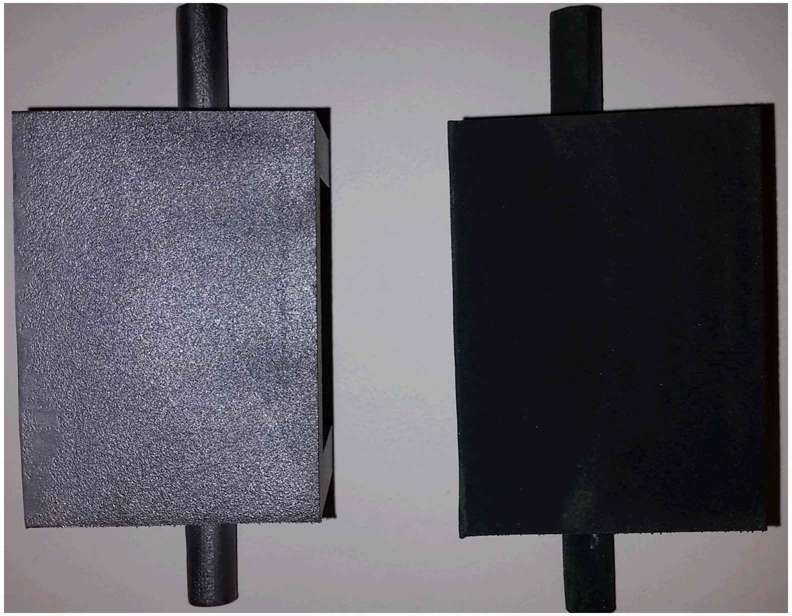
FLUENT: Heat flux profiles can be imported to be used as boundary conditions.



Reflectance Measurements

The samples were oxidized for 20 hours at 800°C in order to achieve the solar absorptivity

Surface Optics
410-Solar Reflectometer



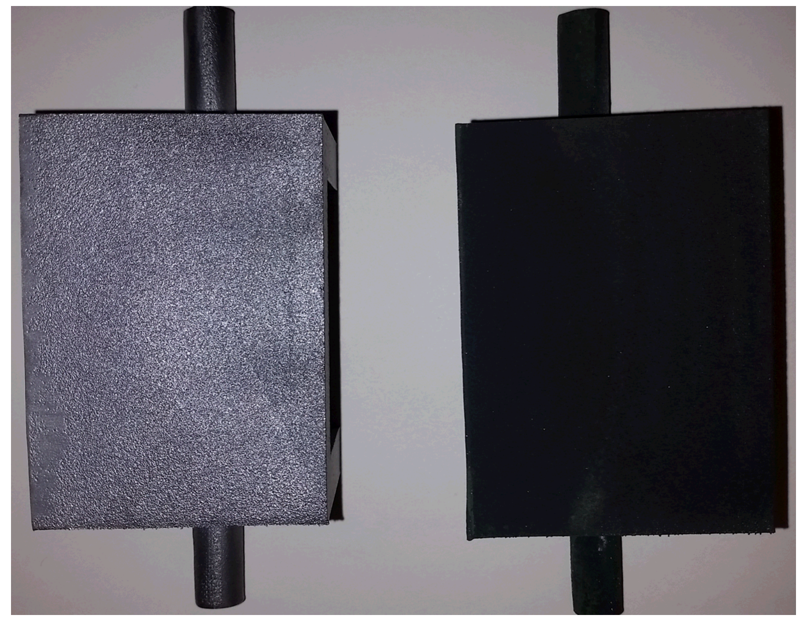
Reflectance change

- $\rho = 0.403 \pm 0.001$
- $\rho = 0.096 \pm 0.003$

Emittance Measurements

The samples were oxidized for 20 hours at 800° C in order to achieve the solar absorptivity

Surface Optics
ET100-Thermal Emissometer

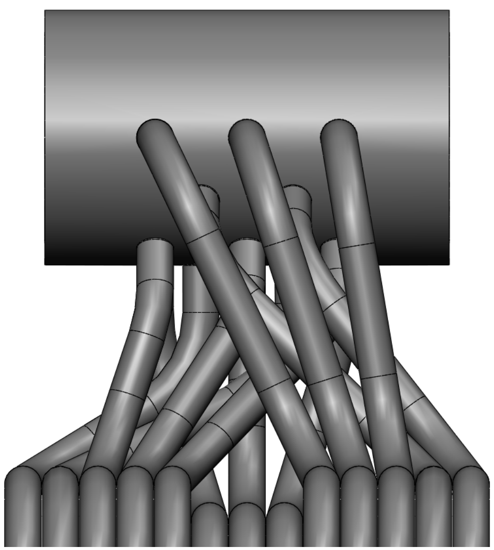


Emittance change

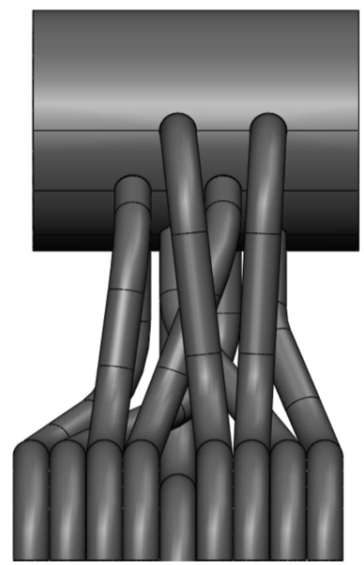
- e = 0.426±0.001
- e = 0.804±0.008

Header Design

- The headers were selected to be made out of 3” Inconel 625 pipe (3.5” or 88.9 mm O.D.) to have enough space for the tubes and be able to select the smallest thickness possible
- Nonetheless, suppliers’ stock is typically limited to schedule 40 and 80 in these alloys



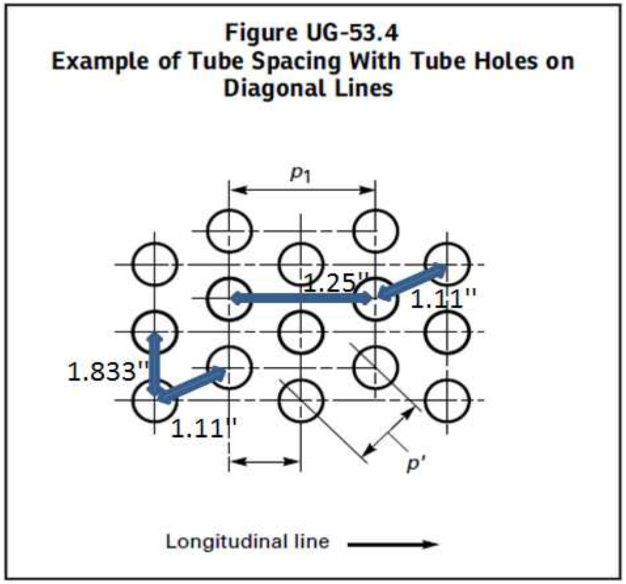
Back Panels (13 tubes)



Fin Panels (9 tubes)

Header Design

- The joint or ligament efficiency can be estimated from UG-53 by selecting the lowest of the efficiencies calculated based on the location of the holes



Longitudinal efficiency, % = $E_{long} = [(p_1 - d)/p_1]\,100$

Diagonal efficiency, % $= \dfrac{J + 0.25 - (1 - 0.01E_{long})\sqrt{0.75 + J}}{0.00375 + 0.005J}$ $\quad J = (p'/p_1)^2$

Header Design

3" sch40 pipe		
PIPE OD (D)	88.9	mm
PIPE WALL (t)	5.4864	mm
DESIGN PRESSURE (P)	20	MPa
DICTICATING EFFICIENCY (E)	0.6	
MANUFACTURING TOLERANCE	0.5	%
DESIGN TEMPERATURE	700	°C
ALLOWABLE STRESS (S)	84.3	MPa
MINIMUM THICKNESS (tmin)	20.3	mm

3" sch80 pipe		
PIPE OD (D)	88.9	mm
PIPE WALL (t)	7.62	mm
DESIGN PRESSURE (P)	20	MPa
DICTICATING EFFICIENCY (E)	0.6	
MANUFACTURING TOLERANCE	0.5	%
DESIGN TEMPERATURE	700	°C
ALLOWABLE STRESS (S)	84.3	MPa
MINIMUM THICKNESS (tmin)	19.2	mm

Header Design

- The calculations are based on the UG-27 and UG-53 equations for the tubes and pipe connecting to the header

3" sch80 pipe		
PIPE OD (D)	88.9	mm
PIPE WALL (t)	7.62	mm
DESIGN PRESSURE (P)	15	MPa
DICTICATING EFFICIENCY (E)	0.6	
MANUFACTURING TOLERANCE	0.5	%
DESIGN TEMPERATURE	650	°C
ALLOWABLE STRESS (S)	137.9	MPa
MINIMUM THICKNESS (tmin)	7.62	mm
MAXIMUM ALLOWABLE WORKING PRESSURE	15.2	MPa
MEMBRANE STRESS	135.8	MPa

$$MAWPpipe = \frac{SEt}{R + (.6t)} \qquad t = \frac{PR}{SE - 0.6P} \qquad MEM\ STRESS = \frac{P(R + .6t)}{Et}$$

Tube/Pipe Design

1/2" Tube		
PIPE OD (D)	12.7	mm
PIPE WALL (t)	1.651	mm
DESIGN PRESSURE (P)	15	MPa
DICTICATING EFFICIENCY (E)	0.6	
MANUFACTURING TOLERANCE	0.5	%
DESIGN TEMPERATURE	650	°C
ALLOWABLE STRESS (S)	137.9	MPa
MINIMUM THICKNESS (tmin)	0.67	mm
MAXIMUM ALLOWABLE WORKING PRESSURE	40	MPa
3/4" sch40 pipe		
PIPE OD (D)	26.67	mm
PIPE WALL (t)	2.8702	mm
DESIGN PRESSURE (P)	15	MPa
DICTICATING EFFICIENCY (E)	0.6	
MANUFACTURING TOLERANCE	0.5	%
DESIGN TEMPERATURE	650	°C
ALLOWABLE STRESS (S)	137.9	MPa
MINIMUM THICKNESS (tmin)	1.34	mm
MAXIMUM ALLOWABLE WORKING PRESSURE	32.5	MPa

End Cap Design

- A similar procedure to estimate the thickness of a flat caps using the same design conditions is depicted in UG-34
- These caps are flat instead of ellipsoidal to reduce the costs and lead time of manufacturing Inconel 625

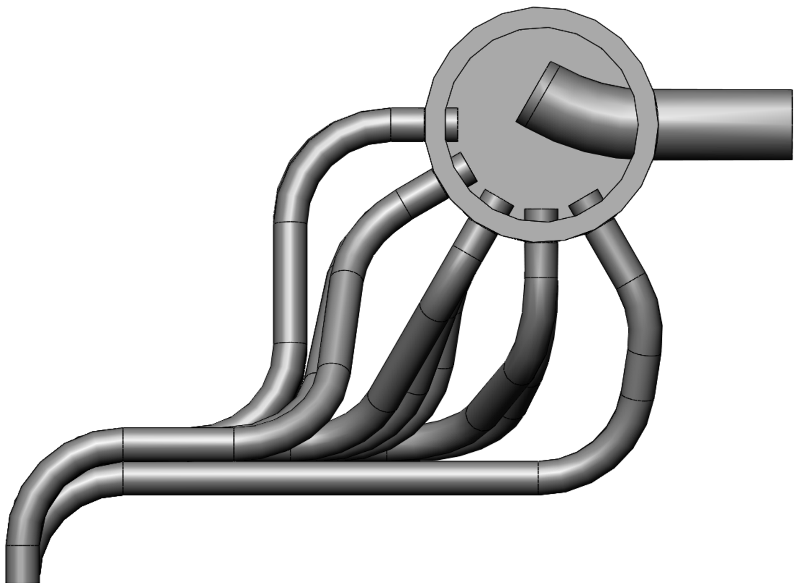
$$t = d\sqrt{CP / SE}$$

$$MAWP = \frac{(t/R)^2 * SE}{C}$$

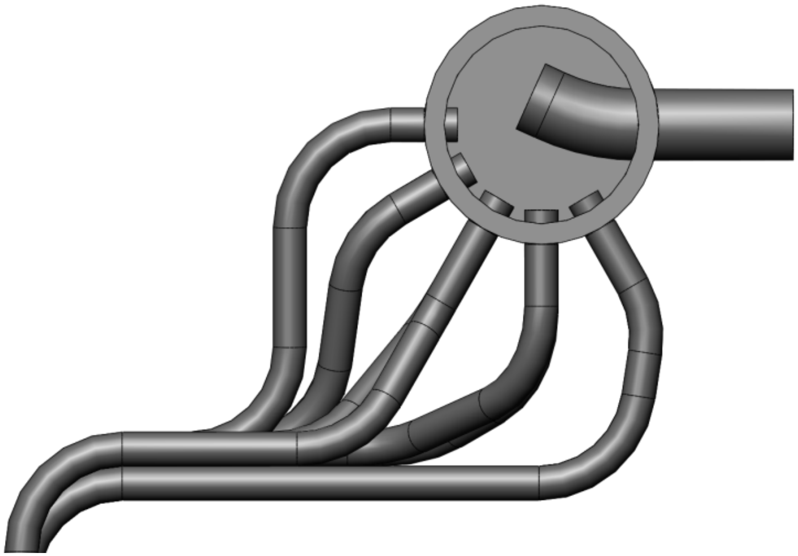
3/4" plate		
PIPE OD (D)	88.9	mm
PIPE WALL	7.62	mm
DESIGN PRESSURE (P)	15	MPa
DICTICATING EFFICIENCY (E)	0.85	
MANUFACTURING TOLERANCE	0.5	%
DESIGN TEMPERATURE	650	°C
ATTACHMENT COEFFICIENT (C)	0.3	
ALLOWABLE STRESS (S)	137.9	MPa
PLATE THICKNESS (t)	19.05	mm
MINIMUM THICKNESS (tmin)	14.56	mm
MAXIMUM ALLOWABLE WORKING PRESSURE	32.5	MPa

Tube/Pipe Design

- The tubes and inlet/outlet pipes were selected to be made out of ½" (12.7 mm O.D.) Inconel 625 tube and ¾" (1.05" or 26.67 mm O.D.) Inconel 625 pipe
- The same design conditions are used in the tube and pipe



Back Panels (13 tubes)

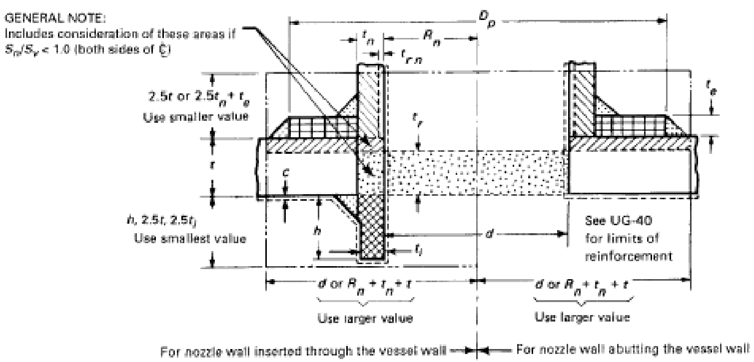


Fin Panels (9 tubes)

Welds

- The weld design requirements for the area of reinforcement can be found in UG-37 while the weld strength analysis is located in UG-41 of *Section VIII*

Figure UG-37.1
Nomenclature and Formulas for Reinforced Openings



Without Reinforcing Element

$= A \quad = d\,t_r\,F + 2t_n\,t_r\,F(1 - f_{r1})$	Area required
$= A_1 \begin{cases} = d(E_1 t - F t_r) - 2t_n(E_1 t - F t_r)(1 - f_{r1}) \\ = 2(t + t_n)(E_1 t - F t_r) - 2t_n(E_1 t - F t_r)(1 - f_{r1}) \end{cases}$	Area available in shell; use larger value
$= A_2 \begin{cases} = 5(t_n - t_{rn})\,f_{r2}\,t \\ = 5(t_n - t_{rn})\,f_{r2}\,t_n \end{cases}$	Area available in nozzle projecting outward; use smaller value
$= A_3 \quad = 5\,t\,t_i\,f_{r2};\ = 5\,t_i\,t_i\,f_{r2};\ = 2\,h\,t_i\,f_{r2}$	Area available in inward nozzle; use smallest value
$= A_{41}$ = outward nozzle weld = $(\text{leg})^2 f_{r2}$	Area available in outward weld
$= A_{43}$ = inward nozzle weld = $(\text{leg})^2 f_{r2}$	Area available in inward weld
If $A_1 + A_2 + A_3 + A_{41} + A_{43} \geq A$	Opening is adequately reinforced
If $A_1 + A_2 + A_3 + A_{41} + A_{43} < A$	Opening is not adequately reinforced so reinforcing elements must be added and/or thicknesses must be increased

With Reinforcing Element Added

A = same as A, above	Area required
A_1 = same as A_1, above	Area available
$A_2 \begin{cases} = 5(t_n - t_{rn})f_{r2}t \\ = 2(t_n - t_{rn})(2.5t_n + t_e)f_{r2} \end{cases}$	Area available in nozzle projecting outward; use smaller area
A_3 = same as A_3, above	Area available in inward nozzle
$= A_{41}$ = outward nozzle weld = $(\text{leg})^2 f_{r3}$	Area available in outward weld
$= A_{42}$ = outer element weld = $(\text{leg})^2 f_{r4}$	Area available in outer weld
$= A_{43}$ = inward nozzle weld = $(\text{leg})^2 f_{r2}$	Area available in inward weld
$= A_5 = (D_p - d - 2t_n)\,t_e\,f_{r4}$ [Note (1)]	Area available in element
If $A_1 + A_2 + A_3 + A_{41} + A_{42} + A_{43} + A_5 \geq A$	Opening is adequately reinforced

GENERAL NOTE: This figure illustrates a common nozzle configuration and is not intended to prohibit other configurations permitted by the Code.

NOTE:
(1) This formula is applicable for a rectangular cross-sectional element that falls within the limits of reinforcement.

Results: Thermal Efficiciency

- The data collected in the steady-state region was used to compute the thermal efficiencies as a function of the power incident on each receiver

$$Thermal\ Efficiecncy = \frac{\sum \dot{m} \int_{Tin}^{Tout} C_p(T)\,dT}{\dot{Q}_{incident}}$$

- where is the total mass flow rate of air per section, and are the Inlet and outlet air temperatures, is the heat capacity of air and is the total power incident on the receiver

Thermal efficiency of pressurized air through Bladed receiver as a function of the incident average irradiance