HIGH FLUX MICROCHANNEL SOLAR RECEIVER DEVELOPMENT WITH ADAPTIVE FLOW CONTROL

Kevin Drost (Principal Investigator)

Oregon State University (Prime Contractor)

Bob Wegeng

Pacific Northwest National Laboratory (Subcontractor)

Start Date – 10/1/2012

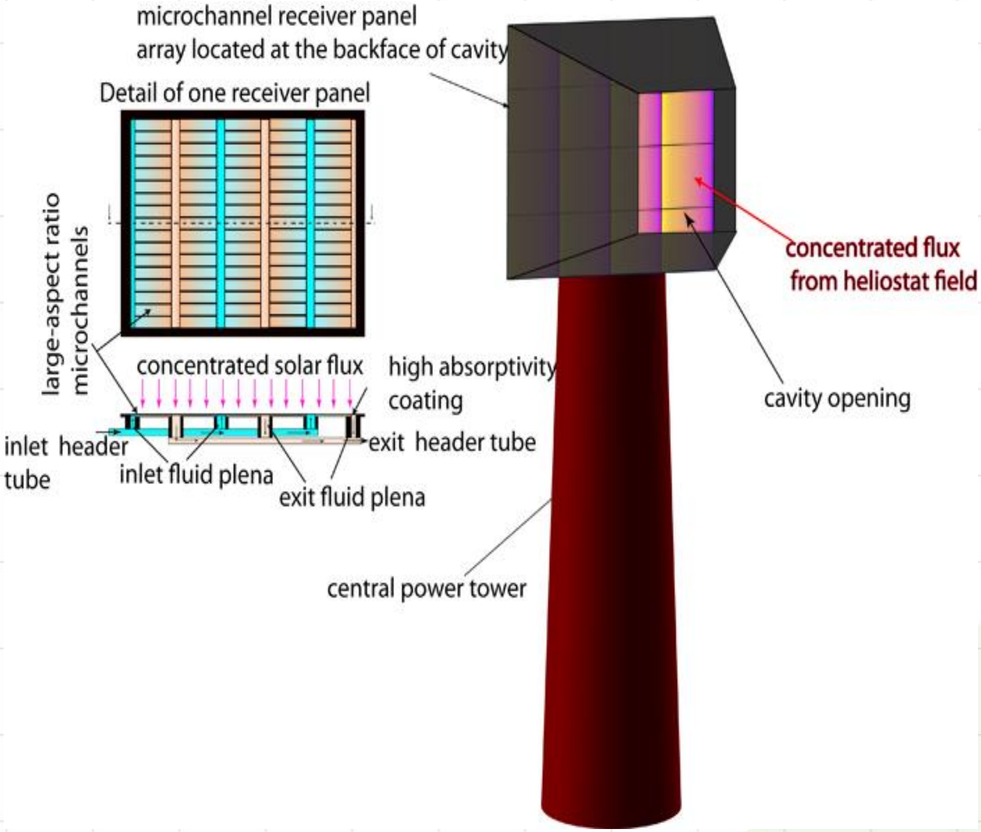
This presentation does not contain any proprietary, confidential, or otherwise restricted information

Presentation Outline

- Project Description
- Objectives and Goals
- Introduction to Microtechnology and Microfabrication
- Innovations
- Key Technical Results
- Challenges and Barriers
- Future Work

Project Description – Arrayed Microchannel Receiver Concept

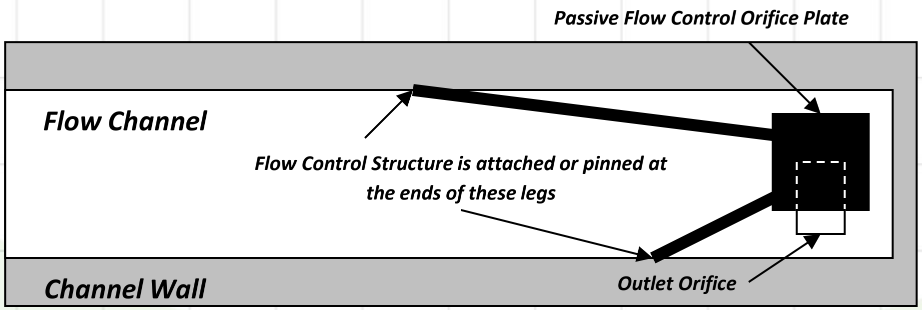
- By reducing the diffusion length in the heat transfer fluid, arrayed microchannels have the potential to significantly increase the allowable flux in solar thermal receivers.
- The concept (shown for a cavity type solar central receiver) involves using a large number of short parallel microchannels to transfer thermal energy in the incident solar radiation to the heat transfer fluid
- Headers on a substrate behind the heat transfer channels distribute the heat transfer fluid
- Arrays of microchannels and headers are fabricated in 1.0 sq meter modules which are then used to assemble a complete receiver.
- This is a seedling project focused completing a proof-of-principle demonstration of the concept



Microchannel Receiver Concept
For a Solar Central Receiver

Project Description

- Adaptive flow control
  - Objective: Deliver proportional flow to regions that have higher or lower solar flux
  - Approach: Exploit differences in thermal expansion in different metals/materials, to throttle flow as needed to various solar receiver regions
  - General Concept:



Objectives and Goals

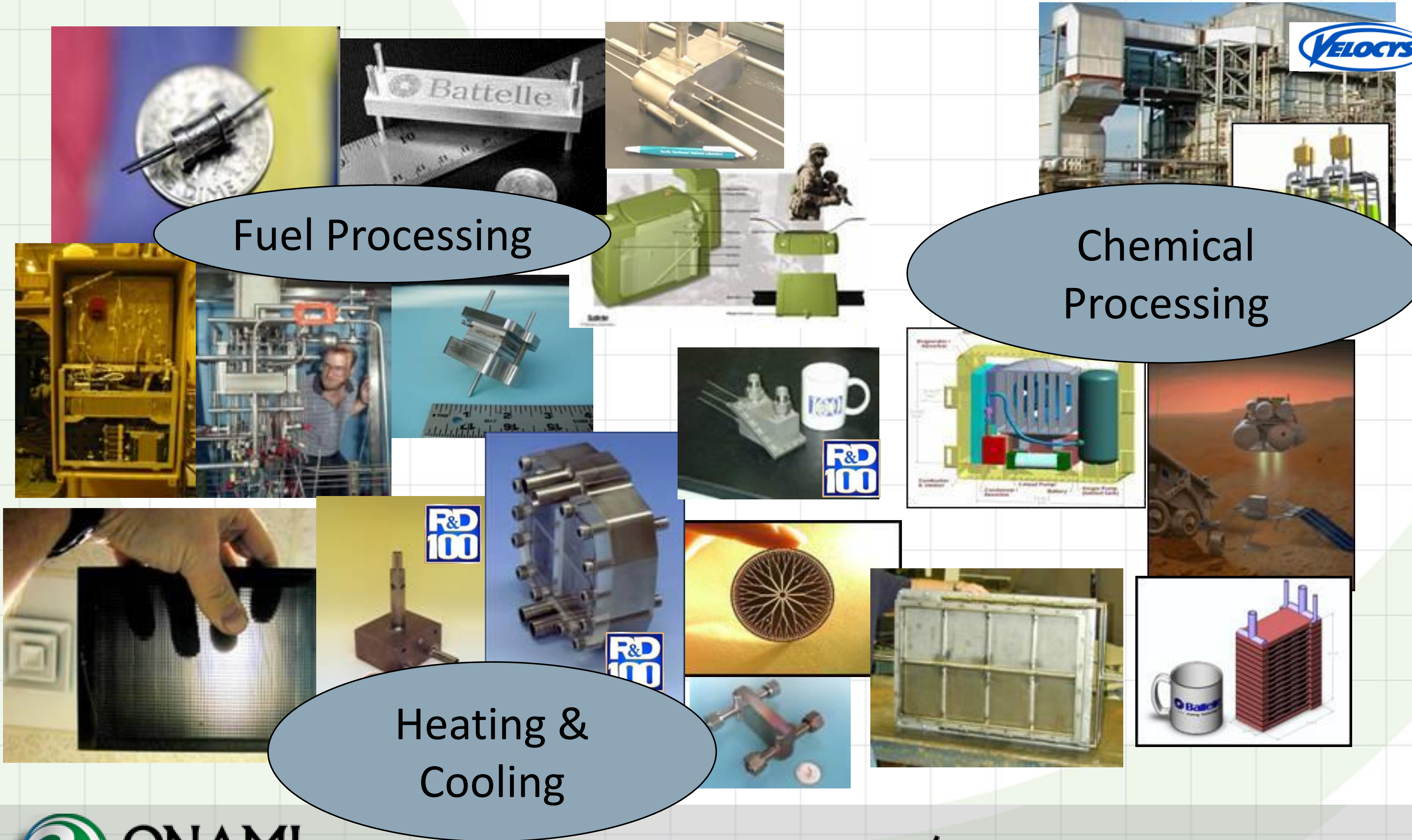
Objective: We are developing two microchannel solar receiver design proof of concept test articles, one for a liquid cooled microchannel receivers and one for gas cooling. Metrics for the supercritical CO_2 receiver will be based on "on sun" experimental results. Metrics for the other design will be based on laboratory test results and modeling and simulation.

- **Liquid Heat Transfer Fluid Microchannel Receiver Metrics** - Our performance metrics are to: 1) Use simulation to demonstrate our ability to design a molten salt cooled microchannel receiver operating at a fluid exit temperature of 600 ºC capable absorbing an average flux of 400 W/cm^2; with a receiver thermal efficiency of >90% and 2) In laboratory testing, this receiver will be experimentally demonstrated for a heat flux of 400 W/cm^2 but the exit temperature of the solar salt will be limited to 550 º C due to the temperature limits of existing salts.
- **Gas Heat Transfer Fluid Microchannel Receiver Metrics** - Our metric for gaseous coolants is to use simulation and analysis to demonstrate our ability to design a supercritical CO_2 receiver operating with a receiver exit temperature of ≥650 ºC and capable of absorbing an average flux of 100 W/cm^2. We will keep pressure drop below 0.35bar. The surface temperature of the receiver will be consistent with a receiver thermal efficiency of 90%. Using supercritical CO_2 as the working fluid, this receiver design will be experimentally demonstrated in laboratory testing and also demonstrated on the PNNL solar dish.

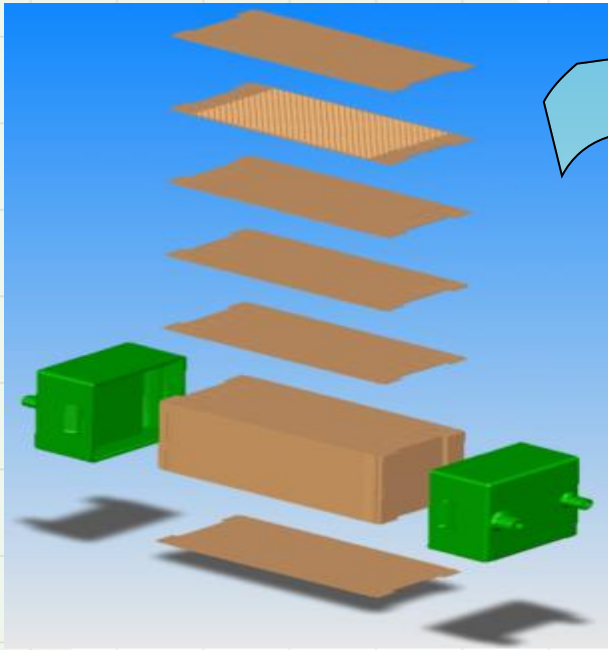
Why Microtechnology?

- We are exploiting one fundamental phenomena - **The time it takes a fluid to come into thermal equilibrium with the walls of a channel, and consequently the size of the device deceases as the square of the diffusion length**
- By using arrays of a large number of parallel microchannels we can, in theory, attain extremely high heat fluxes. This phenomena has been exploits in a large number of applications.
- We optimize a unit cell and then using microlamination to **“Number Up” rather then “Scale Up”** by fabricating large numbers of unit cells operating in a parallel arrangement
- Microlamination is a commercialized production technique with an existing supply chain and commercial products with sizes up to one sq meter.

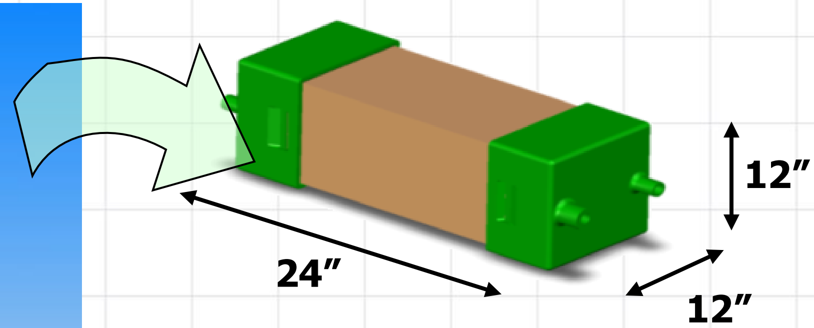
What is Microchannel Technology - Applications



Microlamination



Microlamination of Reactor



Microchannel Reactor

Patterning Options

- *-Chemical Etching*
- *-EDM*
- *-Electro-chemical Etching*
- *-Stamping*

Bonding Options

- *-Diffusion Bonding*
- *-Laser Welding*

Status

-Widely applied to fabrication of microchannel heat exchangers and reactors

-Existing Supplier base

-Applied by commercial organizations to substrates up to 1 square meter

*W. Ehrfeld, V. Hessel, H. Löwe, Microreactors: New Technology for Modern Chemistry, Wiley-VCH, 2000.

Innovations

Innovation: This use of microchannel geometries for heat transfer can attain allowable receiver fluxes of 100 W/cm^2 for supercritical CO_2 receivers and 400 W/cm^2 for molten salt receivers while operating with heat transfer fluids at temperatures up to 600 C. This should be compared to a maximum allowable flux of 30 to 100 [1]W/cm^2 for current receiver technology.

Impact: If successful this will result in …

-A factor of three to four reduction in receiver size

-A receiver operating with heat transfer fluid exit temperatures of 600 C-650 C

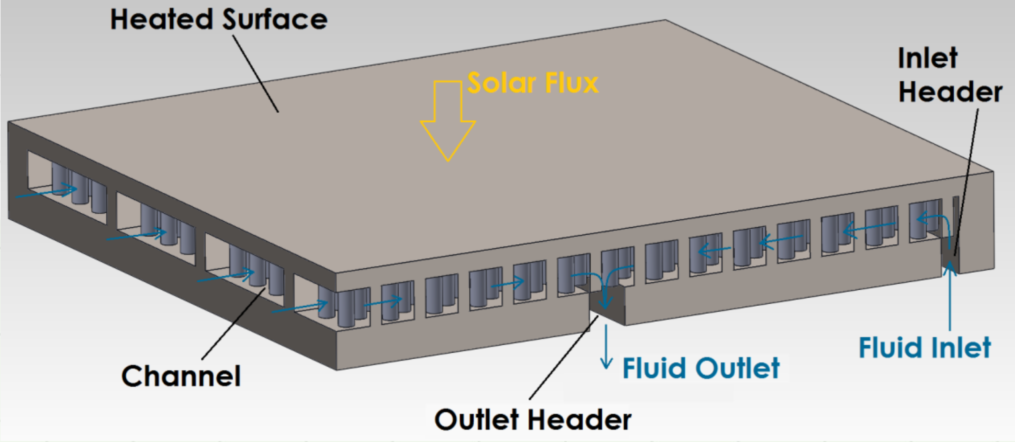
-With receiver thermal efficiencies for an open receiver of between 92% and 95%

Key Technical Results

- Task 1 Modeling
  - Subtask 1.1: Identify the optimal pin-fin characteristics (diameter, pitch, height) that satisfy the flow and heat transfer constraints as well as manufacturability constraints
  - Subtask 1.2: Identify the thickness of the top plate that meets the structural strength and surface efficiency requirements
  - Subtask 1.3: Design the inlet and outlet headers that reduce flow maldistribution, maintain structural integrity and satisfy the flow and heat transfer constraints
- Task 2 Test Article Fabrication
- Task 3 Experimental Investigations
  - Subtask 3.1: Flux Concentrator Development
  - Subtask 3.2: Molten Salt Test Loop
  - Subtask 3.3: Supercritical CO2 Test Loop
- Task 4 Adaptive Control

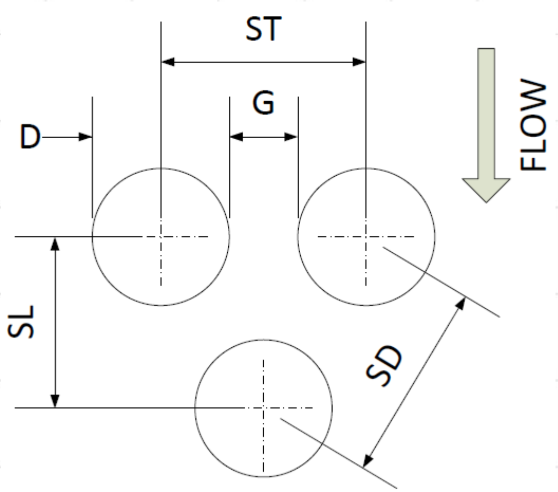
Task 1 Numerical Modeling

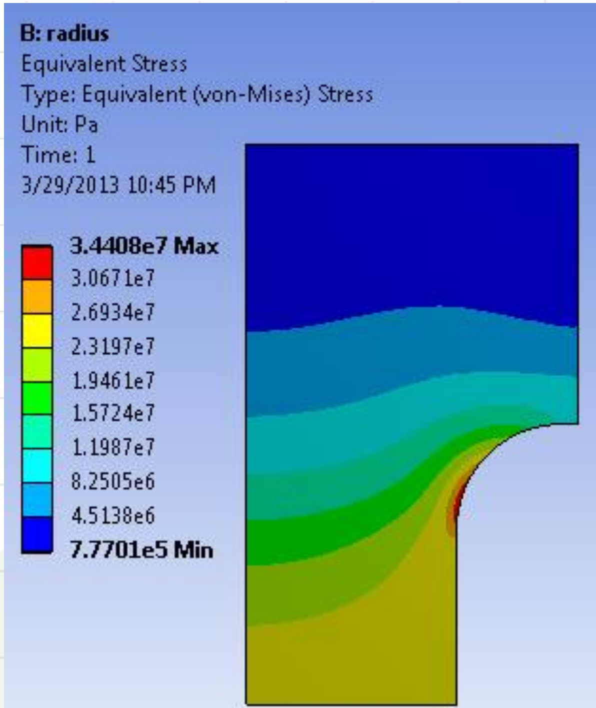
- Summary of initial scoping studies
  - Three different designs varying the length-to-width ratios of microchannels considered
  - A staggered, hexagonal packed circular pin array was found to satisfy the design constraints with best performance
  - Haynes 214 was chosen based on its high-temperature strength, etching and bonding ability



Task 1 Numerical Modeling

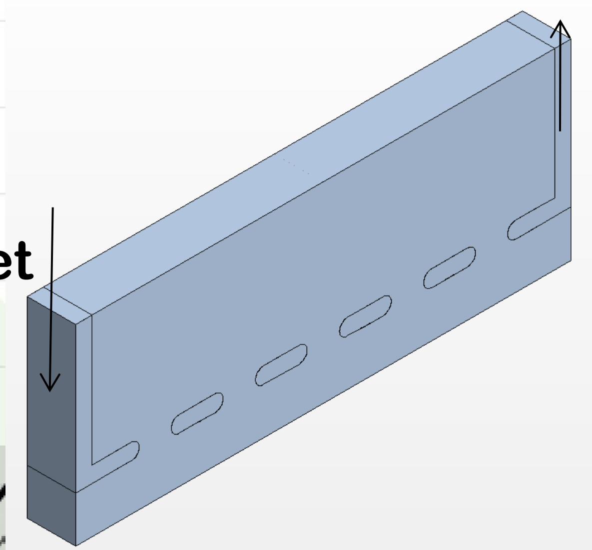
- Subtask 1.1: Pin design
  - Test apparatus and concentrator design constrains the channel length to 1cm
  - Manufacturing Constraint
    - For isentropic etching, the height of the channels is limited to the minimum distance between etching (H/G = 1)
    - Uniform transverse and diagonal pins (ST=SL)
  - Structural constraint
    - From ANSYS structural analysis of the pin-fins, a pitch (ST/D or SL/D) of 1.5 gives a factor of safety of 2 at 1200K (based on maximum top plate temperature) and 10-hour rupture strength of 76MPa

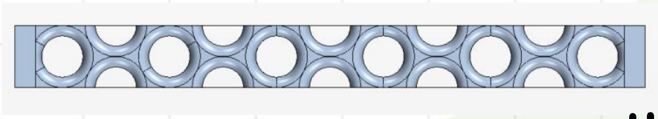




Task 1 Numerical Modeling

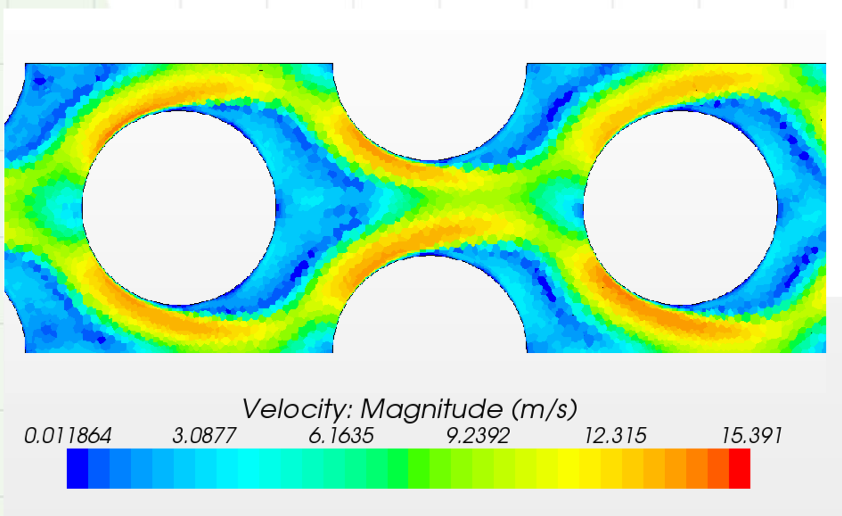
- Subtask 1.1: Pin diameter
  - For H/G=1 and Pitch=1.5, obtain pin diameter that satisfies flow and heat transfer constraints
    - Heat and flow conjugate problem
    - Top plate thickness assumed at 1mm
    - Simple inlet/outlet headers with cross-sectional dimensions equal to that of channels minus the pins

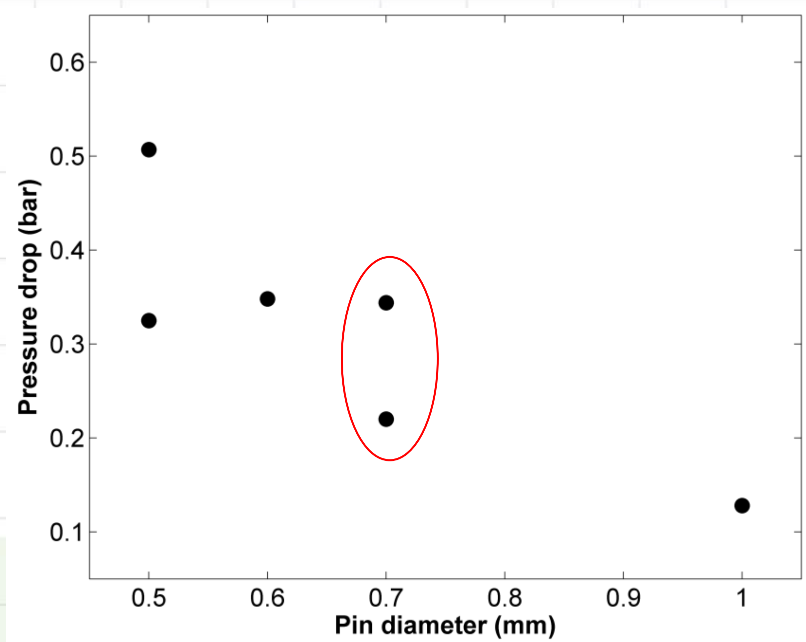




Task 1 Numerical Modeling

- Subtask 1.1: Pin diameter (Pressure Constraint)
  - Pressure constraint (< 0.35 bar pressure drop inside the channel) met by pin diameter 500 micron and higher
  - Scatter is due to different lengths of the channel to account for whole number of pins
  - Pressure in headers included



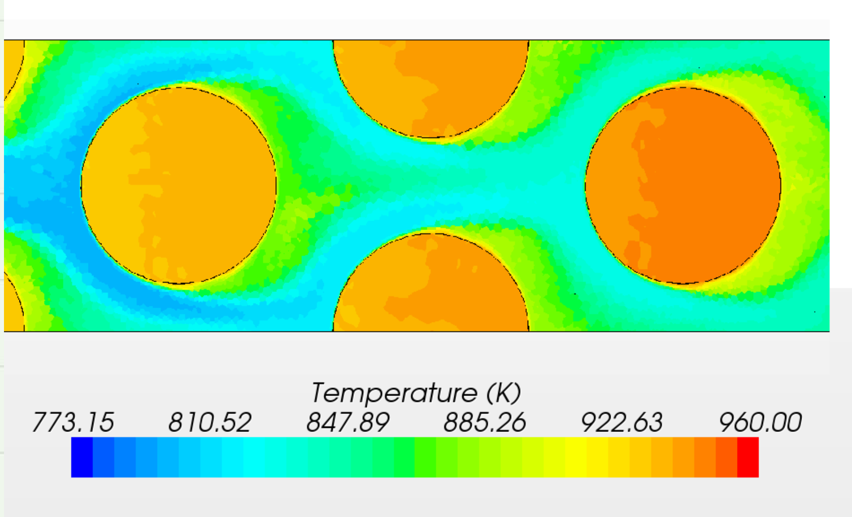


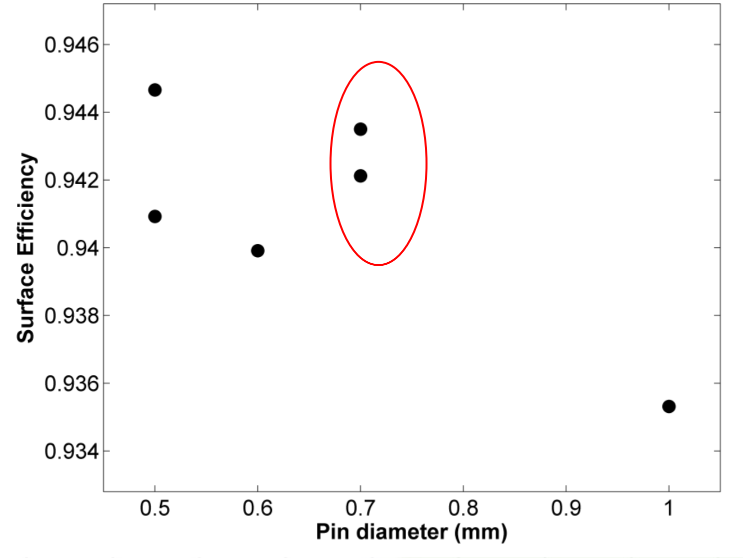
Task 1 Numerical Modeling

- Subtask 1.1: Pin diameter (Surface Efficiency)

$$\eta = \frac{q}{q + q_{loss,conv} + q_{loss,rad}}$$

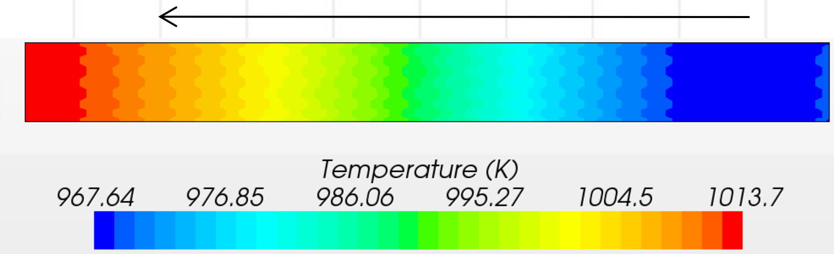
  - Efficiency constraint (> 0.9) met by most sizes considered; differences in efficiency small
  - Scatter due to slight variations in lengths for different pin sizes keeping whole number of pins



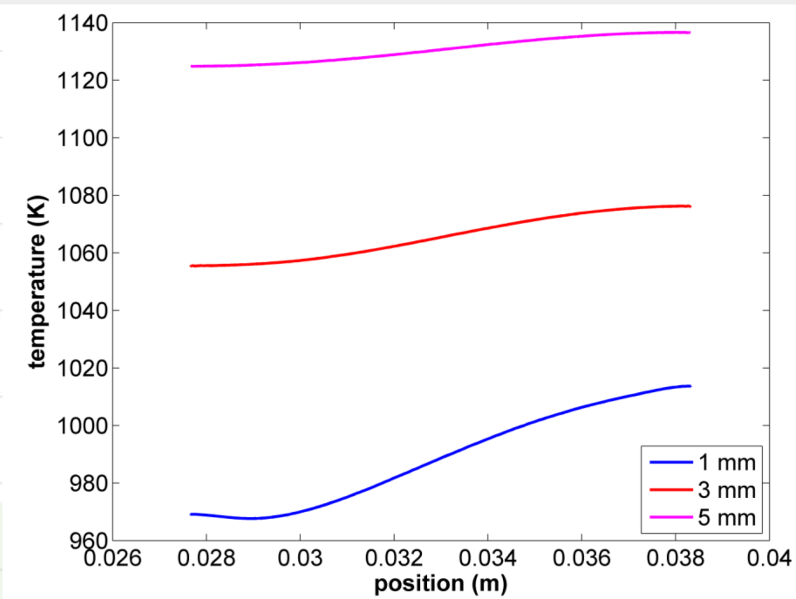


Task 1 Numerical Modeling

- Subtask 1.2: Top plate thickness
  - Top surface temperature distribution should avoid hot spots and have small gradients for better structural stability at high temperatures

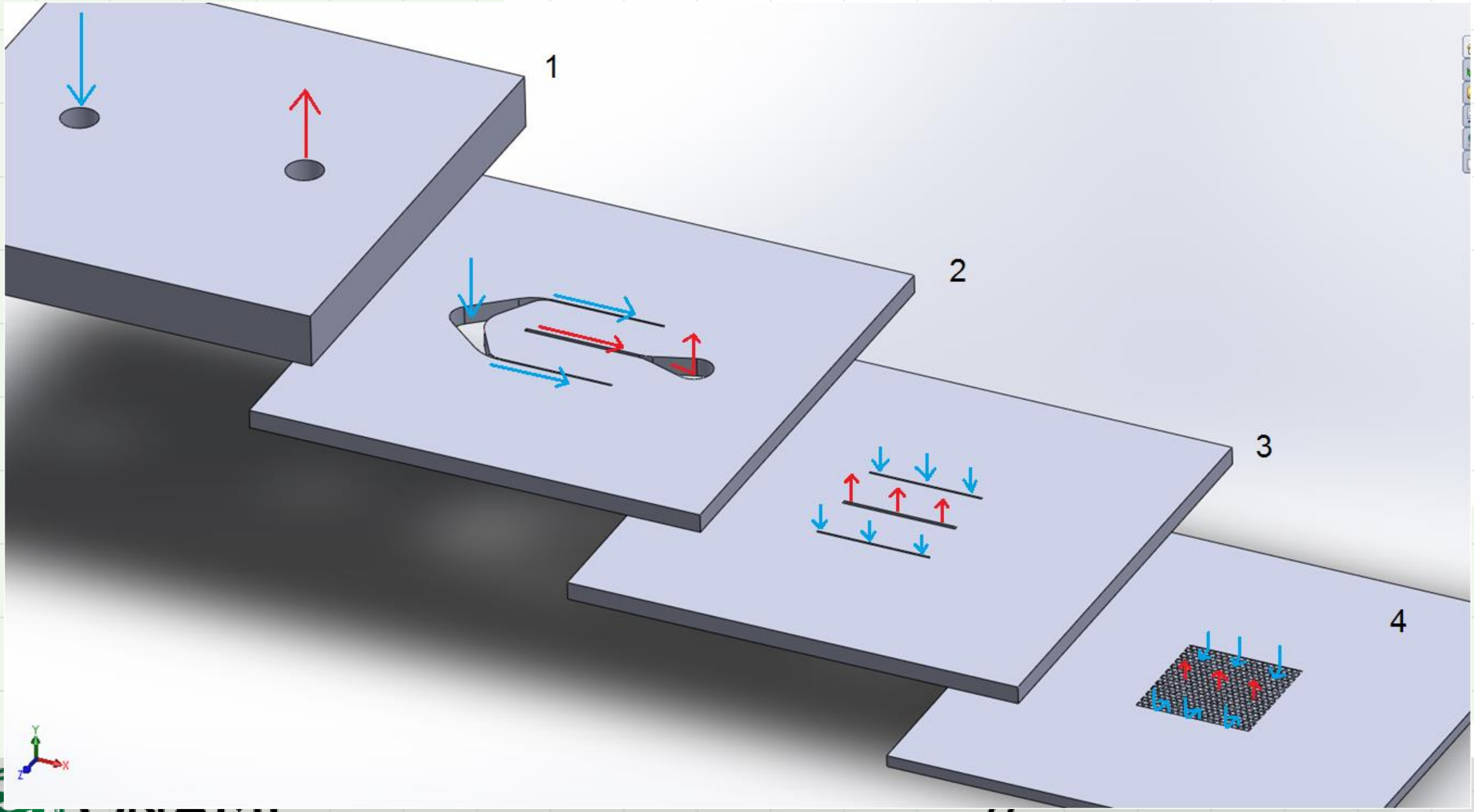


	Average Top Surface Temperature (K)			
Top Plate Thickness (mm)	Computed	1-D Model Prediction	Prediction Error	Surface Efficiency
1	989			94.2%
3	**1066**	**1053.5**	**1.2%**	**92.5%**
5	1130	1118.0	1.1%	90.9%



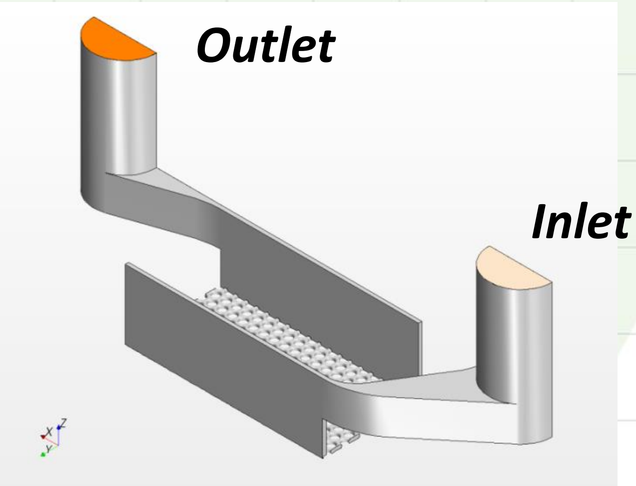
Task 1: Numerical Modeling

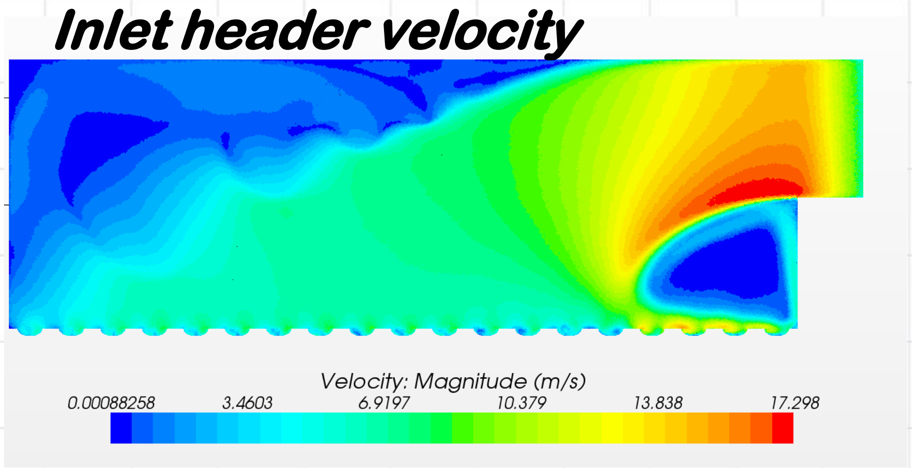
- Subtask 1.3: Complete design with headers

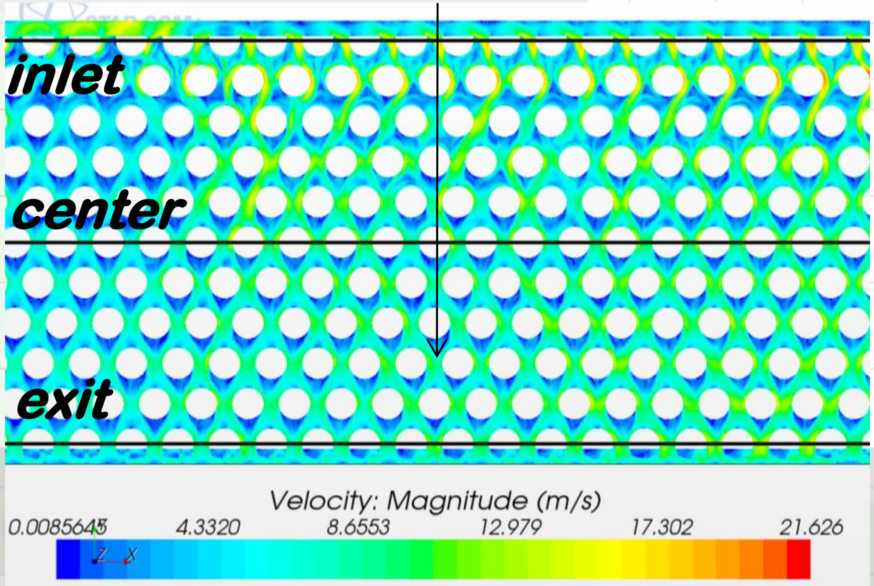


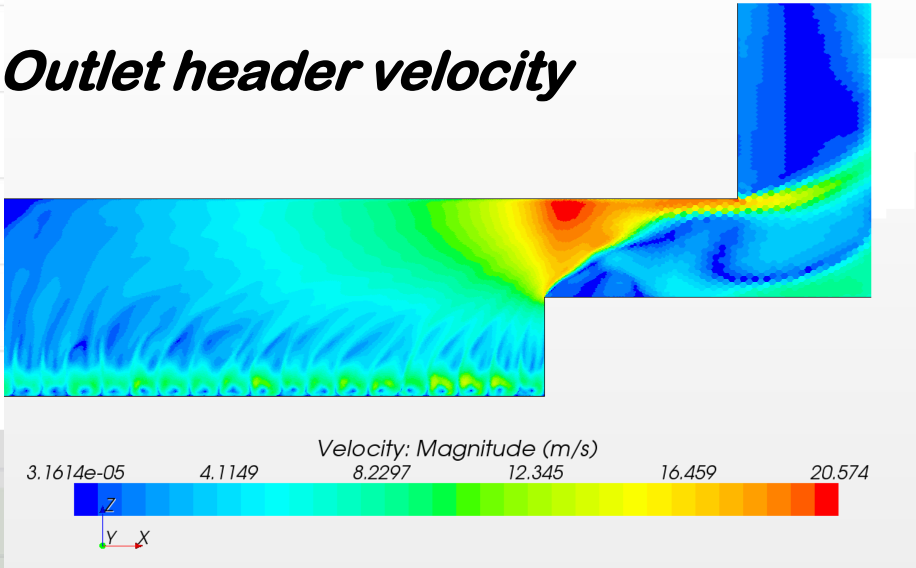
Task 1: Numerical Modeling

- Subtask 1.3: Complete design (preliminary results)



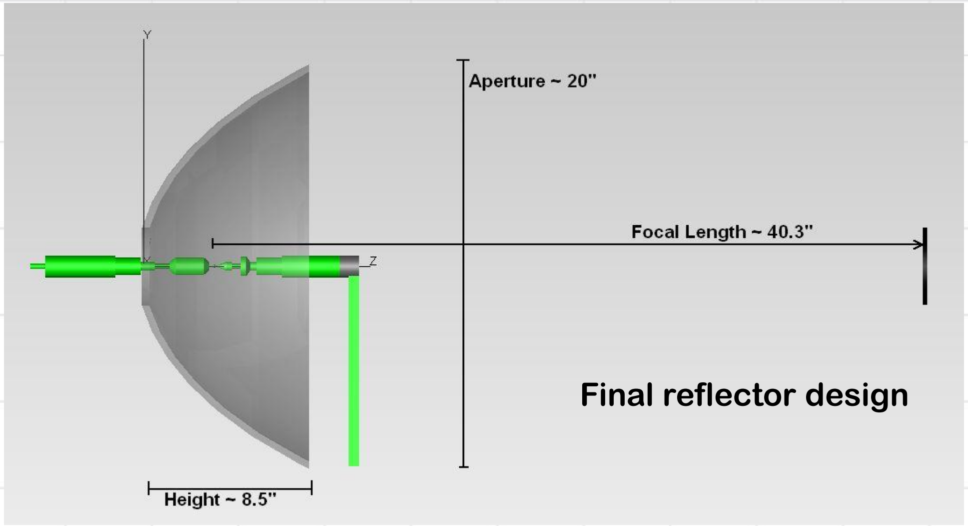


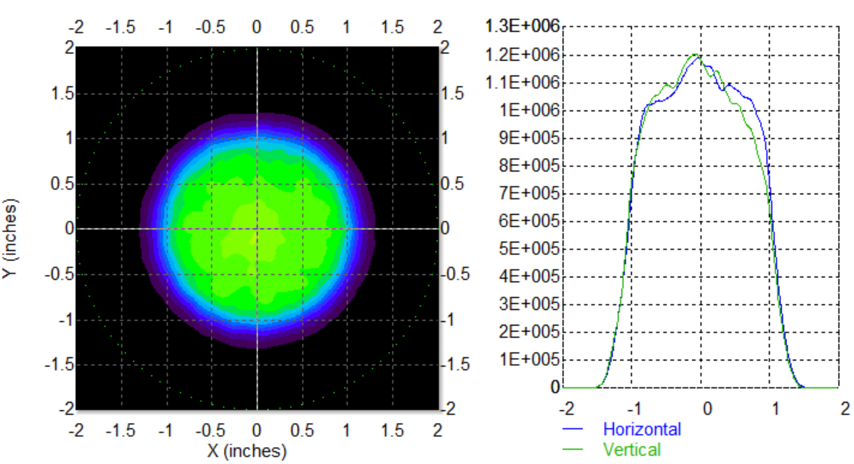




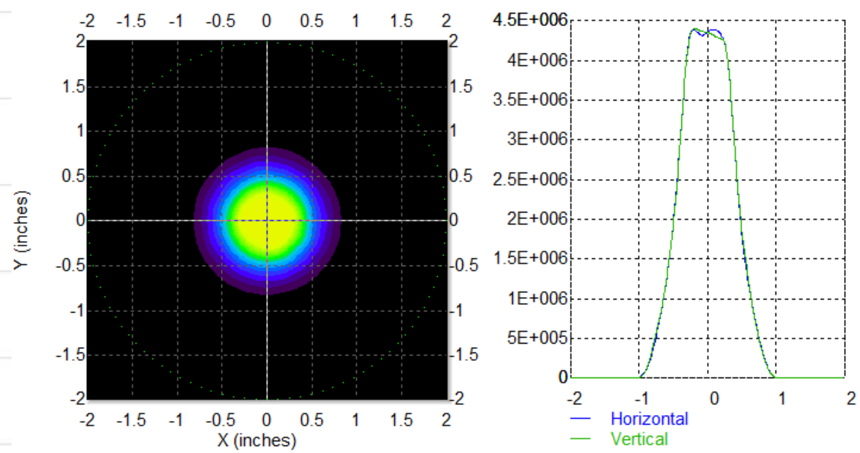
Task 3.1 - High Flux Concentrator

- Purpose: Laboratory scale testing of the receivers
- Approach: single 6kW Xenon short arc lamp with a precision reflector
- Design: Ray tracing simulations for reflector shape
- Fabrication: CNC machining, diamond turning, silver coating



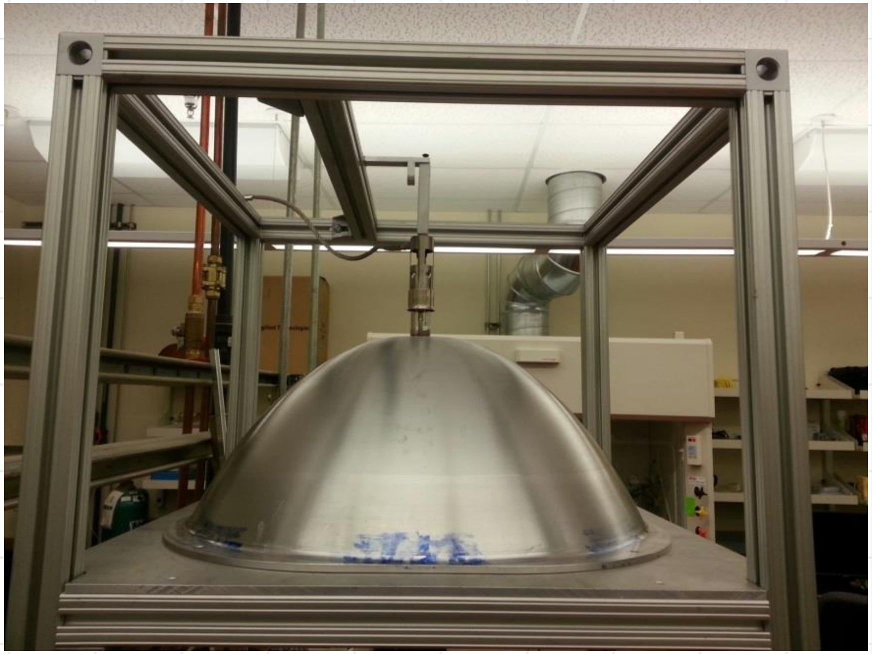


Final design, 100 W/cm² flux distribution



Final design, 400 W/cm² flux distribution

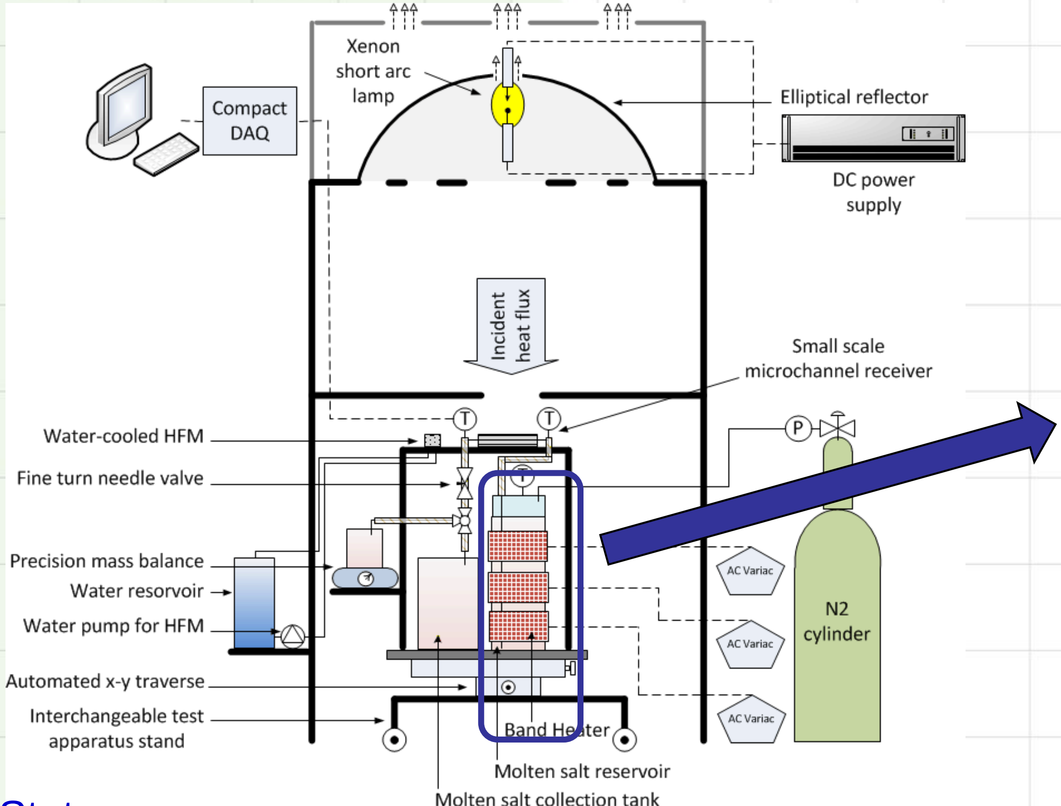
Task 3.1 - High Flux Concentrator

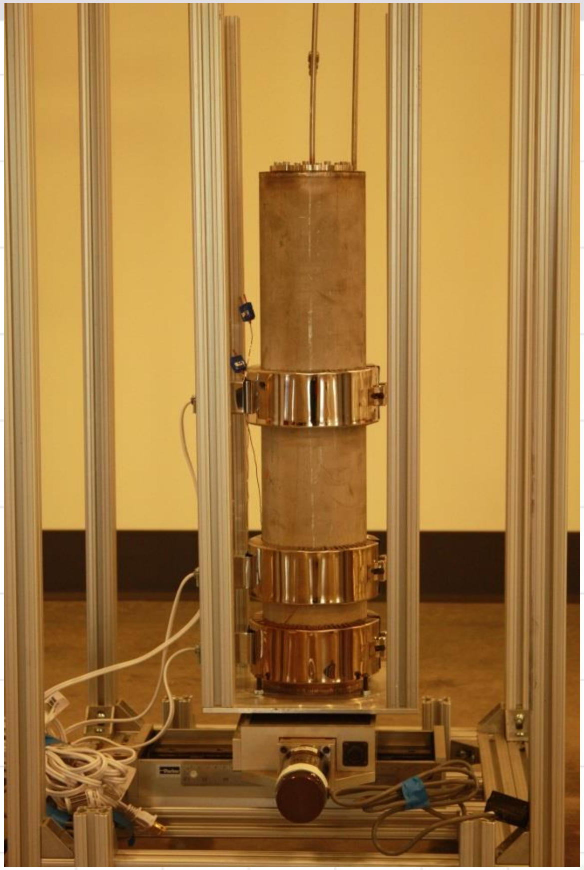


Status:

- Reflector: CNC machining completed; diamond turning & silver coating in progress
- Lamp and power supply procured; Lamp being tested
- Heat flux gage procured; 2-D automated traverse set up
- Apparatus frame: assembly completed
- Completion timeframe: May 15th 2013

Task 3.2 - Molten Salt Test Loop

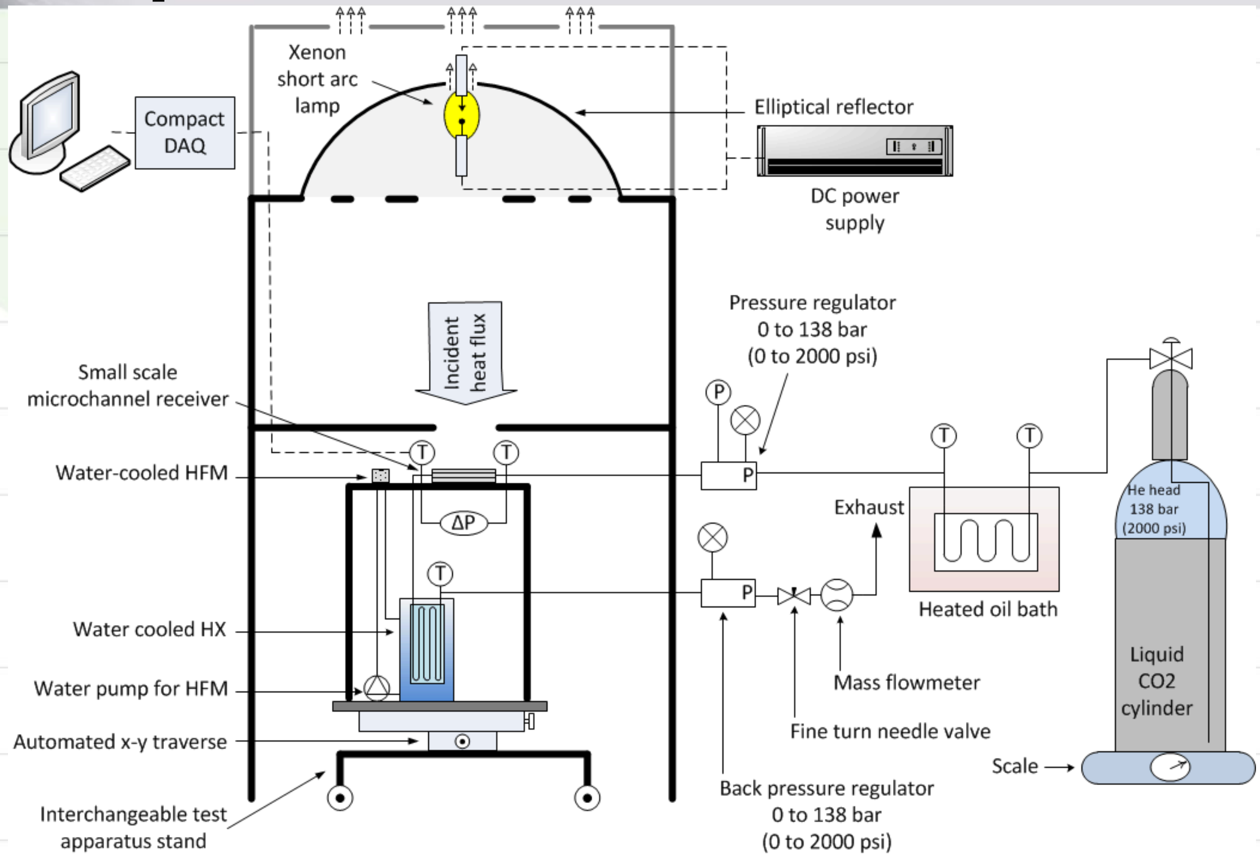




Status:

- Design complete; Facility being assembled; major components procured
- Open loop with catch and weigh for mass flow rate determination
- Pumping of salt using pressurized gas demonstrated
- Completion timeframe: May 30th 2013

Task 3.3 - Supercritical CO2 Test Loop



Status:

- Design complete; major components ordered
- Open flow loop; Airgas will supply us a CO2 cylinder with a 2000 psi Helium head
- Initial testing will take place with high pressure nitrogen gas
- Completion timeframe: June 30th 2013

Key Technical Results

- Adaptive flow control
  - Startup on this task has been delayed due to the requirement for negotiation and approval of a Cooperative Research and Development Agreement (CRADA) with our cost-share partner
  - Once work has begun, PNNL will perform finite element modeling using COMSOL Multiphysics to understand the extent to which solar flux inhomogeneities create flow maldistribution, including how the design of adaptive flow features can compensate for variations in solar flux
  - The finite element model along with correlation-based tools will be used to develop designs for adaptive flow control devices, for fabrication and testing within small-scale units during the fourth quarter of Phase 1

Challenges and Barriers -

- Fabrication limitations for prototype development
- Issues associated with moving from a proof of principle test to industrial scale (1 square meter) are not subject of this study but we need to be aware of them
  - Headering
  - Thermal stresses
- Issue associated with long duration operation not subject of this study but we need to be aware of them
  - Corrosion and fouling
  - Thermal cycling

Future Work

- Phase 1 (Present to 7/31/2013)
  - Complete fabrication of supercritical CO_2 test articles with a successful pressure test
  - Complete assembly and start-up of CO_2, molten Salt test loops and flux concentrator
- Phase 2 (8/1/2013-7/31/2014)
  - Complete laboratory testing of CO_2 test article
  - Design and fabricate a proof of principle CO_2 test article for testing on a dish concentrator at PNNL
  - Complete design and fabrication of a laboratory molten salt test article
  - Complete laboratory testing of a molten salt receiver