Compact Diffusion Bonded Heat Exchanger Fatigue Life Simulations

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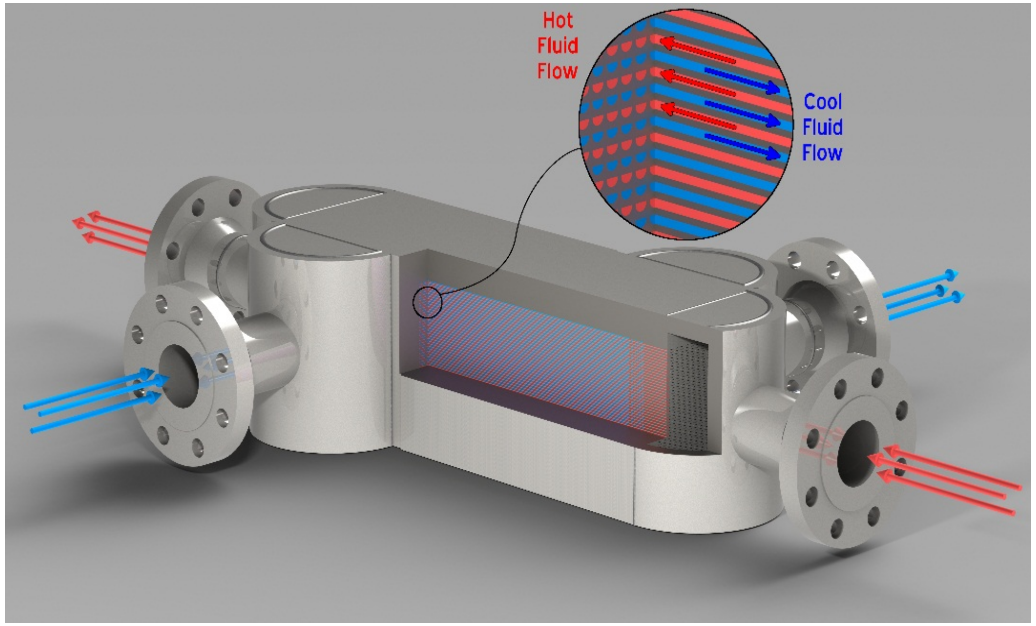
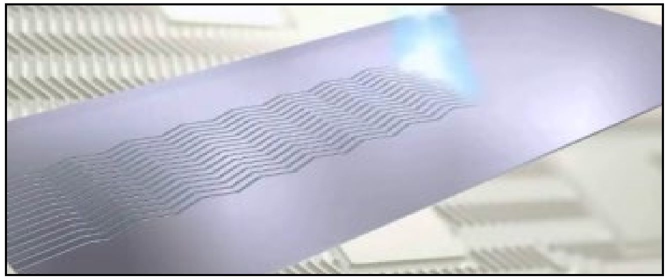
Compact Diffusion bonded heat exchangers - use and benefit

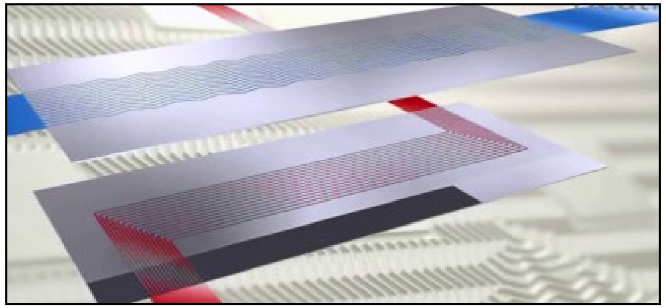
- Referred to as Microchannel Heat Exchangers (MCHEs) or Printed Circuit Heat Exchangers (PCHEs)
- Ideal for high pressure and temperature applications
  - ✓ Temperature cryogenic to 950C (1740 F) and Pressure as high as 110 Mpa (16,000 psi)
  - ✓ Compared to shell and tube HEXs for high pressure,
    - 10 x smaller, 4x lower cost
- Applications include
  - ✓ Supercritical CO2 power cycles (HT recuperators and coolers)
  - ✓ Hydrogen vehicle filling stations
  - ✓ Liquified natural gas processing
  - ✓ Gas turbine fuel preheating
  - ✓ Molten salt and particle high temperature thermal storage, IHX

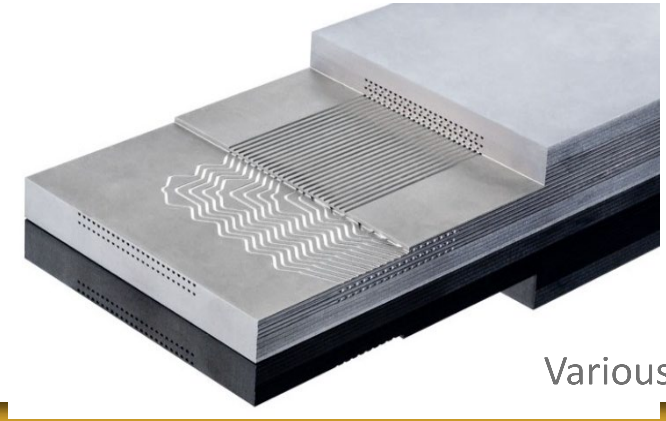


Compact Diffusion Bonded Heat Exchanger Construction

Channel forming & plate stacking

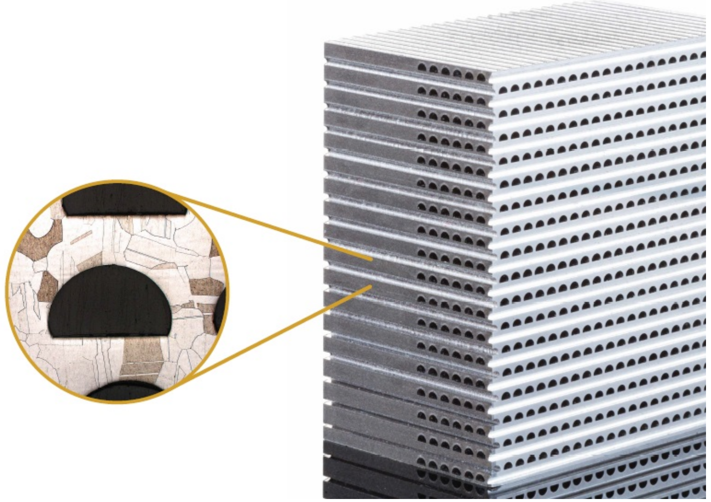




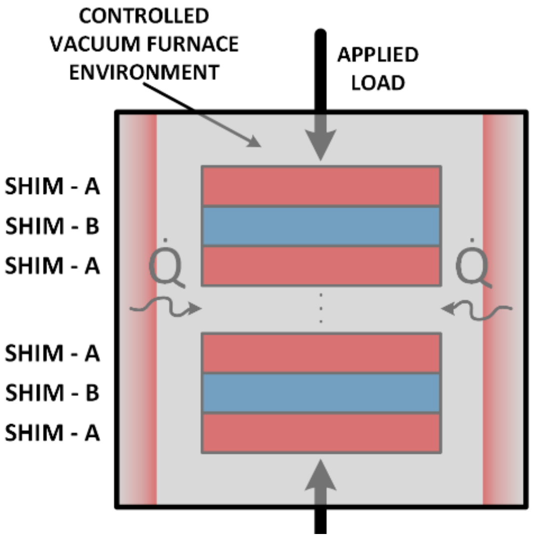


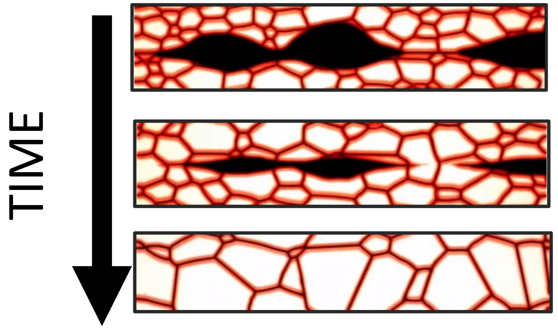
Diffusion bonding process is a solid state (grain growth based) joining process with no interlayer, braze material or gasket. It has a parent material strength

Qualified as per Appendix 42 of ASME Section VIII, Div 1



Diffusion bonding (Monolithic block)

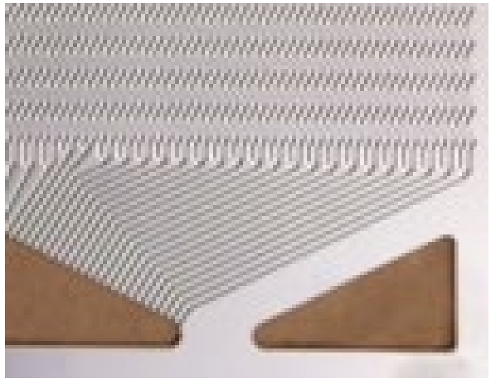


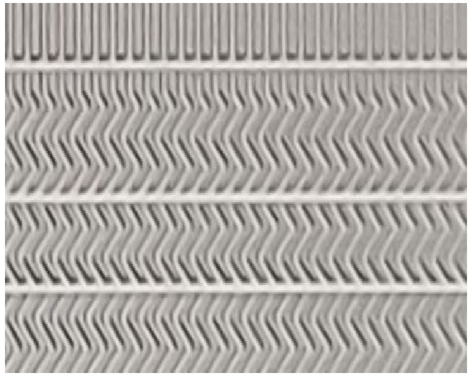


Various proprietary surface preparations employed to promote grain growth for high nickel superalloys.

Compact Diffusion Bonded Heat Exchanger Construction

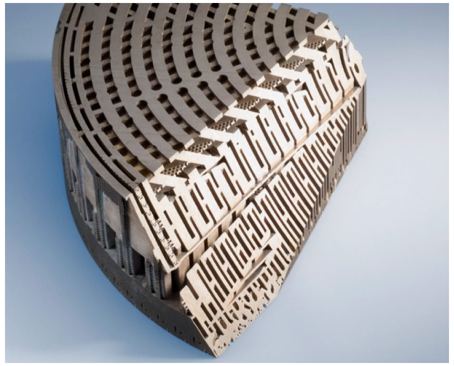
- Fluid flow paths designed using proprietary algorithms has nearly unlimited layout (only limitation of being able to draw within a 2-D space). Allows ability to significantly enhance heat transfer enhancement with a balanced pressure drop.
- The flow passages are formed by either photo chemical etching, electro chemical machining or other CNC machining methods.
- Cost is optimized using innovative channel layout that utilize pure counter flow as well as channel heat transfer enhancement using zig-zag, hard-ways, lanced, and bypass.
- Mechanical design of channels, and headers meet ASME BPVC, Section VIII, Div 1.



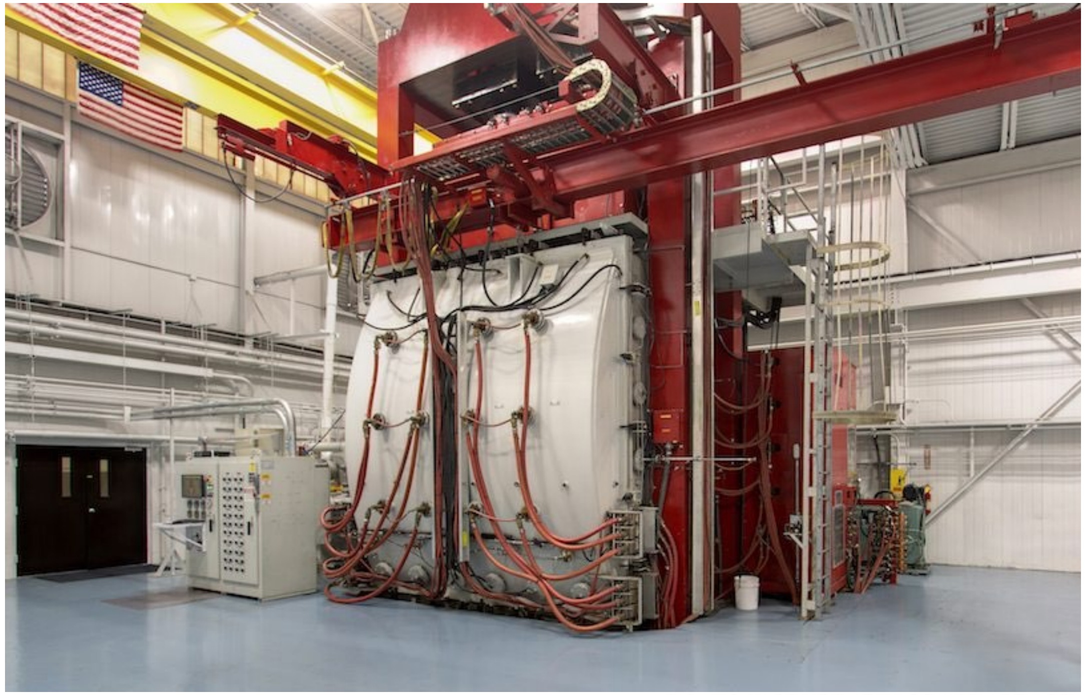


Vacuum Process Engineering, Inc. (VPE) is the most experienced domestic manufacturer of MCHEs

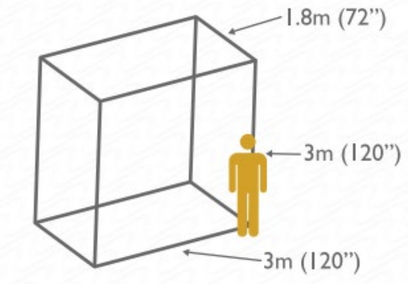
- Operates four (4) facilities in Sacramento, CA
- 40+ years of diffusion bonding experience
- 150,000 sq. ft. of space
- World’s largest vacuum hot press



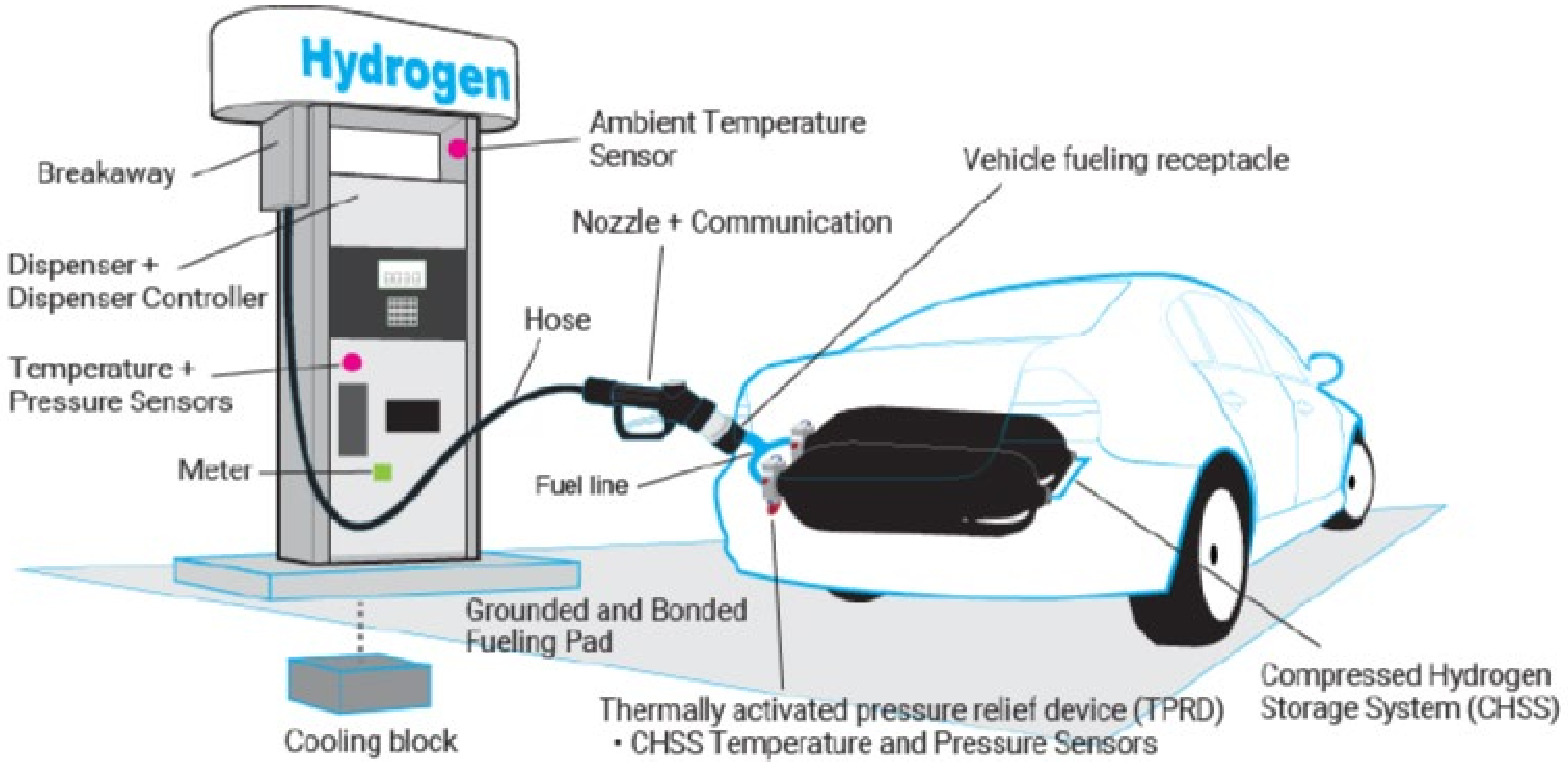
Many complex geometries possible



Large vacuum furnace with twin hot press



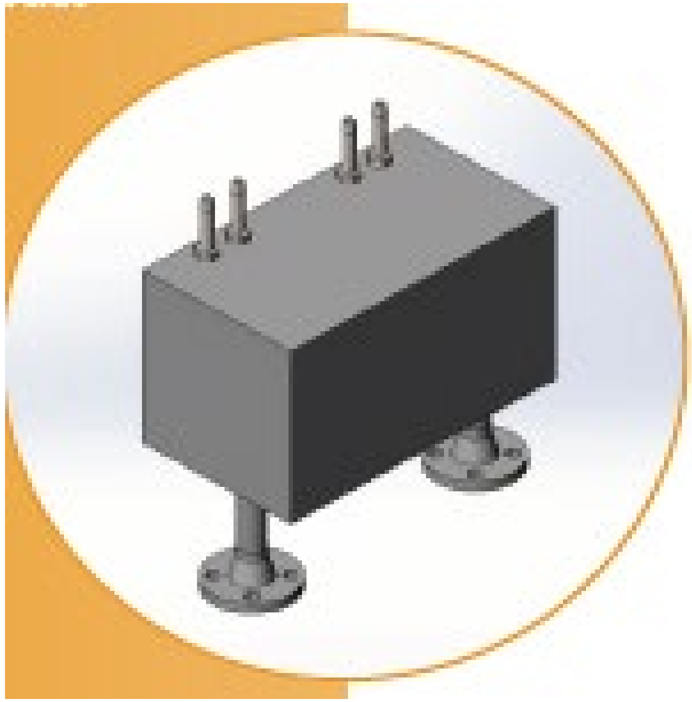
Compact diffusion bonded heat exchangers are used in hydrogen fuel stations - high pressure cyclic / fatigue service

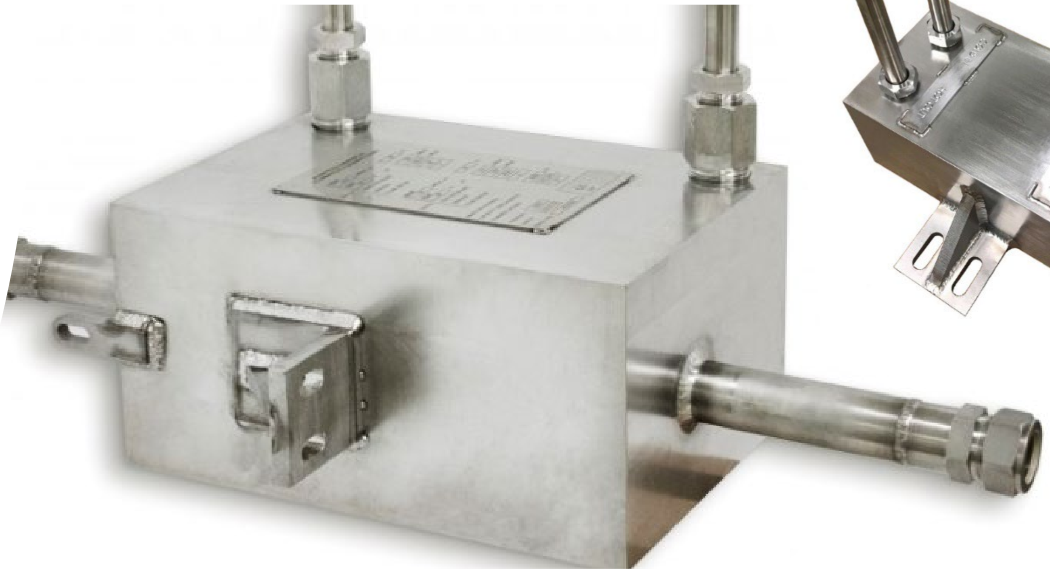


https://h2stationmaps.com/hydrogen-stations

Ultra-high pressure hydrogen precoolers (H2PC™) for hydrogen vehicle fueling stations

- Hydrogen precoolers operate at very high pressure (5000 psi – 14000 psi)
- Designed to cool high pressure hydrogen from approximately 40 °C to -40 °C.
- Use liquid coolants and refrigerants including Syltherm XLT, Dynalene HC, R452, R449. CO2 for cooling H_2
- They are subject to high pressure cycles - every fill requiring pressure ramp up from zero / tank pressure (~1000 barg) to 14,000 psi.
- VPE designs and fabricates various compact high pressure hydrogen precooler models for light and heavy duty vehicles as well as mobile filling stations.
  - Extremely low helium leak rates
  - 10E-09 atm cc/sec standard
  - 10E-07 cc/sec typical for alternative equipment





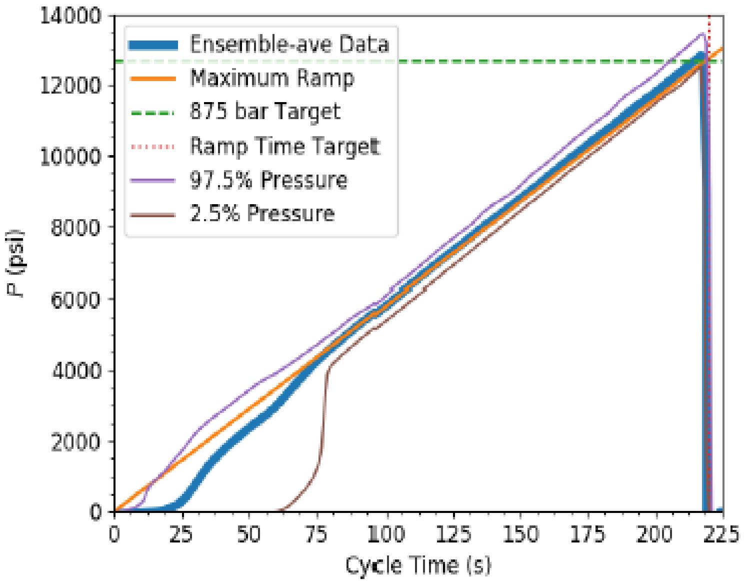
High pressure hydrogen precooler fatigue test and numerical simulations

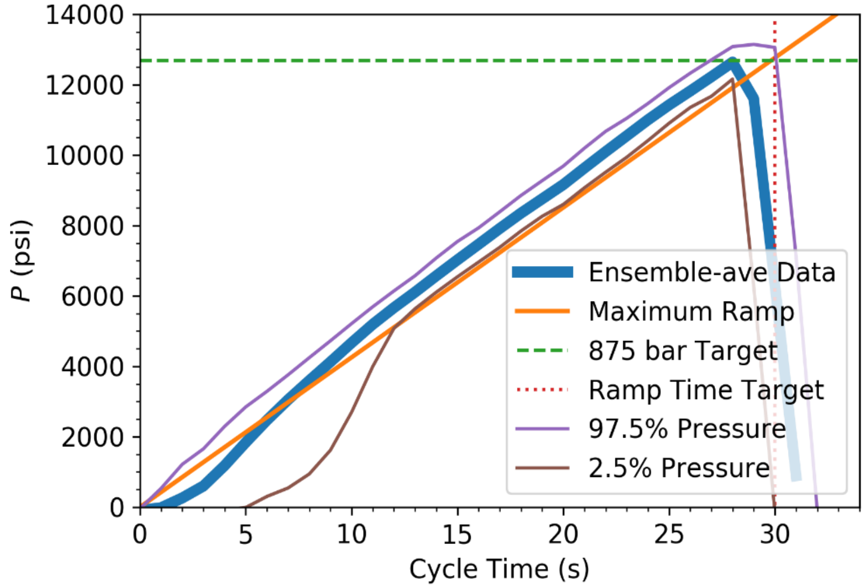
<u>Experimental test set up at Sandia National Laboratories</u>

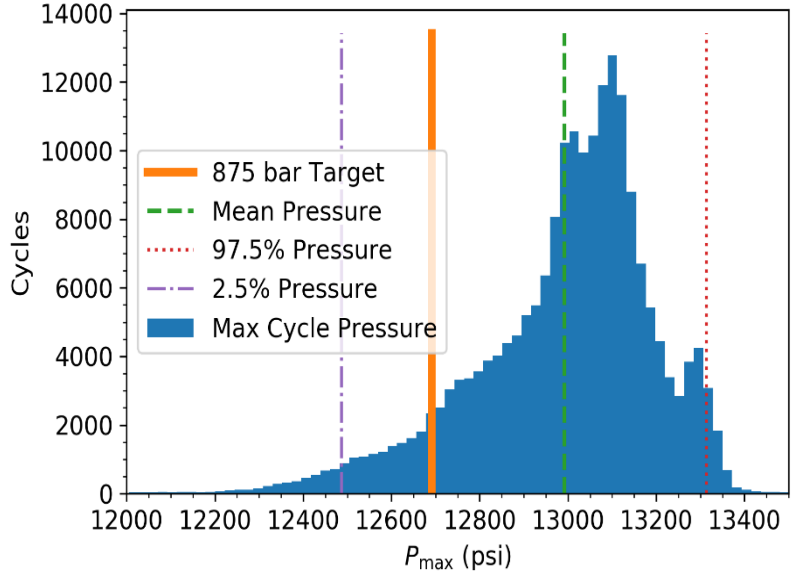
- Controlled pressures between 500 and 60000 psi (34 to 4100 bar)
- Fully automated for long duration tests
- The pressure vessel test rig includes:
  1. Pressure vessel test cart
  2. Control system
  3. H2PC™ heat exchanger
  4. Helium leak check enclosure
  5. Secondary containment

Precooler designed for a 2 min fill of a 6 kg tank
- 11 x 6 x 7 inches (280 x 155 x 175 mm)
- 80 lbs (36 kg)

Experimental Methods and Results





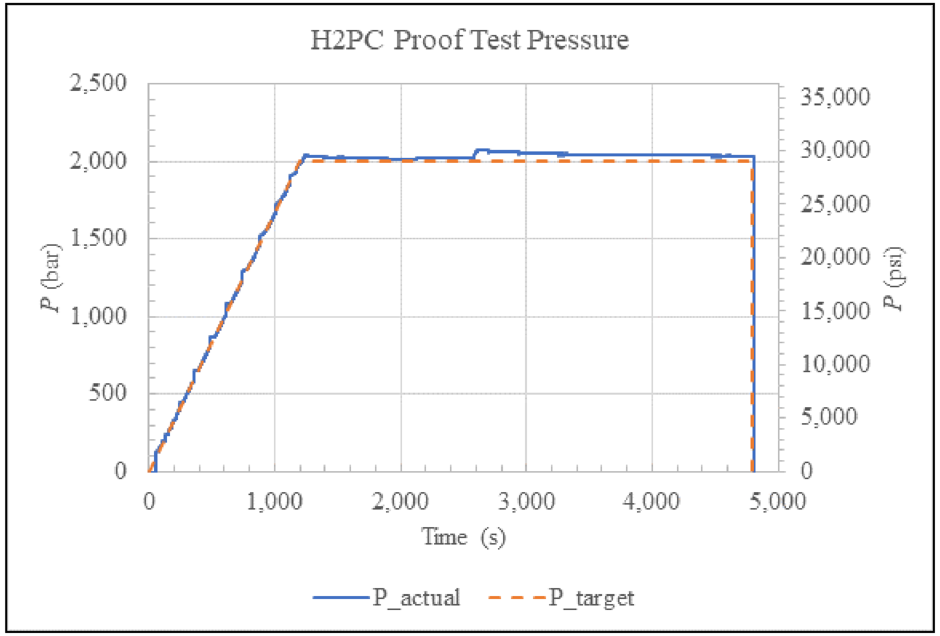


- 12700 psi (875 bar) target pressure
- 3480 psi/min (240 bar/min) ramp rate target from SAE J2601
- Helium leak check every 104 cycles
- Calibrated with a 1.3x10E-07 source
- Pressure ramped up 7.5X fast after finishing 100K to 300K cycles

- 97.5% of cycles met or exceeded the target
- No observable signs of failure in 300k cycles
- No detectable helium leak rate in 10 tests
- Below the 1x10E-08 cc/sec floor of the sensor

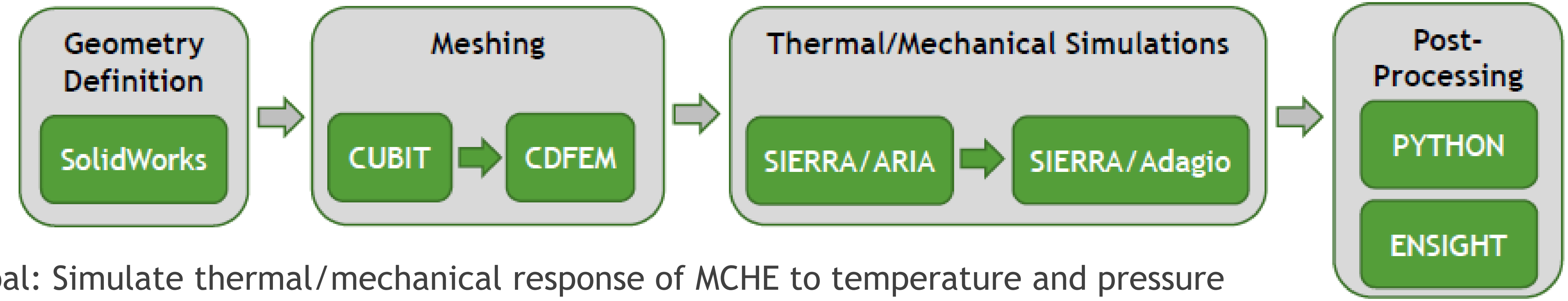
Proof pressure test conducted after 300K fatigue cycle test

- After 300k pressure cycles and helium leak test, the precooler was proof tested 2X design pressure 29,000 psi (200 Mpa) for one hour as per code.
- Pressure ramped up at 100 bar per minute.
- No detectable leaks down to 10E-08 atm cc/s



Numerical Simulation – conducted by Sandia National Laboratories

Workflow



Goal: Simulate thermal/mechanical response of MCHE to temperature and pressure

- Conformal Decomposition FEM (CDFEM) decomposes a non-conforming background mesh into sub-elements that conform to interfaces defined by a level set method

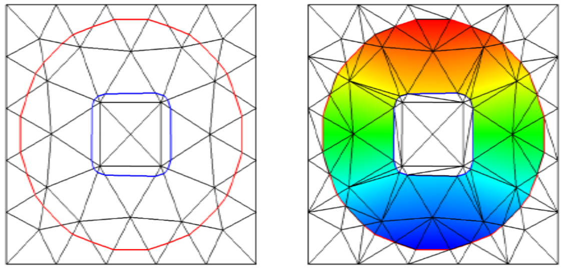
- SIERRA/Aria is a finite element method (FEM) for solving systems of partial differential equations (PDEs) used here to solve the thermal advection-diffusion equation

- SIERRA/Adagio is a three-dimensional, implicit solid mechanics code used to solve for quasi-static, nonlinear deformation of solids.

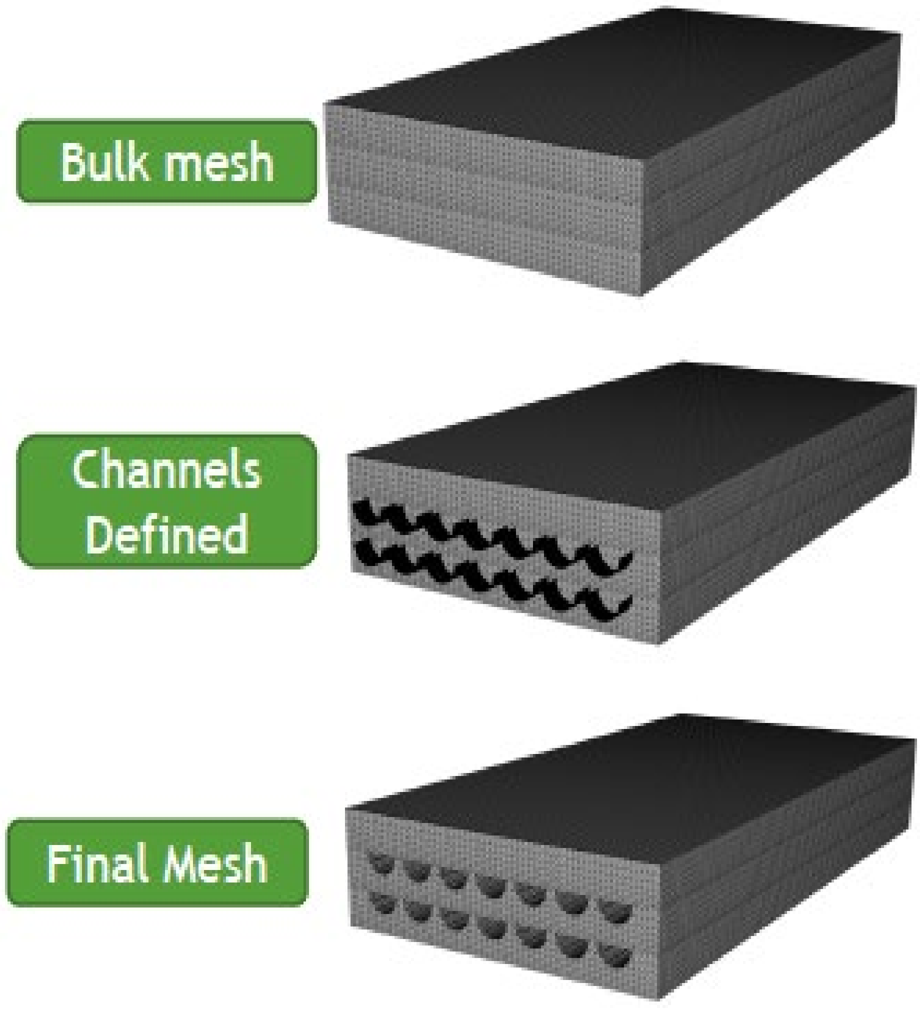
Numerical Simulations - meshing

Conformal Decomposition Finite Element Method (CDFEM)

- CDFEM is an alternative meshing approach to traditional volumetric schemes.
  - Use one or more level set fields to define materials or phases
  - Decompose non-conformal elements into conformal ones
  - Obtain solutions on conformal elements



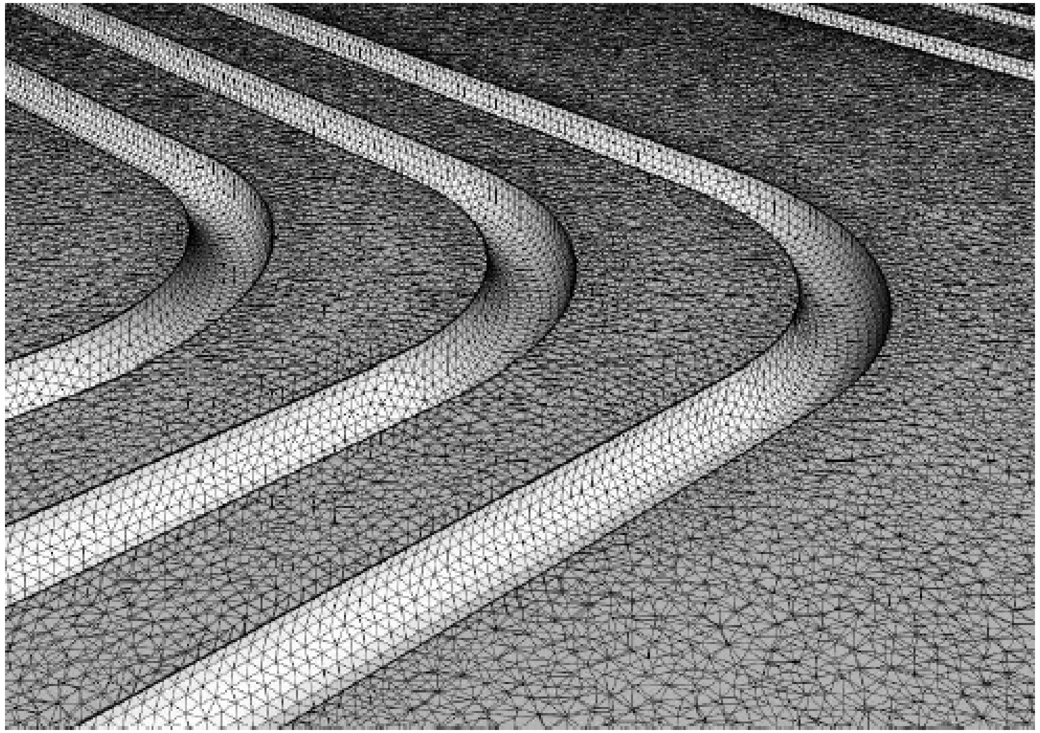
- Procedure:
  - Mesh the domain using tetrahedral elements
  - Use STL geometry descriptions of microchannel volumes to create level set fields that cut the background mesh to produce entities for thermal/mechanical simulations



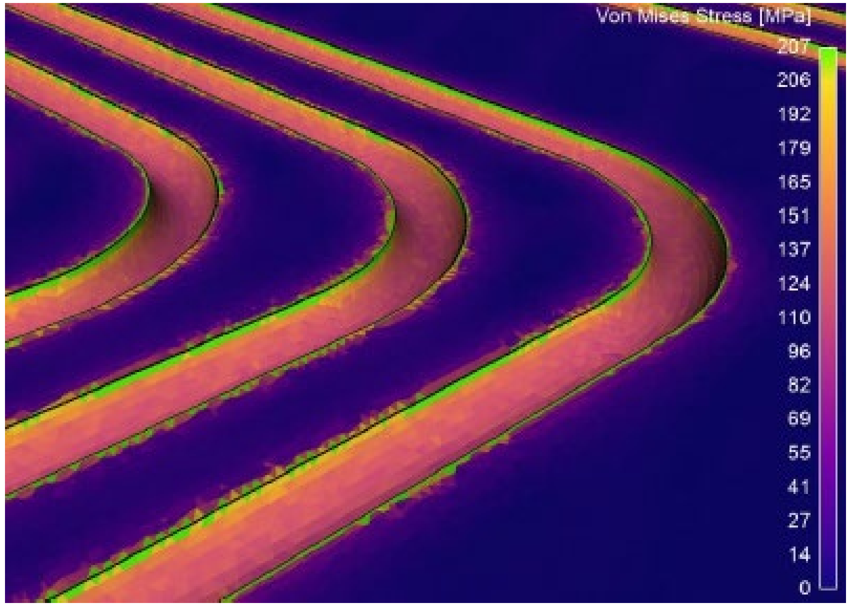
Numerical Simulations – Pressure Loading

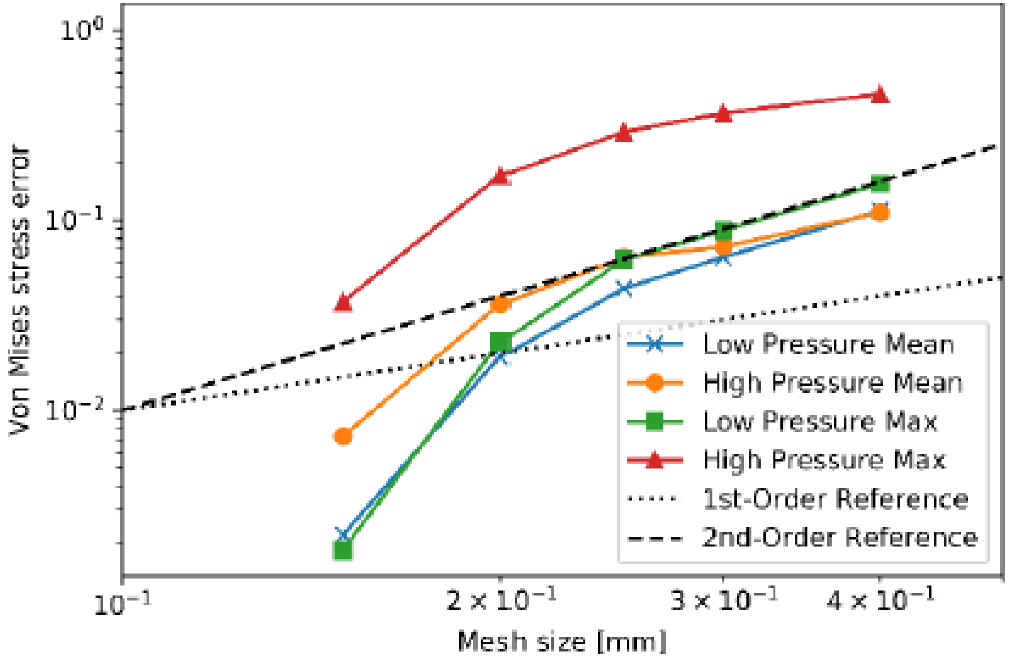
- Model created in Sierra Solid Mechanics
  - Single unit cell slice of the full unit
  - 133 million quadratic tetrahedral elements
  - Mesh refined near corners and surfaces

- Material properties and loading conditions
  - 875 bar / 35 bar on ‘hot’ / ‘cold’ sides
  - 200 GPa Young’s modulus
  - 0.265 Poisson’s ratio
  - Linear elastic stress model



Numerical Simulation – Results



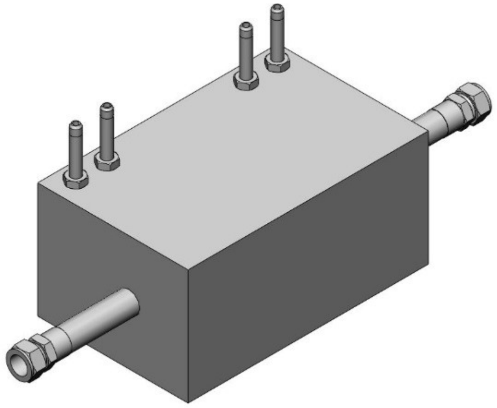


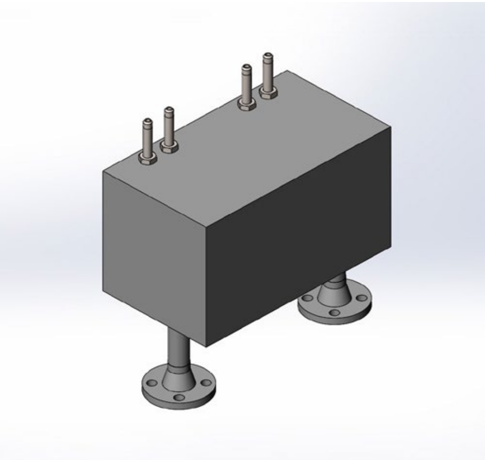
- Stress magnitudes averaged over due to high local stress concentrations at sharp corners
- Code limit = 1.5 x 138 MPa = 207 Mpa
- Small areas of high stress concentration plastically deform and are negligible
- VIII Div II allows up to 3x allowable

- Mesh refinement study of key parameters demonstrated second order convergence
- Local refinement near gradients
- Indicates of good mesh and model

Conclusion

- ✓ No failure, deformation, or reduced holding pressure seen after 300k cycles and proof test at 2X design pressure.
- ✓ The fatigue test and simulation results validated VPE Hydrogen precooler design for long duration use >300k pressure cycles in hydrogen vehicle fueling stations





VPE
Vacuum Process Engineering

VPE

Vacuum Process Engineering

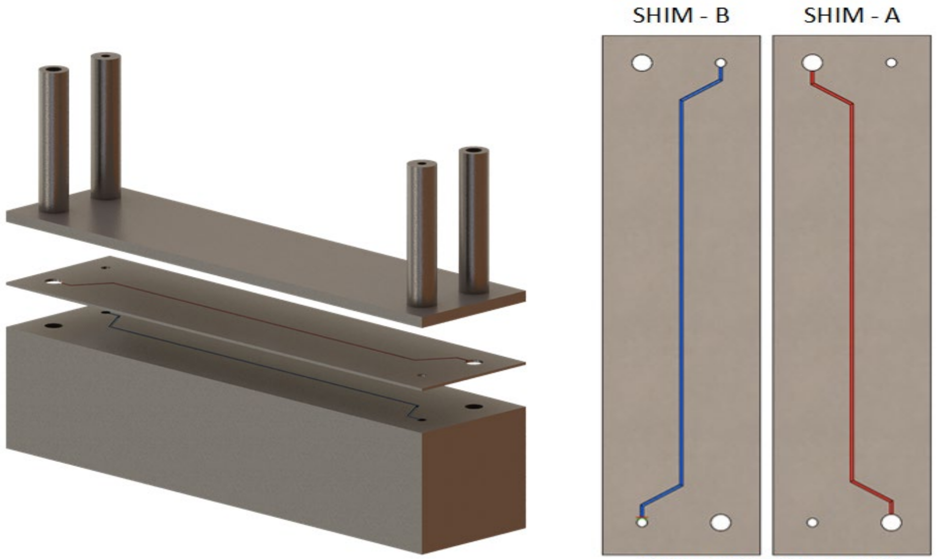
Compact Diffusion Bonded PCHE Development Using Nickel Superalloys for Highly Power Dense and Modular Energy Production Systems

Project Goal

Develop a very high temperature diffusion bonded compact heat exchanger using Nickel based superalloys (Alloy 740 H, HR230, HR 282). PCHEs capable of operating to very high temperature (>800 ^{0}C) and high pressure (>250 barg) services.

Produce an optimized modular design that enables < \$2000 ^{0}C/kWth for stationary modular power generations, including, CSPs, Gen IV nuclear systems (SMRs and VSMRs).

Project Team: National Energy Laboratory (NETL)
Sandia National Laboratories (SNL)
Special Metals Inc
Echogen Power Systems



SHIM SIMPLIFIED LINE-DIAGRAM