SANDIA PROGRESS ON ADVANCED HEAT EXCHANGERS FOR SCO2 BRAYTON CYCLES

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ABSTRACT

Supercritical carbon dioxide (SCO2) closed Brayton cycles have been proposed for nuclear, concentrating solar, fossil energy, and heat recovery power generation applications, with various modifications in layout, fluid composition, and materials used to tailor the general concept to each specific application. All applications require significant recuperation in addition to the heat input and removal required of any closed cycle to achieve desired performance. This paper reviews recent work at Sandia National Laboratories to advance both near-term and medium-term SCO2 Brayton cycle heat exchanger technologies including printed circuit heat exchangers (PCHEs) and cast metal heat exchangers (CMHEs). Both styles of heat exchanger are suitable for high operating temperatures and pressures. PCHEs have been used for heat exchange in most existing SCO2 test loops, and have demonstrated scaling to larger units produced for other applications. CMHEs are a new patent-pending concept from Sandia National Laboratories which may offer performance similar to or better than PCHEs at less than 1/5 the cost while allowing for more flexibility in material selection and channel geometry.

Heat Exchange in SCO2 Brayton Cycles

Heat exchangers play a critical role in supercritical carbon dioxide (SCO2) Closed Brayton Cycles (CBCs). Recuperation allows for the high efficiencies associated with recently proposed cycles, while the need to avoid the pinch point that is possible in the low-temperature end of the recuperation process dictates many of the existing cycle layouts (Dostal, Driscoll, & Hejzlar, 2004). As the largest components expected in any SCO2 CBC they will be the difficult to procure in terms of both time and money even after technical challenges associated with their performance are addressed (Gibbs, Hejzlar, & Driscoll, 2006).

The heat exchangers associated with CBCs operating with a SCO2 working fluid face significant mechanical, thermo-mechanical, and thermal-hydraulic challenges. The range of temperatures, pressures, differential pressures, and thermodynamic effectiveness of the heat exchangers in three typical cycles under steady-state conditions are shown in *Table 1*. Transient conditions can impose even higher stresses than those at steady-state depending on the specific components used and the nature of the transient (daily power cycling vs. fast accident scenarios), requiring more detailed mechanical analysis and larger safety margins. Although a great variety of conditions exist, proposed Brayton cycles are typified by high pressure and temperature heat input exchangers, high pressure but low temperature heat rejection units, and high pressure, high temperature, high effectiveness recuperators.

Table 1. A summary of performance requirements for various Brayton cycle layouts.

	Recompression (Dostal et al., 2004)	**Cascading** (Kimzey, 2012)	**Allam** (Allam et al., 2012)**
Heat Input [#]	1	2 (High and Low Temp)	1 or 2
T Range [°C]	400 – 750	75 – 600	750 – 1150
P Range [MPa]	20 – 30	27	20 – 40
dP Range [MPa]	13 – 30	27	N/A (combustion)
Heat Rejection [#]	1	2 (Main and Intercooler)	3
T Range [°C]	30 – 70	36 – 90	30 – 70
P Range [MPa]	7.5 – 10	5 and 9	3
d Range P [MPa]	7.5 – 10	5 and 9	3
Recuperation [#]	2 (High and Low Temp)	2 (High and Low Temp)	1
T Range [°C]	60 – 580	90 – 425	70 – 775
P Range [MPa]	7.5 – 10 and 20 – 30	5 and 27	3 and 20 – 40
dP Range [MPa]	7.5 – 22.5	22	17 – 37
*Duty/Heat Input [q_{rec}/q_{heat}]**	1.7 – 2.3 and 0.59 – 0.69	0.25 – 0.35	1.1
*Effectiveness [q/q_{max}]**	0.96 – 0.98 and 0.91 – 0.96	0.9 and 0.95	Very High (> 0.96)

* Values estimated from available data, not directly provided in references cited.
** Does not include heat exchangers involved in the air separation unit and other chemical processes.

Printed Circuit Heat Exchangers

Description of PCHEs

Printed circuit heat exchangers are the most widely used heat exchanger technology for SCO2 Brayton cycle test platforms, including those operated by Sandia National Laboratories and Echogen. These units are produced by chemically milling channels roughly 1 mm (0.04 in) wide by 0.5 mm (0.02 in) deep into plates measuring up to 600 by 1500 mm (23.6 by 59 in). These plates are stacked up to 600 mm (23.6 in) high and diffusion bonded into a heat exchanger core, with a suitable header welded onto manifold locations on the core for fluid distribution (Musgrove, Pittaway, Vollnogle, & Chordia, 2014).

According to American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) requirements the bond produced must have mechanical performance equivalent to that required of the base alloy, essentially treating the block as a single cast unit. This strength, combined with the subtractive manufacturing process of chemical milling, allows for the production of heat exchangers with small channels and thick channel walls, resulting in very compact heat exchangers with high pressure containment potential.

This high static pressure containment is demonstrated in *Figure 1* by a plot of maximum cross-sectional area ratio versus pressure containment ratio or maximum design differential pressure for 316L stainless steel at a design metal temperature of 550 °C. Cross-sectional area ratio is effectively the porosity of the PCHE core, demonstrating that design differential pressures up to 20 MPa (2900 psi) can be achieved with core porosities around 40%.

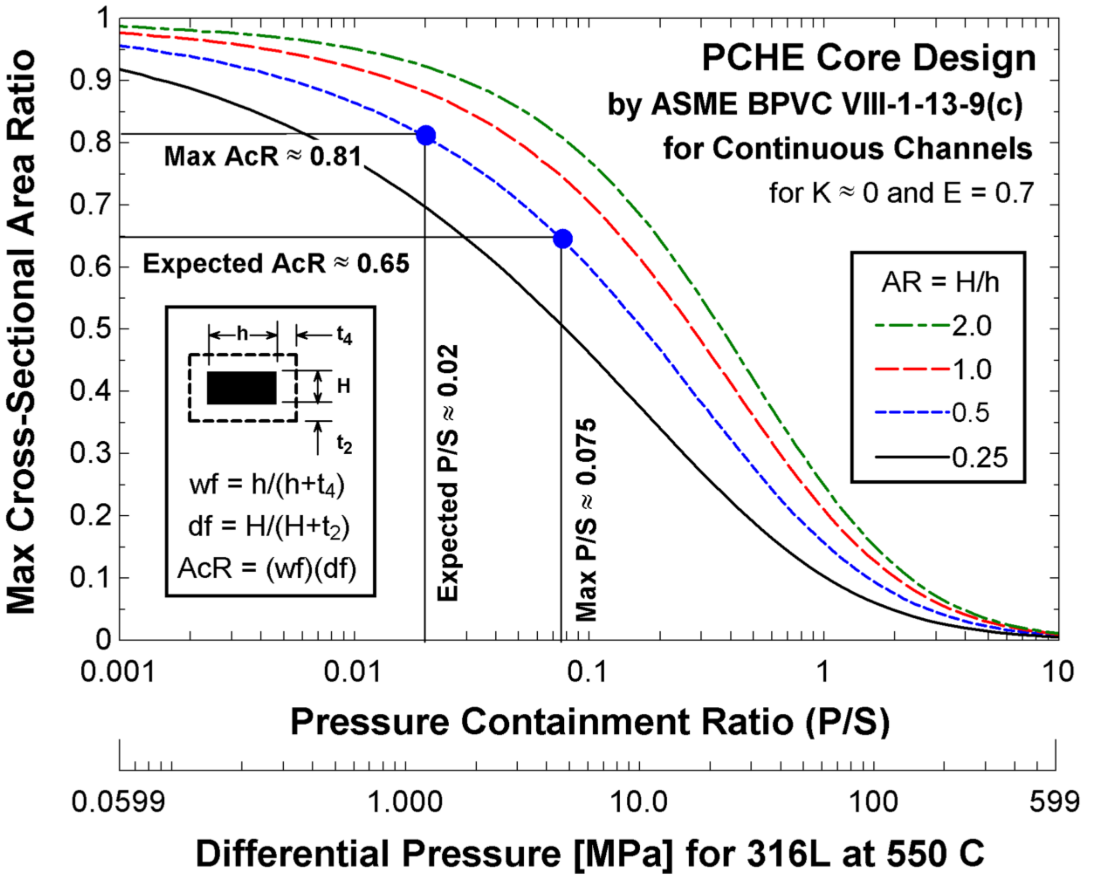

Figure 1. A plot of PCHE core cross-sectional area (or porosity) versus pressure containment ratio or the design differential pressure of a 316L unit for a design metal temperature of 550 °C.

Critical Research Areas for PCHEs

Due to the safety factors contained in ASME BPVC design and the low joint efficiency allowed in BPVC calculations of 70% PCHEs have been reported to survive up to 10 times their design pressure under static test conditions and twice their design pressure under 5e6 pressure cycles without failure (Gezelius, 2004). However thermal stresses and corrosion remain significant uncertainties for the use of PCHEs in nuclear systems.

In the same workshop reported by Gezelius it is suggested by Heatric that a typical PCHE would fail in 300 to 800 complete thermal cycles. More recent testing by Pra et al. (Pra, Tochon, Mauget, Fokkens, & Willemsen, 2008) of a Heatric PCHE under severe thermal transient conditions for 100 cycles demonstrated significant measured thermal stresses on the exterior of the unit on the order of the yield stress for 316L stainless steel, with accompanying simulations suggesting significant plastic deformation and fatigue damage was accumulating in the headers of the unit. The unit did not leak during testing with estimates for fatigue life using nuclear codes suggesting failure would occur closer to 200 cycles. More work is needed to understand how to design for and predict thermal fatigue in these units. The hot-side header is a particular area of concern as noted by Pra et al., though their tests were performed with the V-style headers shown in *Figure 2* rather than the petal-style headers suggested for use where fatigue is a concern (Taylor, 1990).

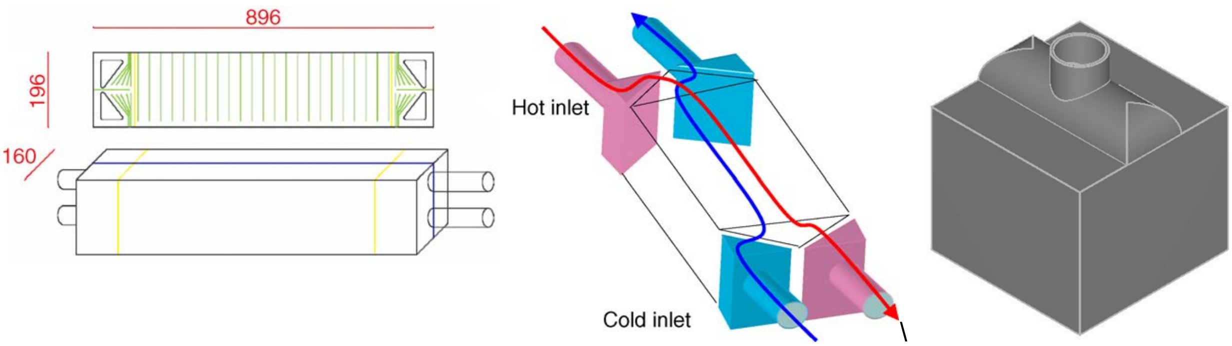

Figure 2. Configuration of the Heatric PCHE tested by Pra et al. (Pra et al., 2008) with V-style headers on the left, as compared with the petal-style header (ALPEMA, 2010).

Even less work has been performed to confirm that the corrosion performance of traditionally-formed 316L stainless steel and other materials is not affected by diffusion bonding. One paper by Ogawa and Azuma evaluating 316L diffusion bonding for joining pipe suggests that pure-metal bonds realized without an interlayer material and under high pressure and temperature will achieve better corrosion performance due to the reduction of intergranular precipitates near the bond zone (Ogawa & Azuma, 1995). However experience reported from operation of the Magnox reactors in England with welded stainless steel suggests that the stress developed in a high-pressure CO2 environment may exacerbate corrosion and lead to stress-corrosion cracking (Moore & Conboy, 2012).

Work between Sandia National Laboratories and Vacuum Process Engineering on PCHEs

Beginning in late May of 2014 Sandia National Labs (SNL) and Vacuum Process Engineering (VPE) began a joint project to develop ASME-certifiable diffusion bonding capability in order to investigate the performance and lifetime predictions of PCHEs. Initial work will demonstrate a pure-metal diffusion bonding process for 316L stainless steel which meets the requirements of Section VIII, appendix 42 of the ASME BPVC for the fabrication of microchannel heat exchangers. This process will be used to develop the first of a series of test articles investigating PCHE performance and failure modes. This collaboration allows for a complete understanding of heat exchanger performance from design and fabrication to full fatigue and corrosion testing which was not before possible.

The first phase of this effort involves evaluating a Diffusion Bonding Procedure Specification (DBPS) as laid out in the BPVC by fabricating a test block at least 200 mm (8 in) on a side and containing at least 50 bond lines (ASME Boiler and Pressure Vessel Code, 2013). At least six samples are taken from this test block including three perpendicular to the bond and three parallel to the bond and tested according to the original material specifications. For this work 96 1.59 mm (1/16 in) plates were bonded for a total block height of approximately 140 mm (5.5 in). Six tensile test specimens were extracted and tested against the material specifications listed in *Table 2* for SA-240 316L.

Table 2. Mechanical requirements for 316L (UNS S31603) plate material from the ASME BPVC.

Property	Unit	Value
Minimum Tensile Strength	ksi	70
	MPa	485
Minimum Yield Strength[a]	ksi	25
	MPa	170
Minimum % Elongation in 2 in or 50 mm	%	40
Maximum Brinell Hardness[b]	-	217
Maximum Rockwell B Hardness[b]	-	95
Charpy Impact Test	-	

a. Determined using the offset method at 0.2% strain according to A370 unless otherwise specified. Alternatively yield strength may be based on total extension under 0.5% load.
b. Either Brinell or Rockwell B may be used.

Stress-strain curves for samples from the first 316L stainless steel block tested at Sandia are shown in *Figure 3*. Of the six samples tested all met the requirements for stress, however sample A just missed the requirements for strain (minimum % elongation in *Table 2*). The samples also showed a common trend in failure mode, with samples A through C failing nearly straight across the sample in a plane parallel to the bond line while samples D through F failed with cup-cone surfaces as typical of ductile materials.

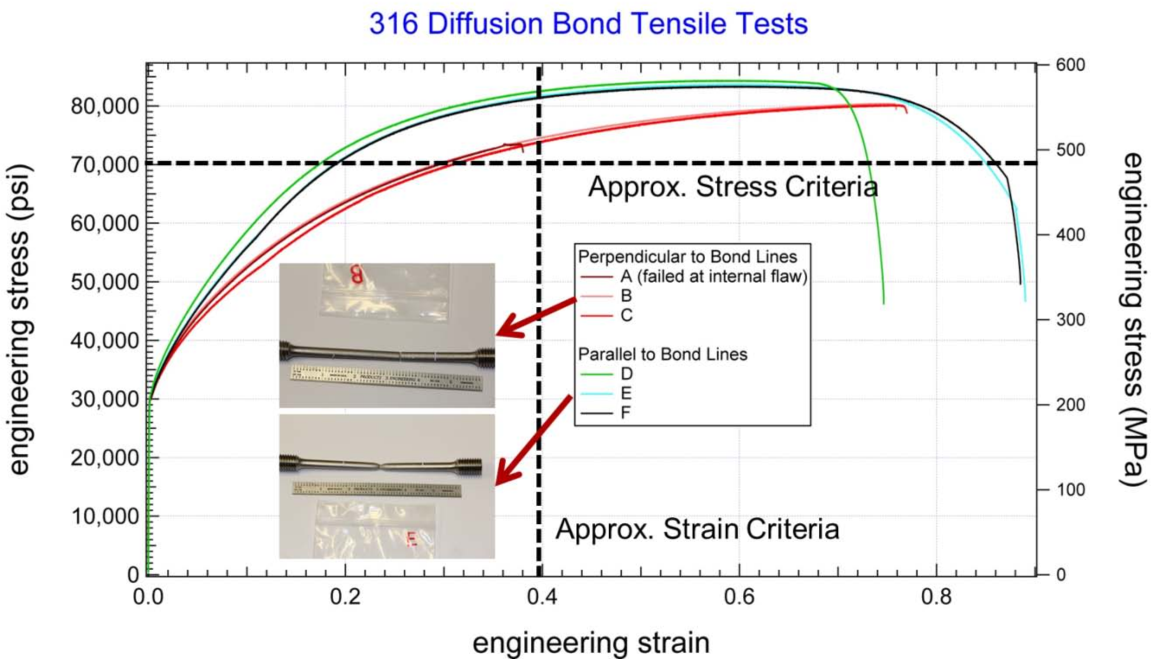

Figure 3. Stress-strain curves from the first set of 316L diffusion bond samples. Minimum stress and strain criteria are overlaid on the plot, with all but sample A meeting criteria.

Further analysis of the failure surface of sample A suggests that a large defect across the surface led to premature failure. This defect is shown in *Figure 4*, appearing like a trench through the width of the sample. This defect is mirror-matched with another on the opposite failure surface suggesting that it is the result of an foreign object inclusion during the bonding process; likely a carbonaceous strip which diffused into the bulk material leaving the trench shown.

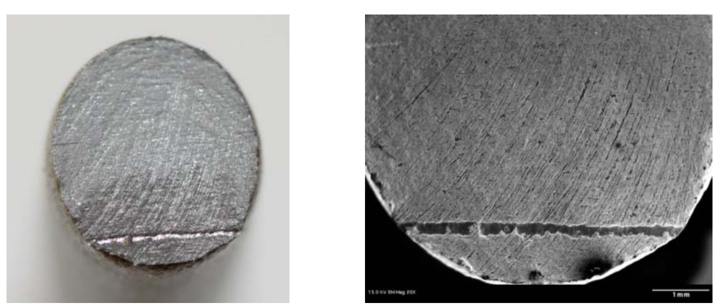

Figure 4. Photograph and SEM image of one side of the failure surface of sample A. The trench shown is likely the result of a foreign object inclusion leading to premature failure.

Testing for additional DBPS blocks is scheduled for the week of August 18th, after the submission of this summary, and results will be shown during the symposium presentation. Interim tests between the first DBPS block and those scheduled have demonstrated that the current process can meet ASME BPVC mechanical and metallographic requirements with all six samples, including when several samples had noticeable defects from foreign object inclusions on the failure surface.

Cast Metal Heat Exchangers

Potential of CMHEs

In parallel to the work on near-term PCHE technology, Sandia is pursuing novel cast metal heat exchangers (CMHEs) as a medium-term solution to the expected high cost of recuperation in high-performance SCO2 Brayton cycles. CMHEs are a patent-pending concept which could offer heat exchanger performance on-par with or better than PCHEs but at less than 1/5 the cost while allowing for greater flexibility in material options and channel geometries.

Casting has long been used to reduce the cost of a part by reducing the number and complexity of the fabrication steps involved. However traditional heat exchangers with discrete channel paths, the far-left PCHE surface in *Figure 5*, would require hundreds or thousands of high-aspect ratio casting cores to be created and supported within the mold. Brazing and diffusion-bonding techniques are well-suited to these types of surfaces, but incur high costs to develop and produce a suitable joint. The CMHE concept was based on the interconnectivity of the flow channels proposed for advanced PCHE surfaces such as the s-shaped and airfoil fins shown in *Figure 5*.

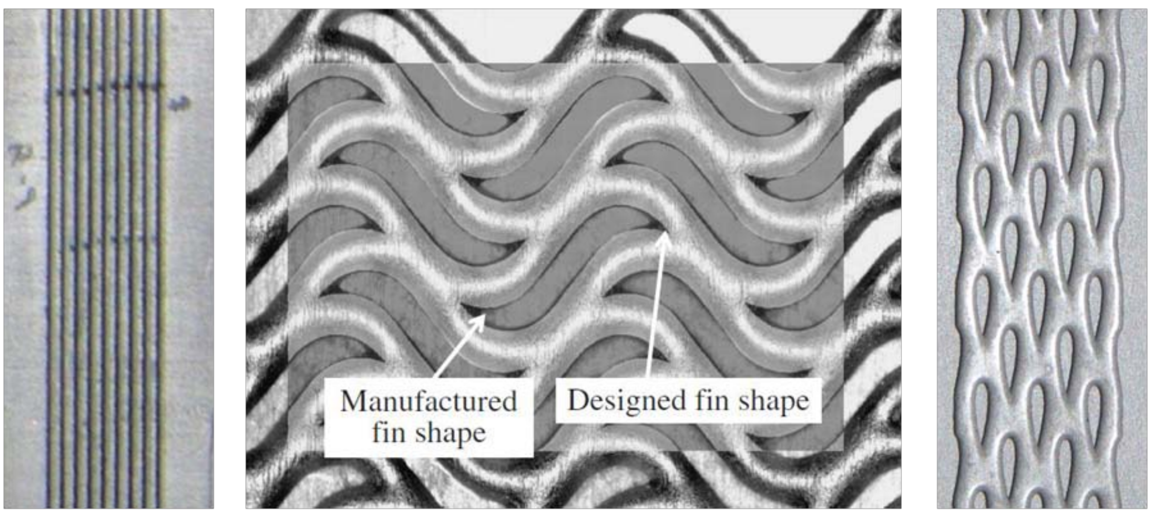

Figure 5. Traditional (far-left), s-shaped fin, and airfoil fin PCHE surface geometries. Directly casting a heat exchanger with flow channels similar to the s-shaped and airfoil fin surfaces could be done using casting cores reminiscent of perforated plates.

Constructing the highly-interconnected channel spaces of these surfaces produces a casting core more like a perforated plate with manageable aspect ratios between each interconnection. This type of casting core can be slotted into polymer-bound sand or investment casting molds to produce a heat exchanger in a single casting operation.

Forming the channel surfaces at low pressures and temperatures as casting cores allows for unprecedented flexibility in channel design. While advanced PCHE surfaces interconnected in two dimensions can be emulated, interconnection can also extend into three dimensions as shown in *Figure 6*. This channel geometry extends the benefits of channel curvature toward enhanced heat transfer with minimal increase in pressure drop from two dimensions to three.

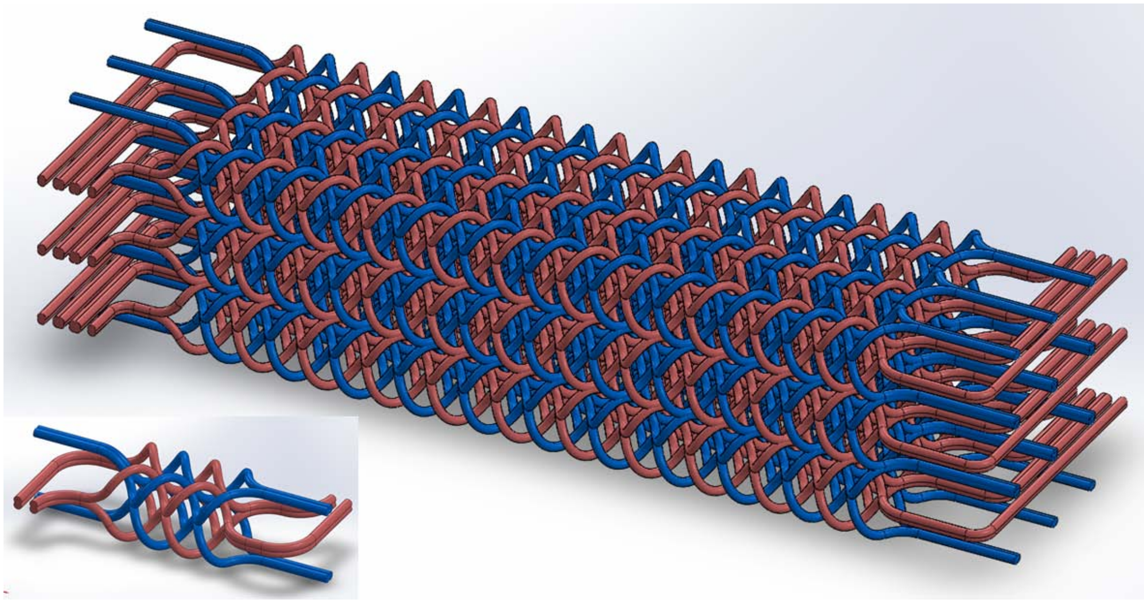

Figure 6. A counter-rotating double-helical geometry proposed for use as a cast metal recuperator between two similar fluids. Red channels depict the "hot" flow side while blue depict the "cold" flow side. Channels from the same side interconnect throughout the body of the unit to themselves and intertwine with channels from the other flow side. Geometric parameters can be optimized to the particular flows involved.

The particular design in *Figure 6* is aimed toward recuperative duties between like fluids with each flow side, red for hot and blue for cold, interconnected to itself and intertwined with the other flow side. Such a casting core could be created using powder-bed 3D printing techniques. This geometry is highly symmetric, but asymmetric and more contoured flow channels could easily be created tailored to the heat exchange duty and size envelope of the unit. Finally surface features including turbulators and condensation ribs can be incorporated directly on the casting cores with minimal increase in fabrication cost and patterned into the final metal heat exchanger.

When cast as a monolithic block a CMHE is sensitive to the same thermal stress and plugging issues encountered when using PCHEs. Where rapid and frequent thermal cycling is required the CMHE concept may still lower production costs for heat exchange elements fabricated into a larger unit, such as the individual plate stacks for the unit-cell heat exchanger proposed by Brayton Energy and depicted in *Figure 7* (Musgrove, Pittaway, Shiferaw, & Sullivan, 2013). This option is particularly attractive for novel high-performance nickel alloys where high strength and creep resistance make the machining required for plate, shell, and wire product forms difficult.

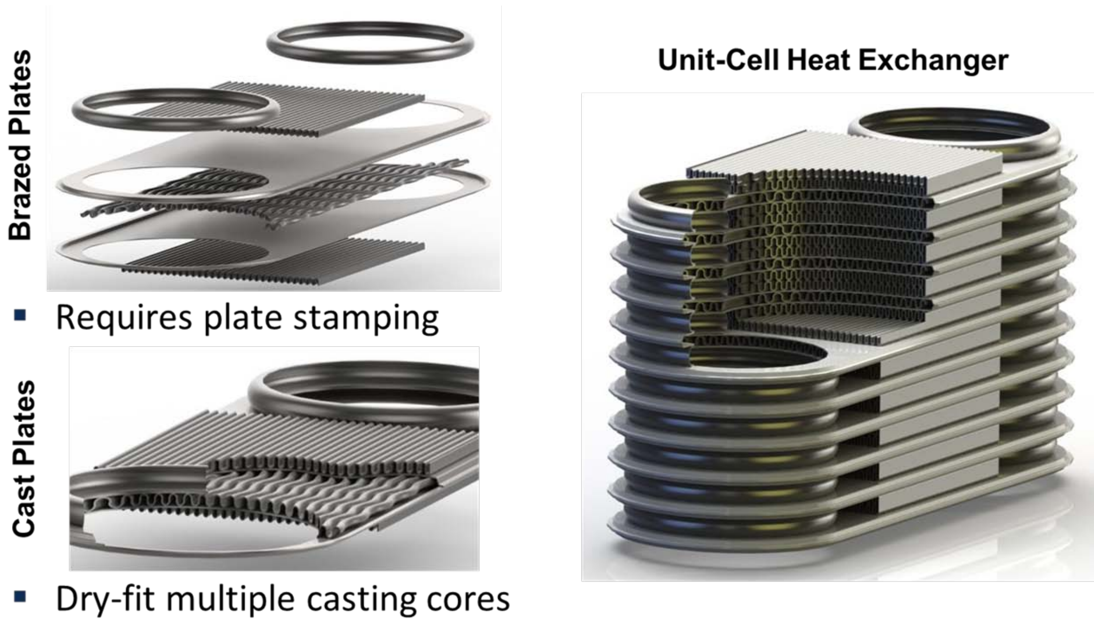

Figure 7. A comparison of the plate processing steps involved in producing a unit-cell heat exchanger using either bonded brazed or directly-cast plates. For the cast plates, finned or island-style surfaces would need to be used rather than the discrete sinusoidal channels shown.

Critical Research Areas for PCHEs

CMHEs hold great potential for reducing the cost of heat exchanger and heat exchange components, but being a relatively new technology they will require development in order to bring them to commercial use. There is limited industrial precedent for parts with similar fabrication techniques, including cast turbine blades, lattice block materials, and both stochastic and ordered metal foams as shown in *Figure 8*, but none found for the this specific application.

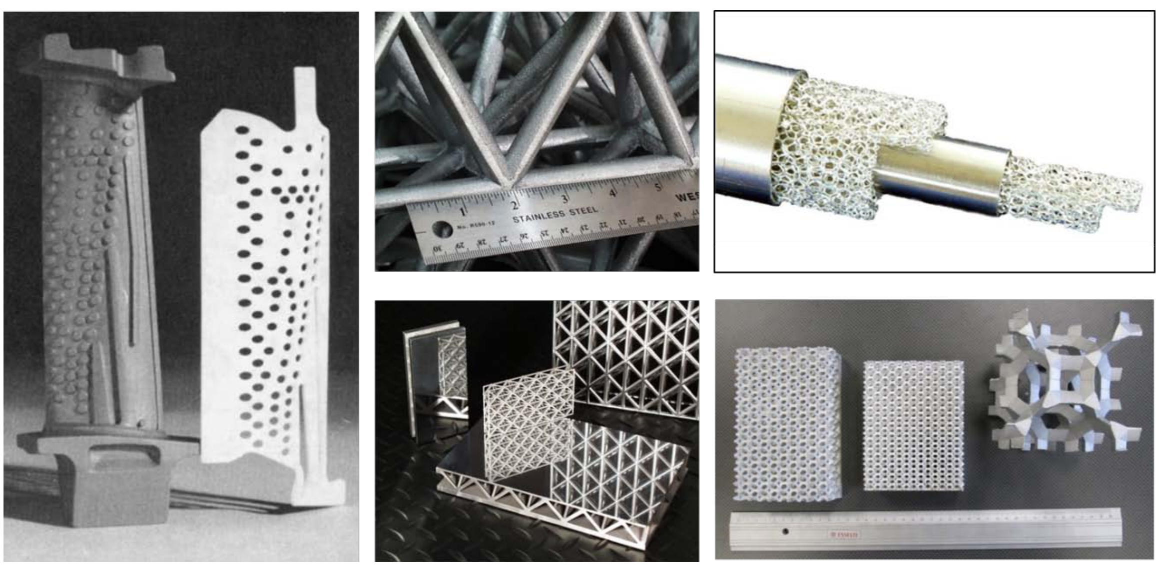

Figure 8. From left to right: internally-cooled turbine airfoil with its intricate casting core, examples of lattice block materials, and both stochastic and ordered metal foams. All of these parts are cast using processes similar to those suggested for CMHEs.

The most critical challenge to be addressed as CMHEs are developed will be methods and techniques for removing casting core material from the finished block. This process will involve a combination of chemical and mechanical means, combining aspects of the leachable casting core material used for turbine blades with the high-pressure water jetting used to remove core material from cast metal foams.

Castability of various heat exchange channel geometries will be the next major challenge, but will be highly-dependent on the specific design of the unit and material involved. Clearances between casting cores will need to be tailored to the flowability of the melt. The cast metal foams shown at the right of *Figure 8* are fabricated from aluminum, but steel, nickel, and other more viscous alloys have been cast into similar foams. Centrifugal or pressure-casting techniques may be needed for very tight clearances with highly viscous melts.

Finally, an ASME code case will need to be developed in order to allow the certification of CMHEs as pressure vessels. It is anticipated that monolithic CMHEs may be certified by a process similar to PCHEs as the material concepts and geometry involved are similar, through more testing may be required for CMHEs to assure uniformity in alloy composition and crystallization throughout the part.

CONCLUSIONS

Sandia National Laboratories is working to advance both near-term PCHE and mid-term CMHE technologies to inform heat exchanger design and selection for commercially-viable SCO2 Brayton cycles. Although several different cycle layouts have been proposed for nuclear, concentrating solar, fossil energy, and heat recovery applications, they all share a common need for significant recuperative heat exchange. Lessons from the history of air Brayton cycles emphasizes that even where strong thermodynamic arguments exist to add recuperation and increase cycle performance, techno-economic optimization accounting for cost scaling of components with cycle performance while strongly influence the commercial potential of SCO2 Brayton cycles.

NOMENCLATURE

SCO2 = Supercritical Carbon Dioxide
PCHE = Printed Circuit Heat Exchanger
CMHE = Cast Metal Heat Exchanger
CBC = Closed Brayton Cycle
ASME = American Society of Mechanical Engineers
BPVC = Boiler and Pressure Vessel Code
SNL = Sandia National Laboratories
VPE = Vacuum Process Engineering
DBPS = Diffusion Bonding Performance Specification
SEM = Scanning Electron Microscope

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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.