Symposium on Supercritical CO2 Power Cycle for Next Generation Systems
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Plate Fin Heat Exchanger Design for the Supercritical CO_2 Cycle

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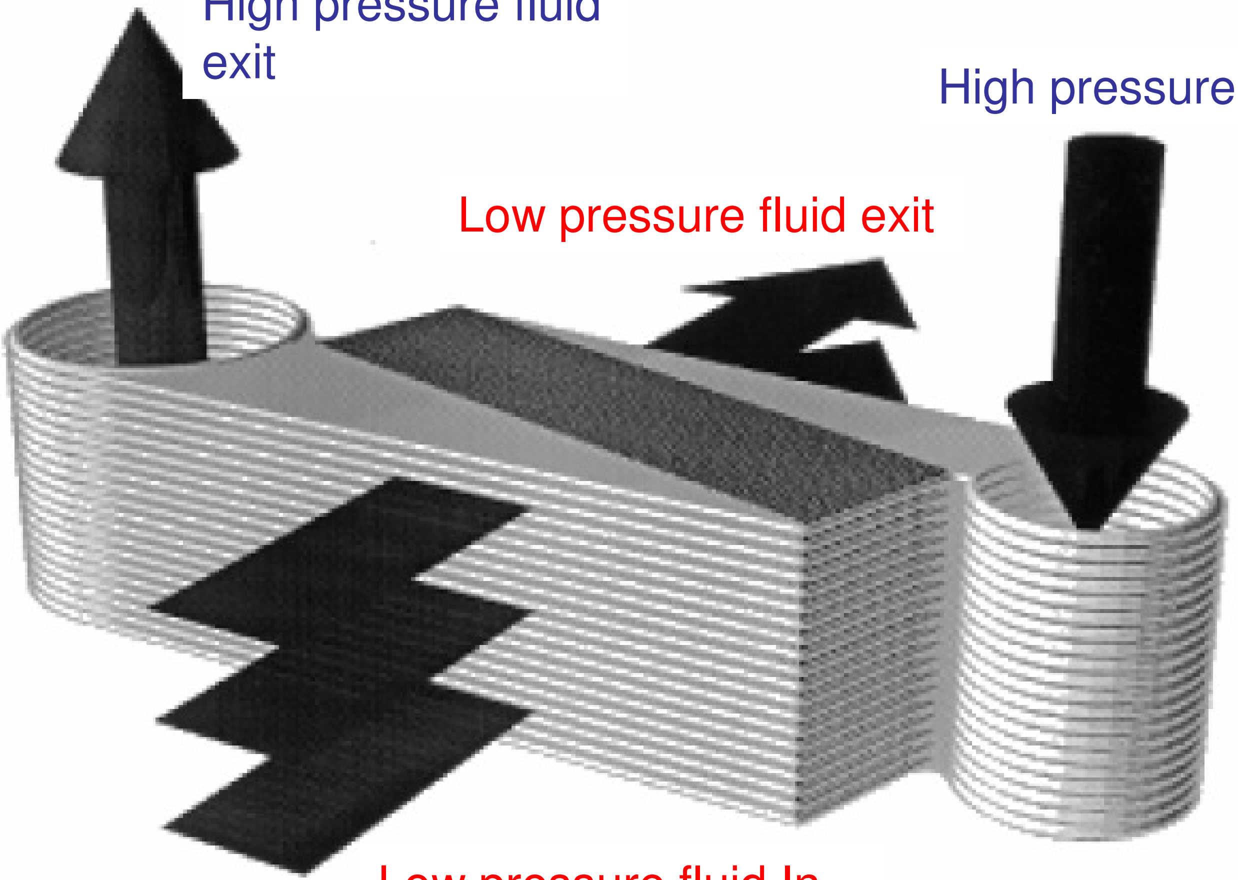
Hampton, NH USA

Presentation overview

- General Description of a Plate Fin Heat Exchangers for a Gas Turbine Recuperator
  - Gas turbine recuperators -500 to 700 C
- Design for high pressures for SCO2
- Performance and sizing for MIT’s 300 MWe SCO2 cycle

EXAMPLE of a PLATE FIN Heat Exchanger by Ingersoll-Rand



High pressure fluid exit

High pressure fluid in

Low pressure fluid exit

Low pressure fluid In

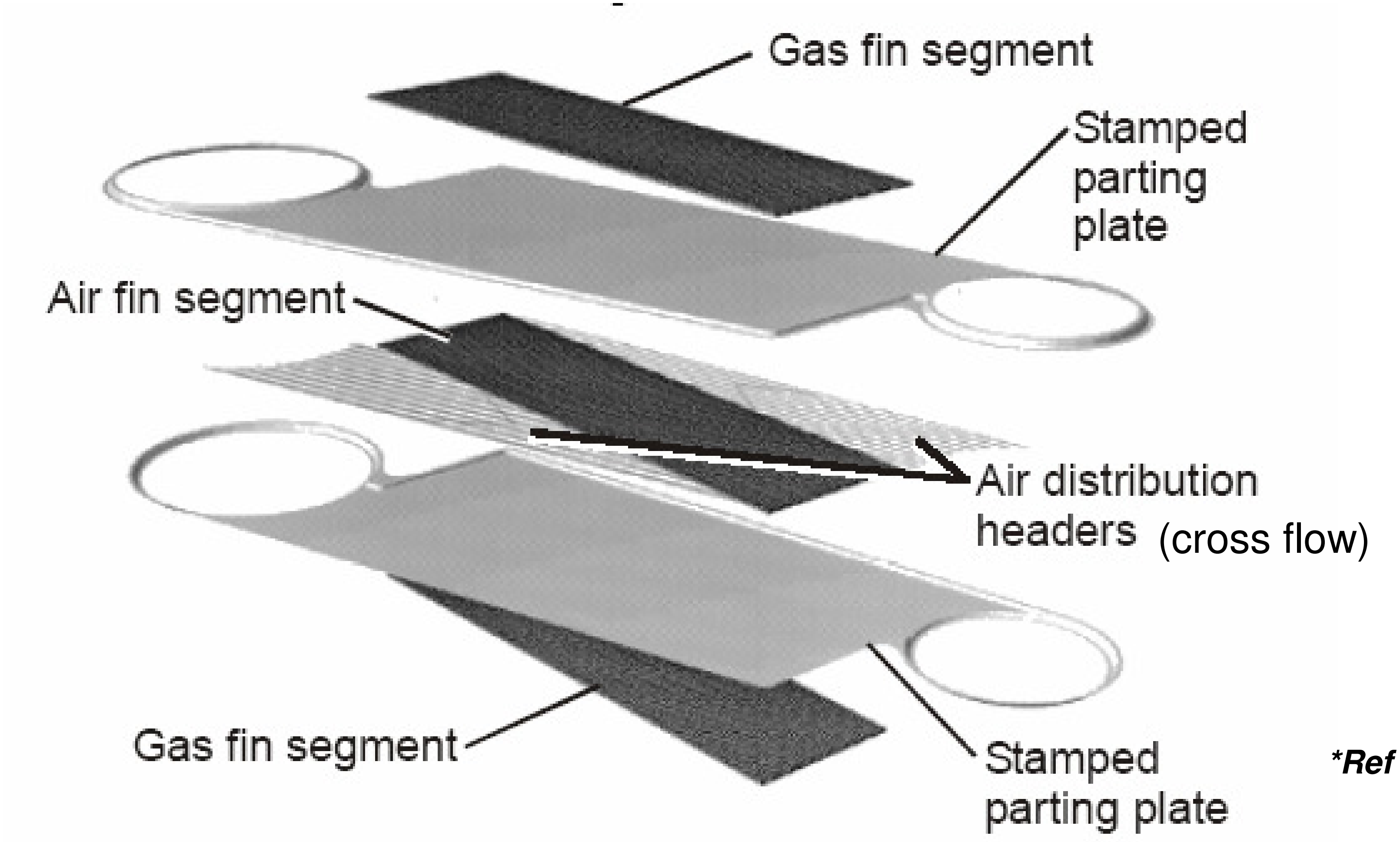
PLATE FIN **Recuperator Flow Paths**

Ref 3 (IR)

Compliant – light weight structure

- design to tolerate large thermal gradients and associated differential expansion

Ingersoll-Rand Gas Turbine PLATE-FIN Recuperator - Proven in Military and Industrial Gas Turbines



Ref 3 (Kesseli)

High pressure is contained within individual cell (in this case the “air fin”)

The low pressure gas is located on the free surface outside the cells pressure boundary

EXAMPLE of a PLATE FIN Heat Exchanger by Ingersoll-Rand

High-pressure fluid in integral manifolds

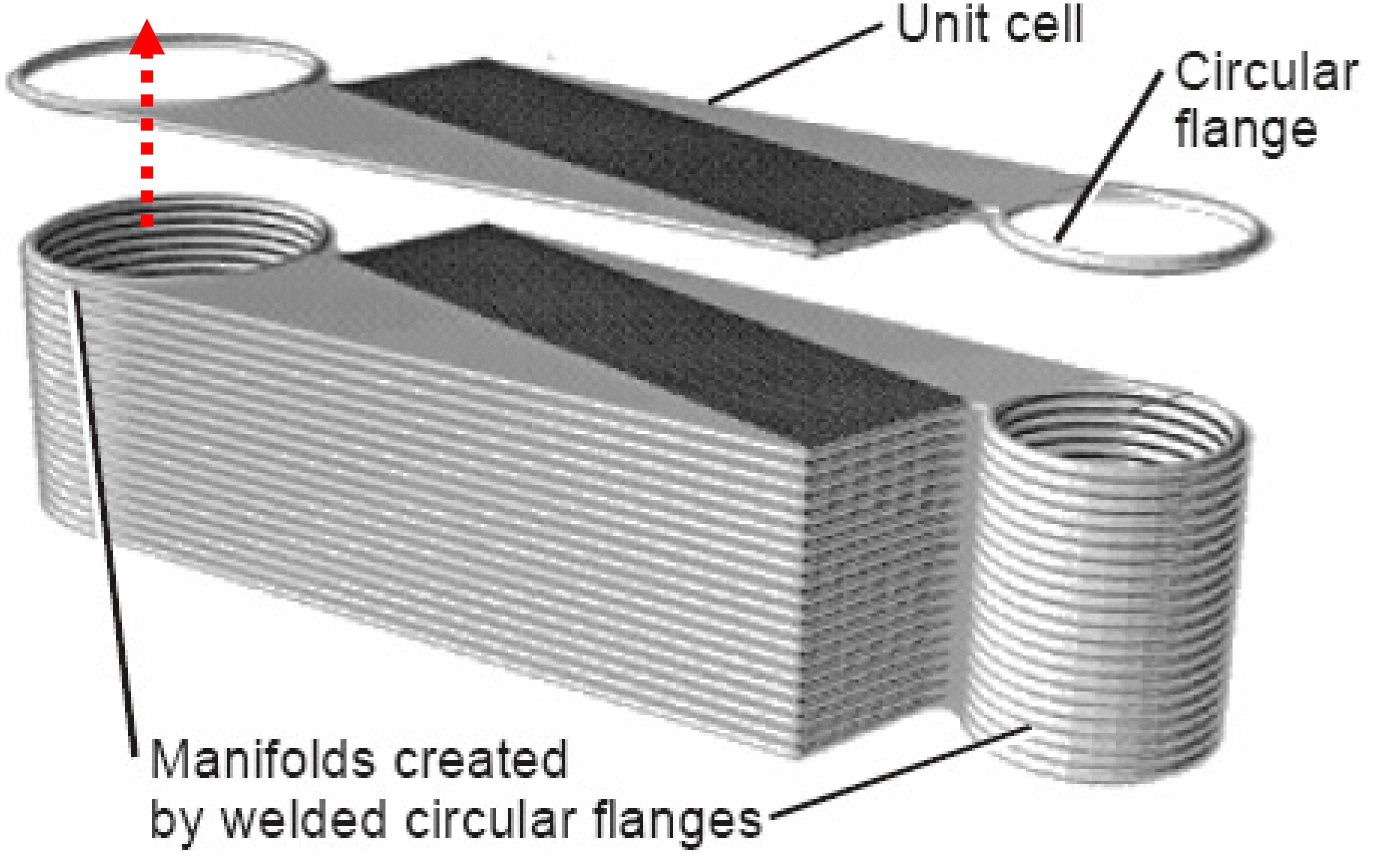


PLATE FIN **Core Fabrication**

Ref 3 (Kesseli)

Individual cells attached at manifolds only, not within the core matrix.
This allows the core have flexibility like “deck of cards”

EXAMPLE OF PLATE FIN
Finished Gas Turbine Recuperator Core – by Ingersoll-Rand

Ref 4 (Kesseli)

Plate fin status for SCO2

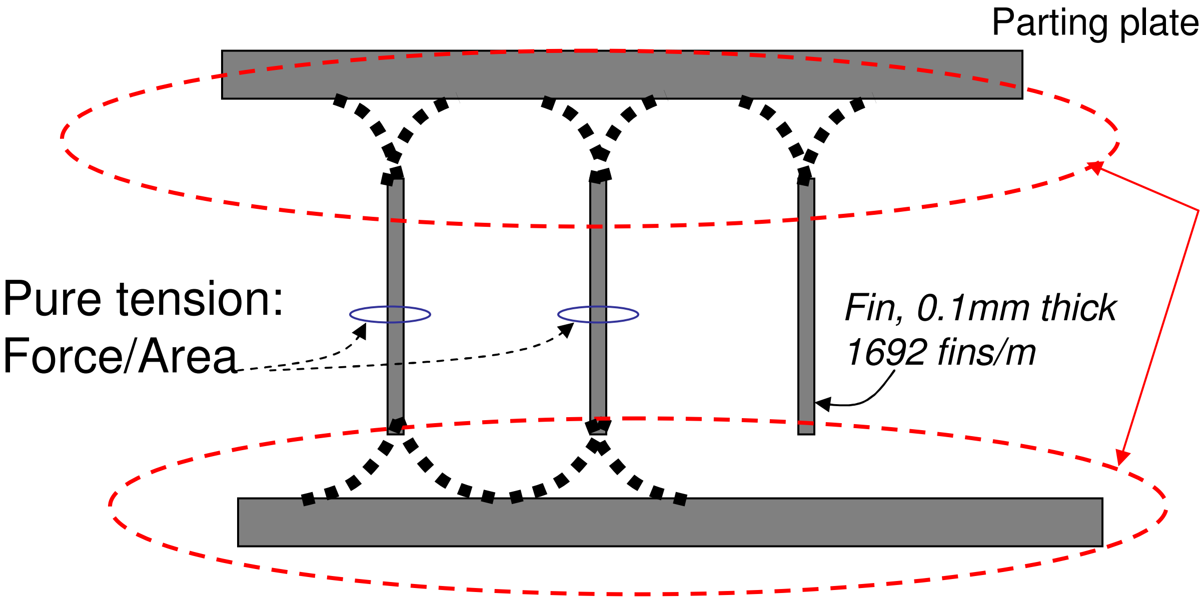
Typical differential Pressure = 12MPa
Typical max LP gas temp = 530 C

- Plate Fin heat recuperators have proved their integrity in the extreme environment of a gas turbine
  - Higher temps than SCO2
  - Higher temperature differentials (potentially higher thermal stress)
  - Rapid thermal transients
  - But moderate differential pressures (<1.5 MPa) (gas turbines)

- Current development of recuperators for NGNP, and helium-Brayton cycles projects have resulted in an expanded design for higher pressures.
  - Pressures differentials of 6 to 9 MPa and

- The following slides review the issues associated with the design for higher pressure

Fin stress – simplified analogy



Complicated stress regime, stress concentration, bending, material properties, braze material diffusion.

Under normal pressure and temperature, the fin will re-align from its manufactured state so that the majority of the ligament is straight and normal to the pressure force. The stress through the cross section of the fin, away from the influence of the braze joint is simply:

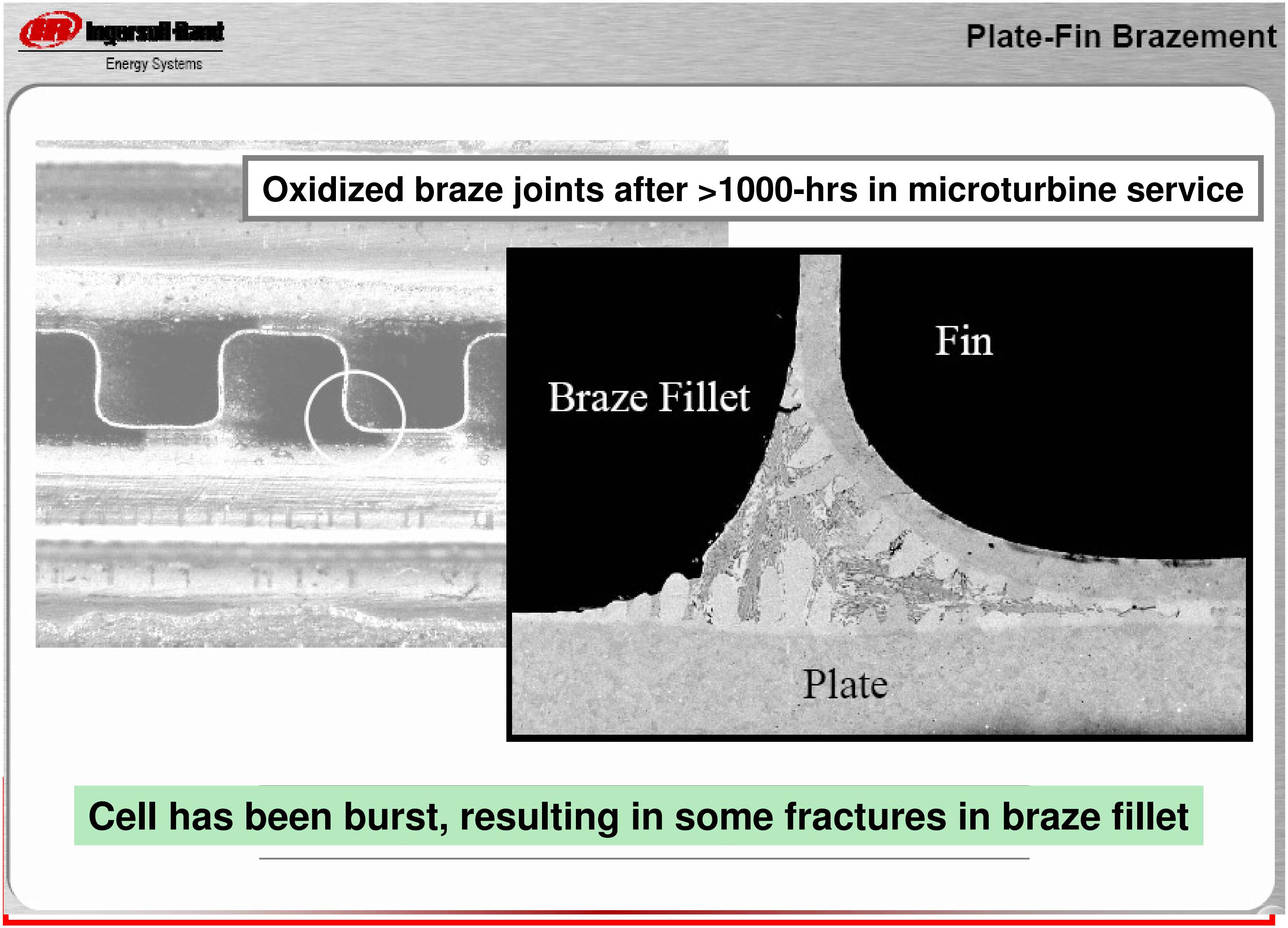
- Force/Area, where
- Pressure x fin spacing/ fin thickness

Various plate fin heat exchangers

A proper braze joint and fillet results in parent metal failure

- review of geometries in the open literature

1. Ingersoll-Rand Corp
2. Nordon Systems Corp.
3. Brayton Energy, LLC



Ingersoll-Rand
Energy Systems

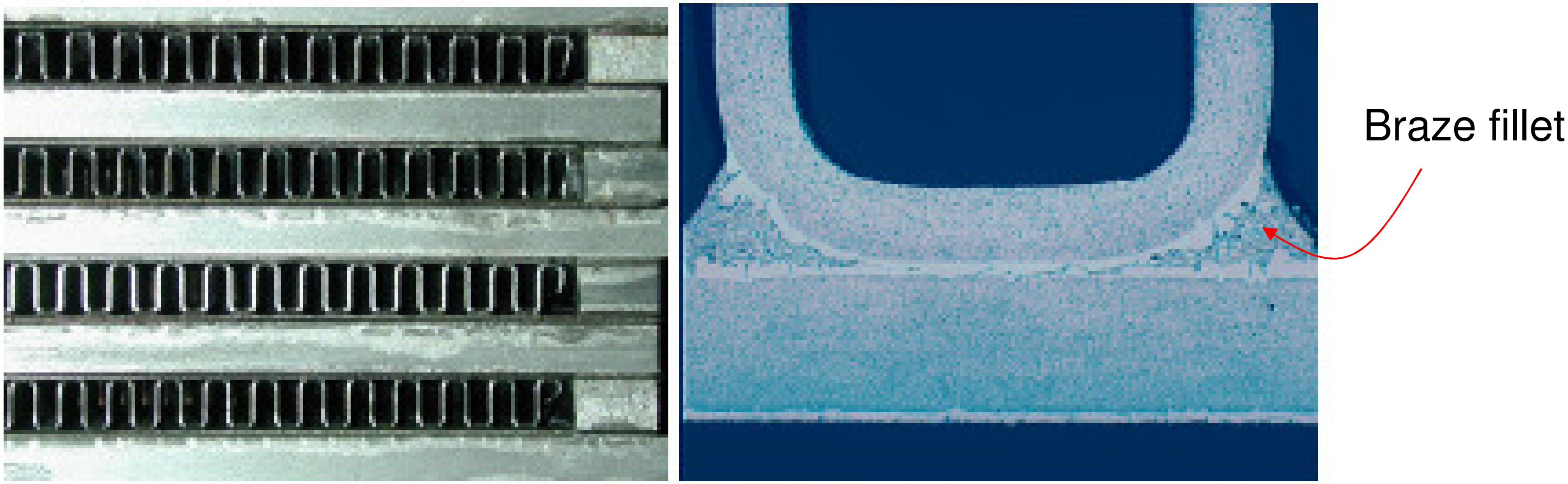
Plate-Fin Brazement

Oxidized braze joints after >1000-hrs in microturbine service

Cell has been burst, resulting in some fractures in braze fillet

From 2005 IGTI conference, author: Jim Nash

Nordon – plate fin



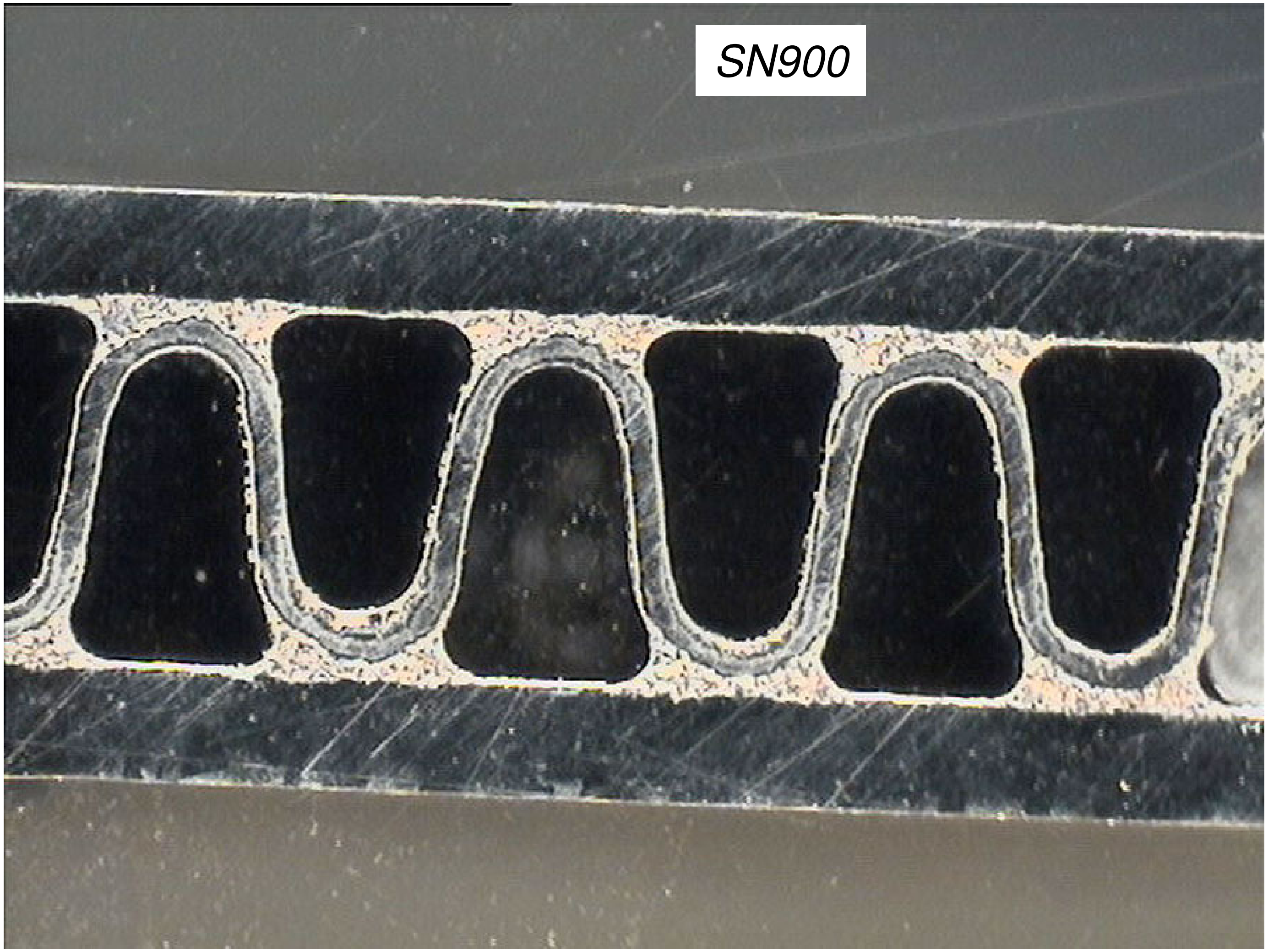
RE 7 - Plate-fin heat exchangers – courtesy of NORDON.

The use of Compact Heat Exchangers technologies for the HTRs recuperator application per proper design

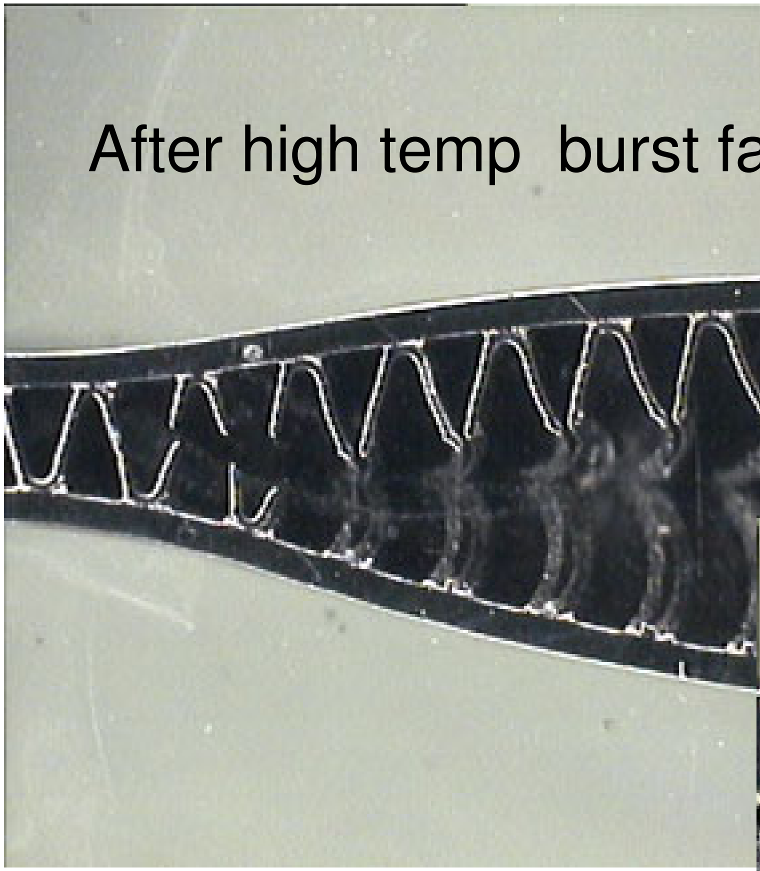
Patrice Tochon(1), Christian Mauget(2) & Frank Pra(1))

Brayton Energy Heat Exchanger – designed for PBMR (6 MPa differential pressure)

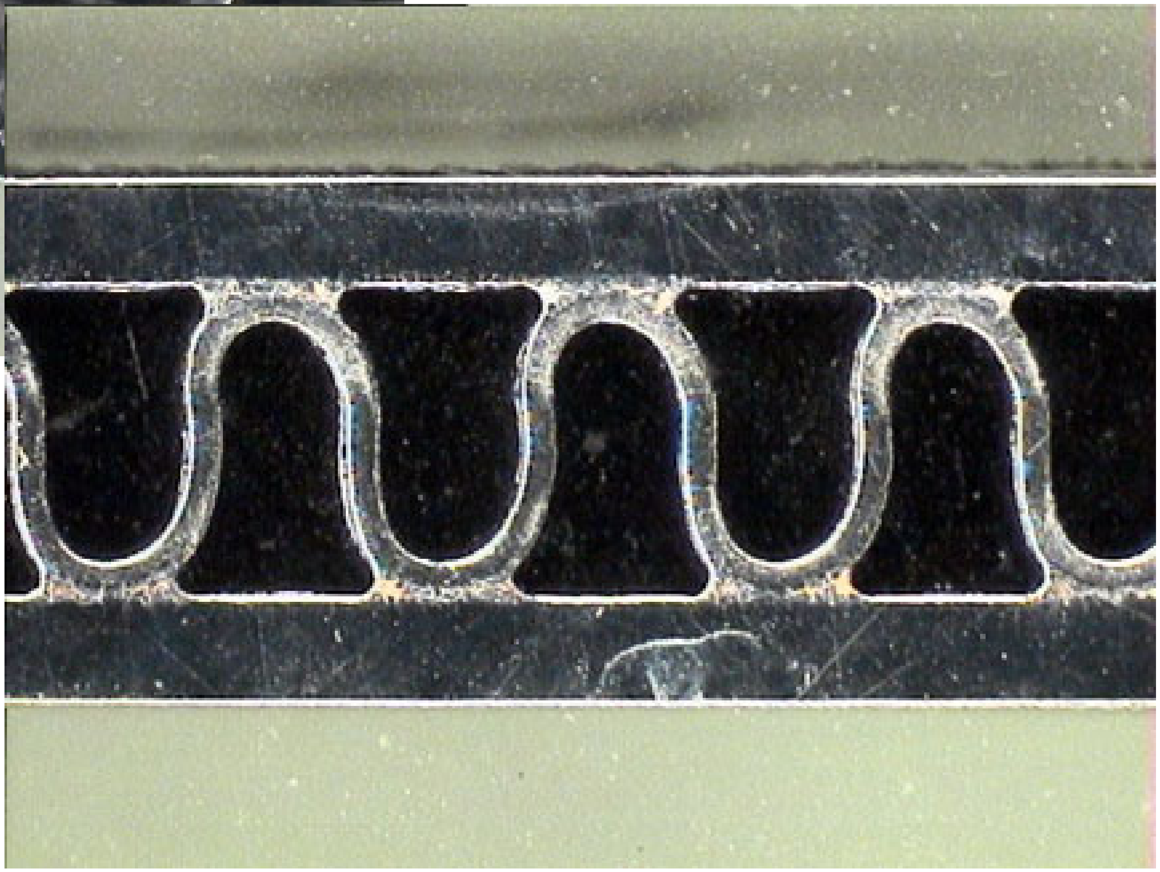
This cell burst at 68.2MPa gas pressure – room temp.



After high temp burst failure – note parent metal failure in fin



Sample of highly
strained, but not ruptured
section of same cell



ASME Creep correlations

- $P=T(c+\log_{10}t)$ *where P is the Larson-Miller parameter*

- with T the temperature in K, c=20 a constant and t the time in hours.
- Figure 5 (next slide) shows the master curve of the Larson-Miller Parameter for Alloy316L
  - for the temperature range 700 K-1100 K and
  - time range of 1 to $3\mathrm{x}10^5$ hr [4].

- Figure 5 shows the values restricted to P>=17,825. A line of best fit is as follows:

$$S.R. = 8065.9-0.897*P+3.371*(10^{-5})*P^2-4.2729*(10^{-10})*P^3$$

- Reference [4]: ASME Code Cases : Nuclear Components. Case N-47-30, Section III, Division 1. 1992 ASME Boiler and Pressure Vessel Code.

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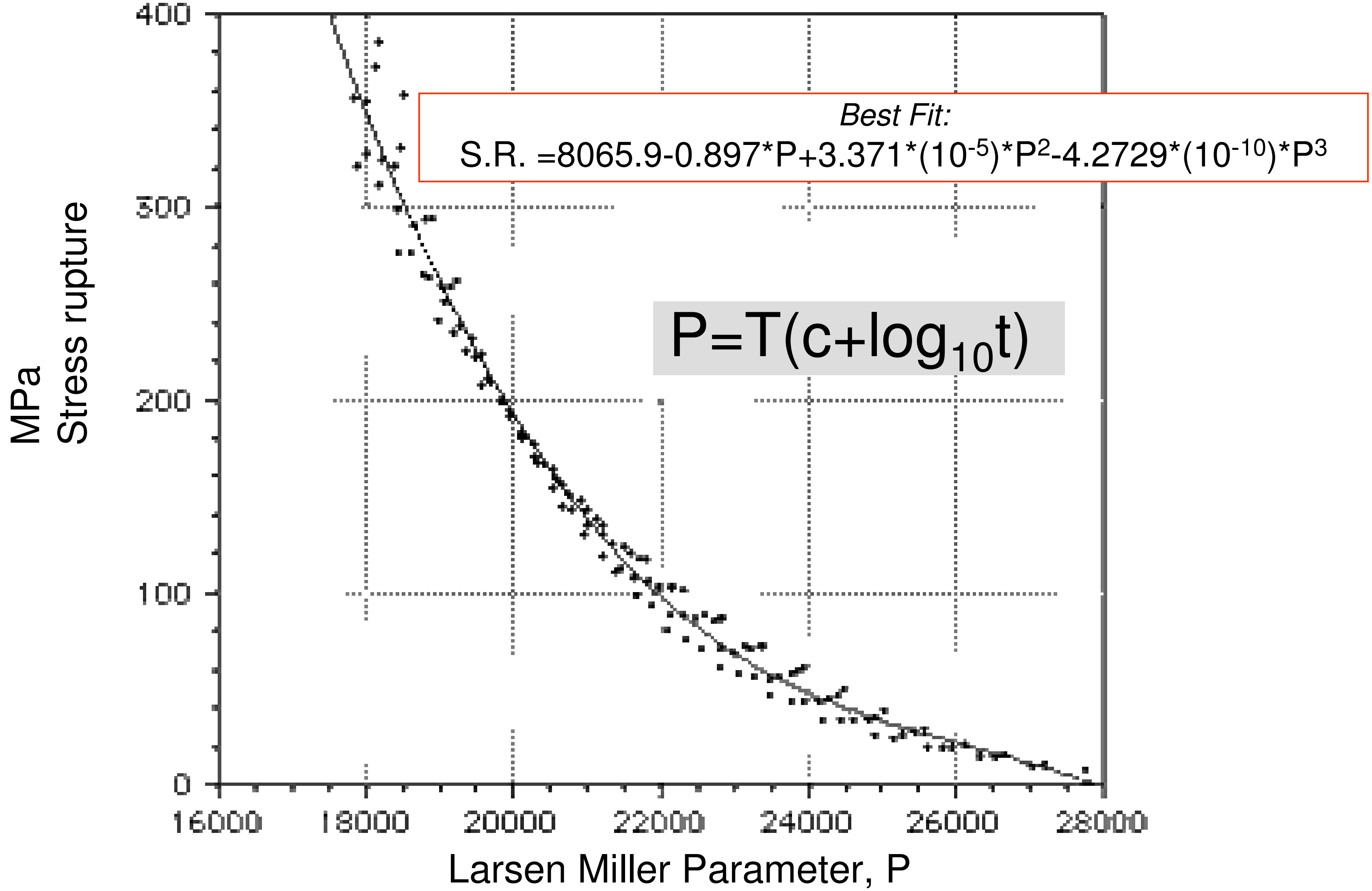


Best Fit:

$$S.R. = 8065.9 - 0.897*P + 3.371*(10^{-5})*P^{2} - 4.2729*(10^{-10})*P^{3}$$

$$P = T(c + \log_{10} t)$$

Figure 5 : Larson-Miller parameter versus stress to rupture

Recommended Plate fin layout

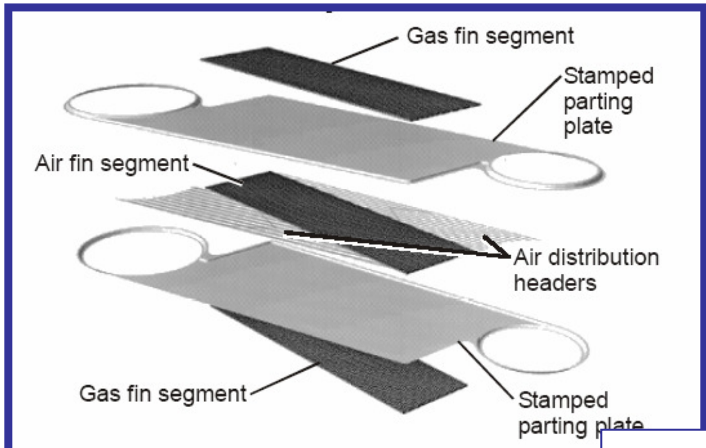
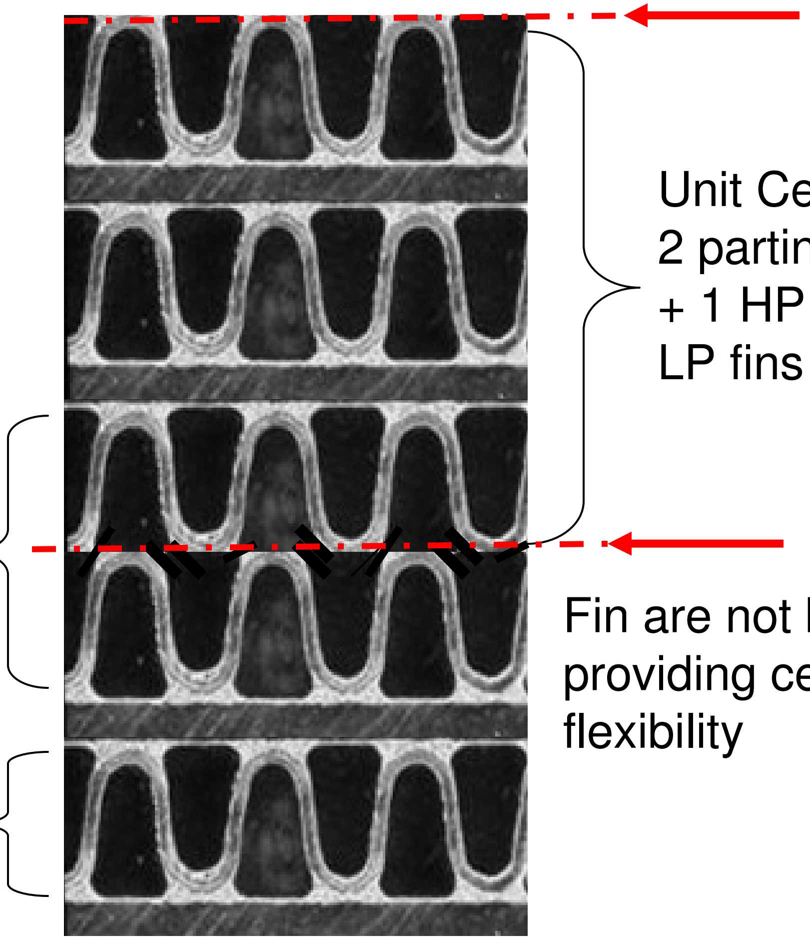


Figure 1. Recuperator Unit Cell (Exploded)

Ref 3



Unit Cell =
2 parting plates
+ 1 HP fin + 2
LP fins

Fin are not bonded, providing cell to cell flexibility

Stacked fin on Low Pressure side

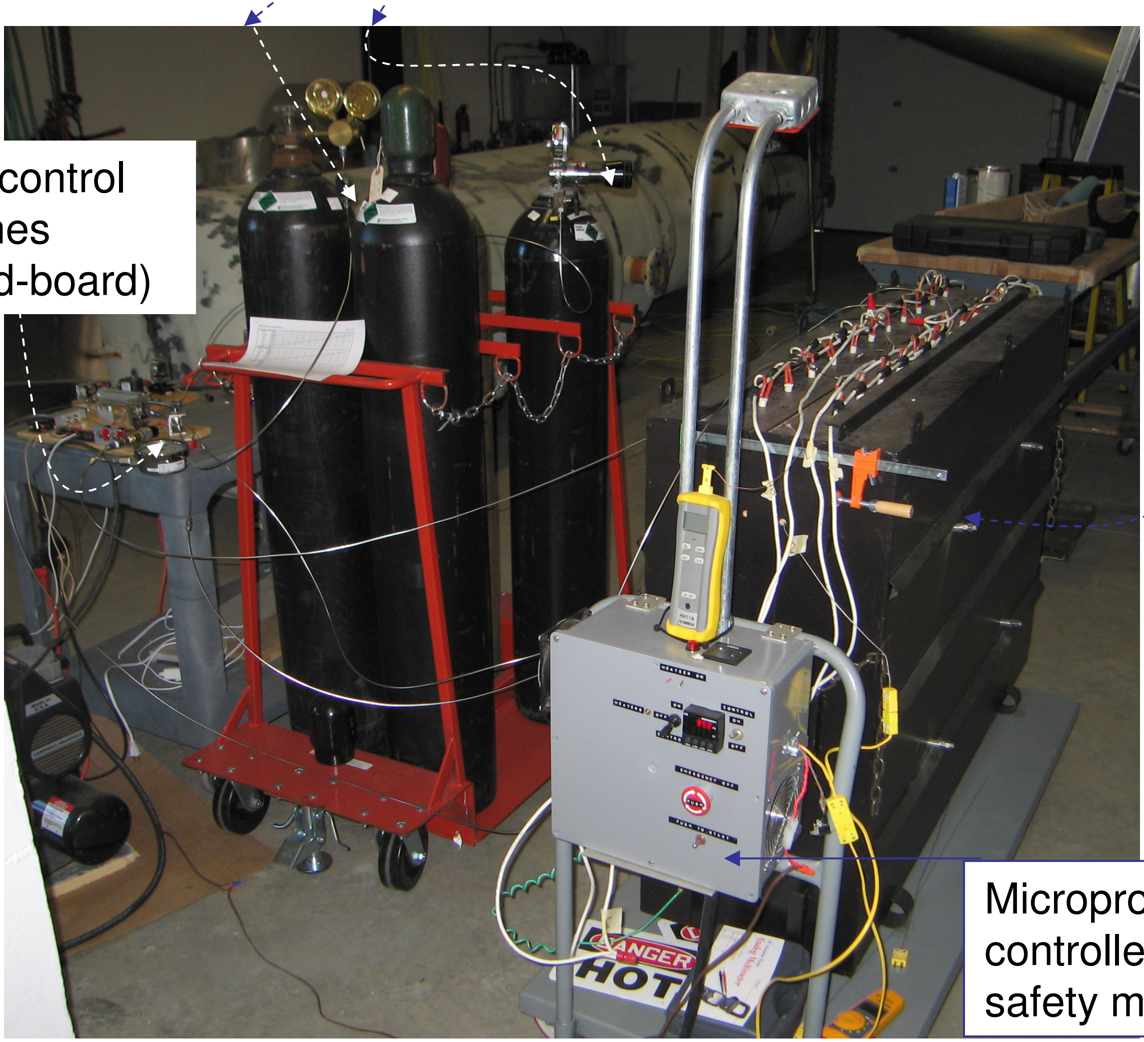
- total freedom to select fin height and density suited for fluid properties
- Non-structural

Single high-pressure side

- contains pressure

For SCO2 Case studies, 43 to 55 fins/inch, 0.1mm thick fins

Brayton Creep Test Experiments – Ongoing characterization of fin structures



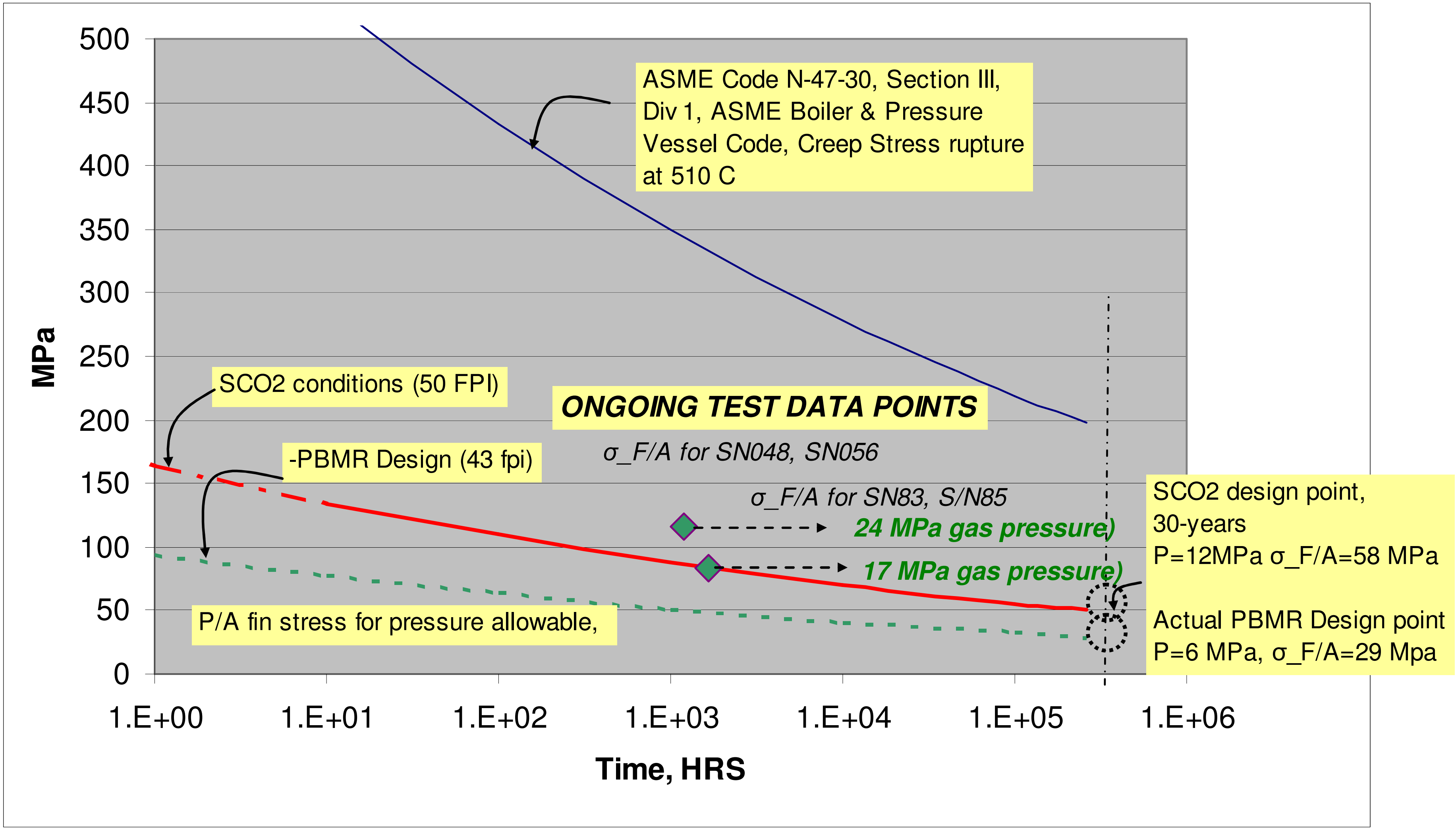
Gas bottles (N2)
- P = 17MPa
- P = 41.3 MPa

Pressure control
switches
(Bread-board)

Test Section
volume
1100x700x150
mm

Microprocessor
controller and
safety monitor

Time-Temperature Extrapolation – showing Brayton test points



ASME Code N-47-30, Section III, Div 1, ASME Boiler & Pressure Vessel Code, Creep Stress rupture at 510 C

SCO2 conditions (50 FPI)

-PBMR Design (43 fpi)

ONGOING TEST DATA POINTS

σ_F/A for SN048, SN056

σ_F/A for SN83, S/N85

24 MPa gas pressure)

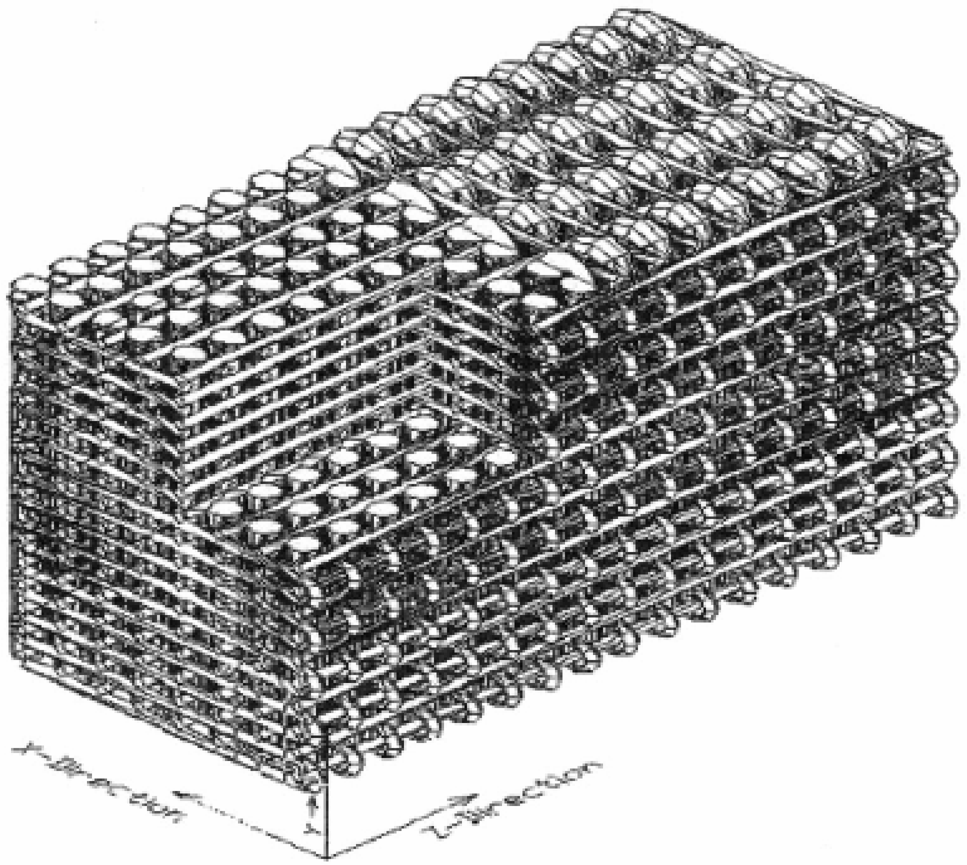
17 MPa gas pressure)

SCO2 design point,
30-years
P=12MPa σ_F/A=58 MPa

Actual PBMR Design point
P=6 MPa, σ_F/A=29 Mpa

P/A fin stress for pressure allowable,

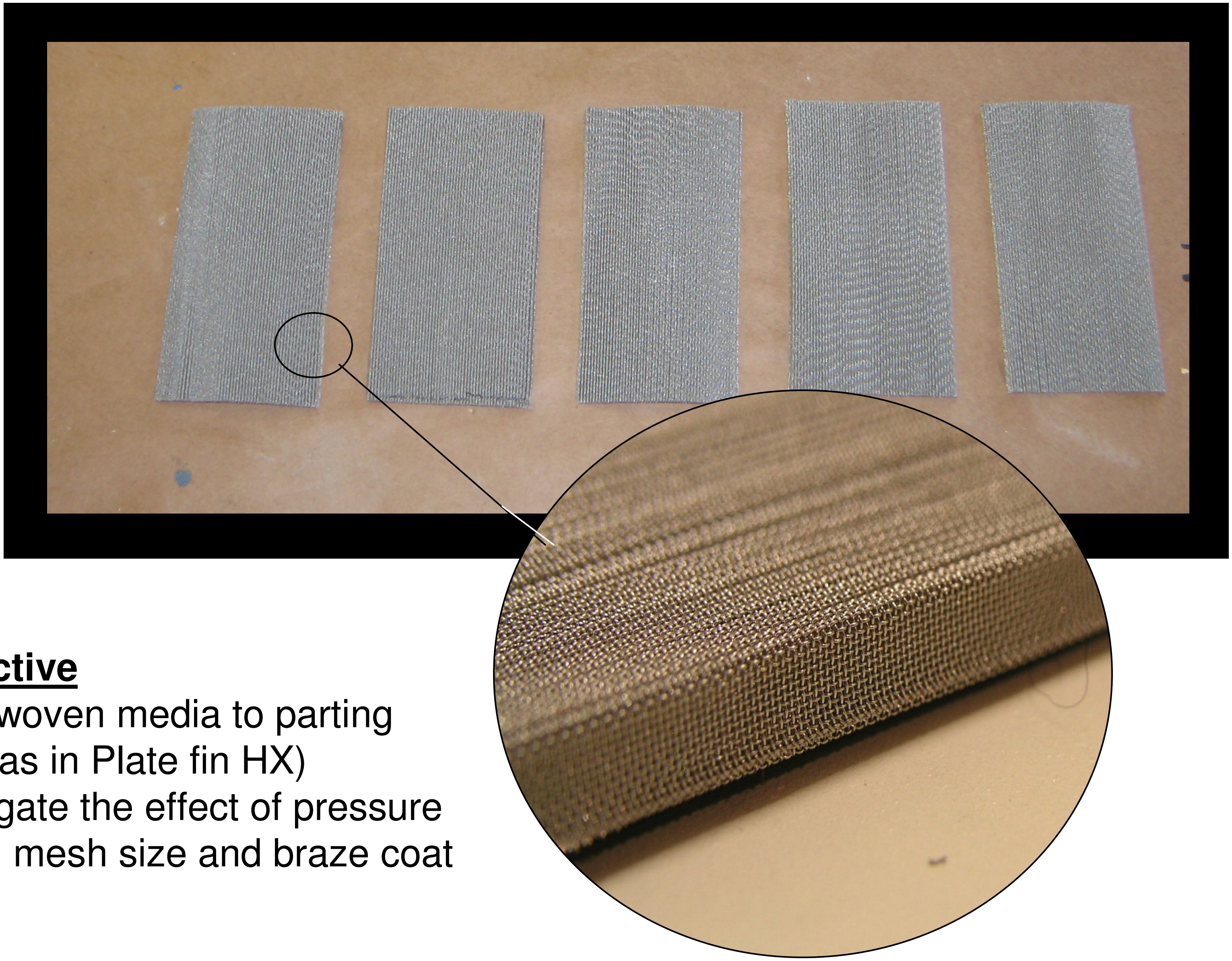
High density woven matrix media has significant benefit for SCO2 heat exchangers



Due to very high pressure and high molecular weight, pressure drop is not a problem. This plus the relatively low K is a strong motivation for:

- Ultra-high surface area
- small hydraulic diameters (<<1mm)
- Developing profile, rather than smooth long channels to elevated heat transfer
- ***Suitable for low pressure side of plates, external fin only – as it caries no load***

Brayton Energy Experimental Analysis of Woven Media

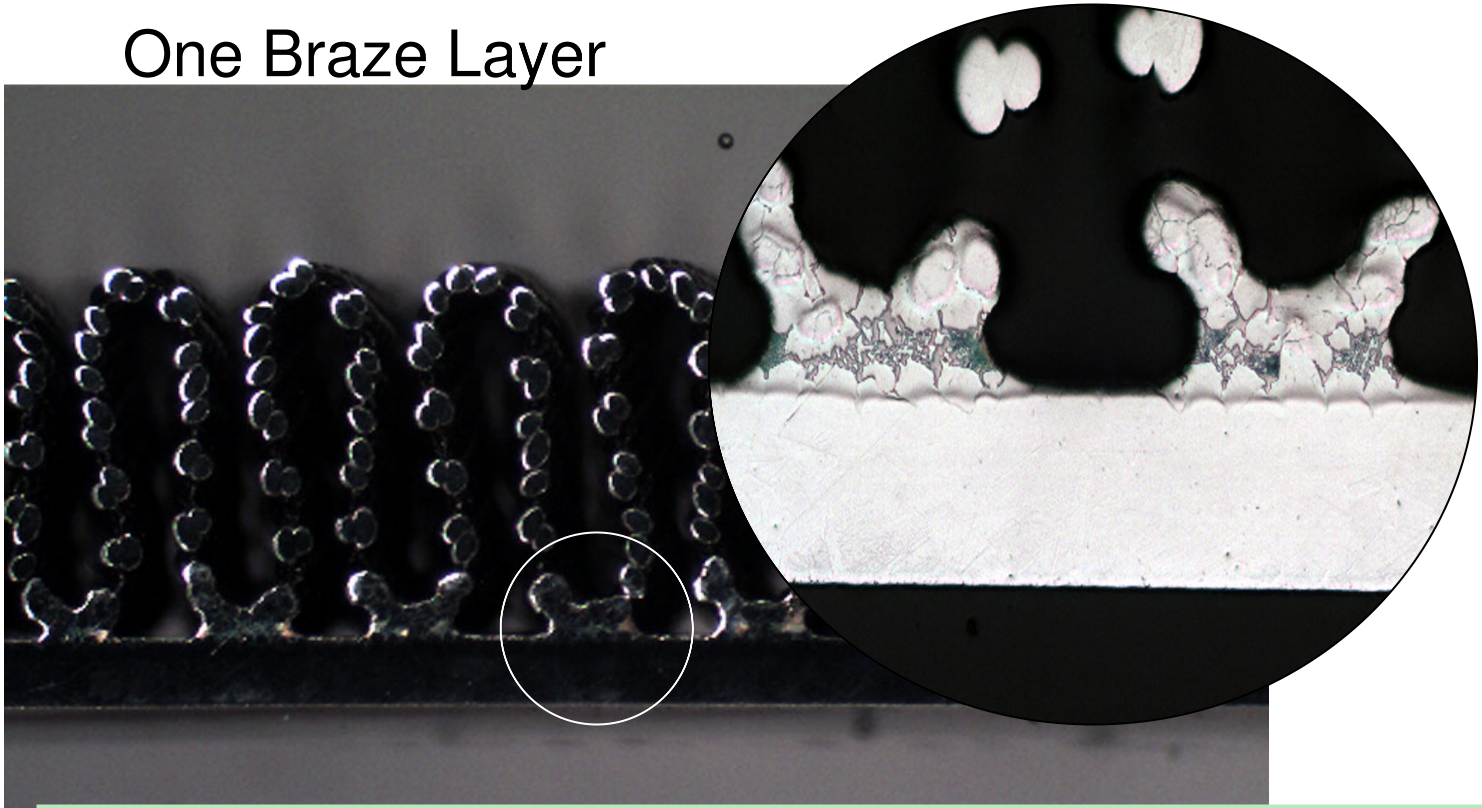


Test Objective

- Braze woven media to parting plates (as in Plate fin HX)
- Investigate the effect of pressure drop on mesh size and braze coat weight

Post-Braze Micrographs of Screen Heat Transfer Matrix

One Braze Layer

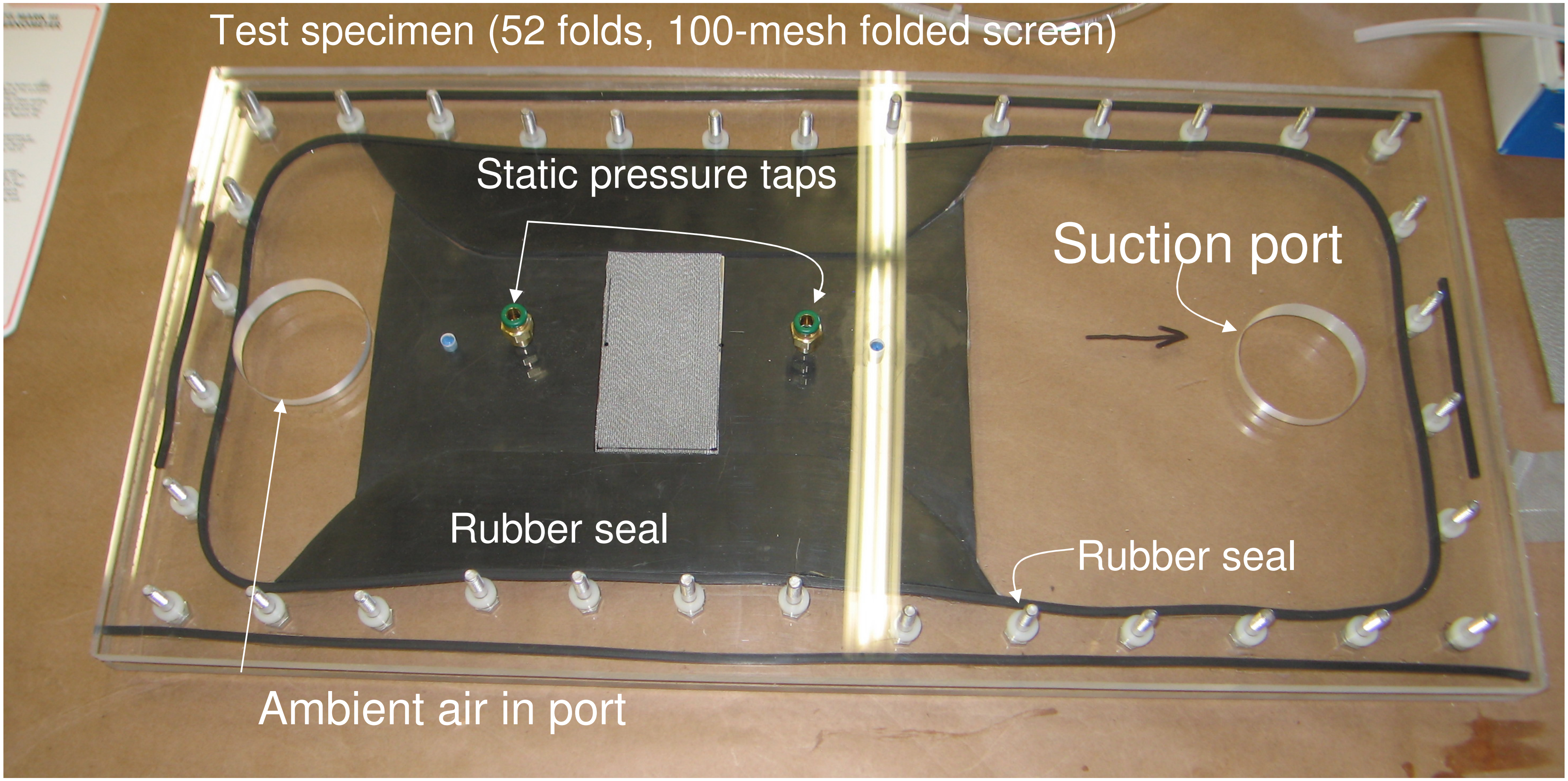


β=surface area/volume

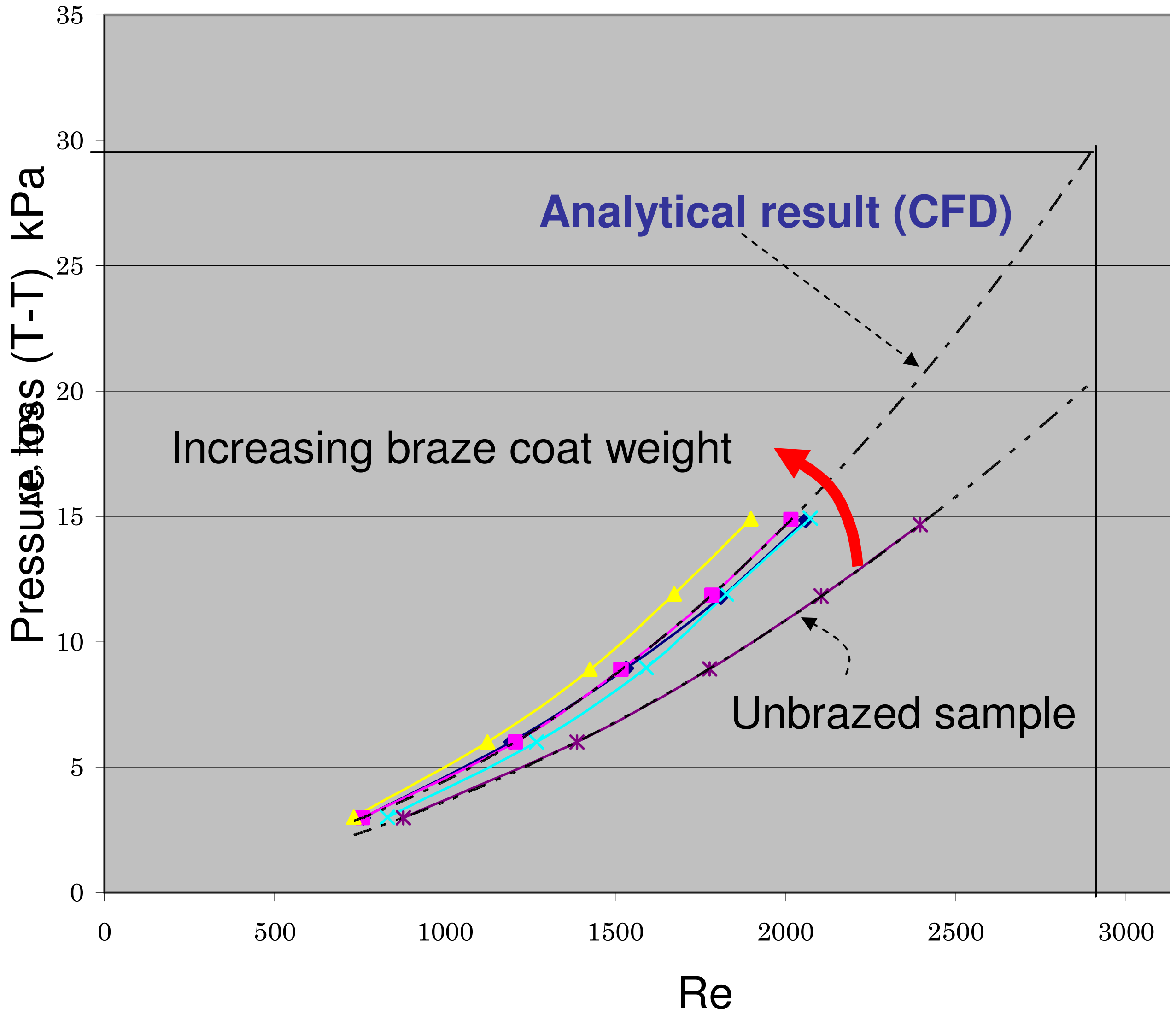
> 8000 m^2/m^3

$A_s*\eta/V$, where η= fin efficiency, $\beta\ \eta$ ~2000

Test Section – to assess braze wicking and propensity to increase pressure drop



BRAYTON ENERGY – WOVEN MATRIX TEST AND ANALYSIS RESULTS



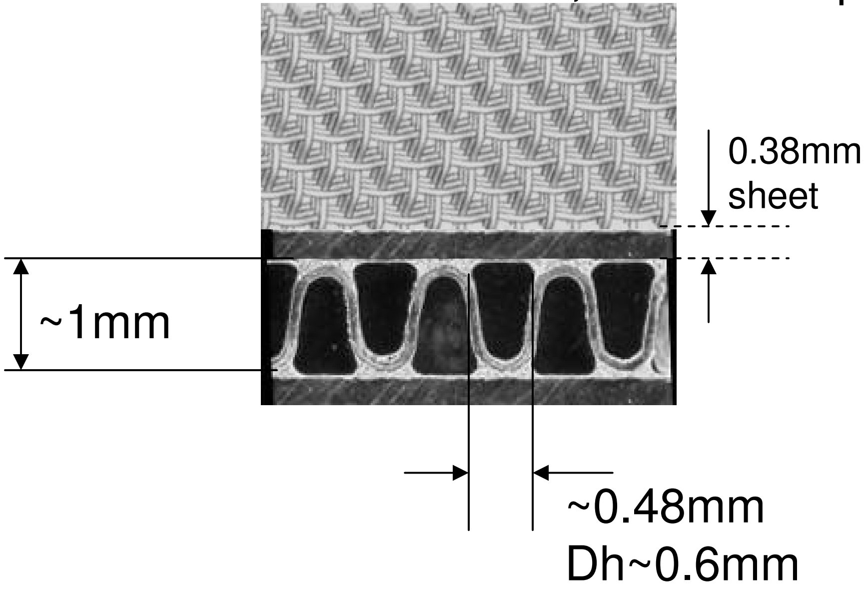
Braze and wicking can increase pressure drop by 40% vs. bare control sample.

It also increases fin surface efficiency, but this is not yet calculated.

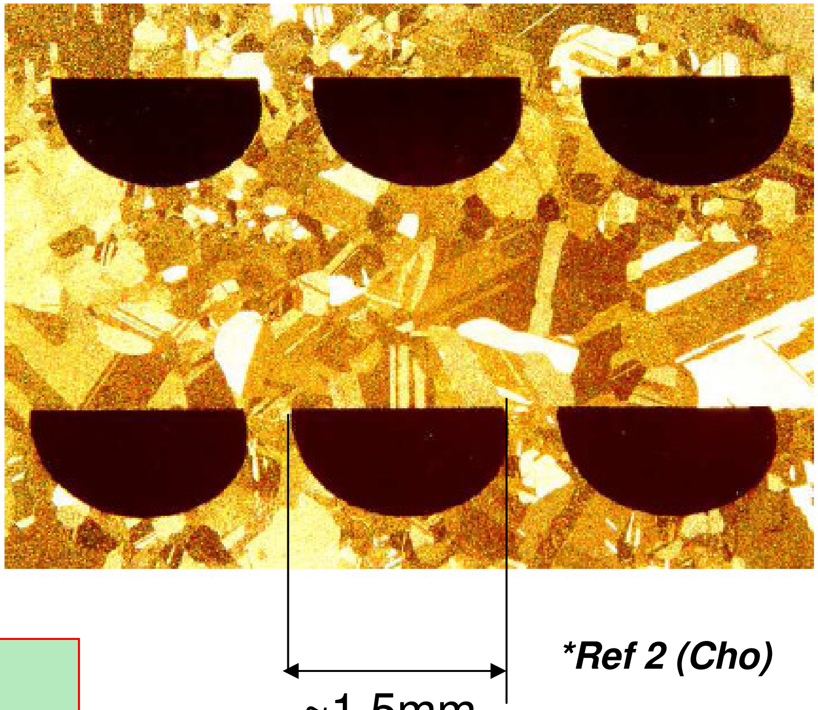
Testing performed in air and room temp

Scaled comparison of Brayton Plate-fin and Heatric

Wire mesh: 0.08mm wire, 0.259mm opening (Dh)



Ref 1 (Tochon)



Ref 2 (Cho)

Wavy fin -Surface area/volume – 4300/m
Screen mesh –surface area/volume ~7000/m
(screen also has elevated NU due to undeveloped velocity profile)

Surface area/volume – 194/m
From ref 3 (Cho) for 21MPa

Model assumptions for the analysis of the MIT SCO_2 300 MWe cycle

- Argonne National Labs, Dr. Anton Moisseytsev, Analysis of concept HX core, chemically etched plate heat exchanger for this conference paper.
  - Half-circular cross section – diameter =1.0mm
  - Plate thickness to passage dimension = 0.8 (attempt to thin plates for reduced pressure spec of 12 MPa)
  - Wavy pattern from Kays & London “Compact Heat Exchangers” friction and Coburn factors
  - “the SCO2 design is not necessary optimized” and is only a representation of the proprietary Heatric core.
  - The model neglects the detrimental impact of axial conduction
- Brayton Energy, J. Nash, A. Corbeil
  - Folded fin wavy pattern from Kays & London “Compact Heat Exchangers” friction and Coburn factors, and calibration tests at Brayton.
  - Screen thermal from “Thermal/Fluid Characteristics of Isotropic Plain-Weave Screen laminates as Heat Exchanger Surfaces, U.Nevada Park, Wirtz) and calibration test at Brayton

Performance comparison and specifications (based on MIT 300 MWe cycle analysis)

	rev3 (28Feb07)	**Brayton**	**Brayton**	**Brayton**
Specification	**Moisseytsev**	**Case 2**	**Case 4**	**Case 3**
Mass flow rate- HP, (kg/s)	2928	2930	2929	2930
Mass flow rate- LP, (kg/s)	2928	2930	2929	2930
Inlet pressure -HP, MPa	19.99	19.99	19.99	19.99
Inlet pressure -LP, MPa	7.93	7.93	7.93	7.93
Tin-LP	529.0	529.0	529.0	529.0
T-out-LP	167.3	167.3	167.3	167.3
Tin-HP, C	159.1	159.1	159.1	159.1
T-out HP	485.6	485.5	485.5	485.5
Energy- HP, (MW)	1222.4	1222.4	1222.4	1222.4
Energy-LP (MW)	1222.4	1222.4	1222.4	1222.4
Cp, avg-HP (J/kg/K)	1279.5	1278.0	1278.5	1278.2
Cp, avg-LP	1154.6	1153.4	1153.8	1153.4
Operating pressure Differencial, MPa	12.06	12.06	12.06	12.06
Pressure drop, LP (kPa)	90.115	112.6	93.8	28.8
Pressure drop, HP (kPa)	41.1	41.3	83.2	156.4
Reduced parameters				
Thermal Effectiveness,	0.9782	0.9780	0.9781	0.9778
DP/P -HP (%)	0.206%	0.37%	0.416%	0.782%
DP/P - LP (%)	1.136%	1.23%	1.183%	0.363%
DP/P-Total Fraction (%)	1.342%	1.599%	1.599%	1.146%

Size comparison

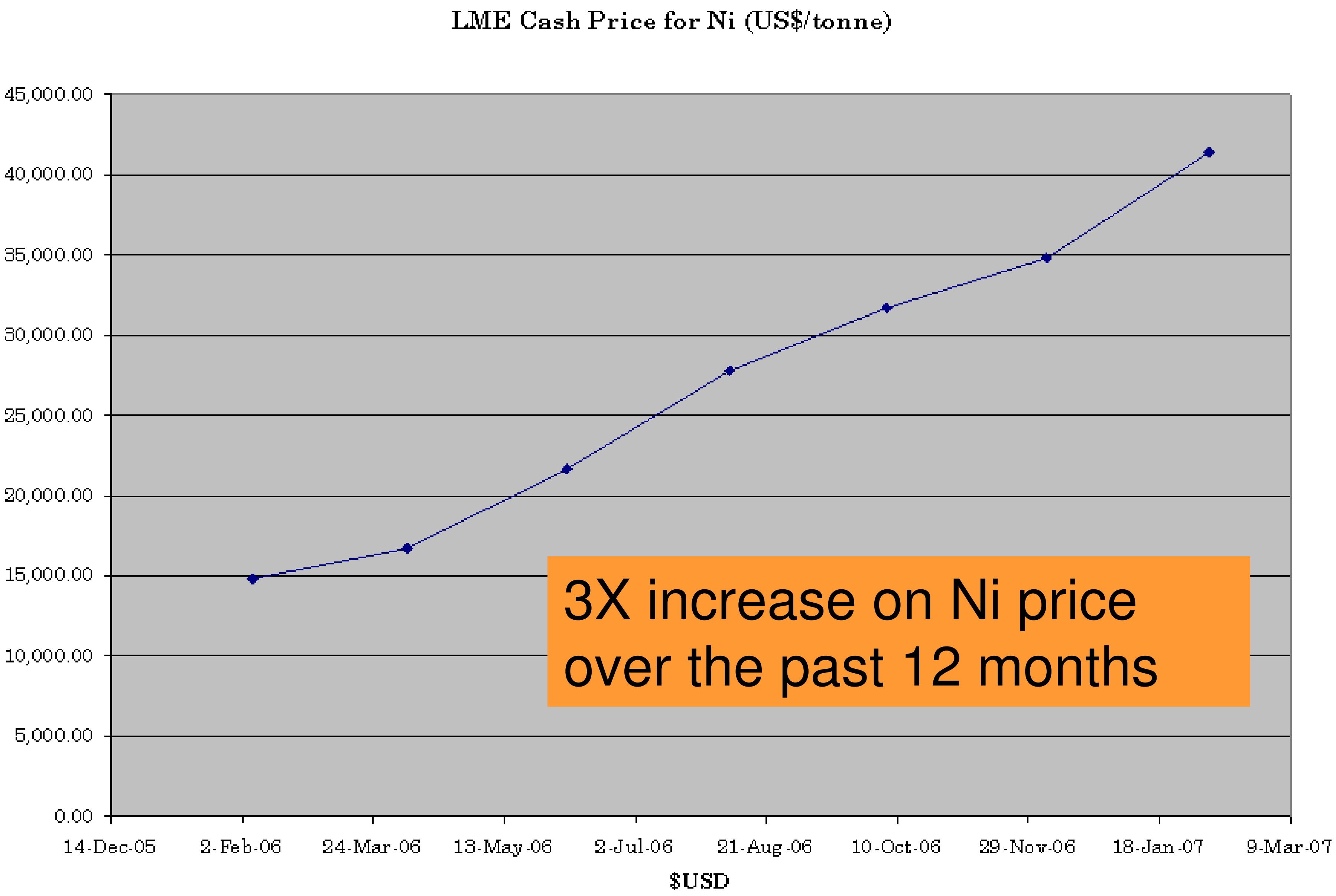
	rev3 (28Feb07)	**Brayton**	**Brayton**	**Brayton**
Specification	**Moisseytsev**	**Case 2**	**Case 4**	**Case 3**
Design Charactoristics				
Surface area/volume, /m		3543.7	4203.9	7058.8
Surface area/volume-effective, /m		2764.0	2996	1444
NU/Dh, HP side, 1/m		99,170	107,433	72,858
NU/Dh, LP side, 1/m		65,402	67,878	262,622
Plate thickness/Dh	0.8	0.2 to 0.4	0.2 to 0.4	0.2 to 0.4
Fin density,HP-side 1/m		1692.48	2164.8	1692.5
Fin density,LP-side 1/m		1692.48	2164.8	screen
Fin type, HP	wavy	wavy	wavy	wavy
Fin type, LP	wavy	wavy	wavy	Screen
Fin height, HP		0.89	1.02	0.889
Fin height, LP (2 each)		0.89	1.02	1.00
Physical Charactoristics				
Total mass, tonnes ('000kg)	264.52	85.91	72.32	63.55
Volume, excludes manifolds, (m3)	52.38	29.30	24.30	20.73
Void fraction	0.361	0.629	0.623	0.612
Manufacturing mass (including scrap)				
Cutting scrap (typical estimate) %	15%	15%	15%	15%
Etching scrap (= void fraction) %	0.361	0	0	0
Total raw material mass, tonnes ('000kg)	476	99	83	73
Specific parameters (bare core only)				
Specific mass or core materials, kg/kWe	1.586	0.3293	0.2772	0.2436
Specific volume (m3/MWe)	0.1746	0.0977	0.0810	0.0691

Comparison between He-PBMR and SCO2 cycles specific mass of HX core

	rev3 (28Feb07)	**Brayton**	**Brayton**	**Brayton**
Specification	**Moisseytsev**	**Case 2**	**Case 4**	**Case 3**
Specific parameters (bare core only)				
Specific mass or core materials, kg/kWe	1.586	0.3293	0.2772	0.2436
Specific mass of He PBMR case study		0.2230		0.1868
Cycle Comparision				
Relative cycles: He /SCO2 specific weight		0.6773		0.7670

Weights for heat exchanger cores only, omitting manifolds, piping, and Class-1 pressure vessel. Only the High Temperature Recuperator for the SCO2 is included.

Metal cost is rising – Designers beware

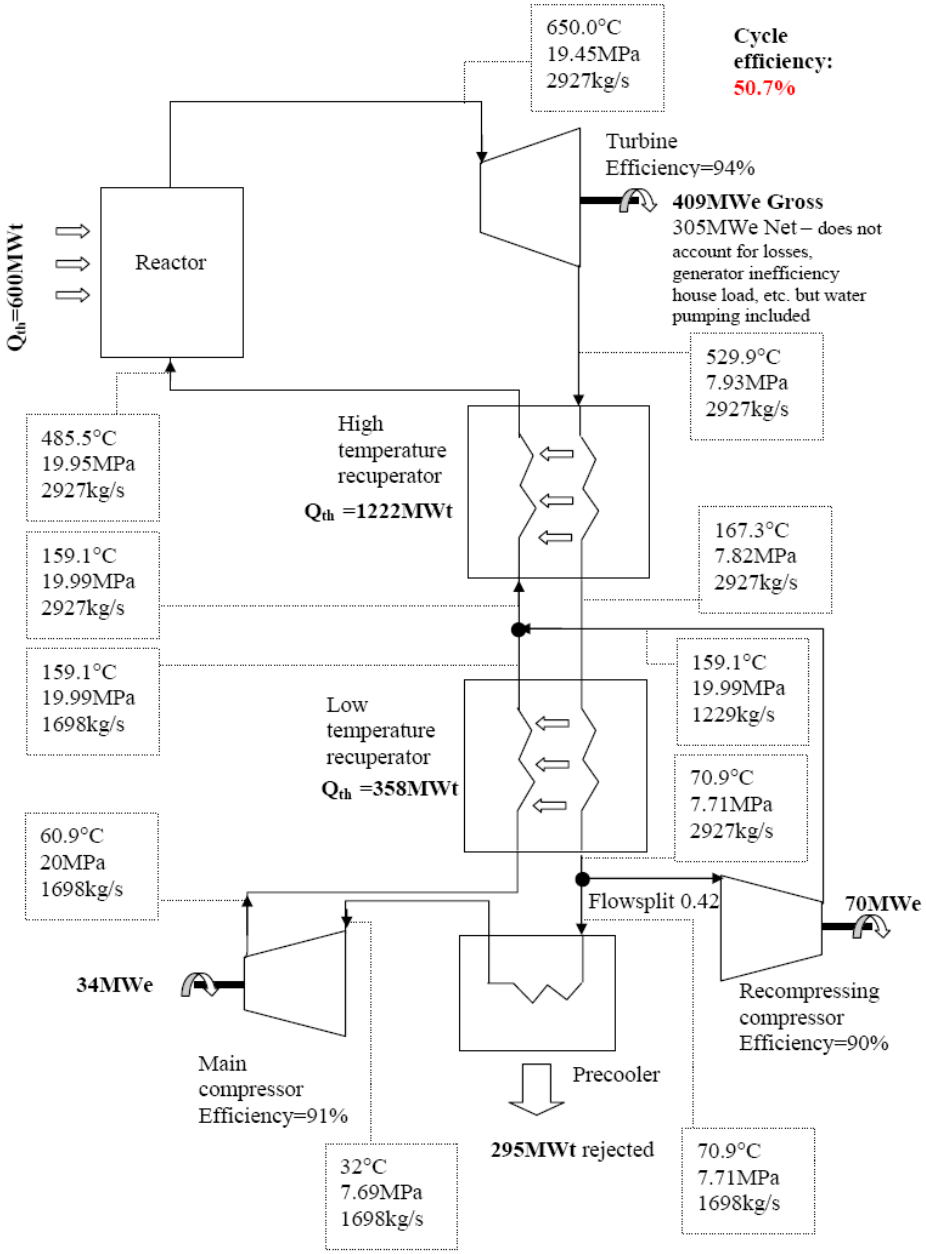


LME Cash Price for Ni (US$/tonne)

3X increase on Ni price over the past 12 months

Pavel Hejzlar, MIT, September 9, 2005

Thermodynamic S-CO2 Cycle State Points - 300MWe (Reference case at 650°C, P=20MPa, T_{low}=32°C)



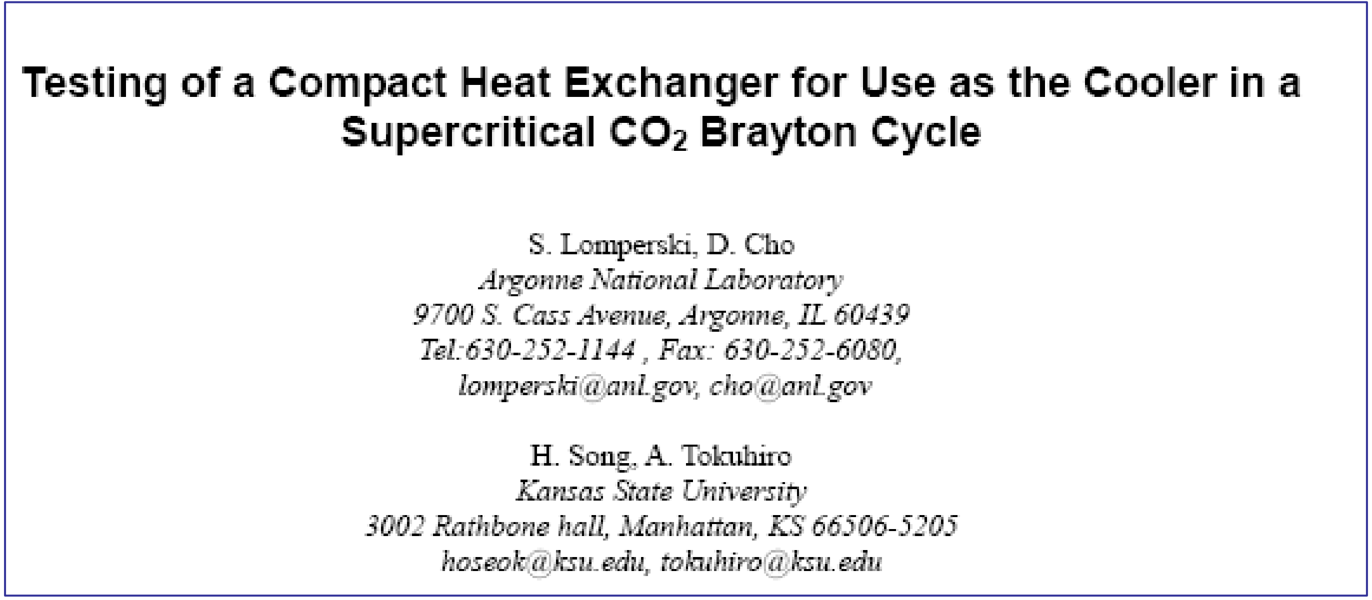
References

Ref 1 (Tochon)

The use of Compact Heat Exchangers technologies
for the HTRs recuperator application per proper design

Patrice Tochon(1), Christian Mauget(2) & Frank Pra(1))

Ref 2 (Cho)



Testing of a Compact Heat Exchanger for Use as the Cooler in a Supercritical CO_2 Brayton Cycle

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Ref 3 (Kesseli)

Proceedings of ASME Turbo Expo 2003, Power for Land, Sea, and Air
June 16–19, 2003, Atlanta, Georgia, USA, GT2003-38938
MICRO, INDUSTRIAL, AND ADVANCED GAS TURBINES EMPLOYING RECUPERATORS
James Kesseli, Thomas Wolf, James Nash, Ingersoll-Rand, Steven Freedman

Ref 4 (Kesseli)

Ceramic MicroTurbine Program by Ingersoll-Rand Energy Systems
MicroTurbine and Industrial Gas Turbine -
Peer Review 12-March 2002
Presented by James Kesseli, Ingersoll-Rand Energy Systems