TECHNOLOGY INSIGHTS

Compact Heat Exchangers for Nuclear Power Plants

Topical Workshop on New Cross-Cutting Technologies for Nuclear Power Plants

Session 2: Advanced Power Conversion for NPP

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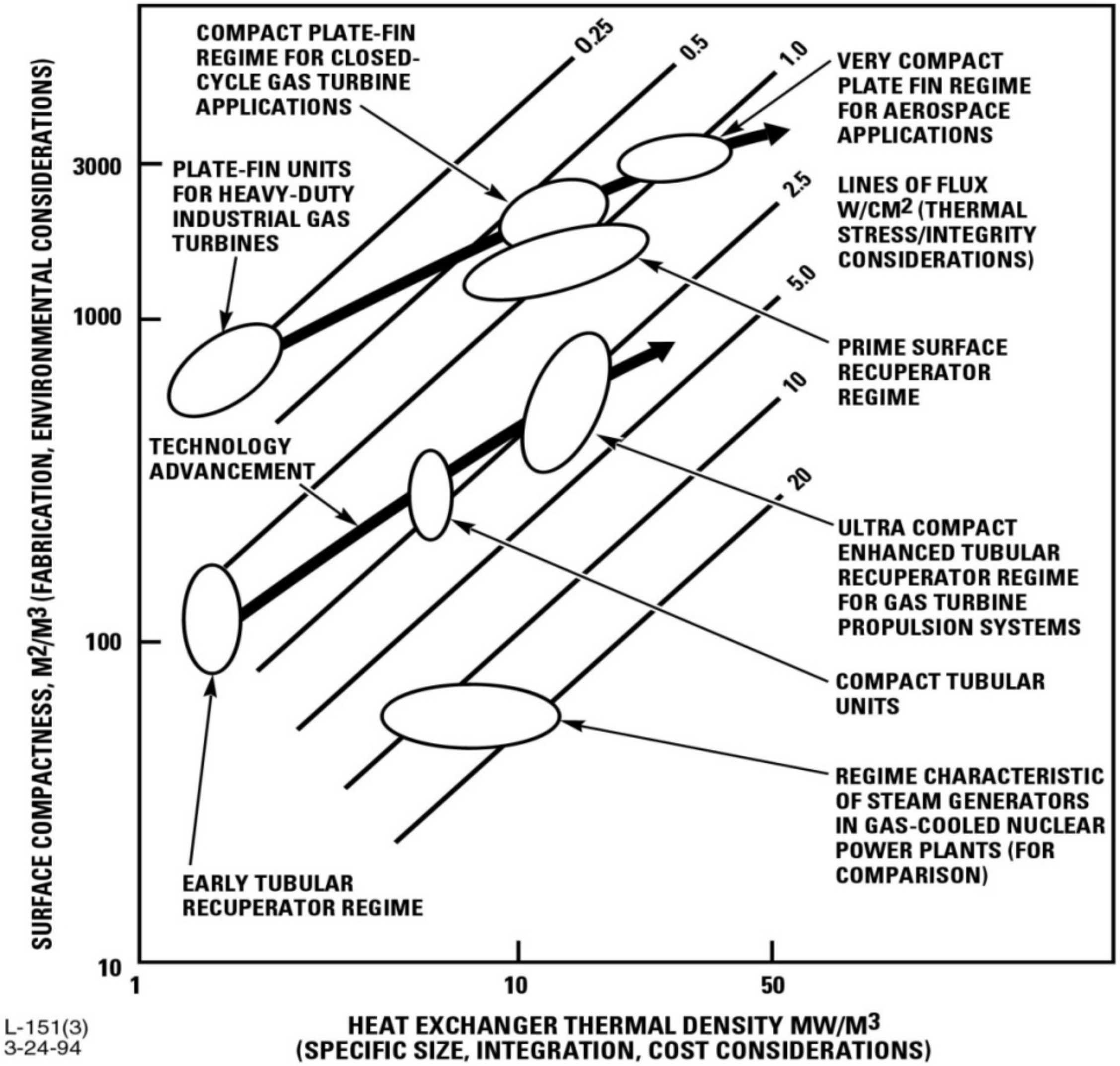
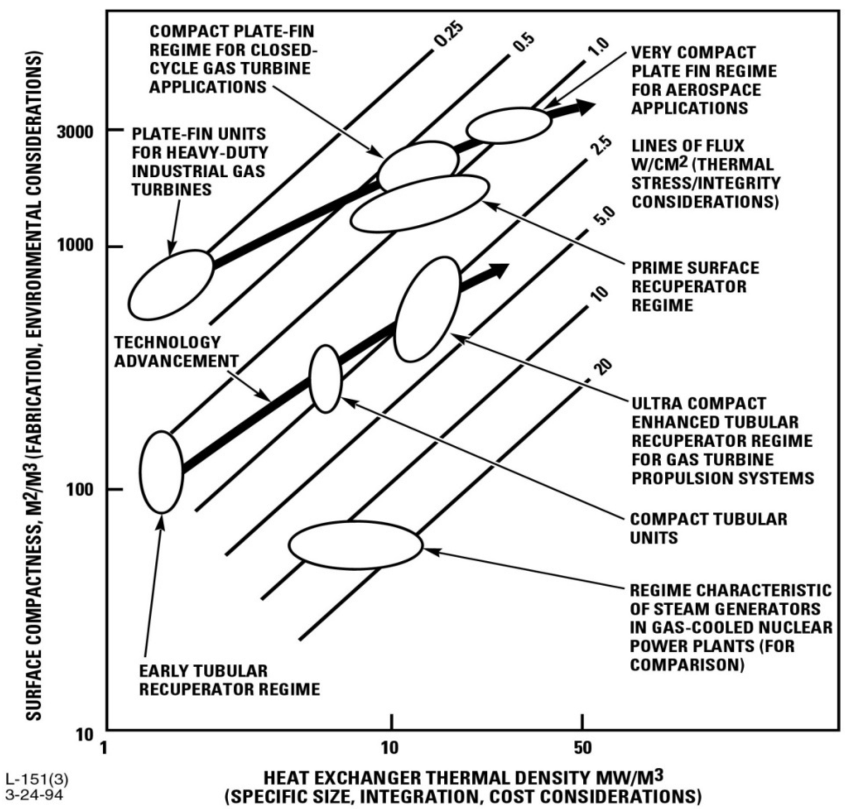
Why Compact HXs?



(Source: Ref. 5)

Why Compact HXs?



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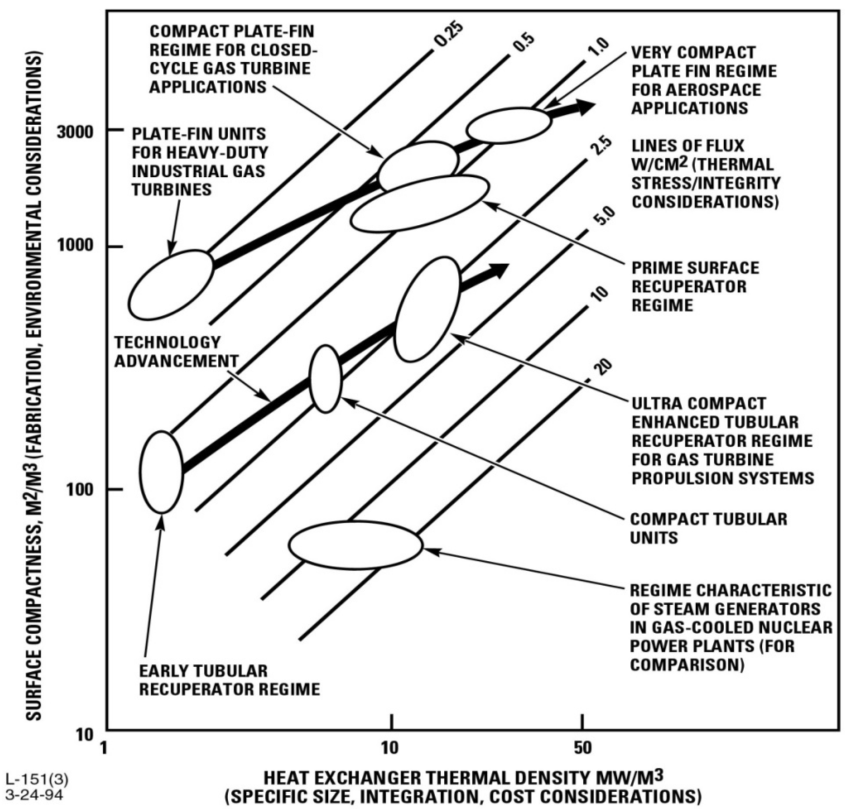
- **At first glance compact HXs would seem to be the obvious choice**
- **However, there is much more that needs to be considered**

Why Compact HXs?



(Source: Ref. 5)

- **At first glance compact HXs would seem to be the obvious choice**
- **However, there is much more that needs to be considered**
- **The selection of HX technology is very much application dependent**

Overview

- **Functions and Requirements**
- **HX Types**
- **Metallic Heat Exchangers**
- **Ceramic Heat Exchangers**
- **Heat Exchanger Incentives and Challenges**
- **Summary Observations**

Functions (What?)

- **Direct flow of fluids**
- **Transfer thermal energy**
- **Maintain pressure boundary integrity**
- **Transfer loads (internal and external)**

Representative Advanced HX Applications

Application	Primary Fluid	Secondary Fluid	Max. Temp. (°C)	HX Class
SFR	Na	Na	500	IHX
SFR	Na	H_2O	475	SG
AHTR	FLiBe	Helium, Air, M-Salt	700	IHX
AHTR	M-Salt	H_2O	670	SG
HTGR-SC	Helium	H_2O	750	SG
HTGR-GT	Helium	N/A	500	Recuperator
HTGR-PH	Helium	Helium, M-Salt	850-950	IHX
HTGR-PH	Helium	Process Fluid	800-900	Process Coupling HX

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Requirements (Under what conditions? How well?)

- **Thermal rating**
- **Chemical composition and properties of fluids**
  - Heat transfer properties
  - Compatibility with HX materials
- **Temperatures, pressures, flow rates**
- **Steady state and transient operating conditions, design lifetime (duty cycle)**
- **Structural loadings**
  - Internal (e.g. flow induced)
  - External (e.g. seismic, vibration)
- **Reliability**
  - Pressure boundary integrity requirements – some variation with application (IHX vs. recuperator)
  - Maintaining performance – fouling, channel blocking, bypass, etc.
- **Maintainability**
- **Economic (initial cost plus contribution to plant O&M cost)**

GT-MHR Nominal Operating Parameters

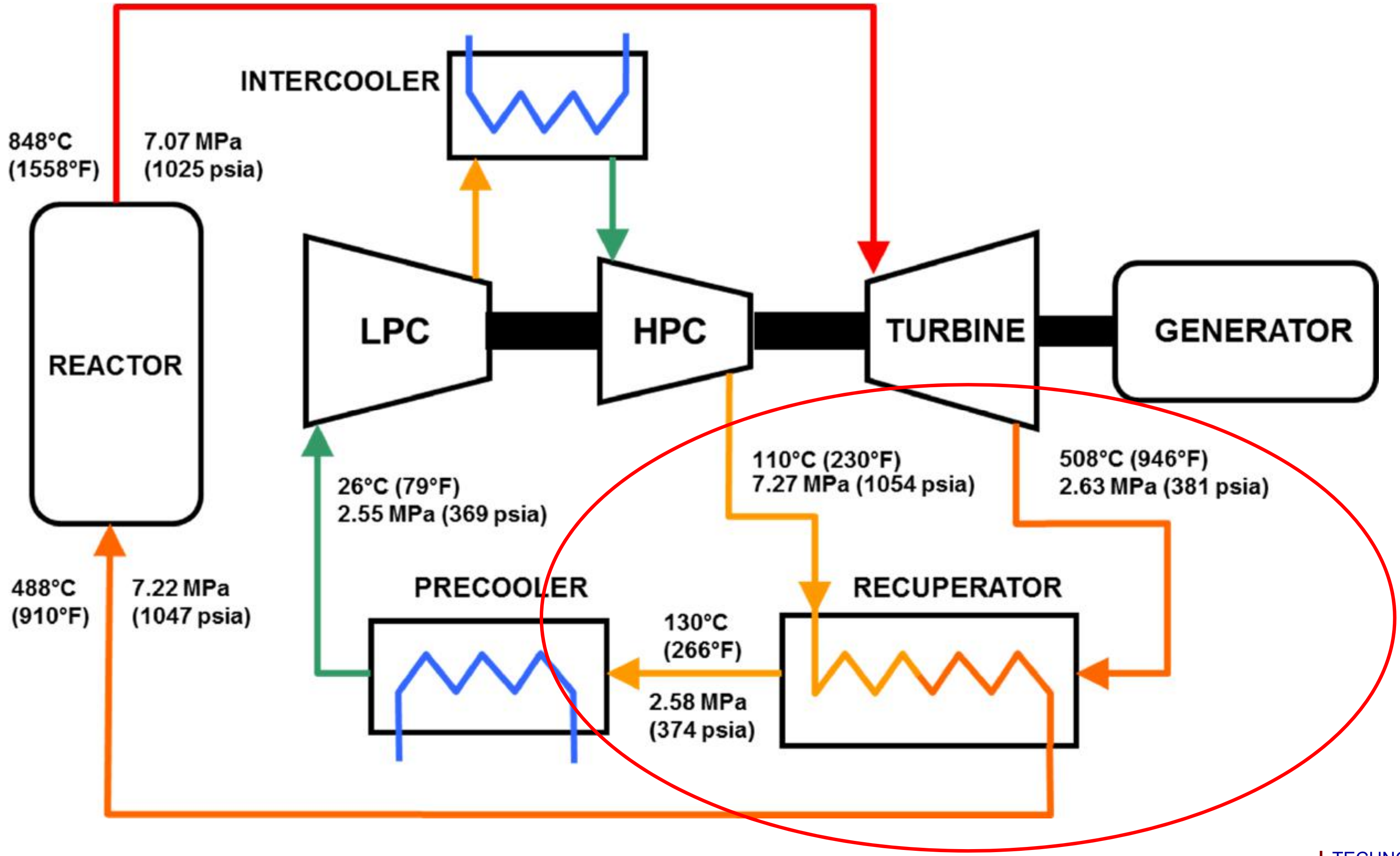

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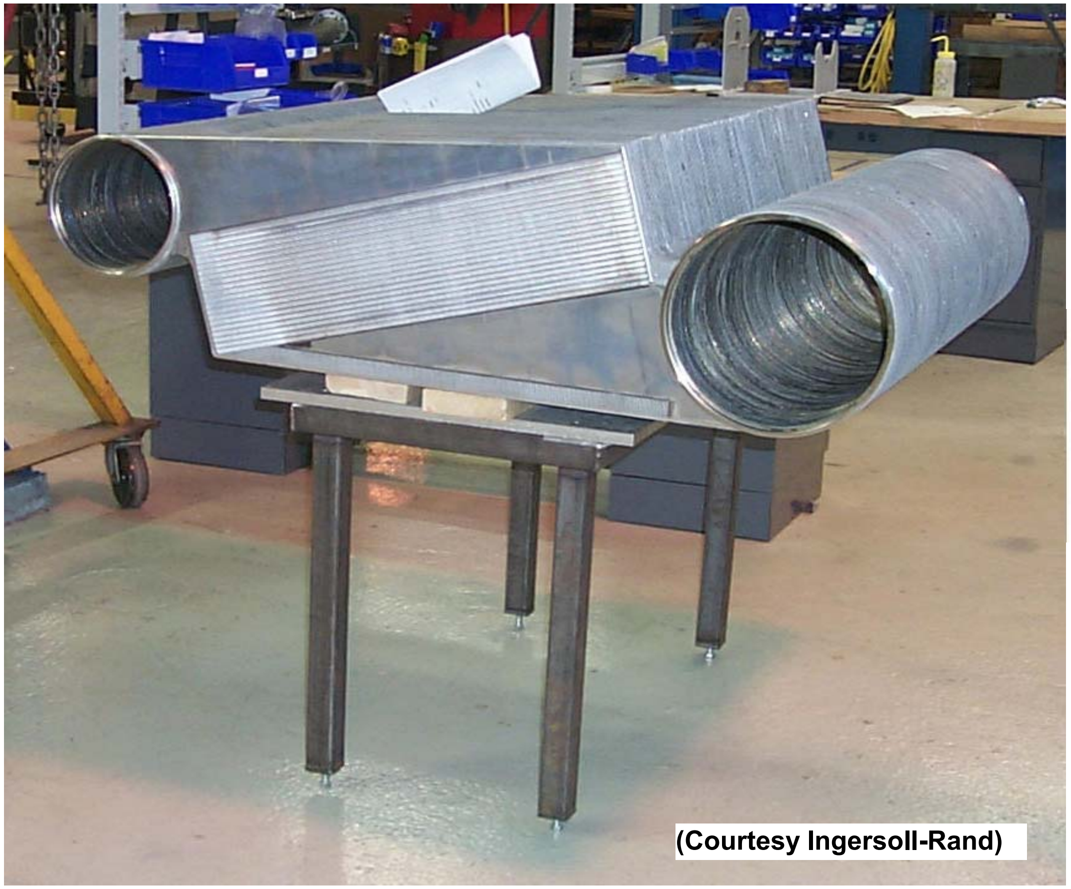
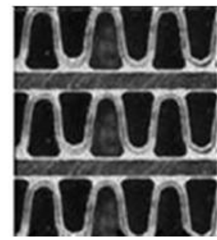
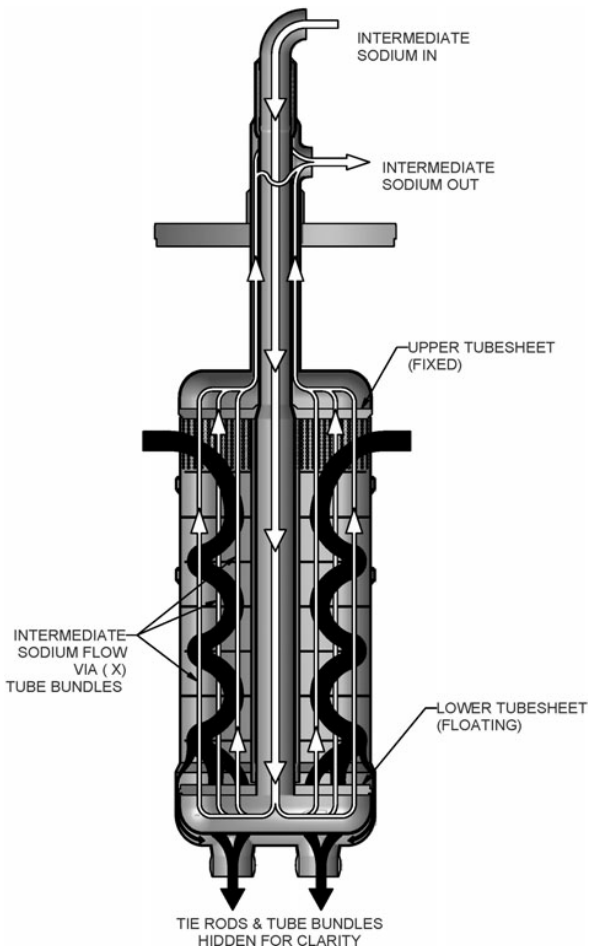
Plate-Fin Recuperator





(Source: Ref. 6)

PRISM IHX

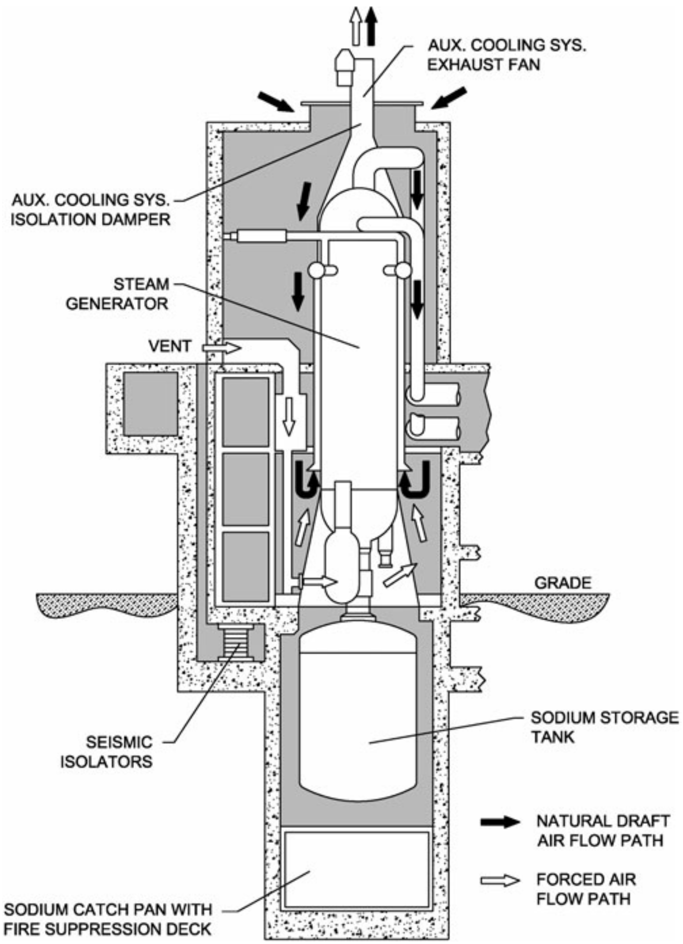


(Source: Ref. 2)

Type: Shell & Tube

Rating (MWt):	**840**
Primary: Shell Side	
Fluid:	**Sodium**
T_{in} (°C):	**499**
T_{out} (°C):	**360**
W (m^3/s):	**5.4**
Secondary: Tube Side	
Fluid:	**Sodium**
T_{in} (°C):	**326**
T_{out} (°C):	**477**
W (m^3/s):	**5.1**

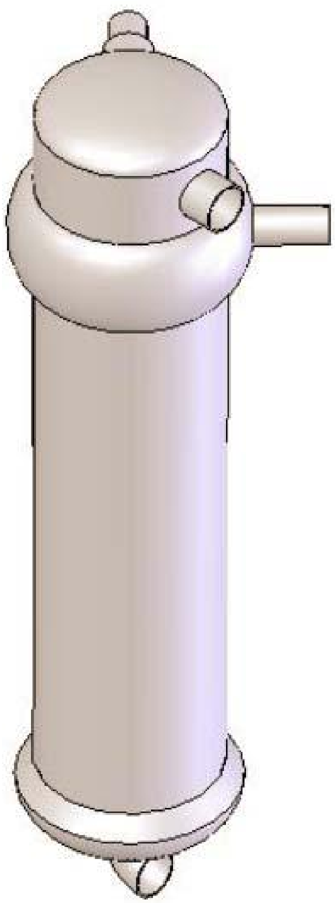
PRISM SG



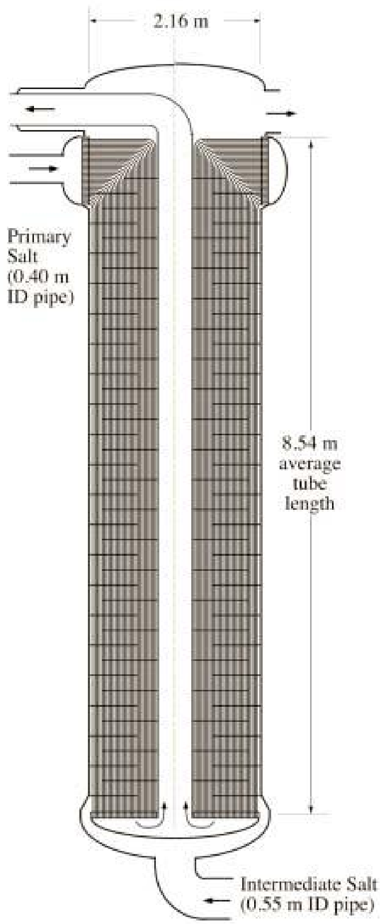
(Source: Ref. 2)

Type: Shell & Helical Tube	
Rating (MWt):	**840**
Primary: Shell Side	
Fluid:	**Sodium**
T_{in} (°C):	**477**
T_{out} (°C):	**326**
W (m^3/s):	**5.1**
Secondary: Tube Side	
Fluid:	**H_2O**
T_{in} (°C):	**216**
T_{out} (°C):	**452**
P_{steam} (MPa):	**14.7**
W (m^3/s):	**5.1**

AHTR IHX



Modular PB-
AHTR IHX



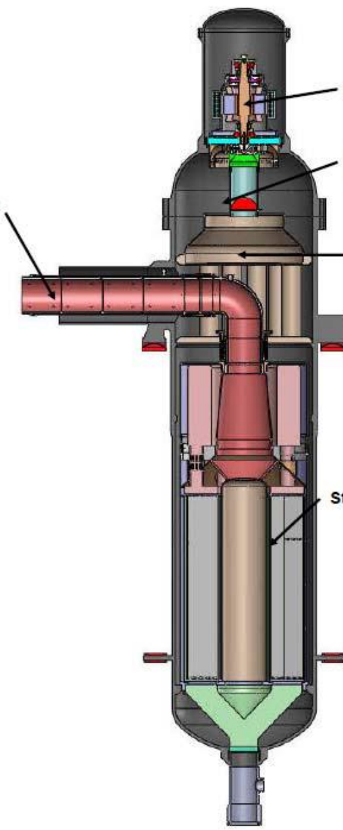
Modular PB-AHTR
Elevation view

Type: Shell & Tube	
Rating (MWt):	**900**
Primary: Shell Side	
Fluid:	**FLiBe**
T_{in} (°C):	**600**
T_{out} (°C):	**704**
W (m^3/s):	**1.9**
Secondary: Tube Side	
Fluid:	**FLiNaK**
T_{in} (°C):	**570**
T_{out} (°C):	**670**
W (m^3/s):	**TBC**

(Source: Ref. 11)

HTGR SG

THTR SG High-Pressure Bundle during Manufacture (Ref. 3)

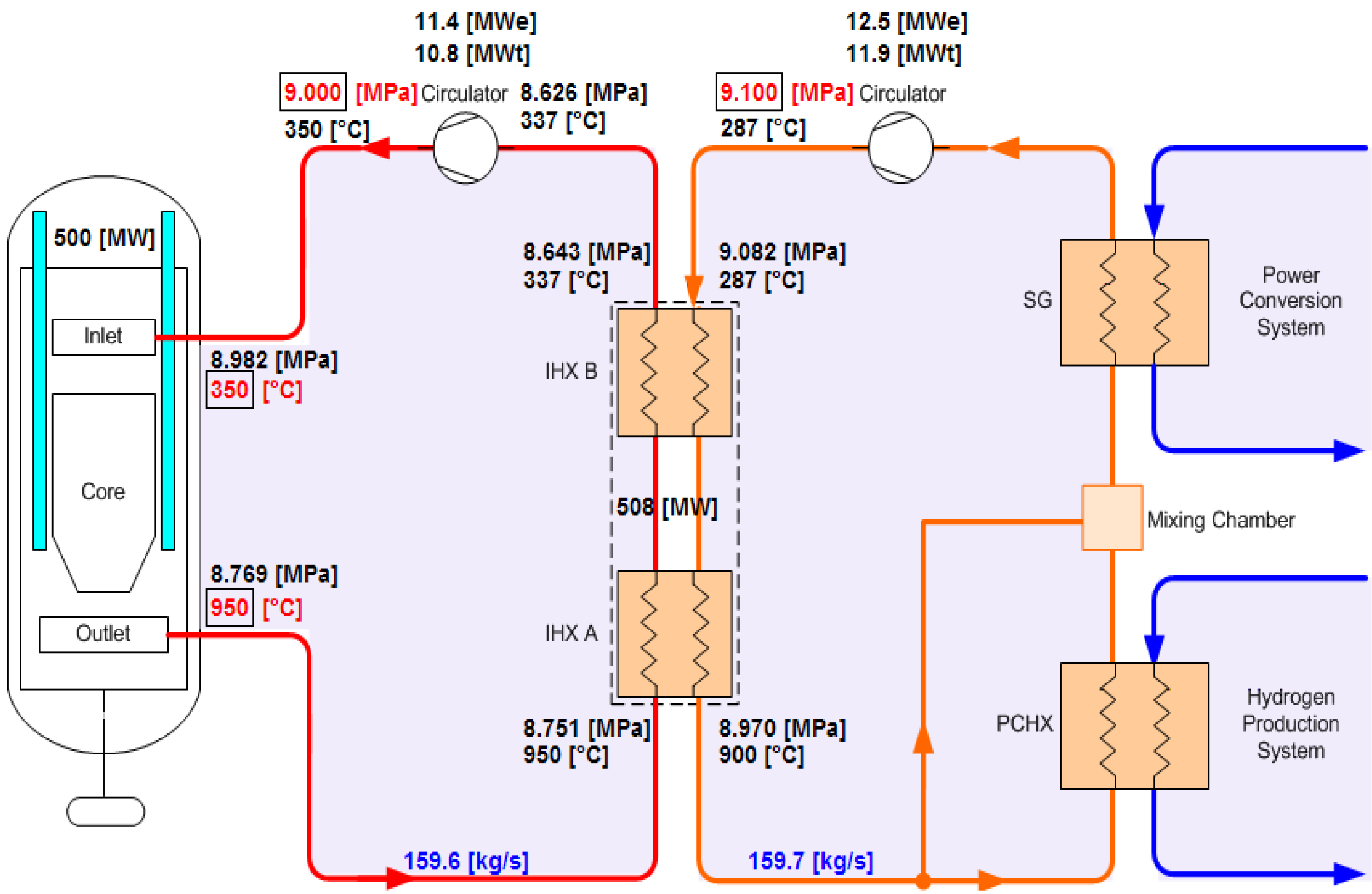


SC-MHR NGNP Demo Plant SG (Ref. 4)

SC-MHR SG Data

Type: Shell & Helical Tube	
Rating (MWt):	**352**
Primary: Shell Side	
Fluid:	**Helium**
T_{in} (°C):	**725**
T_{out} (°C):	**290**
P_{He} (MPa):	**7**
W (kg/s):	
Secondary: Tube Side	
Fluid:	**H_2O**
T_{in} (°C):	**193**
T_{out} (°C):	**585**
P_{steam} (MPa):	**16.5**
W (kg/s):	**130.5**

VHTR Process Heat Application



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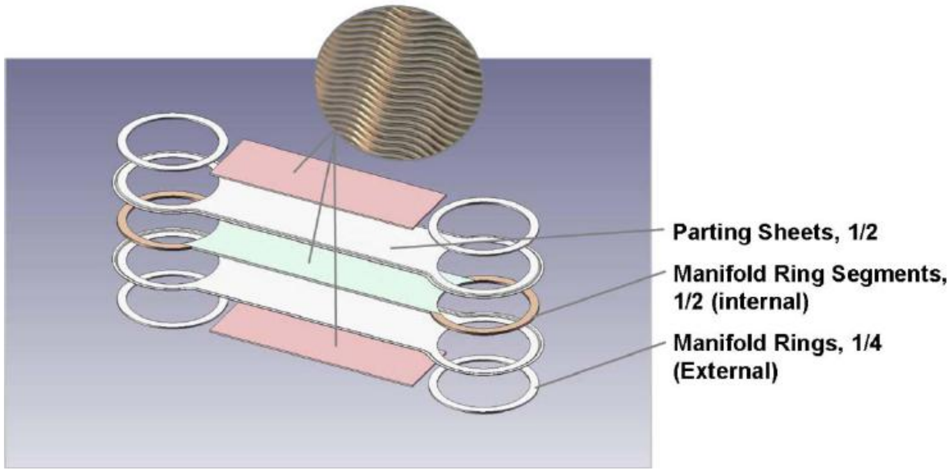
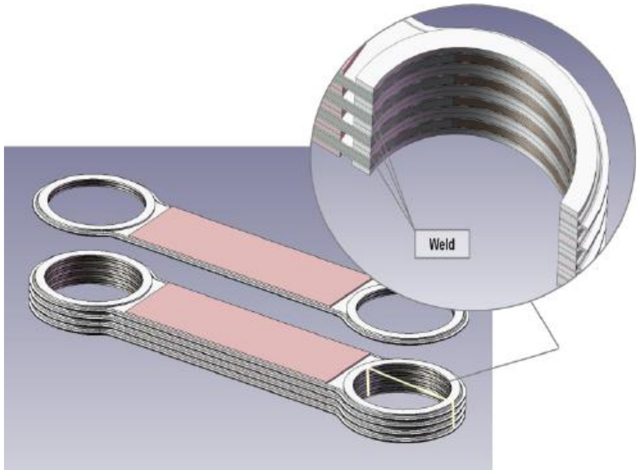
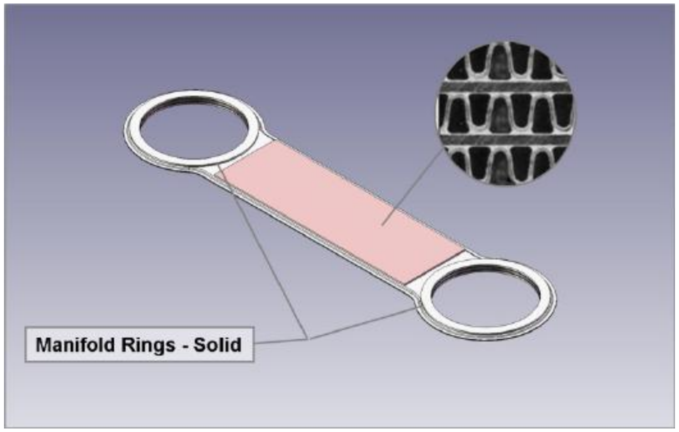
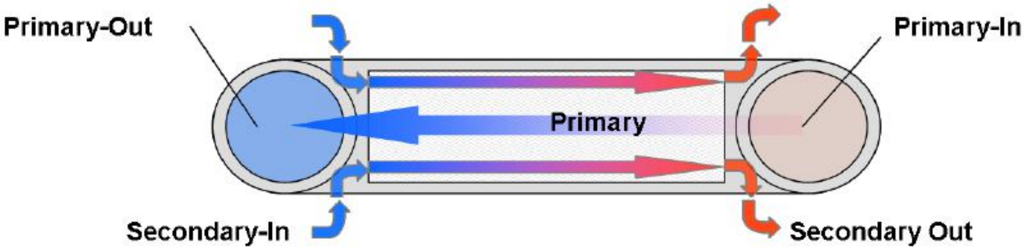
Brayton Energy Unit Cell Plate-Fin IHX



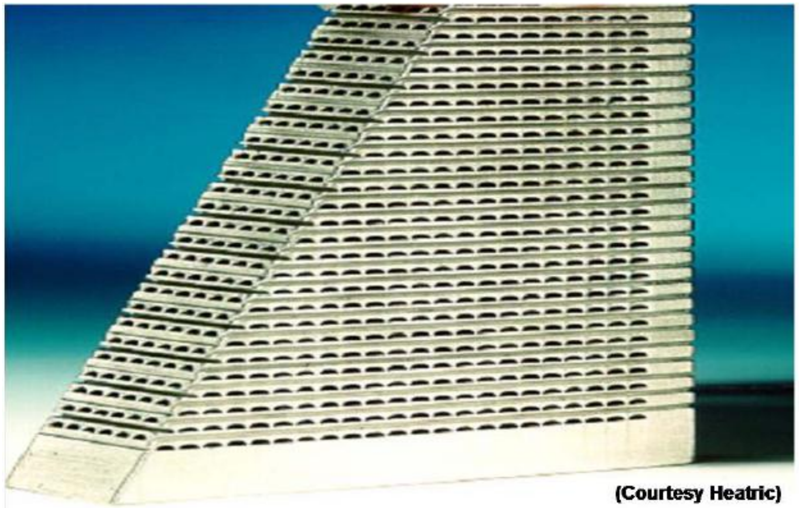


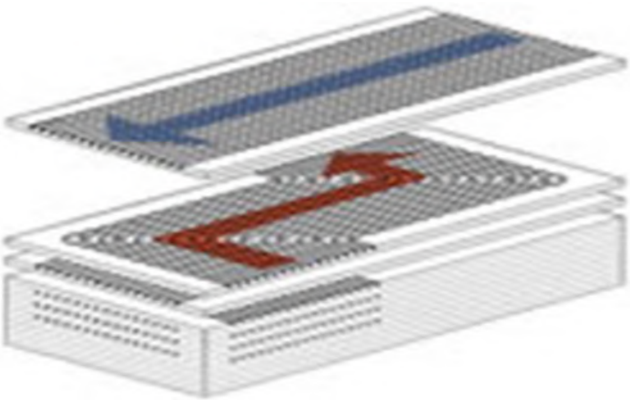




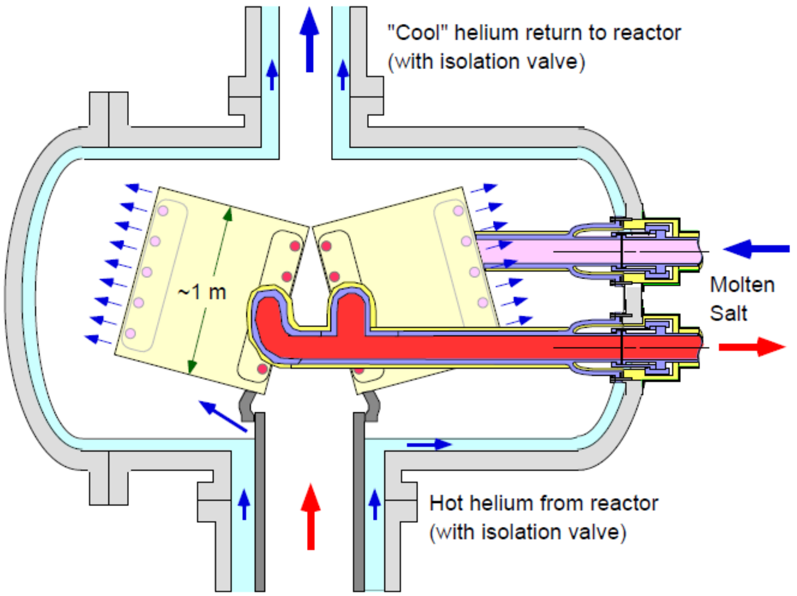
(Source: Ref. 7)

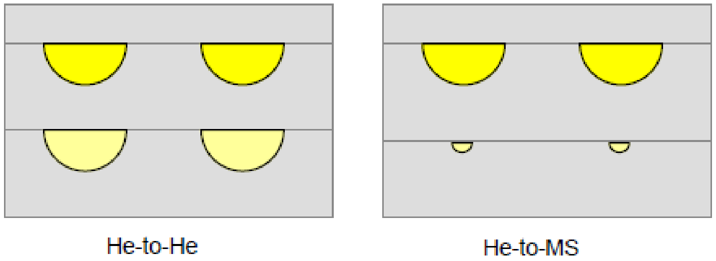
Printed Circuit Heat Exchanger (PCHE)





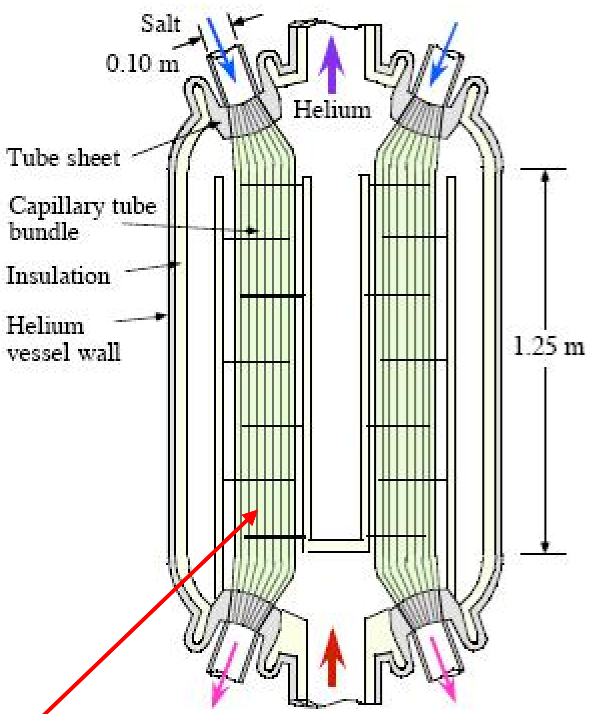
PCHE Concept (Source: Ref. 7)

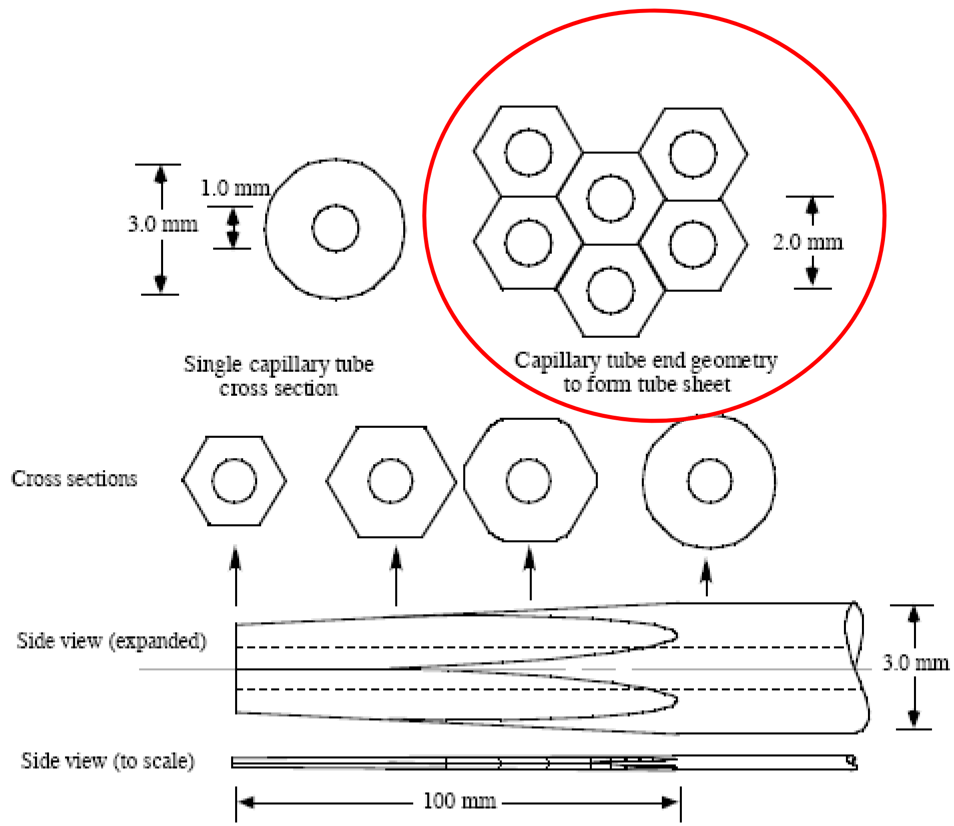




He to Molten Salt IHX (Source: Ref. 8)

Capillary Tube Heat Exchanger

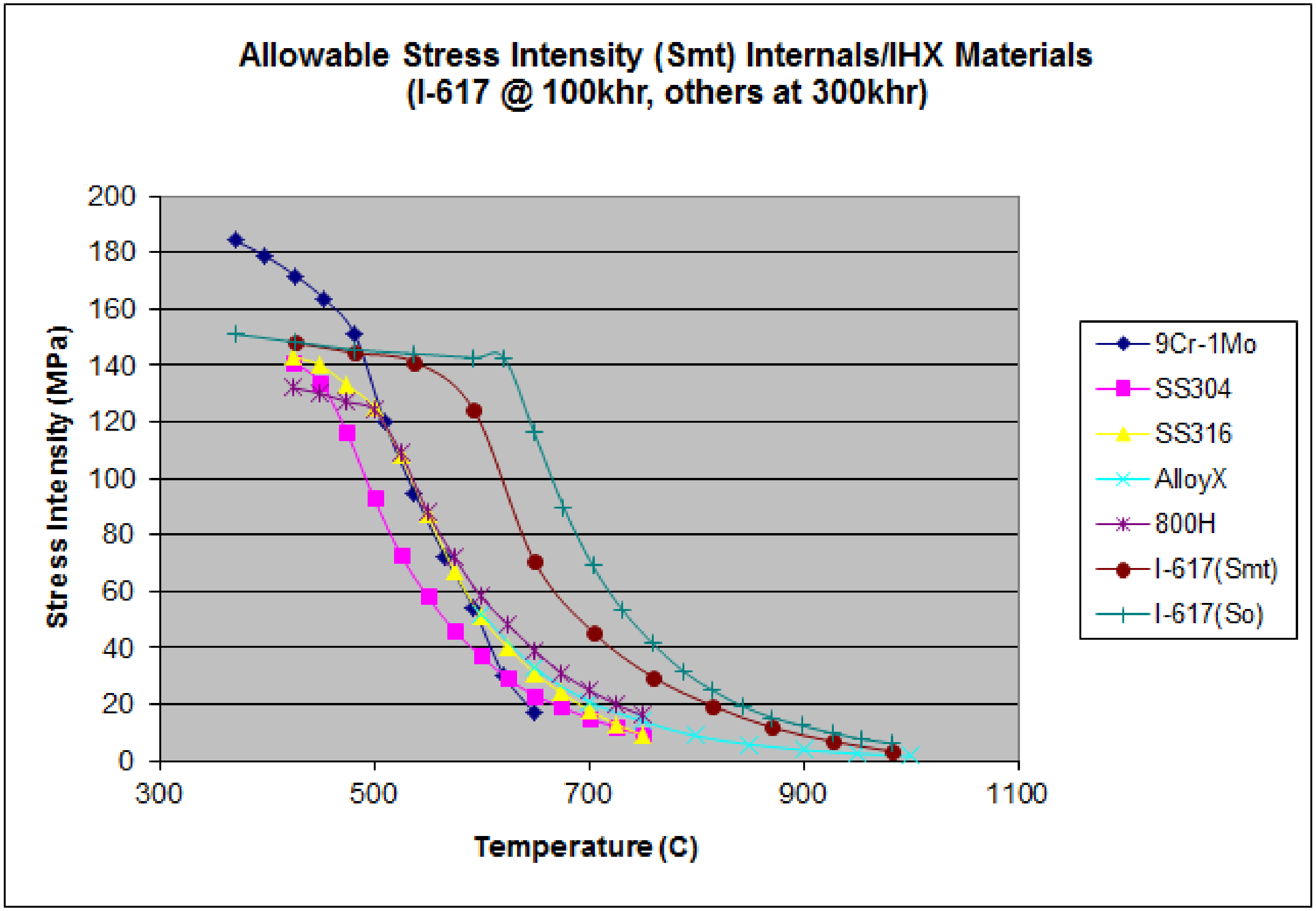




For 50MWt FLiNaK, 10 bundles, 2500 tubes/bundle

(Source: Ref. 10)

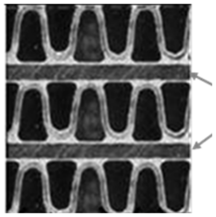
Strength of Metallic HX Materials at High Temperatures

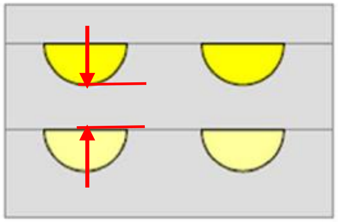


(Note: 300khrs ~ 40 life at design capacity factor)

Corrosion at High Temperatures

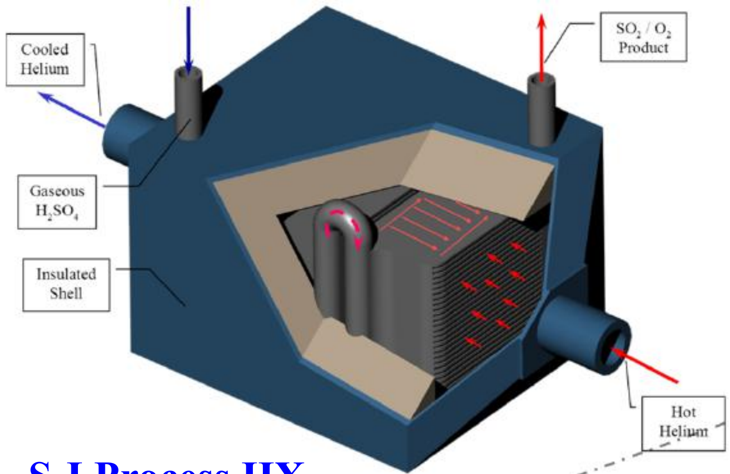
- **Primary side chemistry in VHTRs (≥850°C) poses a challenge for compact metallic HXs due to thin cross-sections (Ref. 7)**
  - Plate-fin HX thickness: Fins 0.102 mm; Plates 0.38 mm
  - In PCHE, plates are typically ≥0.5 mm; however, flow channels reduce the effective thickness to a value comparable to the plates in the plate-fin design





- **Data analyzed in Ref. 7 at 950°C suggest that the predicted depths of internal oxidation could approach or exceed material thickness after only a few years of exposure**
- **Alloy X had the greatest resistance to corrosion, but strength inferior to Alloy 617 at highest temperatures**
  - May be best candidate at ≤850°C

Ceramatec Ceramic (SiC) HX Concept



S-I Process HX

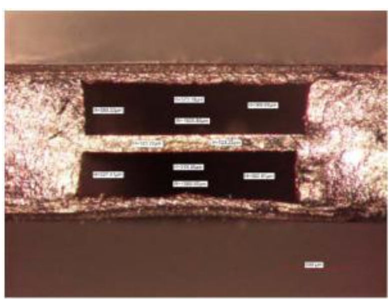
Systems Expertise

Ceramatec Expertise

Assembling-up

Numbering-up

Scale-up



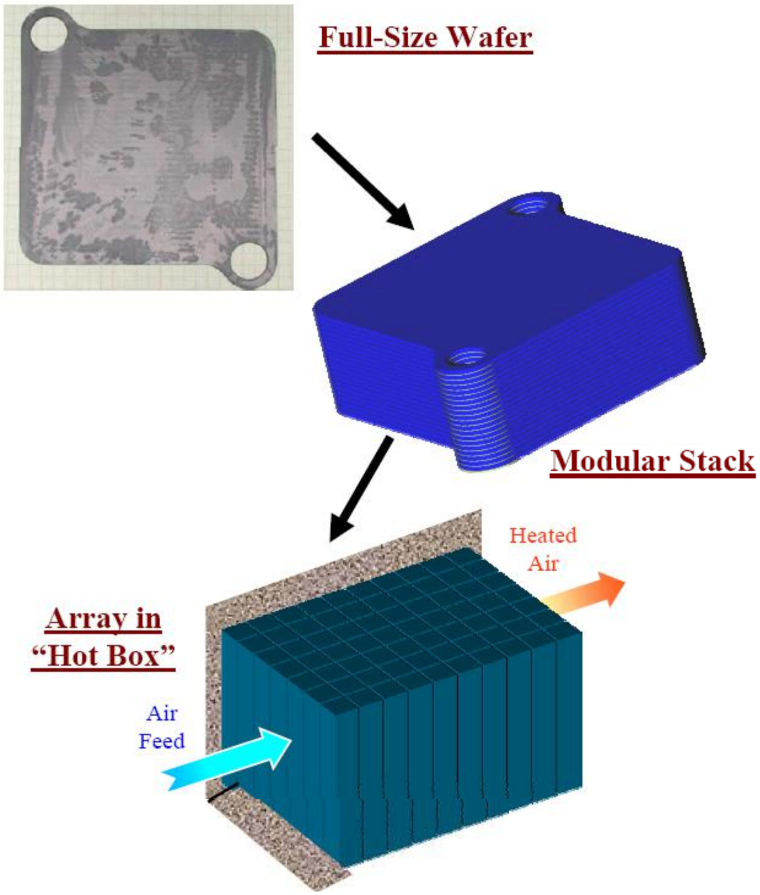
Micro-Channels
(length-scale for heat transfer)

Full-Size Wafer
(common repeat unit)

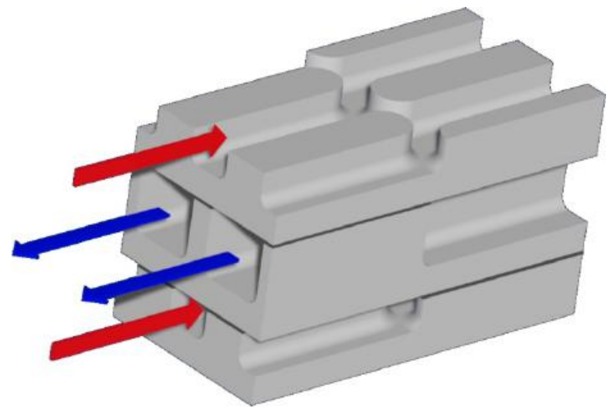
Stack
(modular unit)

(Source: Ref. 9)

Ceramic HX Concepts



SiC HX Concept
(Ceramatec)



Unit cell of offset-fin

Liquid Si Injected composite plate HX
(UC Berkley)

Ceramic HX Tradeoffs

- **Advantages**
  - Temperature capability comparable to VHTR reactor
  - SiC is compatible with a wide range of working fluids
  - Potentially inexpensive materials and manufacture
- **Challenges**
  - Integration with remainder of circuit (ceramic to metallic joints)
  - Reliability (leak tightness, potential for brittle fracture)
  - Significant development effort
- **Observation**
  - 3-D printing may provide basis for breakthrough in compact ceramic microchannel HXs

Characteristics of Typical Advanced HXs

Characteristic	He Steam Generator	Recuperator	Na-Na IHX	He-He IHX	He-MS IHX
Typical HX Type	Shell & Tube	Plate-Fin	Shell & Tube	Plate-Fin; PCHE	PCHE, Capillary Tube
Compact HX	Optional	**Required for Economic Viability**	Optional	**Required for Economic Viability**	Optional?
Maximum Temperature	700°C - 750°C	500°C	500°C	850°C - 1000°C	850°C - 1000°C
Pressure Differential	Large	Intermediate, potentially varying	Low	Low	Large
Materials	Alloy 800	Alloy 800, Alloy X	SS	Alloy X, I-617, Ceramics	I-617, Ceramics
Materials Compatibility w/Working Fluid	Good	Good	Good	Metallics: Concern w/primary side corrosion (thin x- sections) Ceramics: Potentially good	Metallics: Concern w/primary & secondary side corrosion Ceramics: Potentially good
Pressure Boundary Integrity	High integrity required	Some leakage acceptable - degrades	High integrity required	High integrity required	High integrity required
Reliability/Lifetime	Good	Good	Good	Metallics: Life limited by creep, corrosion Ceramics: Potentially good	Metallics: Life limited by creep, corrosion Ceramics: Potentially good
Duty Cycle/Transients	OK	Good	OK	P-F: Good; PCHE: ?	?
Economics	Higher $/kWt	Good	OK	Potentially good	Potentially good
Development Status	Current SOA	Current SOA	Current SOA	Developmental	Developmental
Additional Issues		Channel blockage		Channel blockage, Ceramic-metal joints	Channel blockage, Ceramic-metal joints

Closing Observations

1. **Heat exchanger design selections must be driven by functions and requirements**
   - Optimum designs will vary significantly with application and requirements
   - Compact HXs are essential for some applications, e.g., HTGR-GT recuperators, HTGR-PH IHX
   - In other applications, incentives are not so clear, e.g. SFR and AHTR IHX
2. **Compact metallic HXs are practical to ~850°C in pressure balanced applications**
   - Corrosion may govern life at higher temperatures

Closing Observations

4. **Compact ceramic HXs would be potentially enabling for higher temperatures and for challenging working fluids**
5. **Advanced manufacturing (3-D Printing) may enhance potential for very high temperature compact HXs:**
   - Reduction of wasted material during manufacture of PCHEs
   - ODS Alloys (current manufacturing processes degrade properties)
   - Ceramic HXs

References

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Compact Heat Exchangers
for Nuclear Power Plants

BACKUP SLIDES

IHX Comparisons

Metric	Shell & Tube	Capillary Tube	PCHE	Plate-Fin & Prime Surface
Cost/Performance Indicators				
Compactness (m^2/m^3 & MW/m^3)	Poor	Intermediate	Good	Good
Calc t/MWt	13.5	0.88	1.16	0.25
Materials Utilization (t/MWt)	Poor: (13.5 t/MWt) Unlikely to be commercially viable	Good (0.9 t/MWt)	Good: (estimated to be 1.2 to 1.5 times plate-fin in final form; needs confirmation)	Best: (0.25 t/MWt) Most compact, least materials
Manufacturing Cost	Established manufacturing process	Manufacturing process looks to be very labor intensive and expensive.	Established manufacturing process, amenable to volume manufacturing	Established manufacturing process, amenable to volume manufacturing
State-of-the-Art				
Experience Base	HTTR, German PNP Development	None	PBMR DPP Recuperator, other commercial products	Conventional GT recuperators
Design & Manufacturing	Proven designs and manufacturing processes.	Proposed tubesheet manufacturing process not obviously feasible. Shell-side baffling will be very difficult with very large numbers of very small tubes	Proven designs and manufacturing processes.	Proven designs and manufacturing processes.

(Source: Ref. 7)

IHX Comparisons

Metric	Shell & Tube	Capillary Tube	PCHE	Plate-Fin & Prime Surface
Robustness				
Normal operation	Best: Simple cylindrical geometry, stresses minimized in HT area. Header interfaces can be easily isolated from HT area.	Simple geometry of tubes a plus. Temperature effects on "tubesheet" unknown.	Good: Thicker plates; local debonding does not immediately affect pressure boundary.	Concern: Thin plates with brazed joints in pressure boundary; stress risers in pressure boundary joints (but normally operate in compession). Small material and braze defects more significant.
Transients	Good: Simple cylindrical geometry avoids stress concentrations in HT area. Potential issues in headers, tube/header interfaces.	"Tubesheet" and tube/tubesheet interfaces are potentially problematical	Differing thermal response characteristics of inner HT core vs. solid outer boundary surrounding HT core raises potential for higher transient thermal stresses vs. plate-in.	Best: Thin sections and flexible design minimizes the effects of transients.

(Source: Ref. 7)

IHX Comparisons

Metric	Shell & Tube	Capillary Tube	PCHE	Plate-Fin & Prime Surface
Environmental Compatibility				
Coolant chemistry/ corrosion effects (Assumes PHTS on tube side or inside of compact HX cells, SHTS on shell/outside)	Best: Thick tubes provide maximum resistance	Favorable tube-side geometry. Intermediate section thickness and susceptibility to corrosion effects.	Intermediate section thickness and susceptibility to corrosion effects. Potential greater for "hideout" effects than tubular designs.	Worst: Thin plates and fins, potentially aggrevated by "hideout" locations, may be more susceptible to coolant chemistry effects.
Dust, erosion (Assumes PHTS on tube side or inside of compact HX cells, SHTS on shell/outside)	Best: Large tube IDs, thick tubes make dust/erosion an non-issue.	Intermediate: Will be more prone to dust collection due to smaller diameters, but low likelihood of direct impingement	More prone to dust deposition and erosion (small passages, potentially with features to enhance HT). PCHE cross-sections are thicker than plate-fin/prime surface.	More prone to dust deposition and erosion (small passages, with features to enhance HT). Fin cross-sections are thinner than PCHE cross-sections.
Tritium transport	Best: Thick tubes provide maximum resistance.	Intermediate. Thinner tubes	Worse. Average PCHE cross-sections thicker, but minimum cross-sections comparable to plate-fin/prime surface.	Worst: Thin plates provide least resistance to tritium transport.
Reliability & Integrity Management (RIM)				
Detection of degradation and/or leaks during operation (Assumed SHTS to PHTS pressure bias)	Equivalent. Essentially pressure balanced during normal operation with SHTS at slightly higher pressure. Indication of significant leakage would be manifested as inability to maintain higher SHTS pressure and/or increased injection of SHTS helium and increased withdrawal of PHTS helium.			
Detection of degradation and/or leaks during outages	Large tube diameters may allow internal inspection of individual tubes to assess condition.	Design allows access to individual tubes to identify presence of leaks. However, a lot of tubes	Leaks can be detected at module level with concept similar to that proposed for plate-fin	Concept developed to detect leaks at module level.
Leak location; isolation, repair or replacement of failed components	Design allows location of leaks in individual tubes and plugging.	Design allows location of leaks in individual tubes and plugging. However, a lot of tubes.	Leaks can be isolated at module level with concept similar to that proposed for plate-fin.	Concept developed to locate and isolate leaks at module level.

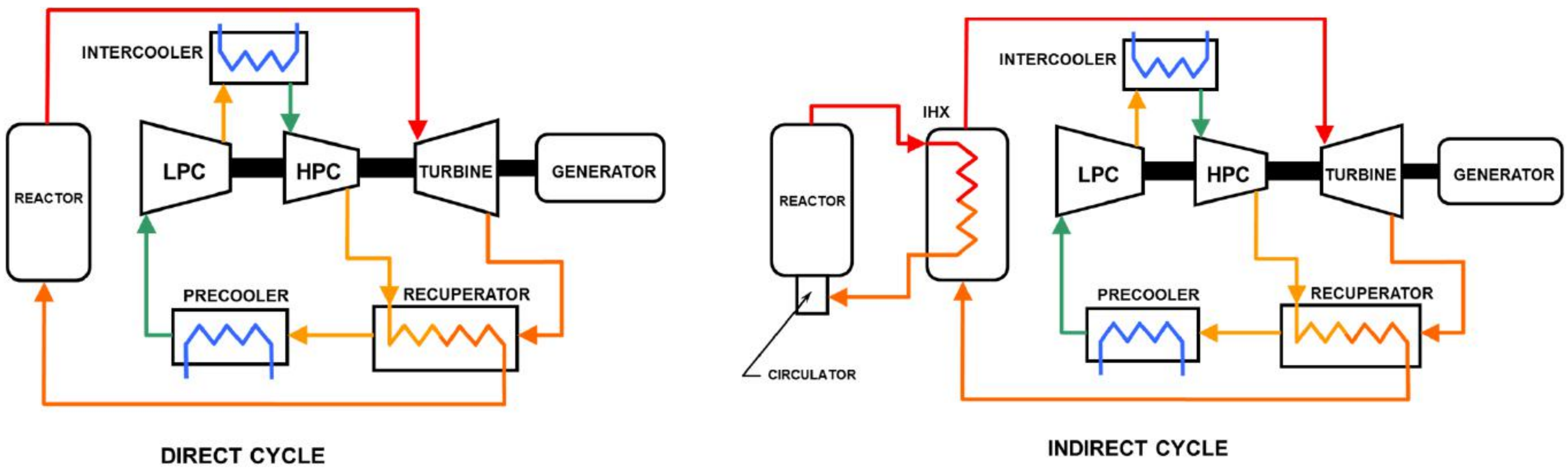
(Source: Ref. 7)

IHX Comparisons

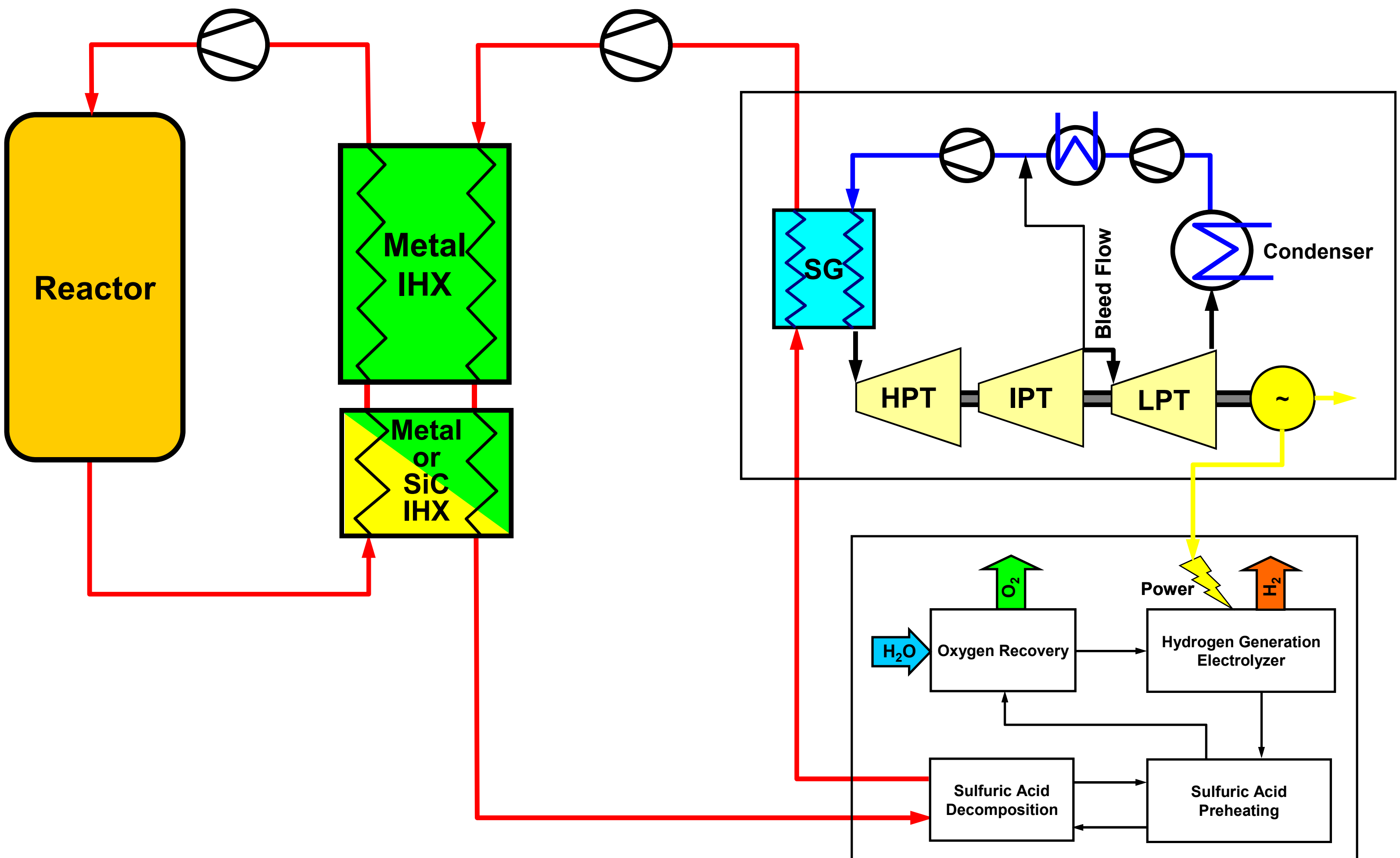
Metric	Shell & Tube	Capillary Tube	PCHE	Plate-Fin & Prime Surface
HX Integration				
Integration with Vessels & Piping	Headers and HX-vessel integration demon-strated (e.g., HTTR, German PNP)	Integration with piping needs further evaluation	OK (by inference from plate-fin work).	OK
Compatibility with Multi-Stage IHX Designs	Large vessels tend to make less attractive	High manufacturing costs would make less attractive.	Compatible with multi-stage designs.	Compatible with multi-stage designs.
Compatibility with Multi-Module IHX Designs	Large tubes, headers likely incompatible with multi-module designs.	High manufacturing costs would make less attractive.	Compact cores are good match with multi-module designs.	Very compact cores are best match with multi-module designs.
Compatibility with Alternate HT Fluids (PHTS to SHTS)	Poor tube-side HT characteristics problematical for alternate gases with lower conductivity. Potentially best choice for LS designs with LS on tube side (drainable). Headers would be an issue for high-temperature outlet.	Poor tube-side HT characteristics problematical for alternate gases with lower conductivity. May be OK for LS designs with LS on tube side (drainable). Tubesheets would be an issue for high-temperature outlet.	Design provides flexibility for matching characteristics of differing HT fluids, including LS. May be difficult to develop drainable design for LS.	Likely not compatible with liquid salt HT fluids. Good flexibility for matching HT characteristics of alternate gases.
Design/Licensing				
Code Basis for Design	Existing Sect VIII Code design basis for tubular geometries and likely header designs	Existing Section VIII Code design basis for tubes, but header design has no Code precedents.	No existing design Code basis	No existing design Code basis

(Source: Ref. 7)

Typical GT Applications



Typical Process Heat Application



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