Development of a Microchannel High Temperature Recuperator for Fuel Cell Systems

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Abstract

This report summarizes the progress made in development of microchannel recuperators for high temperature fuel cell/turbine hybrid systems for generation of clean power at very high efficiencies. Both Solid Oxide Fuel Cell/Turbine (SOFC/T) and Direct FuelCell/Turbine (DFC/T) systems employ an indirectly heated Turbine Generator to supplement fuel cell generated power. The concept extends the high efficiency of the fuel cell by utilizing the fuel cell's byproduct heat in a Brayton cycle. Features of the SOFC/T and DFC/T systems include: electrical efficiencies of up to 65% on natural gas, minimal emissions, reduced carbon dioxide release to the environment, simplicity in design, and potential cost competitiveness with existing combined cycle power plants.

Project work consisted of candidate material selection from FuelCell Energy (FCE) and Pacific Northwest National Laboratory (PNNL) institutional databases as well as from industrial and academic literature. Candidate materials were then downselected and actual samples were tested under representative environmental conditions resulting in further downselection. A microchannel thermal-mechanical model was developed to calculate overall device cost to be later used in developing a final Tier 1 material candidate list.

Specifications and operating conditions were developed for both SOFC/T and DFC/T systems. This development included system conceptualization and progression to process flow diagrams (PFD's) including all major equipment. Material and energy balances were then developed for the two types of systems which were then used for extensive sensitivity studies that used high temperature recuperator (HTR) design parameters (e.g., operating temperature) as inputs and calculated overall system parameters (e.g., system efficiency). The results of the sensitivity studies determined the final HTR design temperatures, pressure drops, and gas compositions. The results also established operating conditions and specifications for all equipment in the SOFC/T and DFC/T systems. Capital cost and Cost of Electricity (COE) sensitivity analyses have been completed for MW-scale SOFC/T and DFC/T systems.

Environmental testing consisted of 1000-hour and 2000-hour dry air oxidation testing on leading candidate materials, used to rank order and, in part, develop a final Tier 1 material candidate list. A thermal-mechanical model was subsequently used to provide material and manufacturing cost estimations for microchannel HTR's to further refine the Tier 1 candidates. A capital cost and 20-year levelized cost of electricity (COE) was developed for a MW-scale version of the SOFC/T system concept as well as for a MW-scale version of the DFC/T system concept. Test frameworks were established for subsequent long-term materials stability testing, including oxidation resistance and mechanical strength. Mechanical strength testing was then carried out by a third-party test laboratory.

Technology demonstration vehicles (TDV's) were designed and fabricated. Several iterations of TDV's were fabricated, each improved over the previous build as far as fabrication techniques. Two of three fabricated TDV's were integrated with the TDV Test Facility for hot-testing at simulated operating conditions. The second of these two was successfully hot-tested for over 1000 hours at simulated temperature and pressure. Post-test leakdown assessment showed negligible leakage at benchtop conditions of 30 psig, a considerable improvement over the previous TDV's.

A 15kW SOFC/T HTR was designed and major fabrication steps were completed: photochemical machining of shims, endplate machining, and nickel plating of shims, endplates, and manifolds.

An alternate concept was developed for the MW-scale DFC/T HTR. The design provides for compliance that is otherwise not achievable in a bonded shim stack of such a large scale device. Stresses are reduced during hot operation. Cost of manufacturing is expected to improve using laser welding techniques instead of diffusion brazing. A solid model was assembled for the MW-scale DFC/T HTR design and was supported by computer analysis of flow properties.

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1.0 EXECUTIVE SUMMARY

Recuperation of heat at high temperatures (900°C) is a crucial component of a high temperature fuel cell system needed for capture of waste heat for use in an unfired gas turbine to produce additional electricity. The overall objective of the proposed work is to advance the commercialization of the fuel cell power plants including solid oxide fuel cell (SOFC) and carbonate fuel cell power plants, by development of low cost and highly effective heat recovery systems. To address this, the proposed project has two main goals: 1) development of microchannel-based high-temperature recuperators (HTR) with very high effectiveness to minimize the required heat transfer area, 2) evaluation, screening, and selection of the high temperature stainless steels and superalloys which are suitable for operation at 900°C and have low cost. The unique structure of a microchannel device, when used as a heat exchanger (recuperator), enables high effectiveness heat transfer at minimal pressure loss as compared to conventional heat exchangers of the same physical size. To achieve the overall objective, the proposed project effort will focus on the following specific objectives:

a) Screen candidate materials and trial components under representative conditions
b) Design, fabricate, test, and analyze both a $15kW_t$ and a $150kW_t$ microchannel HTR.
c) Design a nominal-duty $1.5MW_t$ HTR to be integrated into FCE's carbonate-based Direct Fuel Cell/Turbine 3000 (DFC/T 3000) cycle
d) Using cost and test matrix data from the $150kW_t$ HTR determine the final rating of the nominal-duty $1.5MW_t$ HTR and incorporate the HTR design into the design of the $3MW_e$ DFC/T (DFC/T 3000) toward a production-ready state
e) Employ lessons learned from the DFC/T 3000 integration with microchannel HTR to develop (and support with flowsheet and optimization studies) ultra-high efficiency SOFC/T cycle configurations that integrate unfired gas turbines and microchannel HTRs
f) Perform a detailed economic analysis of the combined cycle DFC and SOFC systems including all balance-of-plant equipment costs.

The purpose of this project is to enhance the development of ultra-high efficiency fuel cell systems including the market-ready Direct FuelCell (DFC) as well as the next generation Solid Oxide Fuel Cell (SOFC) system. Implicit in this purpose is the integration of microchannel high temperature recuperators (HTR's) into combined cycles that integrate unfired gas turbines with the fuel cells. The overall intimacy of these components is the enabler of ultra-high electric efficiency for distributed power generation where waste heat is recovered from fuel cell electrical generation and is utilized in the gas turbine for additional electrical generation. The expected project outcomes include benefits of energy savings and CO, CO_2, and NO_x reductions. The near term energy reductions from the improved hybrid (fuel cell and turbine) power plant is 25% over a simple fuel cell power plant, hence, the efficiency is increased from 47% to 60+%. This work develops a scheme for a high temperature, high pressure microchannel heat exchanger optimization with a detailed system and economic analysis of the hybrid fuel cell system including the turbine integration.

A cost analysis performed on FCE's DFC/T 3000 reveals that cost of the high temperature recuperator (HTR), based on conventional and state-of-the-art compact heat exchanger technology, is actually twenty percent of the entire power plant cost; this is the principal reason for this project. This 20-year levelized cost of electricity (COE) is impacted by the high recuperator capital cost (determined from a spectrum of vendor quotes) and equipment short lifetime resulting in high cost of replacement. The HTR cost can be reduced by decreasing the volume of materials (high temperature alloys) and by reducing the material cost itself. Reduction in material volume is achieved with the development (including manufacturing) and use of microchannel technology where a high surface area to volume ratio results in lower material volume. Reduction is material cost is achieved through material selection, development, and testing. These two thrusts in cost reduction summarize the course of this project. The main technical issues that are being addressed include:

- Identification of stainless steel and superalloy types that perform satisfactorily in 900°C temperatures
- Significant manufacturing cost reduction for successful commercialization of product
- Integration of a high-temperature recuperator and an unfired gas turbine into fuel cell design
- Scale-up of system design for commercial applications

2.0 HIGH TEMPERATURE MATERIALS DEVELOPMENT

2.1 Materials Selection

Candidate materials were initially selected from FuelCell Energy (FCE) and Pacific Northwest National Laboratory (PNNL) institutional databases as well as from industrial and academic literature. The selection was according to functional requirements of the HTR as well as materials selection parameters according to Table 2.1. Key functional requirements imposed on the HTR were: high effectiveness (≥90%), long-term stability under a 10-year device lifetime, high operating pressure (5 atm) on one side of the HTR, and device cost of $5000/unit at a production level of 1000 units/year. The HTR under consideration was a nominal 15 kW_t duty heat exchanger to be used in a nominal 30 kW_e SOFC/T system.

Table 2.1 Materials Selection Parameters

Functional Requirements	Materials Selection Parameters
• Heat transfer from one gas stream to another at high efficiency, while keeping both streams separate; ≥ 90% efficiency • Chemical stability under long-term, high-temperature exposure to the two separate oxidizing gas streams; 10yr lifetime • Maintain pressure boundary (DP ~ 5 atm from one stream to the next) and even gas flow distribution • Low device cost; < $5000/unit @ 1000 units/yr	• High thermal conductivity (generally sufficiently high for metal shim components) • Resistance to oxidation and to substantial metal loss due to scale formation • High-temperature yield strength • Creep resistance • Oxide scale adherence and volatilization • Joinability • Formability • Overall cost

Task 5 of the project, Scale-up to 250kWe-5MWe Design, was focused on analyses and developed functional requirements to be used for materials selection for the 15 kW_t SOFC/T HTR. This is summarized:

- Mission/application needs
- System level needs
  - Example: Cost effective capture of some of the energy otherwise lost in the hot exhaust gas
- Device level needs
  - Example: Increase device efficiency by increasing operating temperature – potential effects on device and system cost

Functional/operating targets from Task 5 analysis are also outlined:

- Example: deliver a X°C feed gas at Y scfm under a pressure of Z psi
- Size/weight targets
- Maximum cost targets
- Start-up rates
- Operational lifetime
- Anticipated transients in device operation
- Etc.

From a black box perspective, Figure 2.1 summarizes the operating conditions for the 15 kW_t SOFC/T HTR.

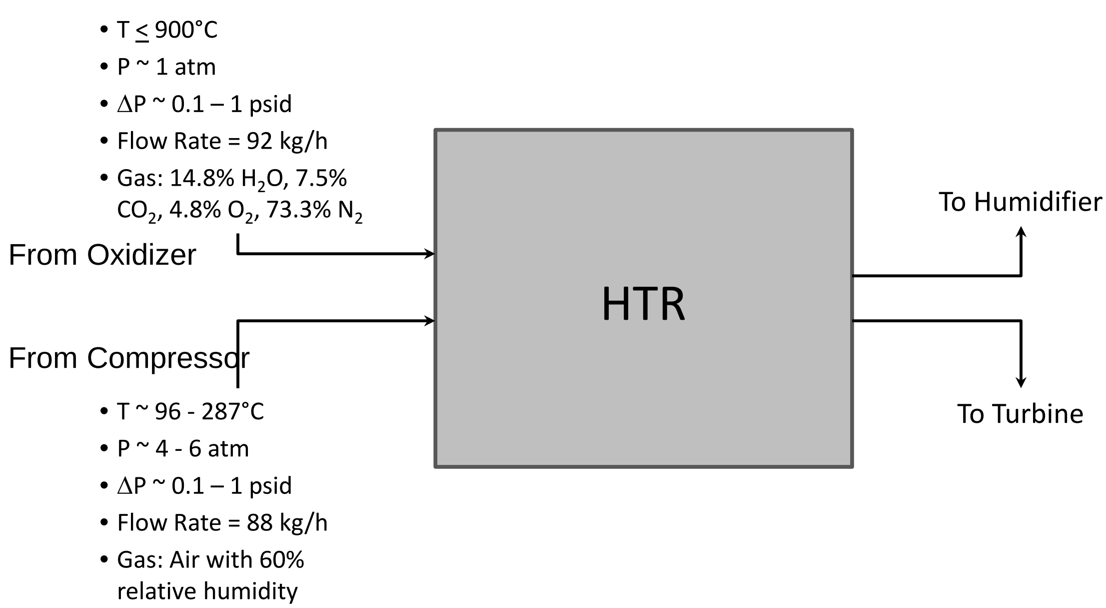


Figure 2.1 Operating Conditions of the Black Box Model

2.2 Oxidation Resistance

There are three key potential failure mechanisms (assuming defect-free manufacture):

- Through-shim oxidation, leading to a loss of the pressure boundary either externally or internally
- Localized shim blow-out due to plastic failure, also leading to a loss of pressure boundary
- Wide-scale channel collapse, leading to a rise in pressure drop through the low-pressure channels

Oxidation resistance is conferred by a stable outer scale layer, typically Cr_2O_3- or Al_2O_3-based. Figure 2.2 depicts chromia and alumina scale formation over time.

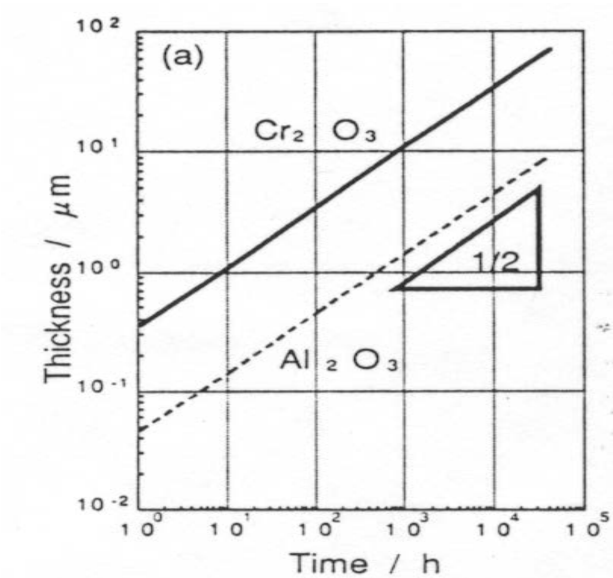


Figure 2.2 Oxide Scale Buildup over Time

Metal loss defines the amount of useful remaining metal in the shim that simultaneously serves as a reservoir of oxidation resistant alloying elements (i.e. Cr and/or Al) and contributes to the shim's structural integrity

The main features of Cr_2O_3- and Al_2O_3-based scales are:

- Scales grow predominantly by outward Cr or Al diffusion along the grain boundaries of the oxide scale. There is some inward O diffusion resulting in oxide formation near the oxide/metal interface. Both phenomena result in large growth stresses
- Growth stresses can lead to convolution and porosity in the scale layer and can spallation (scale detachment)
- Scale layer may also exhibit cracking/spallation at temperature or in response to cooling and/or repeated thermal cycling
- Cr_2O_3 can be susceptible to volatilization above 700°C in a wet environment via the formation of CrO_2OH
- Metal loss can be estimated based on initial pressure boundary thickness and desired high-temperature strength according to:

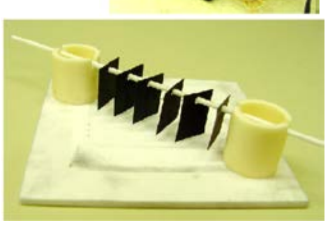
$$\text{Metal loss} < \left(1 - \frac{\sigma_{max}}{\sigma_{YS\ at\ 900°C}}\right) \bullet th_{initial}$$

Figure 2.3 shows the oxidation test setup used at PNNL used for 1000 hour evaluations for a select group of alloys.

1000 hr Environmental Test / 100 hr Evaluations

Material	Family	Sheet Thickness	Total Area	Procurement
Haynes 230	NSA-C	500 um to 1.5 mm	40 cm^2	FCE
Haynes 282	NSA-C	500 um to 1.5 mm	40 cm^2	FCE
Haynes 214	NSA-A	500 um to 1.5 mm	40 cm^2	FCE
HR 120	FSA-C	500 um to 1.5 mm	40 cm^2	FCE
Dieselfoil	FSS-A	500 um to 1.5 mm	40 cm^2	PNNL
Sandvik APMT	FSS-A	500 um to 1.5 mm	40 cm^2	FCE
AL 20-25+Nb	AuSS-C	500 um to 1.5 mm	40 cm^2	FCE
316 SS	AuSS-C	500 um to 1.5 mm	40 cm^2	PNNL

Furnaces Ready
PNNL Testing
Begins 12/1/10



Series 1 : 2x2 Experimental Matrix
T1 = 900C
T2 = 650C
Environment 1 = Combustion Gas Mixture
Environment 2 = 60% RH Air.
Both Environments at Ambient Pressure

Series 2 : 2x2 Experimental Matrix
T1 = 775C
T2 = 475C
Environment 1 = Combustion Gas Mixture
Environment 2 = 60% RH Air.
Both Environments at Ambient Pressure

Figure 2.3 Oxidation Test Setup at PNNL

2.3 High Temperature Yield and Creep Strength

Effective HTR operation requires structural integrity across pressure boundaries in the device over the device's lifetime (not yield under steady-state operation or during the operational transients)

- Creep: T_{oper} ~ 900°C equates to T_{hom} ~ 0.7 for most candidate alloys of interest, t_{life} ~ 80,000 – 90,000 hours
- Yielding: Dp ~ 5atm
- th_{shim} is defined by the most limiting mechanism: through-thickness oxidation, local mechanical failure via a combination of metal loss and hot plastic deformation, or channel collapse via creep

Figure 2.4 below shows the basic framework for long-term creep testing.

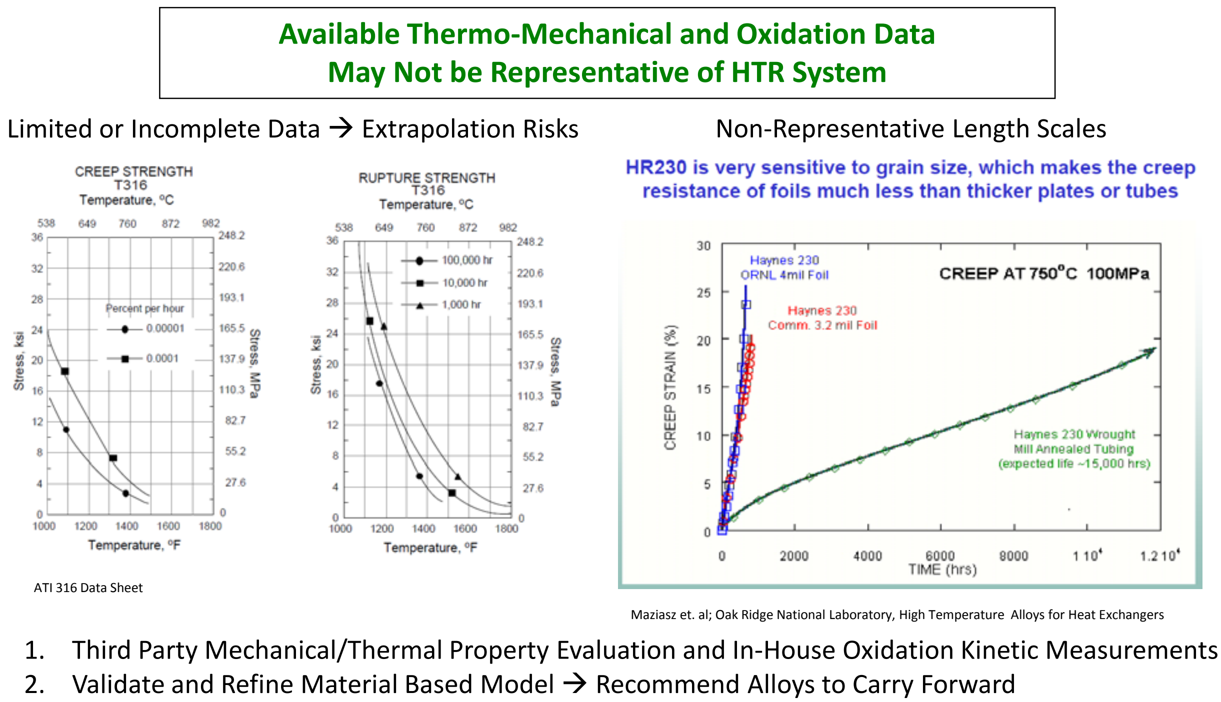


Figure 2.4 Framework for Creep Testing

Figure 2.5 presents a summary of down-selected alloys and the various types of environmental tests to be conducted on the alloys. Figure 2.6 shows creep and tensile strength specimens that were machined at FCE for two alloys of interest. An outside lab conducted the actual tests according to ASTM standards. Specimens were representative of actual shim thicknesses.

1. Third Party Testing of Thermal/Mechanical Properties on Candidate Alloys
2. Representative Sheet Thickness and Heat Treatment
3. Temperatures of Interest – Fill the Gaps in Existing Vendor Data Sheets
4. 2x3 Creep Parameter Space will Enable In-House Creation of Larson-Miller Plots

		Alloy Attributes			Thermal k	1% Creep		Creep Rupture	
	Material	Family	Sheet Thickness	Heat Treat/Temper	Temperature	Time	Temperature	Time	Temperature
Tier 1	316L SS	AuSS-C	500 um	Annealed	550, 700, 850 C	500 hr	550, 700, 850 C	500 hr	550, 700, 850 C
						5,000 hr	550, 700, 850 C	5,000 hr	550, 700, 850 C
	Haynes 230	NSA-C	500 um	Solution Annealed	700, 850, 1000 C	500 hr	700, 850, 1000 C	500 hr	700, 850, 1000 C
						5,000 hr	700, 850, 1000 C	5,000 hr	700, 850, 1000 C
	Haynes 282	NSA-C	500 um	Solution Annealed	700, 850, 1000 C	500 hr	700, 850, 1000 C	500 hr	700, 850, 1000 C
						5,000 hr	700, 850, 1000 C	5,000 hr	700, 850, 1000 C
	Haynes 282	NSA-C	500 um	Age Hardened[1]	700, 850, 1000 C	500 hr	700, 850, 1000 C	500 hr	700, 850, 1000 C
						5,000 hr	700, 850, 1000 C	5,000 hr	700, 850, 1000 C
	Haynes 214	NSA-A	500 um	Solution Annealed	700, 850, 1000 C	500 hr	700, 850, 1000 C	500 hr	700, 850, 1000 C
						5,000 hr	700, 850, 1000 C	5,000 hr	700, 850, 1000 C
	HR 120	FSA-C	500 um	Solution Annealed	700, 850, 1000 C	500 hr	700, 850, 1000 C	500 hr	700, 850, 1000 C
						5,000 hr	700, 850, 1000 C	5,000 hr	700, 850, 1000 C
	Dieselfoil	FSS-A	500 um	TBD	550, 700, 850 C	500 hr	550, 700, 850 C	500 hr	550, 700, 850 C
						5,000 hr	550, 700, 850 C	5,000 hr	550, 700, 850 C
	Al 20-25+Nb	AuSS-C	500 um	Annealed	550, 700, 850 C	500 hr	550, 700, 850 C	500 hr	550, 700, 850 C
						5,000 hr	550, 700, 850 C	5,000 hr	550, 700, 850 C
	Sandvik APMT	FSS-A	500 um	Cold Rolled	700, 850, 1000 C	500 hr	700, 850, 1000 C	500 hr	700, 850, 1000 C
						5,000 hr	700, 850, 1000 C	5,000 hr	700, 850, 1000 C

1. High Strength Condidtion Requires 2-Step Age Hardening Process: 2 hrs at 1010C then Air Cooled followed by 8 hrs at 788 C / Air Cooled
2. All Samples Must be Clearly Labeled and Returned to PNNL or FCE for Microstructural Analysis

Figure 2.5 Environmental Test Matrix

Figure 2.6 Creep and Tensile Strength Test Specimens

2.4 Fabrication and Overall Cost

A key factor is the potential to employ low-cost manufacturing practices, specifically component (shim) fabrication and joinability.

- Shim manufacture plays a significant role in overall device cost and is related to material properties
  - Options include: photochemical machining, blanking, stamping, and coining
- Shim-to-shim joining is critical in forming a hermetic, high-performance device
  - Also impacts device cost
  - Can affect the oxidation and mechanical behavior of individual shims
  - Options include: diffusion bonding, laser welding, and brazing

A key trade-off is shim thickness (as defined by alloy composition and the above mechanisms) versus device cost (raw material cost plus fabrication cost). Table 2.2 summarizes cost and fabrication considerations.

Table 2.2 Underlying Costs

Material Cost	Shim Fabrication Cost	Joining Cost
· Material composition · Market availability and demand · Material/sheet specifications (e.g. need for sheet rolling/ annealing) · Amount of material required to manufacture each stack	· Method of production/inherent set-up cost · Shim design specifications · Consumables · Shim throughput · Material loss (and potential for reclamation)	· Method of joining/inherent set-up cost · Device design specifications · Consumables · Device throughput (joining cycle)

An initial goal is to develop a set of material specifications that can be used to define a list of viable shim material candidates for the final HTR design with two considerations:

> Will rely on trade-off and sensitivity studies (for both device and system design)

> Need for coatings?

Table 2.3 lists example specifications for the 15 kW_t SOFC/T HTR.

Table 2.3 Example Specifications

Parameter	Unit
Linear rate of oxide scale growth at T_{max} ~ 900°C	mm/10,000 hrs
High temperature yield strength	MPa
Maximum rate of creep at T_{max} ~ 900°C	hr^{-1}
Average metal loss	% of initial metal thickness
Formability, average Erichsen cupping depth	mm (for 1 mm thick sheet)
Joinability	$/unit for 1000 units/yr
Overall cost of the HTR device with respect to raw materials and manufacturability	

In examining potential shim materials for the HTR there are classes of alloys. Four classes are summarized below:

<u>Chromium Alloys</u>
Examples: Ducrolloy (Cr-5Fe-1Y_2O_3)
Advantages:

- Low oxide scale growth rate
- Good scale adhesion
- Typically good creep resistance

Disadvantages:

- Brittle material, therefore low toughness and nonexistent formability – must be processed by more costly powder metallurgy techniques
- High raw materials and manufacturing costs
- Poor weldability

<u>Cobalt Alloys</u>
Examples: AiResist 215 (Co-19Cr-4.5W-4.3Al)
Haynes 188 (Co-22Ni-22Cr-14W-3Fe)
MAR-M302 (Co-21.5Cr-10W-9Ta)
Advantages:

- Well established materials database
- Typically good oxide scale adhesion
- Superalloys exhibit excellent high temperature yield strength and creep resistance, often moderately higher than comparable Fe- and Ni-based superalloys
- Acceptable formability and joinability in many cases

Disadvantages:

- Raw material costs are typically higher than comparable Fe- and Ni- based alloys
- Smaller market for these materials – likely to affect cost and availability
- Some alloy types display challenges with respect to forming and joining

<u>Nickel Alloys</u>
Examples: Haynes 230 (Ni-23Cr-14W-5Co)
Inconel 601 (Ni-23Cr-14Fe-1Al)
Inconel 617 (Ni-24Cr-15Co-10Mo)
Nicrofer 6025 (Ni-25Cr-8Fe)
Haynes 214 (Ni-18Cr-3Fe-4.5Al)

Hastelloy C-22 (Ni-21Cr-5.5Fe-2.5Co-13.5Mo-4W)
Udimet 700 (Ni-15Cr-18.5Co-5Mo-3.5Ti-4.4Al)
Haynes 224 (Ni-27.5Fe-20Cr-3.8Al)

Advantages:

- Well established materials database
- Typically good oxide scale adhesion
- Superalloys exhibit excellent high temperature yield strength and creep resistance
- Acceptable formability and joinability in many cases
- Tolerance to carburization

Disadvantages:

- Raw material costs are typically higher than comparable Fe-based alloys

Iron Alloys

Examples: 430 Stainless Steel (Fe-18Cr)
446 Stainless Steel (Fe-25Cr)
Ebrite 26-1 (Fe-26Cr-1Mo)
Fecralloy (Fe-15Cr-5Al)

X10CrAl 18 (Fe-17Cr-1Al-1Si)
X10CrAl 13 (Fe-12Cr-1Al-1Si)
MA 956 (Fe-20Cr-5Al)
Kanthal (Fe-22Cr-6Al)

Advantages:

- Well established materials database
- Typically lower raw material and fabrication costs relative to Cr- and Ni-alloys
- Superalloys exhibit good high temperature yield strength and creep resistance
- Acceptable formability and joinability in many cases
- Some alloys, in particular those with rare earth additions, show good oxide scale adhesion

Disadvantages:

- In general lower high temperature yield strength and creep resistance than Ni-alloys, though not necessarily across the board

Alloy classes were down-selected for the 15 kW_t SOFC/T HTR. This is shown in Table 2.4. The notation is defined by: NSA-C – chromia-forming, Ni-based superalloy; NSA-A – alumina-forming, Ni-based superalloy; FSA-C – chromia-forming, Fe-based superalloy; FSA-A – alumina-forming, Fe-based superalloy; FSS-C – chromia-forming, ferritic stainless steel; FSS-A – alumina-forming, ferritic stainless steel; and AuSS-C – chromia-forming, austenitic stainless steel (note: no alumina-forming austenitic stainless steels are currently commercially available).

Table 2.4 Alloy Classes Down-Selected for the HTR

Parameter	Alloy Family* NSA-C	NSA-A	FSA-C	FSA-A	FSS-C	FSS-A	AuSS-C
Oxidation Rate** (x 10^{-13} $g^2 \cdot cm^{-4} \cdot s^{-1}$)							
700°C	0.055	0.002	0.04	0.002	0.09	0.009	0.06
800°C	0.69	0.03	0.60	0.035	1.65	0.06	1.2
900°C	7.50	0.35	6.50	0.40	11.5	0.65	13.5
Metal Loss in 1000 hr at 980°C (μm)	65	4	74	5	80	6	500
Coefficient of Thermal Expansion (x 10^{-6} K^{-1}) RT – 900°C	15.4	16.1	17.3	17.5	12.2	12.4	18.8
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$) RT	8.9	8.8	11.4	11.5	25.5	23	16.5
Specific Heat ($J \cdot kg^{-1} \cdot K^{-1}$)							
20ºC	400	450	465	460	460	455	500
900ºC	750	720	660	675	680	670	790
0.2% Yield Strength (MPa)							
20°C	600	550	410	400	240	230	290
900°C	190	170	180	165	15	12	105
Elastic Modulus (GPa)							
20°C	200	200	200	200	200	200	195
900°C	140	140	170	170			
Stress to Rupture in 10000hr (MPa)							
760°C	100	110	80	80	8	7	30
870°C	45	31	55	50	3	3	10
925°C	15	16	30	20	2	2	7

The growth of scale follows the Wagner's parabolic law:

$$\xi^2 = k_p t = \frac{\kappa_g}{(\chi\rho)^2} t = \frac{t}{d^2} . \kappa_g^o . e^{-\frac{E_{ox}}{KT}}$$

where ξ is the thickness of the scale; k_p and k_g are the rate constants in thickness and weight (k_g is listed in Table 2.4), respectively; χ is the weight fraction of oxygen in oxides (for Cr_2O_3, χ= *48/152); ρ* is the density of the oxide scale layer (for Cr_2O_3, ρ=*5.225 g.cm*$^{-3}$*);* and *t* is the time of high-temperature exposure.

Table 2.5 Screening Tests for Various Alloys: Environmental Exposure

Alloy Name	C	Si	N	Cr	Ni	Mn	Fe	Others
AL20/25+Nb	0.08	0.4	0.1	20.0	25.0	1.5	Bal	Nb 0.3, Mo 1.5
310s	0.08	1.5		24.0-26.0	19.0-22.0	2.0	Bal	
Inconel 625	0.1	0.5		20.0-23.0	58	0.5	5	S 0.015, Co 1.0, Al 0.4, Ti 0.4, Mo 8.0-10.0
Incoloy 800	0.1	1		19.0-23.0	30.0-35.0	1.5	39.5min	Ti 0.15-0.6, Cu 0.75, Al 0.15-0.6
Haynes 214	0.05	0.2		16	75 (Bal)	0.5	3	Al 4.5, Zr 0.1,Y 0.01, B 0.05
Haynes 230	0.1	0.5		22	53	0.65	3	Co 5, Mo 2, W 14, Al 0.3, B 0.015, La 0.02
Haynes 224				20	48(Bal)		27.5	Al 3.8 (Ni-27.5Fe-20Cr-3.8Al)
Haynes 282	0.06	0.15		19.5	57	0.3	1.5	Co 10, Mo 8.5, Ti 2.1, Al 1.5, B 0.05
Haynes 120	0.05	0.6	0.2	25	37	0.7	33	Co 3, Mo 2.5, W 2.5, Nb 0.7, Al 0.1, B 0.004
Haystelloy X	0.1	1		22	47(Bal)	1	18	Mo 9, Co 1.5, W 0.6, B 0.008
617				**22**	**52**			**Mo 13, Co 13,**
HR-160				28	37			Co 30, Si 2.7
Haynes-556	0.1	0.4	0.2	22	20	1	31	**Co 18**, Mo 3, W 2.5, Ta 0.6, Al 0.2, La 0.02, Zr 0.02
18SR (AK steel)	0.015-0.03			18.0	0.25	0.25-0.3	Bal	Al 1.8-2.0, Ti 0.4
Crofer 22	0.03	0.5		20-24		0.3-0.8	Bal	Cu 0.5, Al 0.5, Ti 0.03-132, La 0.04-0.2
E-Brite	0.001	0.025		27.0	...	0.01	Bal	
Sanergy HT	0.025	0.05		21.9	0.5		Bal	Mo 0.88, Nb 0.6
PM 2000				19			Bal	Al 5.5, Ti 0.5, Y2O3 0.5
Kanthal		0.7		22		0.4	69.5	Al 5.8
Fecralloy				22			70	Al 4.0-5.0
JFE18-3USR	0.1	1.5		17.0-21.0	0.6	1	Bal	P0.04, S 0.03, Al 2.0-4.0,
JFE20-5USR	0.015	1		19.0-21.0	0.6	1	Bal	P0.04, S 0.03, Al 4.5-6.0, La 0.06, Zn added

Figure 2.7 shows results of weight change analysis for the Tier 1 set of alloys. This dry air oxidation testing was conducted for 1000 hours with cycling every 100 hours. Eventually, 2000 hours of testing was completed. The operating temperature for the test was 950°C.

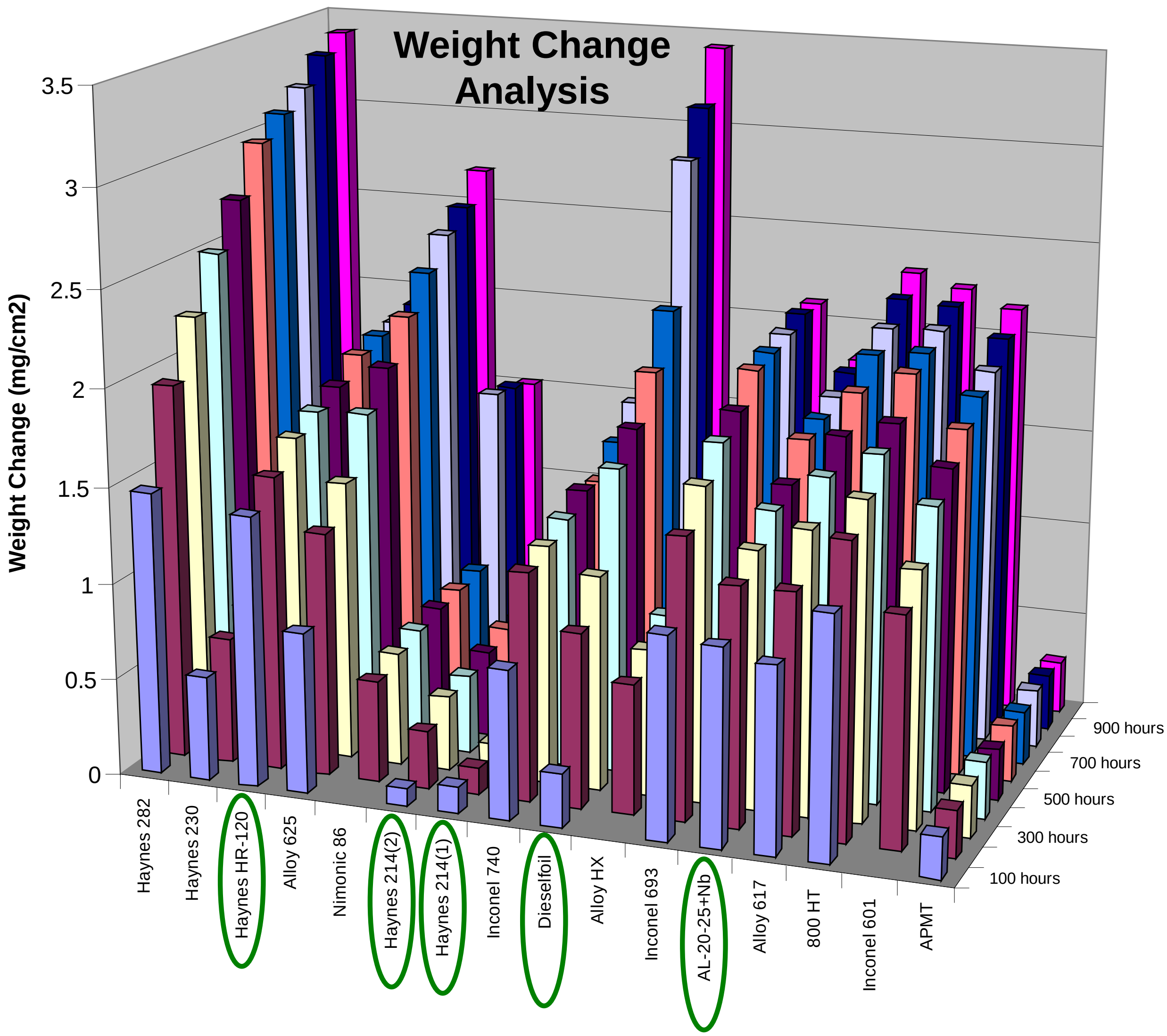


Figure 2.7 Weight Change Analysis

Figure 2.8 shows accumulated spallation debris for the same 2000 hour dry air oxidation test at 950°C.

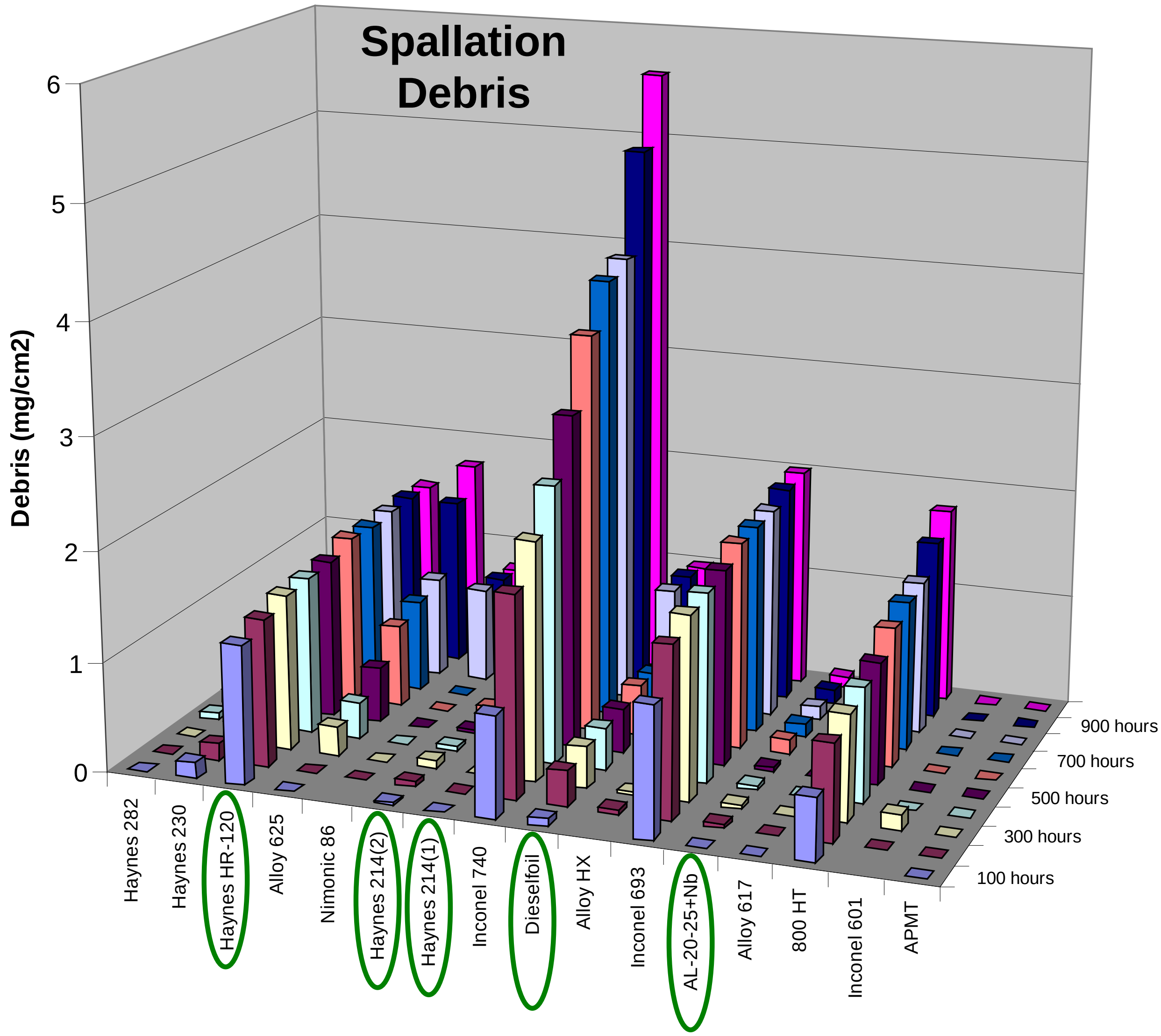


Figure 2.8 Spallation Debris

3.0 MICROCHANNEL RECUPERATOR DEVELOPMENT

3.1 Design Approach

The design approach for the 15 kW_t SOFC/T HTR is best summarized by the list below:

- Identification and prioritization of design criteria
  - > Temperature, Pressure, Pressure Difference, and composition from Task 5 analysis
  - > Lifetime (corrosion, creep)
  - > Cost to manufacture
- Preliminary design and tradeoff study
  - > Identify material families
  - > "Black Box" designs
  - > Identify initial tradeoffs
- Down-selection of materials
  - > Initial narrowing of materials
- Refined design and tradeoff study
  - > Strength, cost, corrosion
- Device test vehicles
- Final design and fabrication

Table 3.1 summarizes the design criteria inputs for the 15kW_t SOFC/T HTR while Table 3.2 summarizes the design criteria fixed targets for the same device.

Table 3.1 Design Criteria Fixed Inputs for 15kW_t SOFC/T HTR

	Cold Stream In (Air feed to SOFC)	Hot Stream In (SOFC/combustor exhaust)
Temperature	209 C	900 C
Pressure	79.0 psia	15.8 psia
Pressure Drop	<1.0 psid	<1.0 psid
Flow	202 lb/hr	194 lb/hr
Composition	Air, ~60% RH	H_2O 12.23% CO_2 6.38% O_2 7.26% N_2 74.13%

Table 3.2 Design Criteria Fixed Targets for 15kW$_t$ SOFC/T HTR

Cost	≤ \$5000
Lifetime	10 yr target (< 10 yr acceptable, but must see significantly reduced production cost)
Volume	~1000/yr
Geometry/Plumbing	No current constraints.
Materials	TBD based on required properties and desired lifetime
Effectiveness	≥ 90%

Table 3.3 is a detailed preliminary design for the 15kW$_t$ SOFC/T HTR.

Table 3.3 Preliminary Design for 15kW$_t$ SOFC/T HTR

Summary of Exchanger Operation	Side 1	Side 2				
Temperature in	243	900	ºC			
Temperature out	889.1	343.5	ºC			
Reynolds @ avg temp	59	46				
Main HX Channel Pressure Drop	0.46	0.67	psi			
Total Device Pressure Drop	0.58	0.97	psi			
% Pressure Drop cont to maldist.	2.7	14.7	%			
Overall Exchanger Data				15	inch	Length of CC HX section
Heat Transferred	19.6	kW		10	mil	Channel height, cold side
Effectiveness	0.983			20	mil	Channel height, hot side
Effectiveness W/O cond.	1.000			0.25	inch	Channel width
Total Volume of exchanger	23.42	L		35		Channels per shim
Core Volume	19.56	L		120		Number of shim pairs
*Calculations neglect flow maldistribution through HX.						
Overall length	41.9	cm	16.5	inch		
Overall Height	23.0	cm	9.04	inch		
Overall Width	24.3	cm	9.58	inch		
Total Shim Volume	23.42	L	1429	cu in		
	note that volume does not include external headers					

Figure 3.1 below shows the creep, cost, and corrosion trade-offs for various Tier 1 alloys.

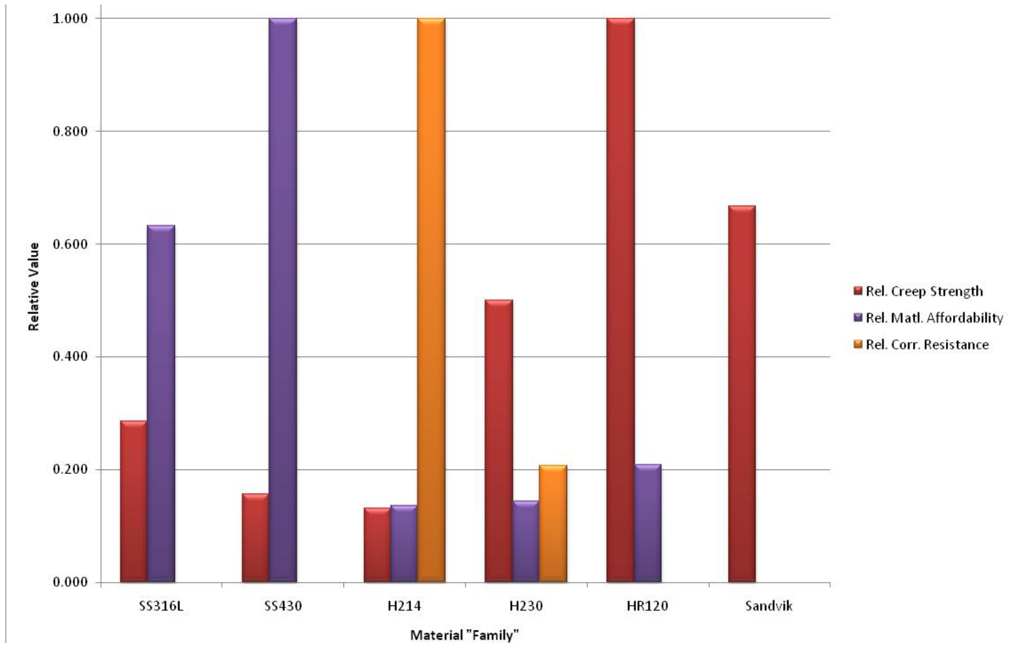


Figure 3.1 Creep, Cost, and Corrosion Trade-offs

In Figure 3.2, a roadmap is presented for the development of the 15kW$_t$ SOFC/T HTR and the cost considerations.

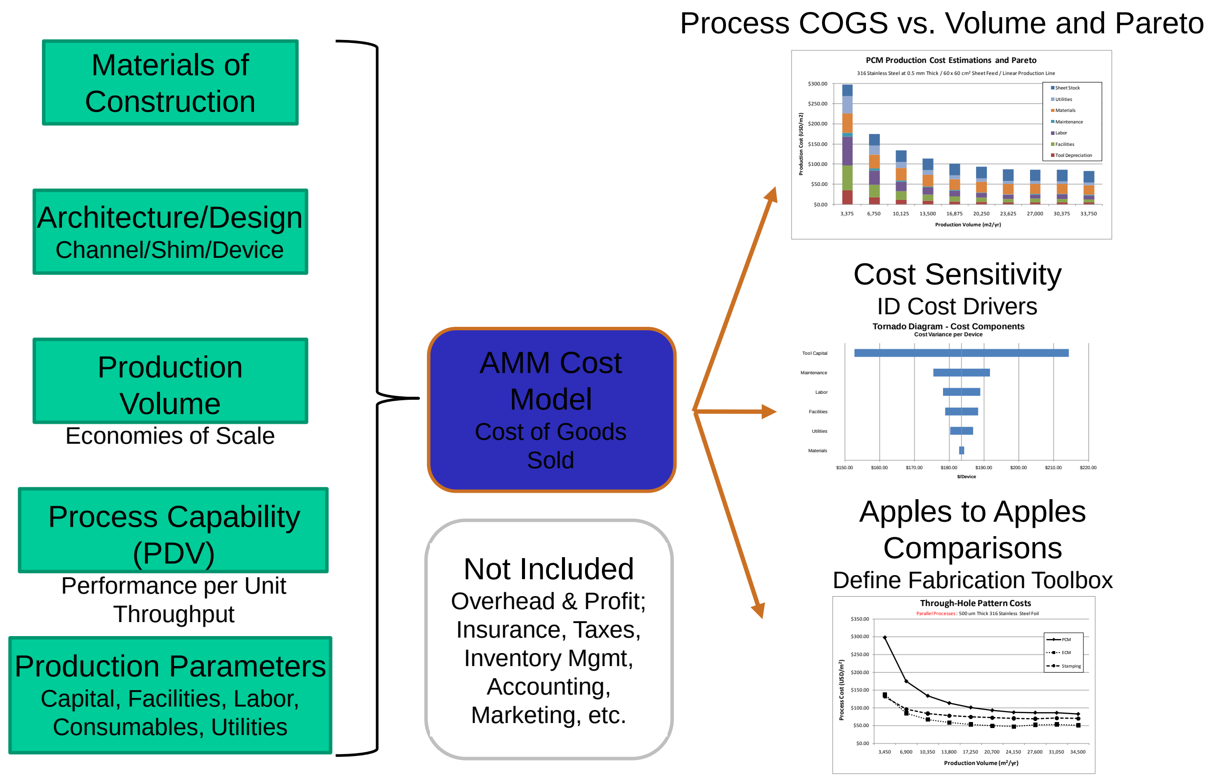
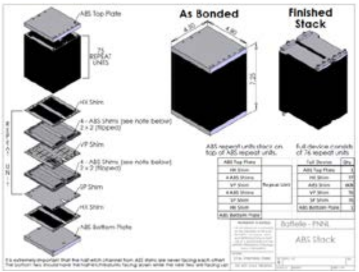


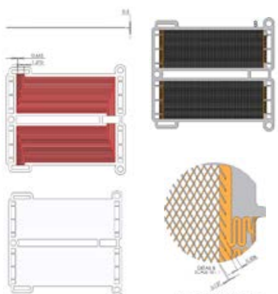
Figure 3.2 Roadmap for Development of 15 kW SOFC/T HTR

Figure 3.3 below lists the relationships between design parameters, process fabrication steps, and costing curves for the microchannel HTR.

1. Design Parameters



Device Level – Number of Shims, Material of Construction. etc.



Shim Level – Through Hole vs. Blind, Cut Perimeter, Thickness, etc.

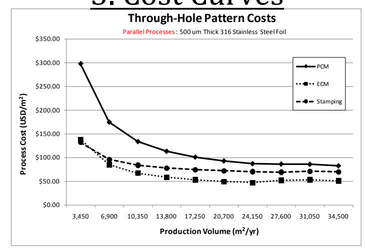
2. Process Flow

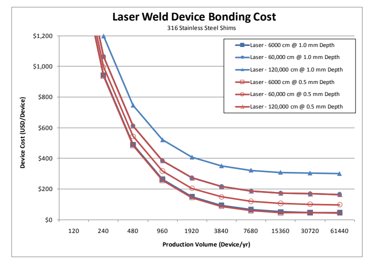
	Component	Process Choice
Pattern	ABS Top	Laser Cut
	ABS Bottom	Laser Cut
	HX	ECM
	ABS	ECM
	VP	ECM
	SP	Laser Cut
Bond	Stack	Laser Weld
Singulate	Stack	Saw
Interconnect	Headers	Form/Draw
	Interconnect	Laser Weld

Design/Fabrication Interaction

General Cost Curves Applied to any Device within Platform

3. Cost Curves





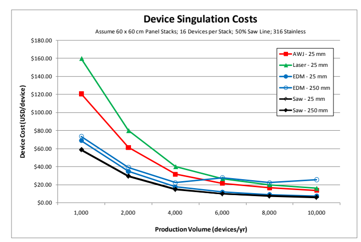


Figure 3.3 Design, Process Parameters, and Costing

In Figure 3.4 a Cost of Goods estimation is made assuming a 316 stainless steel material of construction. A number of assumptions are made:

1. Assume that Raw Material Cost is Representative of Fabrication Cost at Volume
2. Use Literature Creep, Oxidation and Thermal Conductivity Data (Vendor Supplied)
3. Apply Thermo-Mechanical Model to Estimate Total Material Required per Device
4. Device Cost Estimated from Material Mass and Vendor Quotes for Sheet Stock

Figure 3.5 provides an overview of device cost estimation.

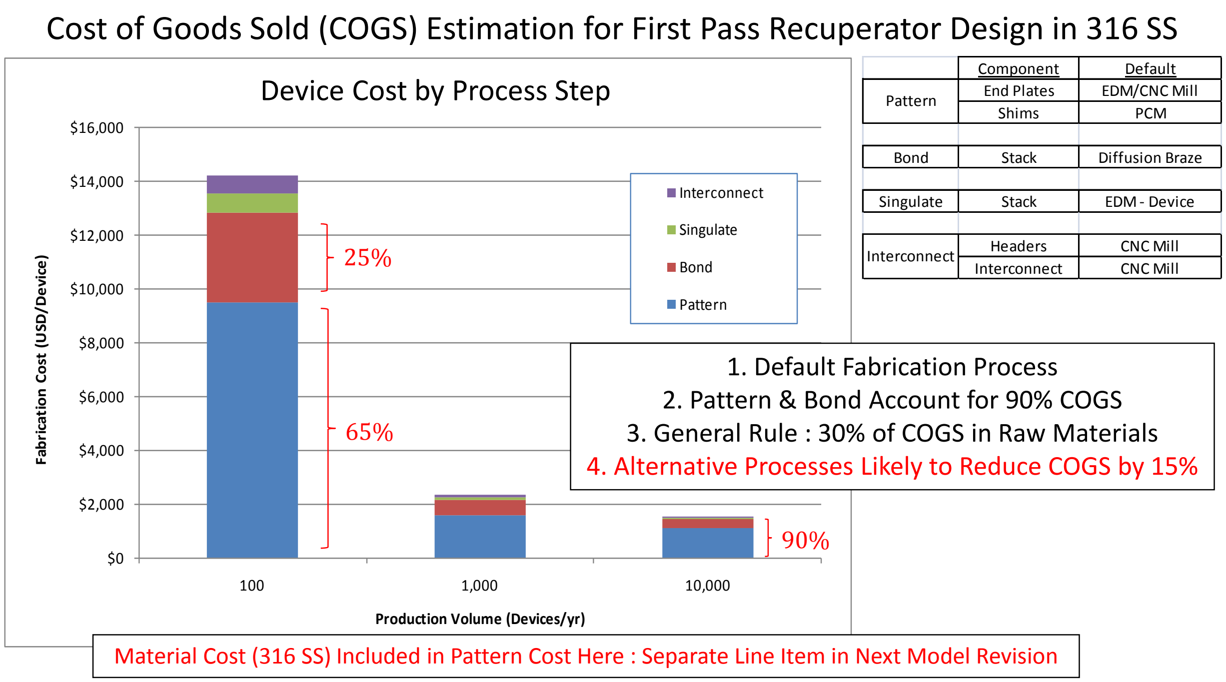


Figure 3.4 Cost of Goods Sold Estimation

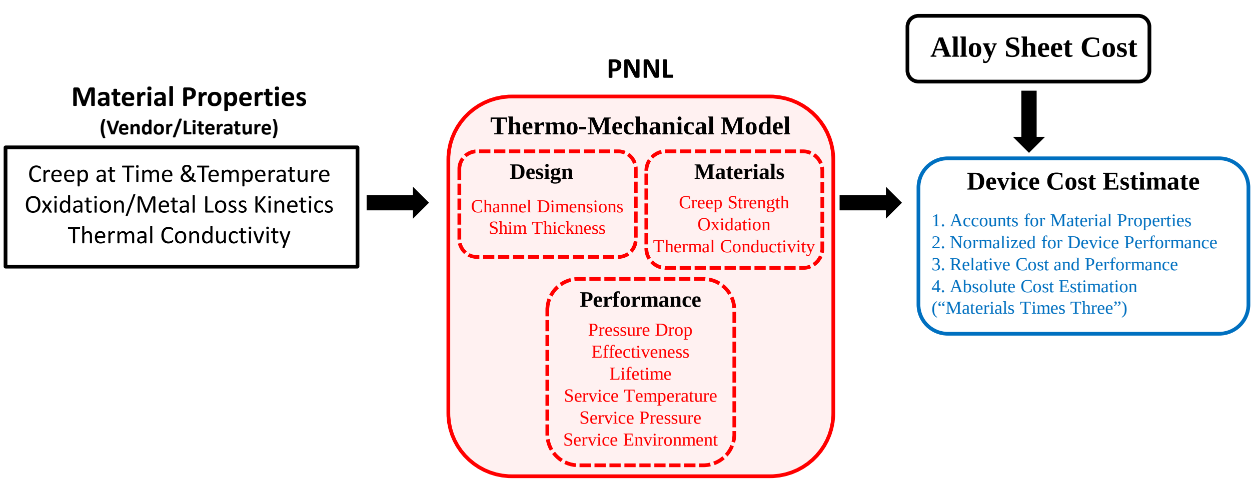


Figure 3.5 Device Cost Estimate

A conceptual HTR cross section is shown in Figure 3.6. In this figure, channel width, shim thickness and rib width are design parameters.

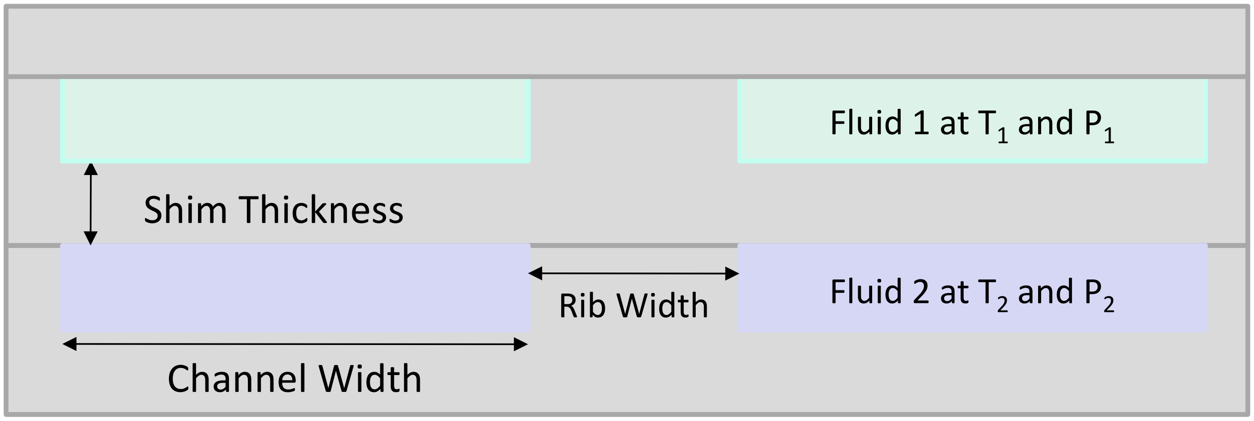


Figure 3.6 Representative Cross Section of HTR

Principle assumptions and design constraints are listed:

1. Fixed Number of Flow Channels → 50 Layers of Hot Channels, 50 Layers of Cold Channels
2. Fluid Pressure Drop = 1.0 psi and HTR Effectiveness = 0.90 → Defines Channel Length @ 3”
3. Rib Width Fixed at 0.508 mm → Channel Width and Shim Thickness “Float”
4. 10 Year End of Life Defines Required Creep Strength at 900^{o}C
5. 2x Factor of Safety Applied to Required Creep Strength

Figure 3.7 shows an approach to down-selection using actual data on Tier 1 materials.

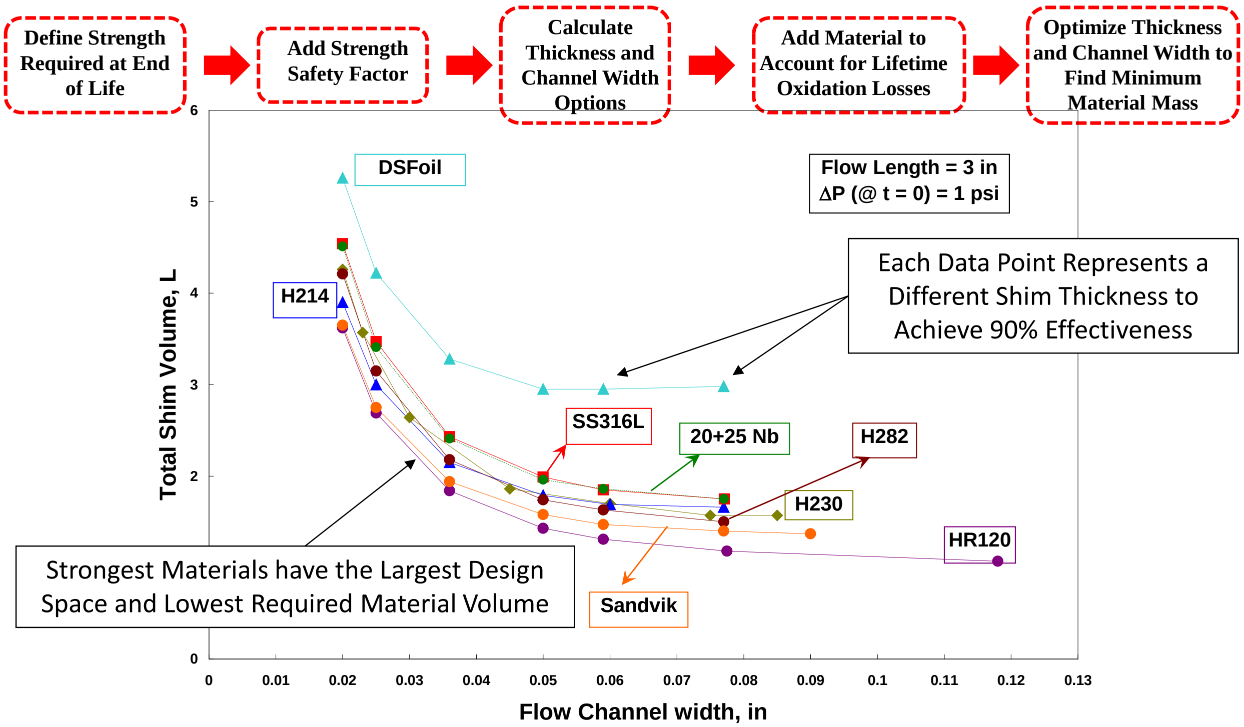


Figure 3.7 Down-Selection Approach

Material costs across the various alloy classes are shown in Figure 3.8.

Material-Based Cost Estimations - FCE Recuperator

Alloy Material	Family	HTR Material Volume (cm3)	Alloy Density (g/cm3)	HTR Material Mass (kg)	Sheet Cost ($/kg)	Material Cost ($)	Device Cost ($)*	Comments
316 SS	AuSS-C	1870	7.99	14.9	$7.70	$115	$345	Creep Data only to 800C and 180 hr
AL 20-25+Nb	AuSS-C	1870	7.96	14.9	$16.50	$246	$737	Oxidation Data to 800C and 1000 hr
HR 120	FSA-C	1070	8.07	8.6	$47.00	$406	$1,218	High Strength; Med Oxidation
DF Clad 430 SS	FSS-A	4100	7.75	31.8	$13.50	$429	$1,287	Diesel/430/Diesel; Data to 800C
Haynes 230	NSA-C	1570	8.97	14.1	$52.25	$736	$2,207	High Strength; High Oxidation
Haynes 282	NSA-C	1500	8.27	12.4	$60.00	$744	$2,233	High Strength; Med Oxidation
Haynes 214	NSA-A	1690	8.05	13.6	$87.50	$1,190	$3,571	Med Strength; Low Oxidation
Sandvik APMT	FSS-A	1370	7.25	9.9	$180.50	$1,793	$5,378	High Strength; Med Oxidation

Alloy Family Abbreviations		Required Material Property Model Inputs
NSA-C	Nickel-based super alloy; Chromia forming	1. Creep Strength at 1 or 2% Strain at Temperature
NSA-A	Nickel-based super alloy; Alumina forming	2. Metal Loss Rate - Based on Oxidation Rate Kinetic Parameter
FSA-A	Iron-based super alloy; Alumina forming	3. Thermal Conductivity at Service Temperature
FSA-C	Iron-based super alloy; Chromia forming	
FSS-A	Ferritic stainless steel; Alumina forming	
AuSS-C	Austenitic stainless steel: Chromia forming	* Device Cost Based on "Material Times Three" Estimate

1. Material Based Cost Estimation Suggests Cost Target Achievable with Range of Alloys
2. Low Cost Austenitic SS Candidates are Likely Not Capable at HTR Service Environment
3. Cost Segregation for "High Confidence" Alloy Choices; Assume +/- 30% on Estimation
4. *Limited Thermo-Mechanical Database (Time @ Temperature for Representative Shim Dimensions)*

Figure 3.8 Alloy Class Material Costs

HTR preliminary design and sizing is shown in the first pass sizing of Figure 3.8. The dimensions and initial material of construction are:

- Length: ~5 inch
- Width: ~4 inch
- Height: ~5 inch
- Based on HR120
- Laminated design
- Material selection is necessary before finalizing the design

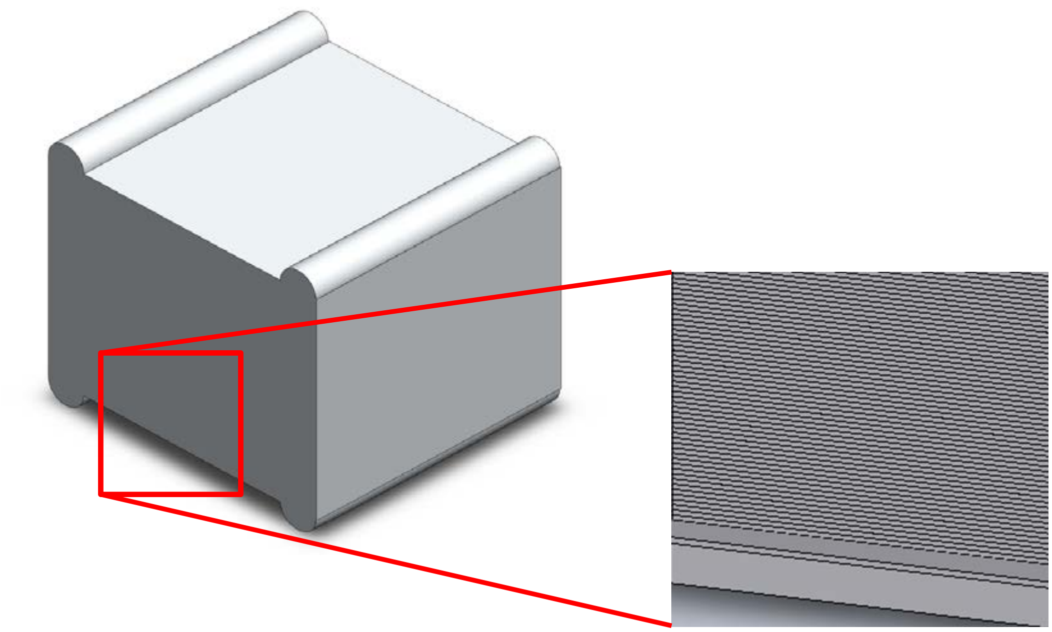


Figure 3.9 First Pass Sizing

4.0 SCALE-UP TO 250KW$_E$ - 5MW$_E$ DESIGN

4.1 SOFC/T System Concept Design and Development

A new integrated SOFC/T cycle was developed under the project work. Key features of the cycle includes:

- Operation on Natural Gas Fuel
- Design Incorporates Fuel Recycle - Enhances Cell Performance and Avoid Continuous Water Consumption
- System Includes Gas Turbine Bottoming Cycle
- High Temperature Recuperator (HTR) Integral to Performance & Cost

Sensitivity studies were carried out for a MW-scale SOFC/T system design. Initial work was based on a system with a cathode recycle blower, an HTR, and Low Temperature Recuperator (LTR). Later work established a new concept with an air preheater and HTR but no cathode recycle blower and no LTR. Under the DOE SECA program an improved SOFC Module was developed which eliminates an external fuel preheater. This improvement has been incorporated into the HTR sensitivity studies. Figure 4.1 below shows the SOFC/T concept that was developed under the program. Figure 4.2 shows a simplified process flow diagram.

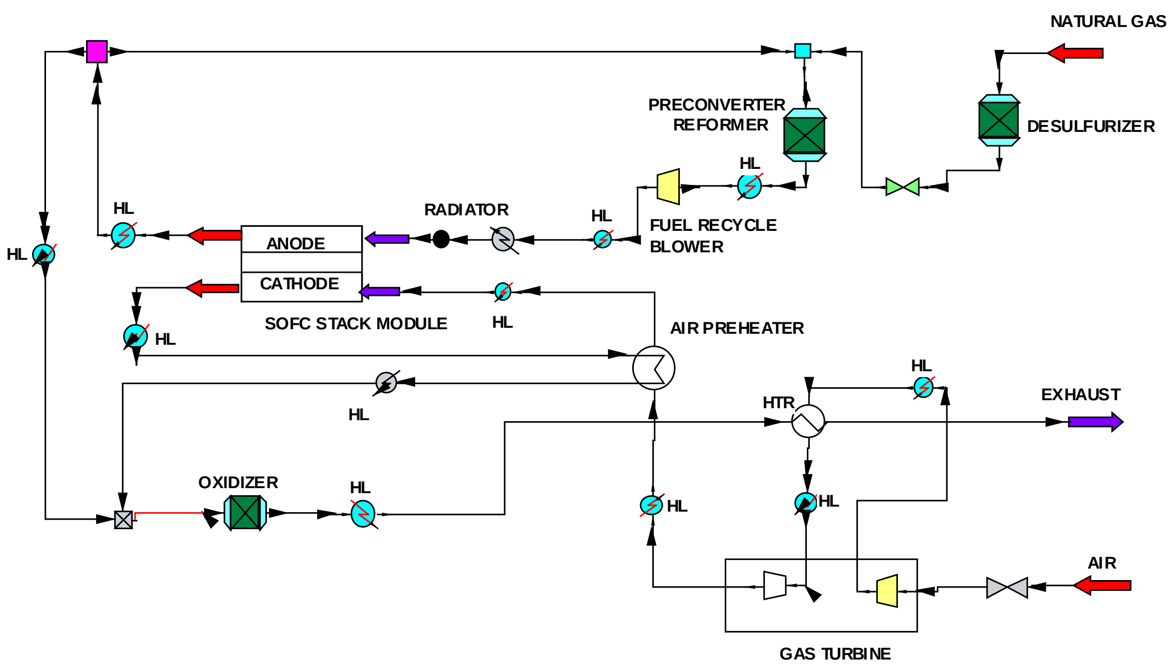


Figure 4.1 SOFC/T Concept (Heat and Mass Balance Format)

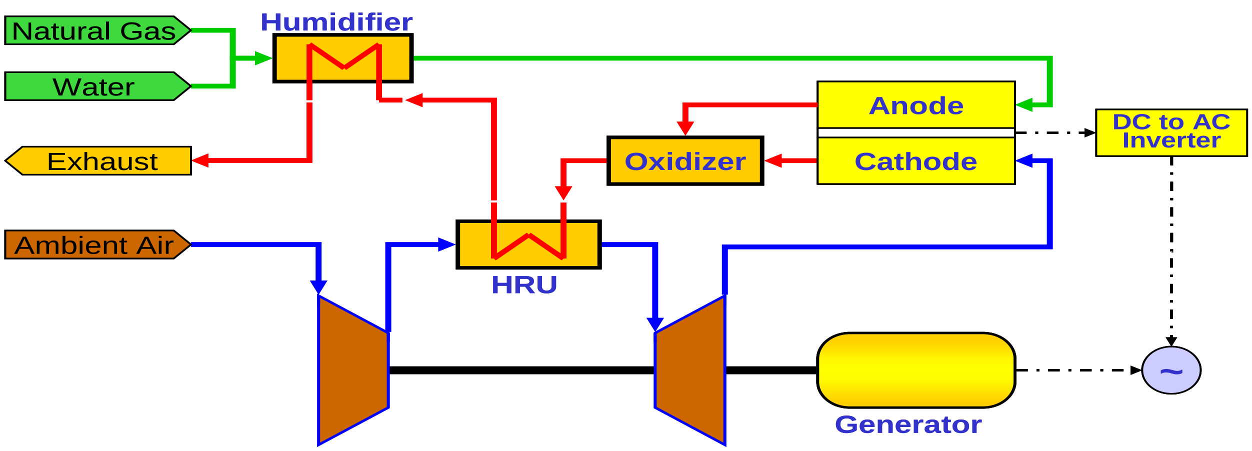


Figure 4.2 SOFC/T Concept (Simplified Process Flow Diagram)

The basis for this concept is the solid oxide technology of Versa Power Systems (VPS), FCE's wholly owned subsidiary. Key parameters of the system include:

- SOFC Cell Voltage from VPS Performance Model at 500 mA/cm^2
- SOFC Cell Fuel Utilization – Variable , ~70% Max
- Overall Fuel Utilization – Variable, ~85% Max
- Fuel Recycle 38% for Steam/CH_4 Ratio 2.5 at Reformer Inlet
- Air Flow Adjusted for 180ºF Cathode Temperature Rise
- Heat Losses in System ~ 4 - 6 % of Fuel Energy
- Gas Turbine Compressor Efficiency 83%
- Gas Turbine Turbine Efficiency 92%

A range of system conditions were investigated in the sensitivity studies. The following inputs were used:

- Gas Turbine Pressure Ratios: 3, 4, 5, & 6
- Heat Exchanger Pressure Losses, 0.1, 0.5, & 1.0 PSI Per Side
- HTR Inlet Temperature Primary Parameter - 1300°F to 2000°F

The following outputs were calculated:

> Net Plant AC Output
> System LHV Efficiency
> Turbine Inlet & Outlet Temperature and Power
> System Exhaust Temperature
> High Temperature Recuperator Size, UA
> Air Preheater Size, UA

Increasing HTR operating temperature increases system efficiency but increases HTR cost. A key question is: How sensitive to efficiency is HTR operating temperature? System heat and mass balances were evaluated using "CHEMCAD" process simulation by CHEMSTATIONS, Houston, TX. Fuel cell heat and mass balances were evaluated using an EXCEL performance model developed by FCE and linked to CHEMCAD. The system concept of Figure 4.1 is an actual CHEMCAD flowsheet model.

Sensitivity studies were conducted using the CHEMCAD flowsheet model. The results are shown in the following figures.

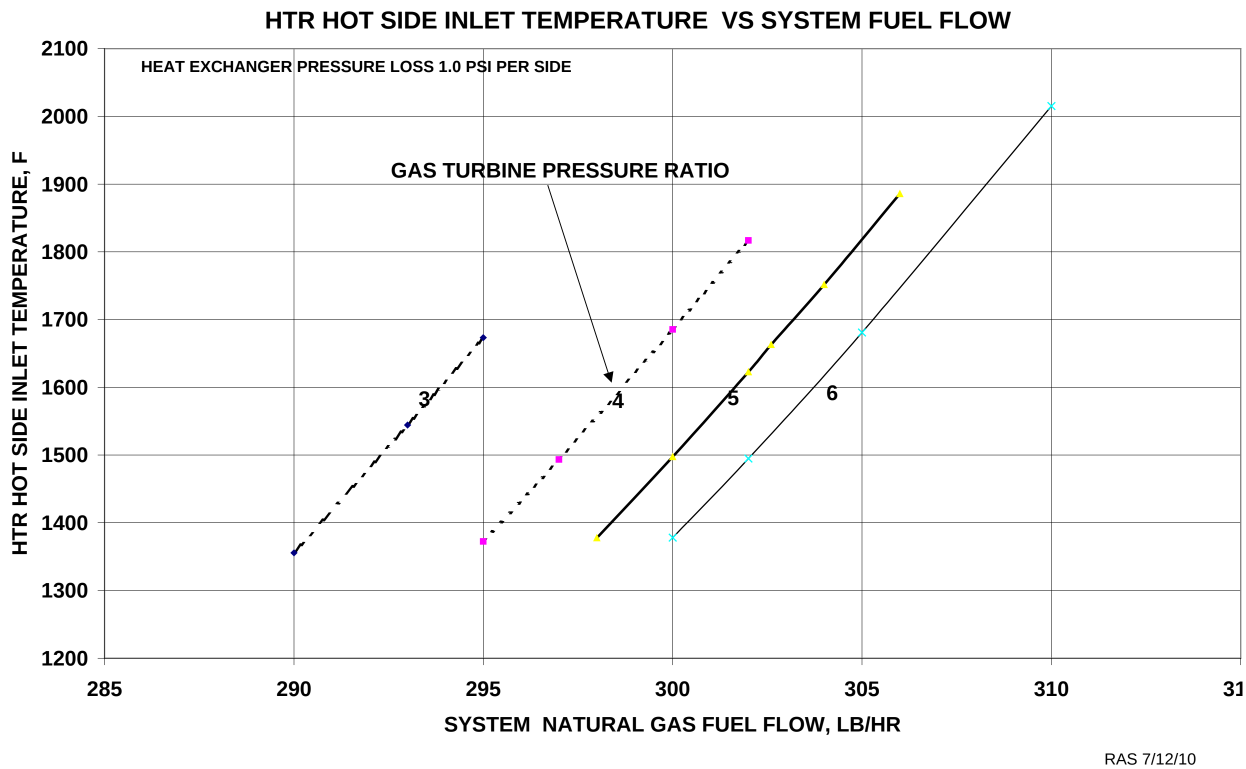


Figure 4.3 SOFC/T Sensitivity: HTR Hot-Side Inlet Temperature

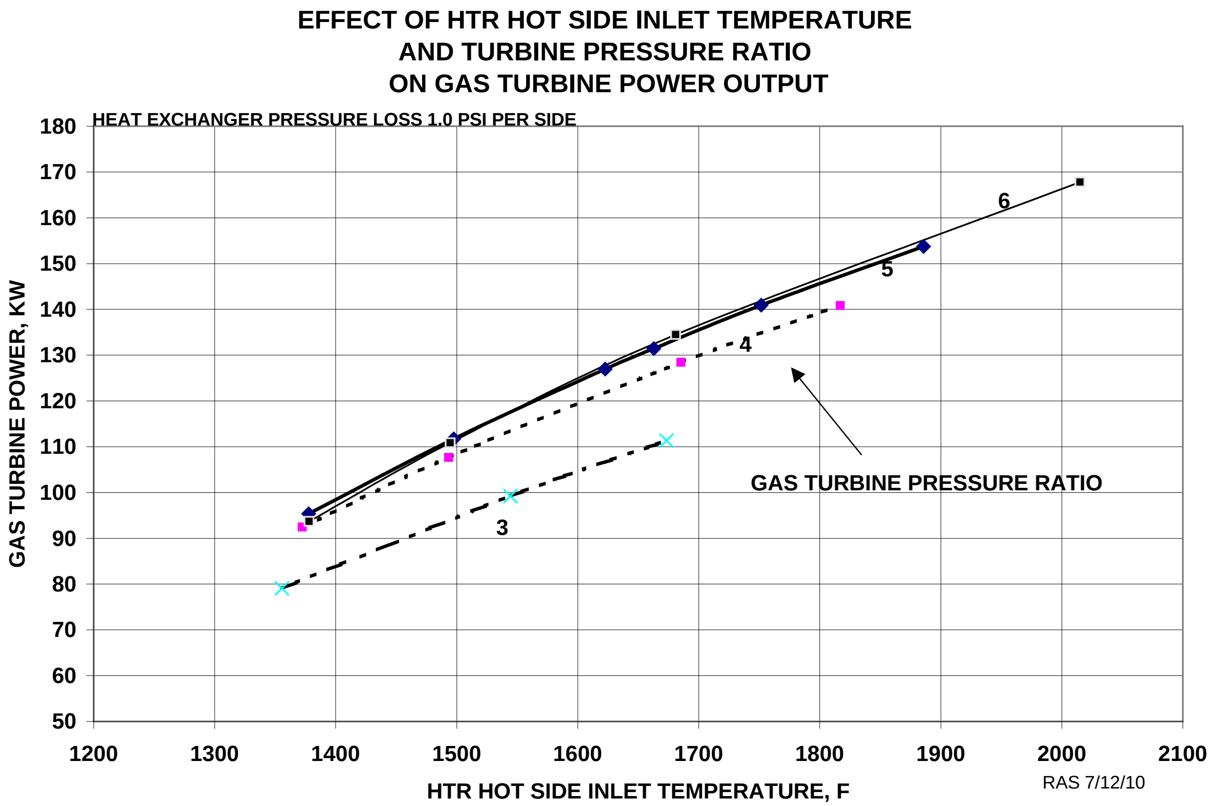


Figure 4.4 SOFC/T Sensitivity: Gas Turbine Power Output

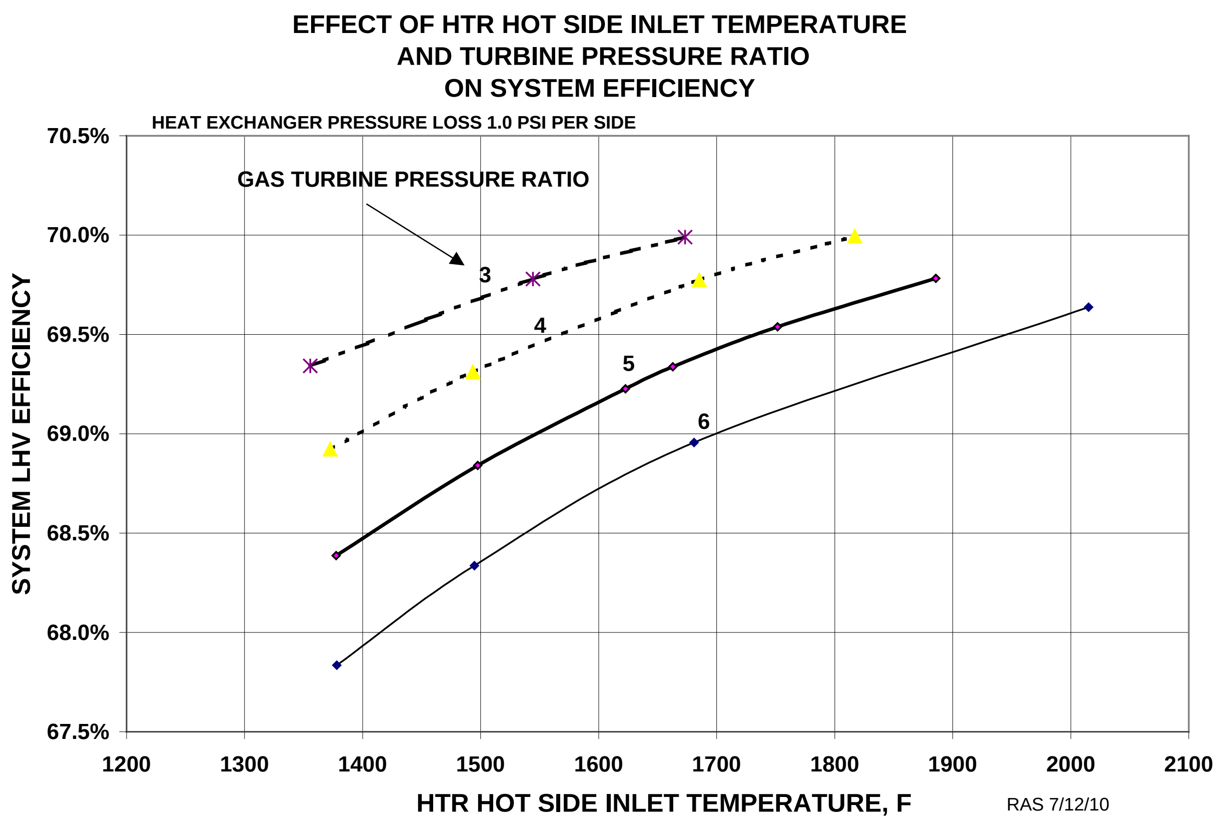


Figure 4.5 SOFC/T Sensitivity: System Efficiency

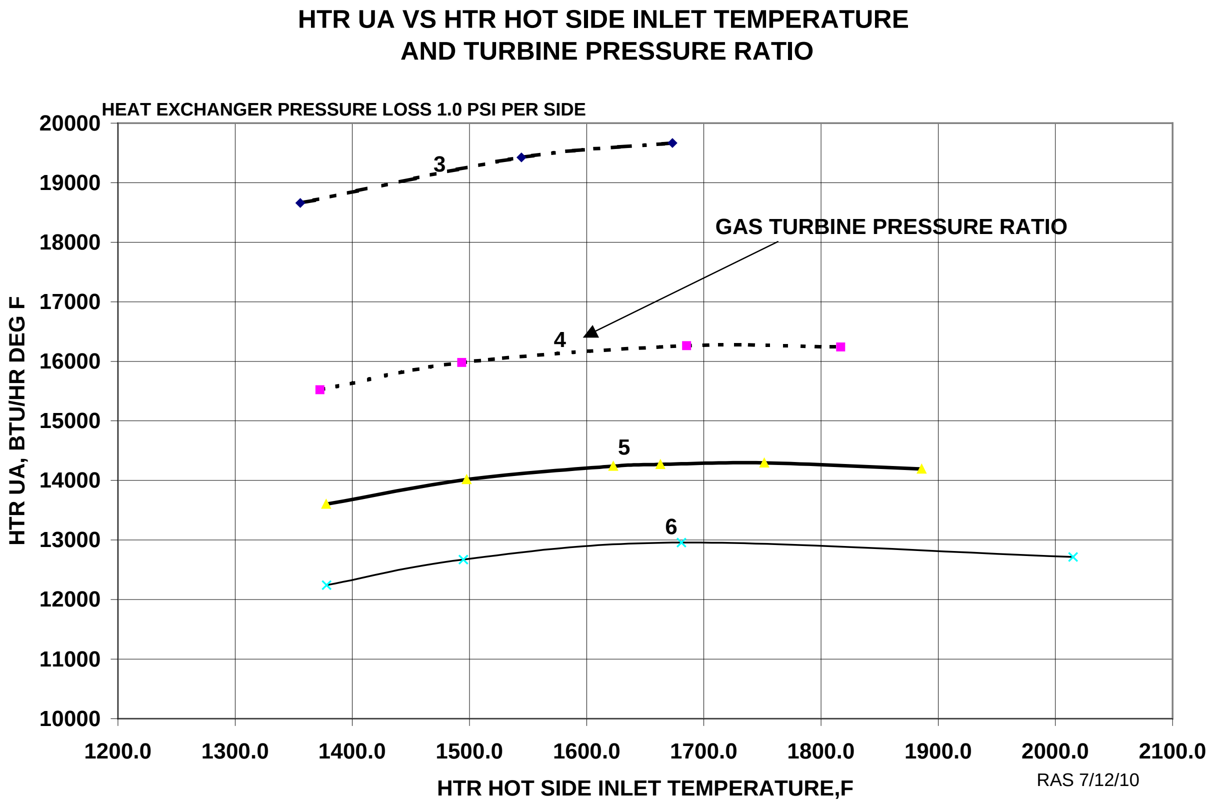


Figure 4.6 SOFC/T Sensitivity: Turbine Pressure Ratio

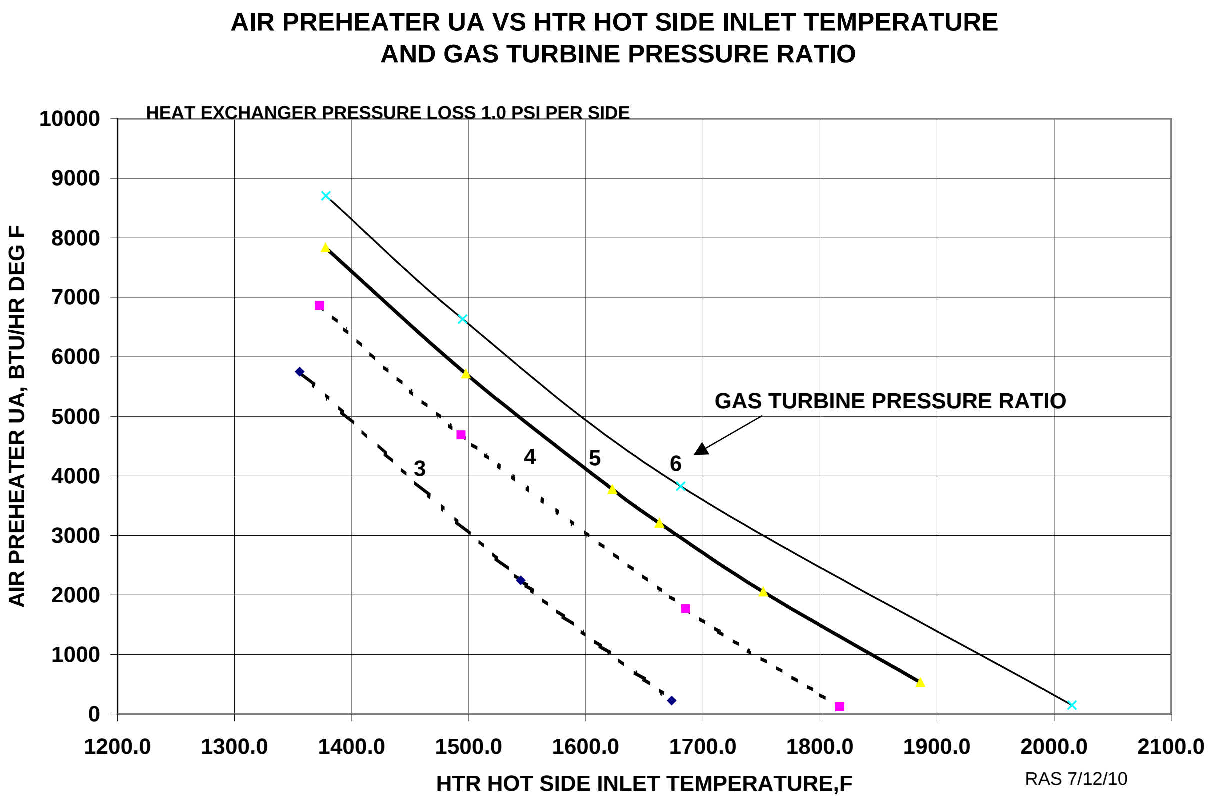


Figure 4.7 SOFC/T Sensitivity: Air Heater UA

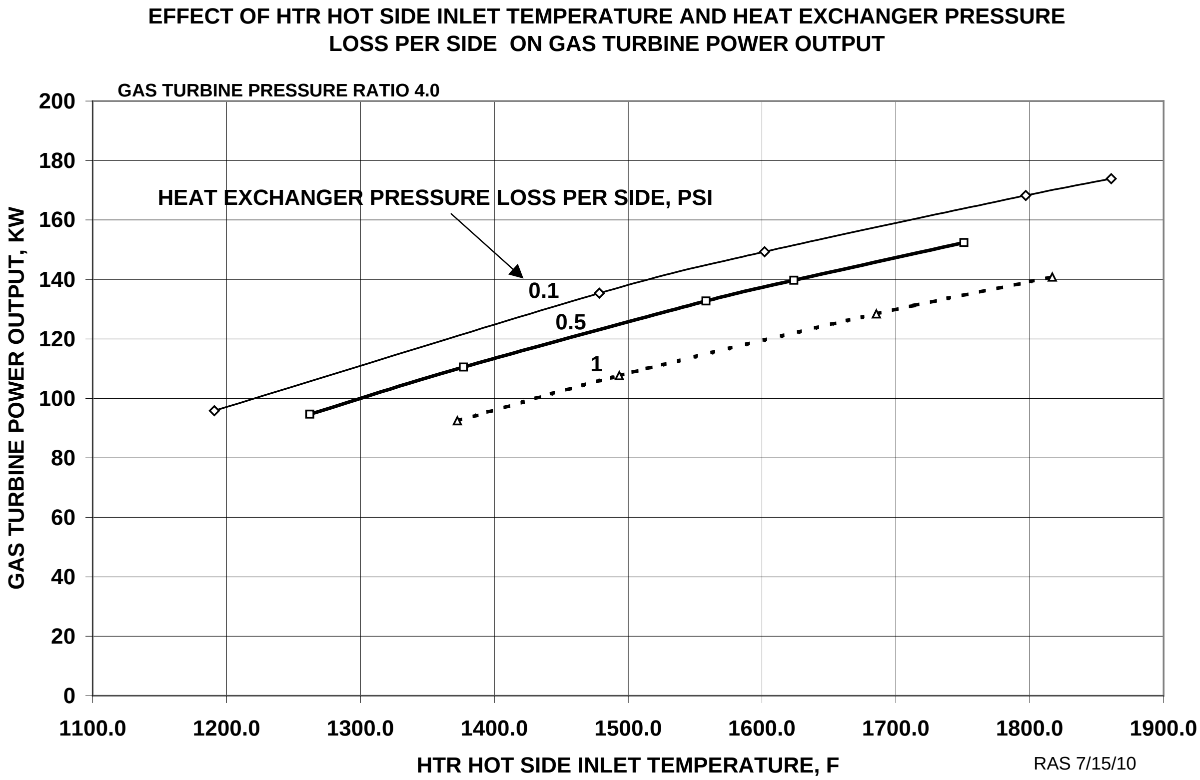


Figure 4.8 SOFC/T Sensitivity: Gas Turbine Power Output

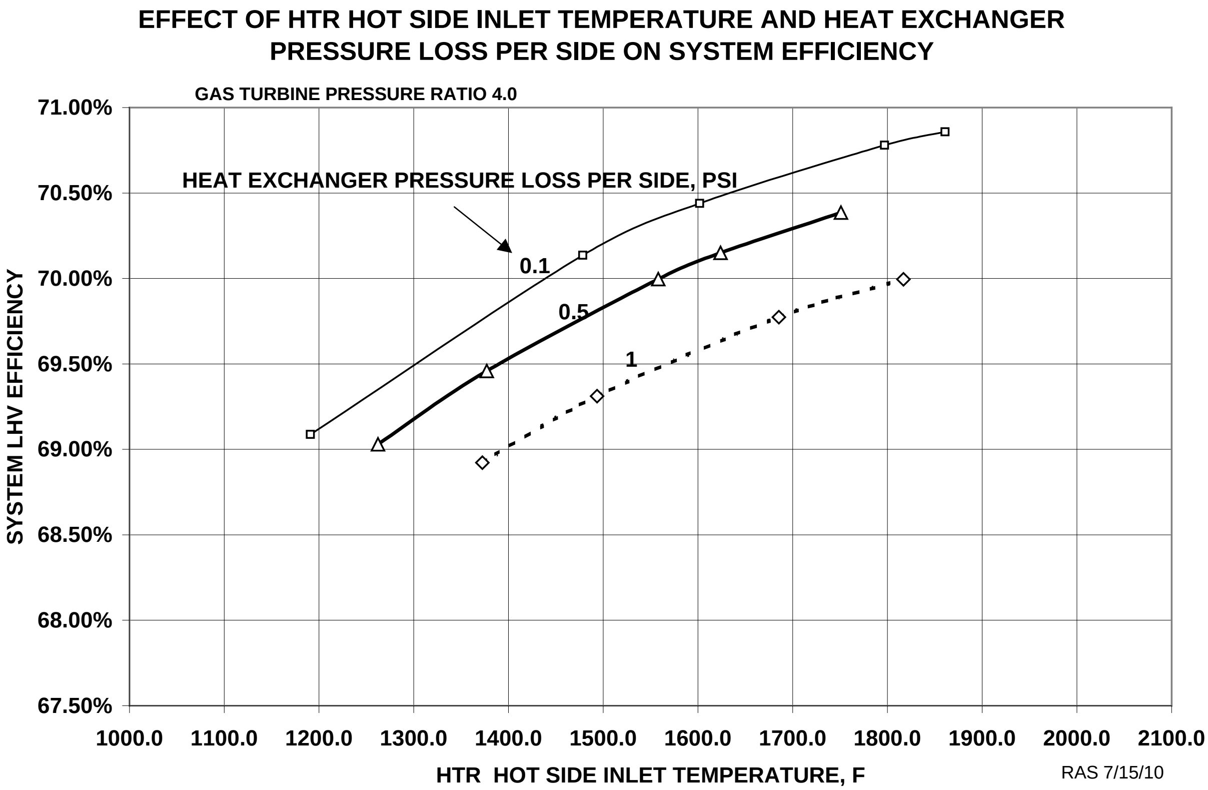


Figure 4.9 SOFC/T Sensitivity: System Efficiency

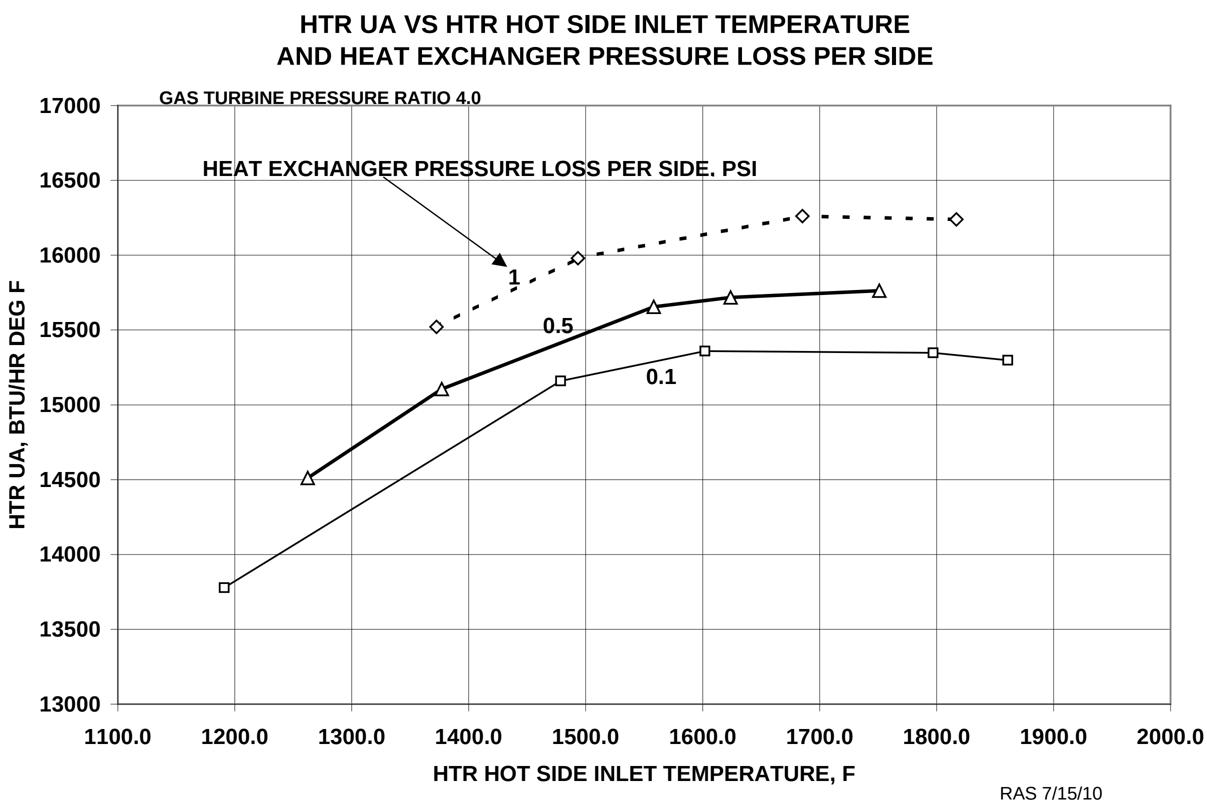


Figure 4.10 SOFC/T Sensitivity: HTR UA

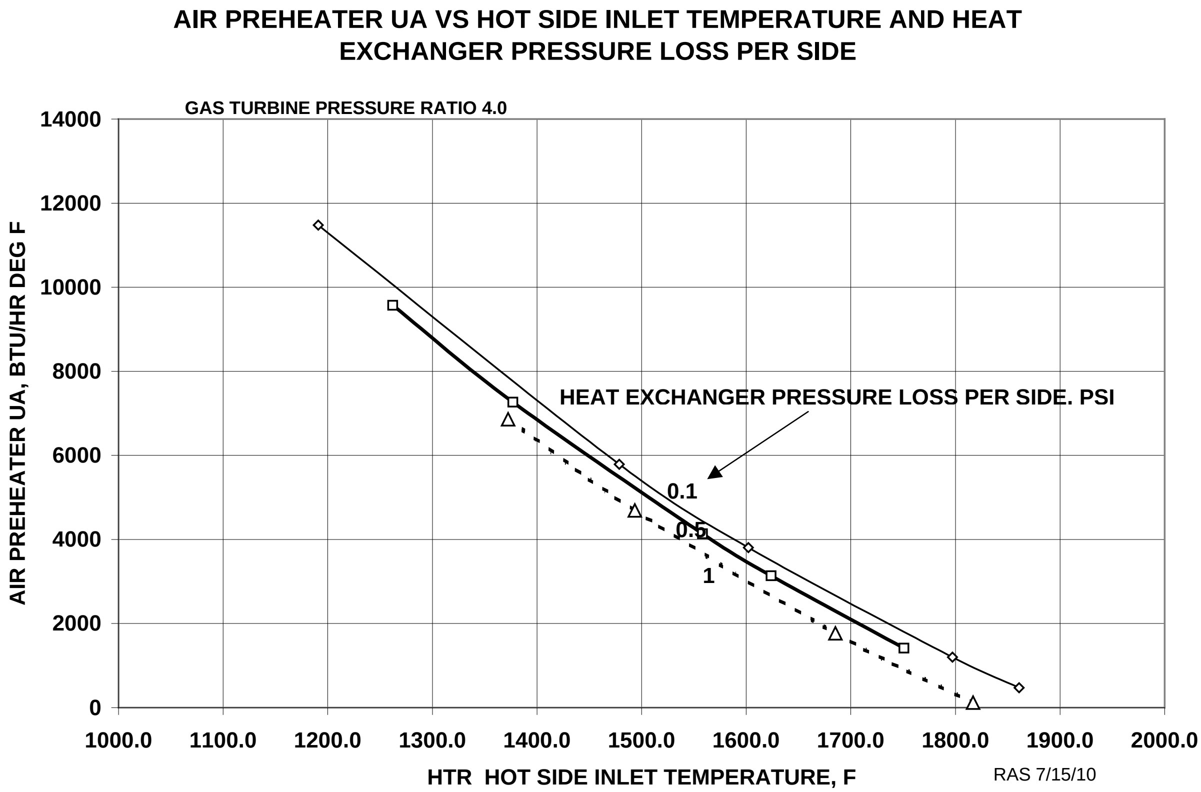


Figure 4.11 SOFC/T Sensitivity: Air Preheater UA

These studies established key design parameters:

1. 900ºC (1650ºF) HTR Design Temp
2. HTR Pressure Drop 1 PSI (both sides)
3. Turbine Pressure Ratio of 5:1

Cost studies that were completed, consisted of:

- Power Plant Capital Cost for 1200 kW SOFC/T
- Capital Cost Estimated for Each Major Equipment Item
- 20-Year Levelized Cost of Electricity (COE)
- Capital Cost Sensitivity to High Temperature Recuperator Cost
- COE Sensitivity to High Temperature Recuperator Cost

The levelized cost included all costs over the power plant lifetime: investment, maintenance, operation, fuel cost, and cost of capital. At a nominal design: 1650ºF HTR inlet temperature, HTR pressure drop 1 psi both sides, and GT Pressure Ratio of 5:1, the AC power output was 1254 kW at an efficiency of 69% based on the LHV of natural gas.

Equipment Included in Cost Studies consisted of:

- Fuel Cell Module (Cell Stacks, Radiator, Enclosure)
- Desulfurizer

- Reformer
- Fuel Recycle Blower
- Oxidizer
- Air Preheater
- Gas Turbine Generator
- High Temperature Recuperator
- Startup Equipment (Water Treatment, Air Heater)
- Piping, Instruments, and Control
- Electrical Balance-of-Plant (Inverter, Transformer, Switchgear)

The basis for capital cost/COE and sensitivities was:

- HTR Cost Assumed to Range from $10/UA to $50/UA
- HTR Inlet Temperature Range from 1400ºF to 1900ºF
- HTR Pressure Drop Fixed at 1 PSI Both Sides
- Turbine Pressure Ratio Range Between 4:1 and 5:1
- SOFC Module and BOP Cost Based on 1.6 MW SECA Study
- Other (Mechanical) BOP Costs Based on FCE's DFC1500 and DFC/T 3000

Additional assumptions used in the studies were:

- Capacity Factor 90%
- Natural Gas Cost $5/MM Btu (HHV)
- One SOFC Module Replacement and One HTR Replacement over 10-Year Period
- Cost of Money 8%
- 30% Investment Tax Credit
- Engineering Costs
- Computed COE Range: 10.2 cents/kWh to 11.4 cents/kWh

Figure 4.12 shows the 1.2 MW SOFC/T plant cost as a function of HTR inlet temperature. This analysis assumes a family of curves for HTR cost in $/UA. Figure 4.13 provides 1.2 MW SOFC/T Cost of Electricity (COE) as a function of HTR inlet temperature. This also assumes a family of curves for HTR cost in $/UA. Finally, gas turbine factory cost used FCE DFC/T actual costs valid for low power rating and utilized information from the Gas Turbine World handbook for higher ratings.

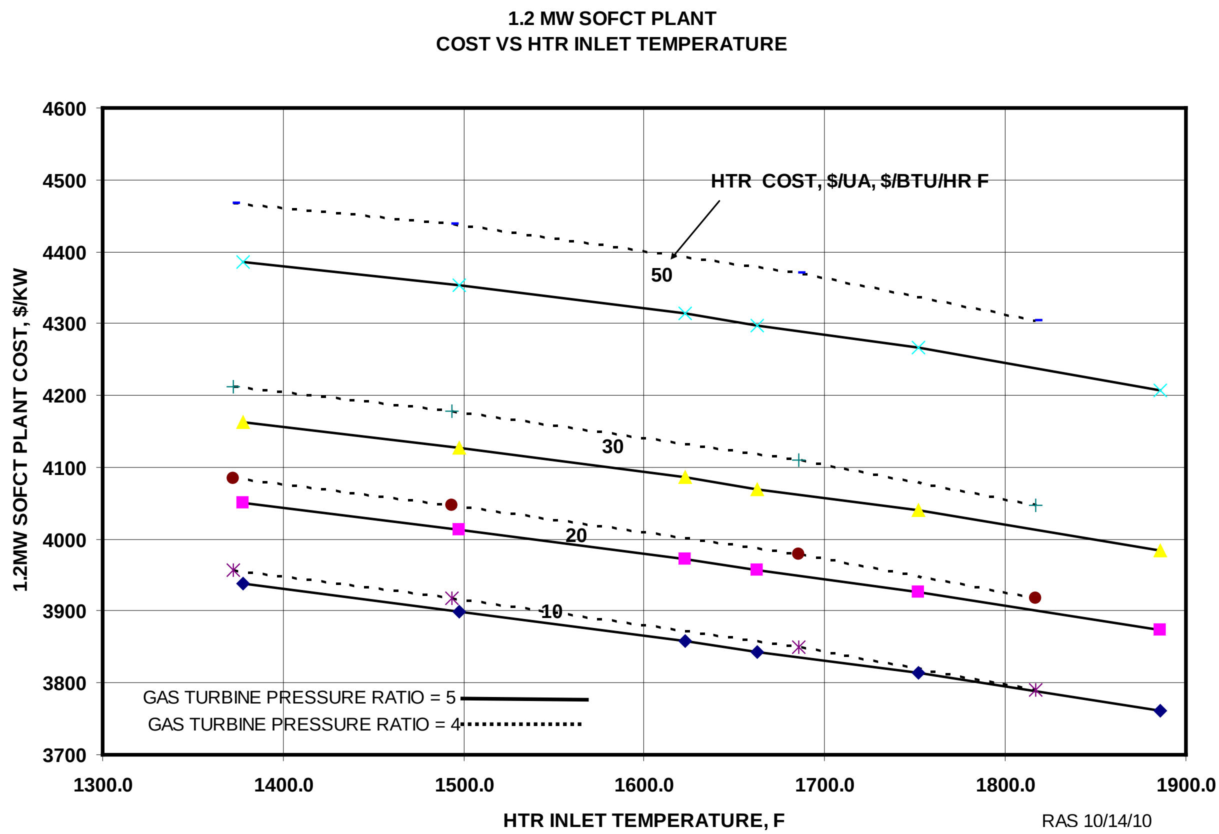


Figure 4.12 SOFC/T Plant Cost vs. HTR Inlet Temperature for Family of HTR Costs

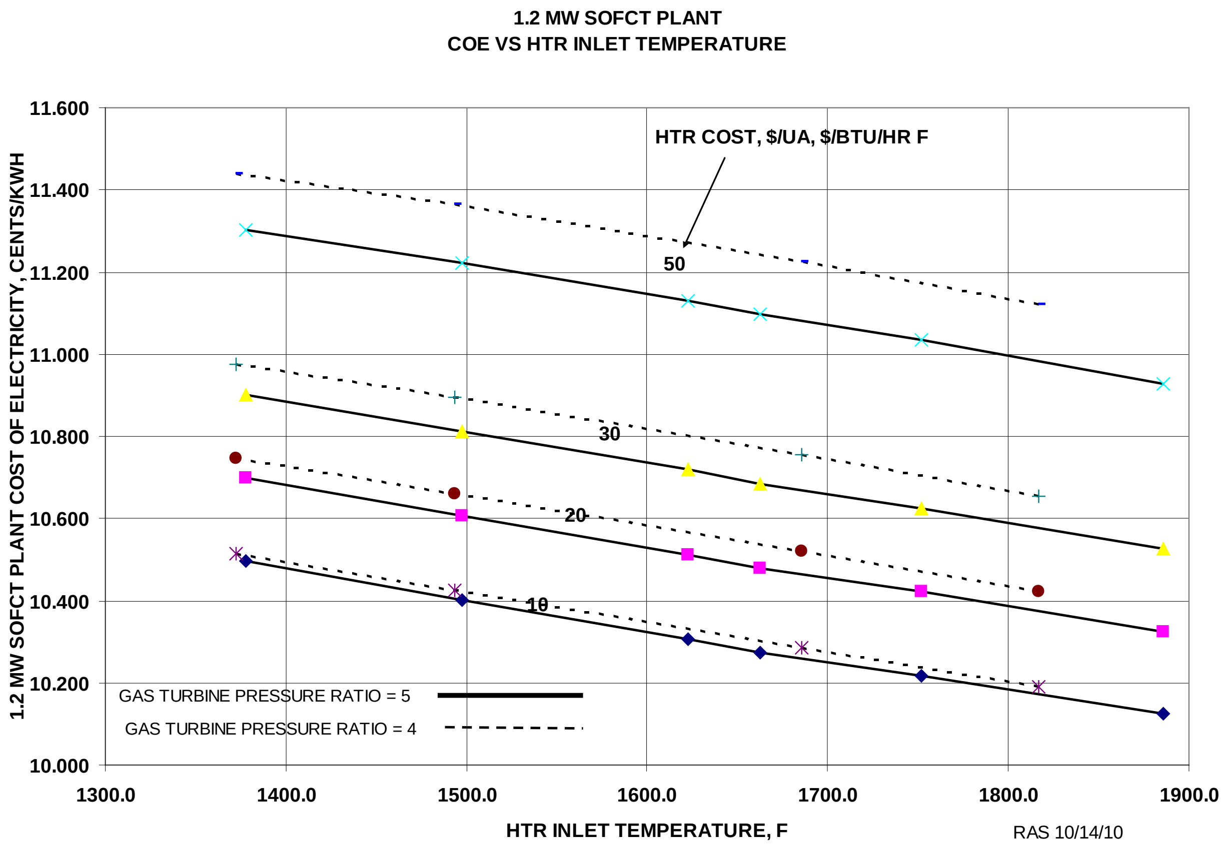


Figure 4.13 SOFC/T Cost of Electricity (COE) vs. HTR Inlet Temperature for Family of HTR Costs

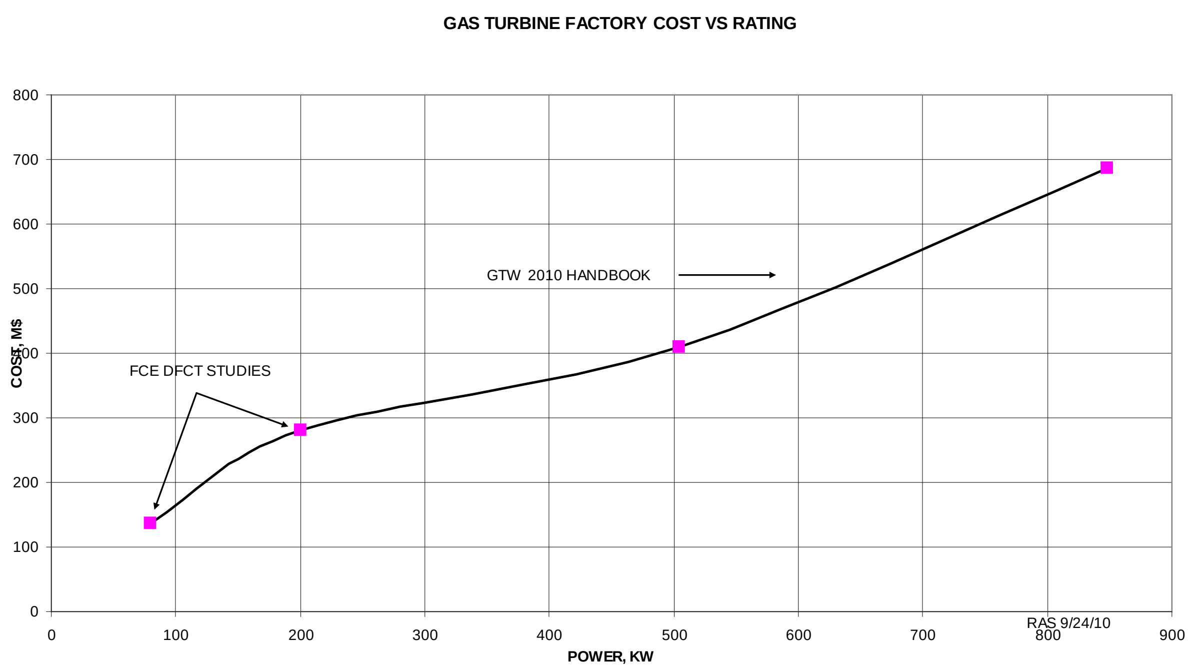


Figure 4.14 SOFC/T Gas Turbine Factory Cost

5.0 RECUPERATOR TESTING

5.1 Technology Demonstration Vehicle

A technology demonstration vehicle (TDV) fabrication and testing program was put in place. The purpose was to prove out fabrication techniques, suitable materials of construction, device integrity, and basic performance at a subscale level. Figure 5.1 shows an example of a TDV.

Several iterations of TDV's were fabricated, each improved over the previous build as far as fabrication techniques. Two of three fabricated TDV's were integrated with the TDV Test Facility at FCE for hot-testing at simulated operating conditions. The second of these two was successfully hot-tested for over 1000 hours at simulated temperature and pressure. Post-test leakdown assessment showed negligible leakage at benchtop conditions of 30 psig, a considerable improvement over all previous TDV's.

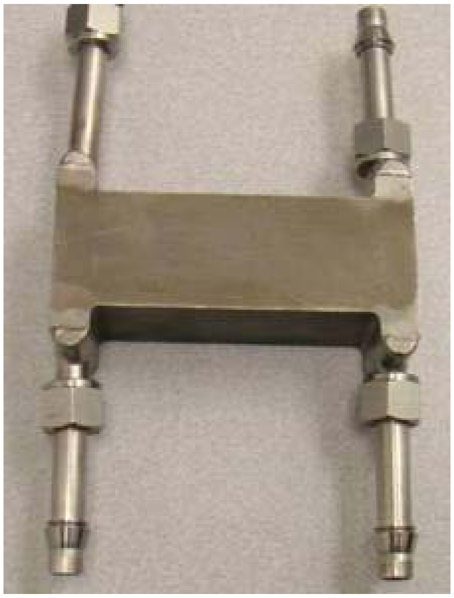


Figure 5.1 Example TDV

TDV shims and endplates were fabricated using Haynes 214 sheet and plate, respectively. Manifolds were fabricated using Haynes 224. Pipes were fabricated using Haynes 230. Figures 5.2 and 5.3 show, respectively, endplate drawings used for the construction process and manifold drawings.

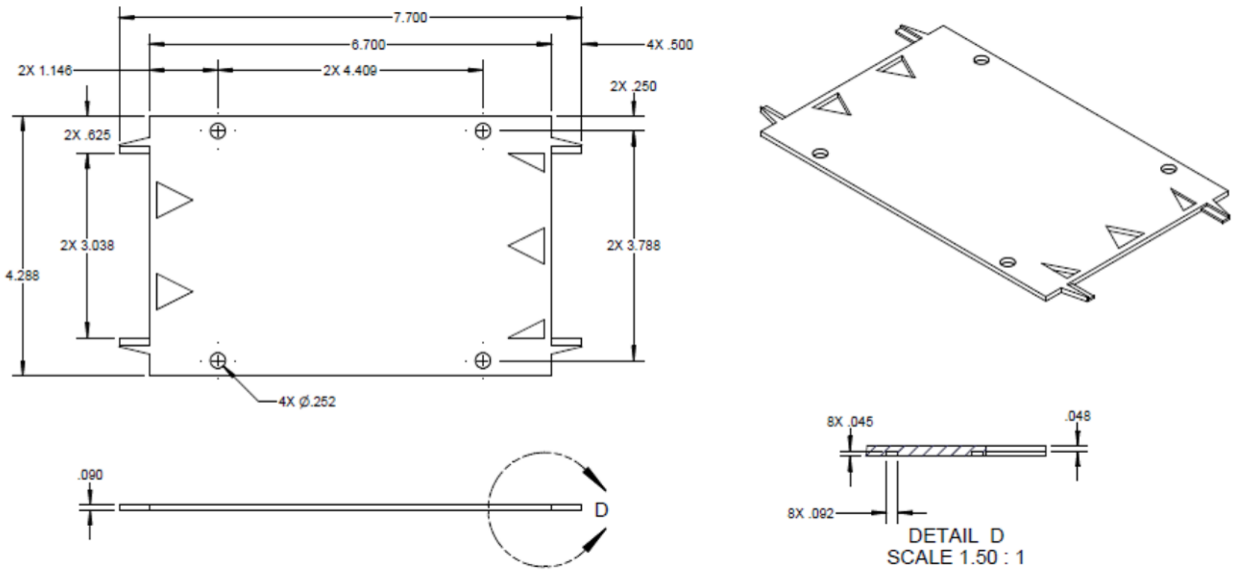


Figure 5.2 TDV Endplates

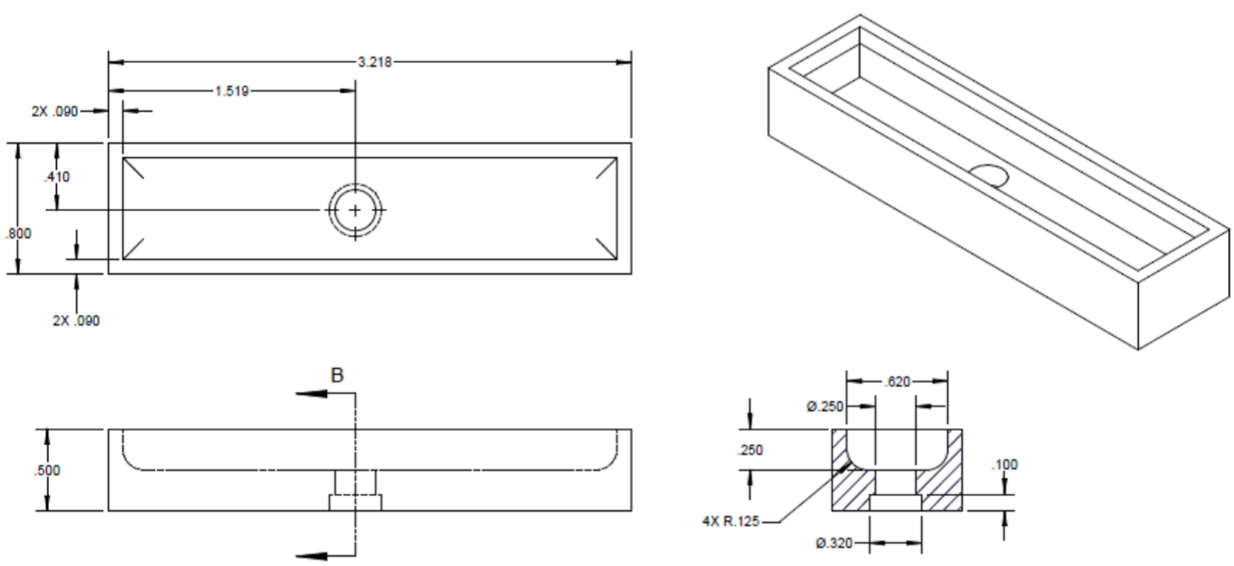


Figure 5.3 TDV Manifolds (Interconnects)

FCE had modified an existing test facility in preparation for TDV testing. This is shown in Figure 5.4. A set of piping and instrumentation diagrams (P&ID’s) for the test facility are shown in Figure 5.5 and Figure 5.6.

Figure 5.4 FCE’s TDV Test Facility

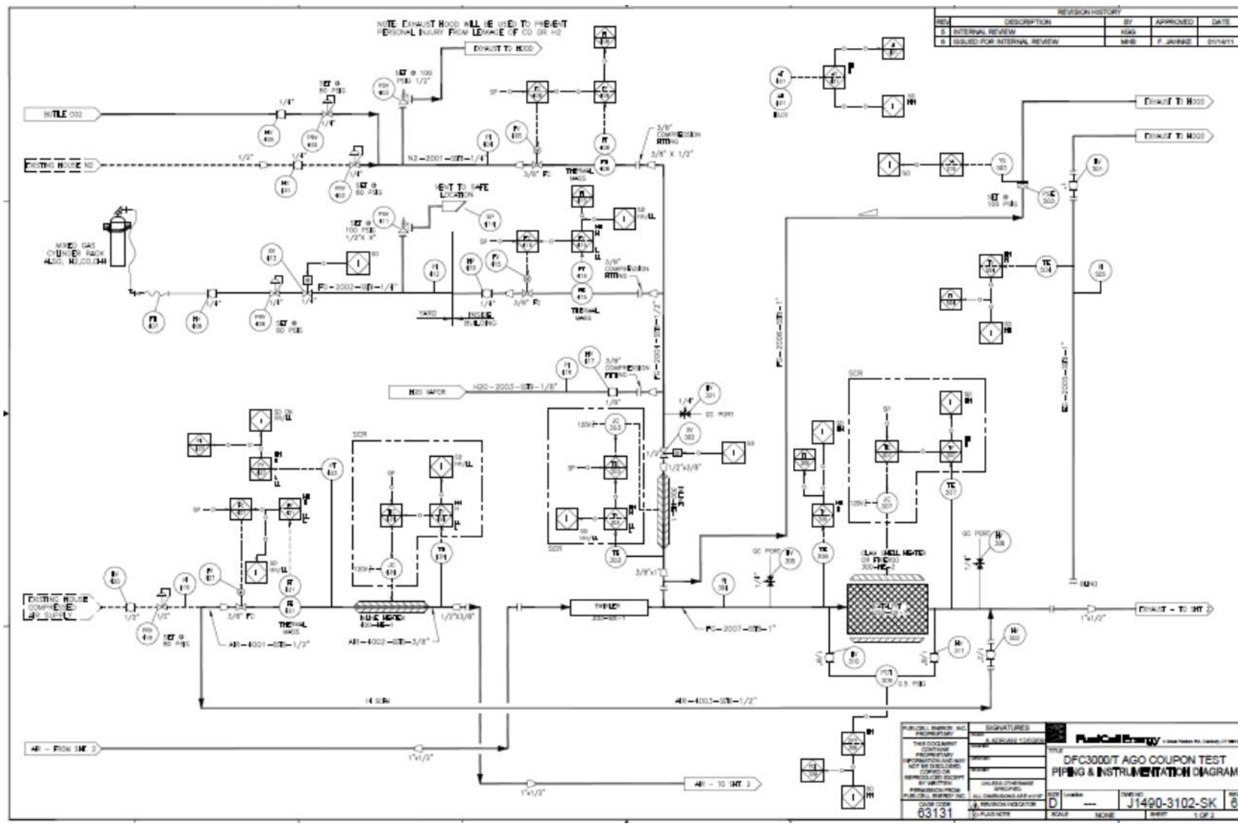


Figure 5.5 TDV Test Facility P&ID (1 of 2)

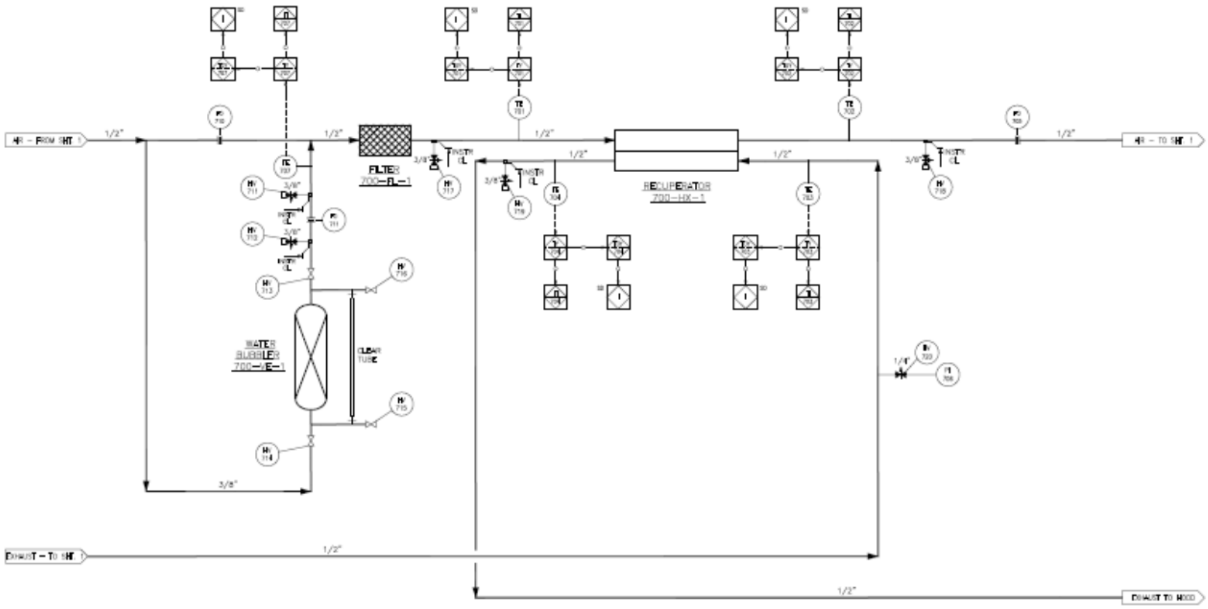


Figure 5.6 TDV Test Facility P&ID (2 of 2)

6.0 CONCLUSIONS

This project was concerned with the development of a high temperature recuperator (HTR) for solid oxide fuel cell hybrid systems and Direct FuelCell hybrid fuel cell systems. The development is concurrent with the emergence of DFC/T hybrid power plants based on integration of internal reforming Direct FuelCell technology with a gas turbine for achieving ultra high efficiency and near zero emissions. The very high electrical efficiency of DFC/T is suitable for power generation where electricity has a premium value. The conclusion of the project marked the achievement of milestones towards the advancement of the fuel cell power plants including:

- Development of a new SOFC/T concept
- Development, testing, and screening of suitable HTR materials of construction
- Detailed design of a 15 kW SOFC/T HTR with completion of major fabrication steps
- Technology demonstration vehicle fabrication and testing
- Cost analysis of devices from kW-scale to MW-scale

Key objectives of the project were to obtain process information and operational data for use in the design MW-scale HTR's. The results of the sub-scale HTR tests indicated effective recuperation of heat and device integrity after 1100 hours of hot-testing.

Cost analysis activities served to establish material and fabrication costs for large-scale HTR's.

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