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High Temperature Heat Exchanger Project: Quarterly Progress Report April 1, 2005 through June 30, 2005

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High Temperature Heat Exchanger Project

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Quarterly Progress Report
April 1, 2005 through June 30, 2005

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July 27, 2005

UNLV Research Foundation
High Temperature Heat Exchanger (HTHX) Project
Quarterly Report (April 1, 2005 to June 30, 2005)

1.0 HTHX FY05 2nd Quarter Highlights

- **Quarterly Collaboration Meeting**. General Atomics hosted a UNLVRF HTHX Project quarterly meeting on June 5 in San Diego, California. The purpose of the meeting was to promote collaboration and communication among the UNLV Research Foundation partners. Collaborators had the opportunity to discuss their research program plan and update their progress. The next meeting will be in September in Berkeley hosted by UC Berkeley.
- **HTHX Computational Design (UNLV)**. Work on optimizing the ceramic offset strip fin compact HTHX design through parametric studies was performed and completed. A simple single channel model was used to perform parametric studies on dimensions and flow rates on the Ceramatec, Inc., compact ceramic HTHX. A single plate model of the heat exchanger was used for studies of flow distribution and pressure drop. The He channel velocity is nearly uniform. The sulfuric acid decomposition channel has a very non-uniform flow distribution and redesign is recommended. Simulation cases and parametric studies have been run in straight-tube heat exchangers assumed to be made from self-catalytic metallic alloys for sulfuric acid decomposition. Analyses using Pt as a catalyst were initiated based on information from Idaho National Laboratory.
- **HTHX Validation Testing (UNLV)**. The heat exchanger experimental apparatus was designed and pressure drops and heat losses in the system were calculated. Heating and cooling elements, liquid pump, temperature measurements, and piping were chosen. 1:3 is the prototype length scale ratio for flow channels. The Reynolds numbers are matched, while the Prandtl numbers and Nusselt numbers are similar. The working fluids are Dow Corning 200 5 cSt silicone oil (hot side) and elevated pressure Helium (cold side). The silicone oil will serve as a fluid analog for molten salts. Alloy 6061 was chosen as the frame material.
- **Metallic Materials Testing (UNLV)**. Tensile properties of Alloys C-22, C-276, 800H, and Waspaloy have been evaluated at temperatures ranging between ambient and 600°C. The susceptibility of all four alloys to stress-corrosion-cracking (SCC) has been determined in an aqueous solution containing sulfuric acid and sodium iodide (S-I) using both constant-load and slow-strain-rate (SSR) testing techniques. The localized corrosion behavior of all four alloys has also been evaluated in a similar environment at 30, 60 and 90°C using cyclic potentiodynamic polarization (CPP) method. Zr-705, a candidate structural material for use in the HIx decomposition process, has also been tested for evaluation of its tensile properties and SCC resistance using similar testing techniques. Metallographic and fractographic evaluations of the tested specimens using optical microscopy and scanning electron microscopy, respectively are also in progress. Evaluations of the surface characteristics of coupons tested at the General Atomics (GA) Laboratory by SEM have also been performed. Based on the results of the screening tests performed at GA, several materials have been selected for investigation at UNLV. These materials include Niobium (Nb)-1 Zirconium (Zr) and Nb-7.5 Tantalum (Ta). Sample preparation using these two alloys has been initiated. The autoclave for high-temperature corrosion studies and the Instron for evaluating the tensile properties, toughness and crack-growth of structural materials at elevated temperatures were installed in the UNLV

Materials Performance Laboratory. Testing using coupons and self-loaded specimens (C-ring and U-bend) was initiated in the autoclave at elevated temperatures.

- **Composite Material and Thermal Design Studies (UC Berkeley)**. Test coupons made of SB-SiSiC and BioKer were sent to SNL for H_2SO_4 decomposition corrosion tests. An initial survey of liquid fluoride salt additives that react with and consume sulfuric acid to permit the safe use of liquid salts for high-temperature heat transport without double-wall S-I process heat exchangers was completed. A preliminary thermal analysis for the core heat transfer region unit cell was finished.
- **HIx Materials Screening (GA)**. The level 2 milestone "Complete Immersion Corrosion Coupon Testing – Materials of Construction Screening" was reached and the associated report will be submitted by 7/15/05. The first experiment using Zr-705 tensile specimens has been performed in the test system that was installed last quarter. The 3.25" diameter of the vessel can accommodate not only coupons but larger specimens such as tensile and Double Cantilever Beam (DCB).
- **Catalyst Alloys (MIT)**. During the period April 22-June 27, 2005 this project was not allowed to expend funds. Resolution was achieved by the transfer of the FY05 program to funding through a contract with the Sandia National Laboratory (SNL). The SNL contract was effective as of June 27, 2005. However, no funds could be expended during the period April 22-June 27, 2005 which, in effect, encompasses the entire quarter. None-the-less, work has continued at the maximum level possible during this period. The student support during this period was provided by Nuclear Science and Engineering Department emergency funds. However, no laboratory work could be performed due to a lack of materials and supplies resources.
- **Efficient Ceramic Heat Exchanger Materials and Design (Ceramatec, Inc.)**. Two high temperature exposure test rigs were designed, equipment ordered and are being assembled. The first test rig is designed to expose ceramic samples to steam/oxygen atmospheres such that their baseline corrosion rates can be measured and compared to literature data. The second test rig will be capable of introducing sulfuric acid and thus quantify the enhanced corrosion rates due to the acid. Each test rig is capable of testing about fifty 4 point bend bars samples simultaneously to temperatures of about $1000^{o}C$ at one atmosphere pressure. The collaborative design and analysis efforts of Ceramatec, Inc. and UNLV are progressing well. The parametric analyses have indicated which design variables are the most significant and can be used for design optimization. A thermal/flow test coupon has been established with design flexibility to parametrically test and validate the analyses and design performance experimentally. Several experimental test methods have been identified to map out the pressure distribution and thermal distribution of these tests.

2.0 UNLV Design and Testing Group

The University of Nevada, Las Vegas Design and Testing Group supports the following two activities in the UNLVRF High Temperature Heat Exchanger (HTHX) Project:

- HTHX Thermal Systems Design
- Scaled HTHX Tests

2.1 HTHX Thermal Systems Design (PI: Yitung Chen, UNLV)

2.1.1 HTHX Thermal Systems Design Objective and Scope

The HTHX design studies have the following objectives and scope:

- Work with the U.S. Department of Energy Office of Nuclear Energy, Science and Technology (DOE NE) nuclear hydrogen research and development program elements on high temperature systems studies for hydrogen production.
- Identify the range of HTHX applications for Gen IV hydrogen production.
- Develop thermal systems concepts/designs and overall heat/mass balances for the range of Gen IV power conversion and hydrogen production concepts.
- Develop design specifications for the intermediate heat exchanger and other HTHXs used in the conceptual designs.
- Undertake thermal hydraulic systems numerical modeling to establish and analyze temperature, pressure, and flow rate requirements.
- Perform thermal, thermal hydraulic, and structural analyses for selected advanced HTHX concepts for hydrogen production.
- Deliver detailed design for candidate intermediate heat exchanger concepts and materials for hydrogen production requirements.

2.1.2 HTHX Thermal Systems Design Highlights

- **3-D Model Development of a Baseline Compact HTHX**. Work on optimizing the HTHX design through parametric studies was performed and completed for the following parameters: (a) channel height, (b) fin thickness, and (c) pitch in the x-direction. The gap length and fin length parameters were studied but not completed; therefore, the results for those two parameters are not outlined in this quarterly report. In general the curved fin edges produced lower pressure drops for every case, and the thermal power was approximately 2% lower for all of the curved fin edge cases, when compared to the rectangular fins.
- **Numerical Analysis based on the Ceramatec High Temperature Heat Exchanger Design for S-I Process – Preheater and Decomposer**. A simple single channel model was used to perform parametric studies on dimensions and flow rates. The temperature difference for S-I (reacting flow) channel was found to be about 225°C. The changes of dimensions do not have significant influence on temperature differences in each channel. The changes of flow rates in each channel have significant influences on temperature differences.

- A single plate model of the heat exchanger was used for studies of flow distribution and pressure drop. The He channel velocity is nearly uniform. The sulfuric acid decomposition channel has a very non-uniform flow distribution and redesign is recommended.
- **Sulfuric Acid Decomposition Heat Exchanger Design**. Simulation cases and parametric studies have been run in straight-tube heat exchangers assumed to be made from self-catalytic metallic alloys. As expected, decomposition increases with decreasing diameter and increasing length. Analyses using Pt as a catalyst were initiated based on information from Idaho National Laboratory.

2.1.3 HTHX Thermal Systems Design Technical Summary

Design Optimization Studies for Baseline Offset Strip Fin Compact HTHX:

Work on optimizing the HTHX design through parametric studies was performed and completed for the following parameters: (a) channel height, (b) fin thickness, and (c) pitch in the x-direction. The gap length and fin length parameters were studied but not completed; therefore, the results for those two parameters are not outlined in this quarterly report. In general the curved fin edges produced lower pressure drops for every case, and the thermal power was approximately 2% lower for all of the curved fin edge cases, when compared to the rectangular fins.

Channel Height:

Channel height studies for both the helium (He) and liquid salt (LS) channels were conducted. The results reveal that the pressure drop in the LS channels decrease as the channel height is increased, and that the thermal power remains fairly constant over the range of channel heights studied. The studies show that the pressure drop in the LS channels level out at h=4.0 mm, and the pressure drop results are six times larger than the base case when the channel height is reduced to h=0.5 mm, as shown in Figure 1. A graph showing how the thermal power on the LS side is unaffected by the changes in channel heights is shown in Figure 2.

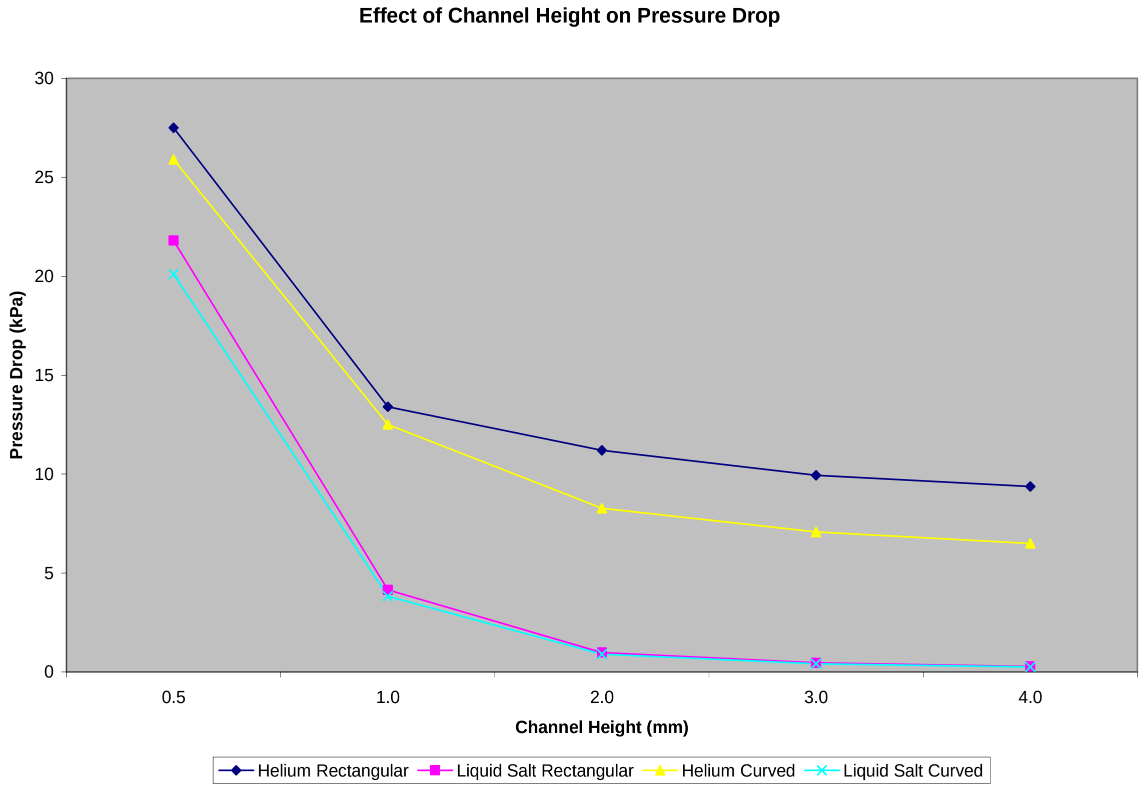


Figure 1. Channel height (mm) vs. pressure drop (kPa) for both He and LS channels.

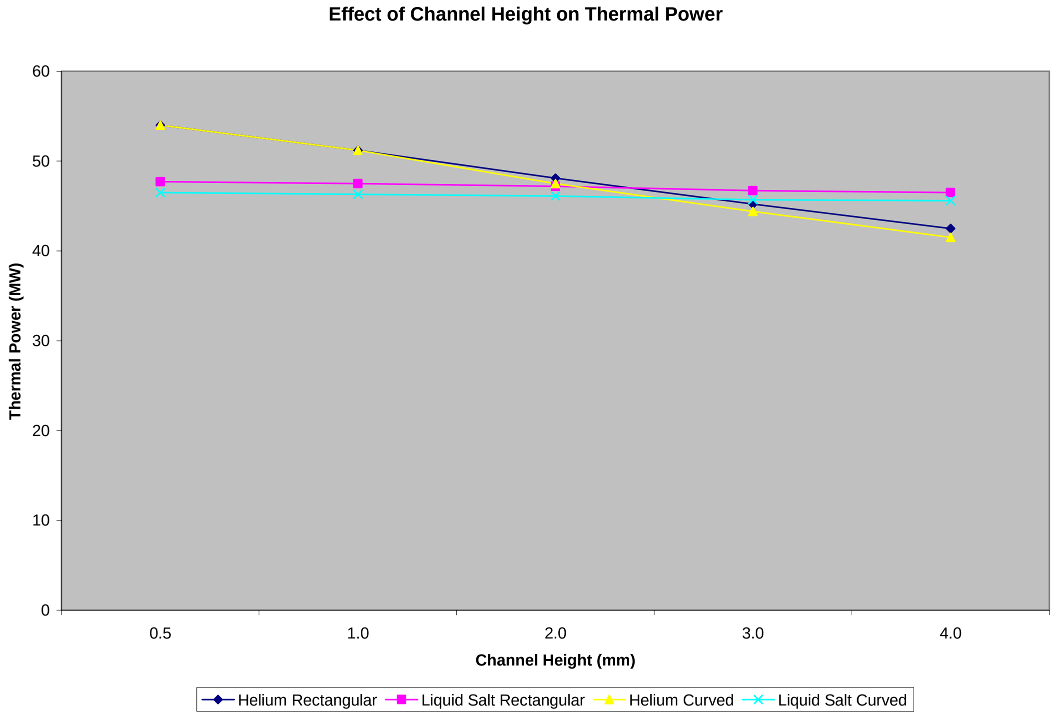


Figure 2. Channel height (mm) vs. thermal power (MW) for both He and LS channels.

Graphs for the performance of the helium channels show a drastic decrease in pressure drop as the channel height is increased, and there is a linear increase or decrease in thermal power as the channel height is increased or decreased. The studies also show that the pressure drop in the helium channels level out at h=4.0 mm, as shown in Figure 1. A graph showing the linear trend for the thermal performance of the helium side can be seen in Figure 2.

Pitch in the x-direction:

Pitch in the x-direction studies for both the He and LS channels show that there is a slight increase in thermal power and pressure drop when the pitch in the x-direction is decreased, and there is a more significant decrease in thermal power and pressure drop as the pitch in the x-direction is increased. The studies also show that the pressure drop for both the helium and LS channels continue to decrease as the pitch in the x-direction is increased but level out at P_x=6.0 mm.

Fin Thickness:

Changes in fin thickness had a slight effect on the thermal power in the helium channels and did not have any effect on the thermal power in the liquid salt channels. However, the slight effect on the helium channel showed that an increase in fin thickness increased thermal power.

The results from pressure drop studies for the helium and liquid salt channels showed that an increase in fin thickness caused an increased pressure drop. It should also be noted that the helium channel was the most sensitive to change, especially in terms of pressure drop.

Summary:

- Thermal power was approximately 2% lower for all of the curved fin edge cases, when compared to the rectangular fins.
- Curved fin edges produced lower pressure drop values for every case.
- The pressure drop values for the LS channels decrease as the channel height is increased.
- The thermal power for the LS channels remains constant over the range of channel heights studied.
- In the helium channels there is a decrease in pressure drop as the channel height is increased.
- There is a linear increase or decrease in thermal power as the channel height is increased or decreased on the helium side.
- For both helium and liquid salt channels the thermal power and pressure drop decrease as the pitch in the x-direction is increased.
- Fin thickness had a slight effect on the thermal power in the helium channels.
- Fin thickness had no effect on the thermal power in the LS channels.
- An increase in fin thickness caused an increased pressure drop, and a decrease in fin thickness caused the pressure drop to decrease for both the helium and LS channels.

Overall Heat Exchanger Optimization Studies for Ceramatec, Inc., HTHX:

A simple single channel model as shown in Figure 3 was used for parametric studies of thermal performance and fluid mechanics of the high temperature heat exchanger for S-I process - preheater and decomposer with the following baseline values:

$$h_{SP} = 0.85\,mm;$$

$$h_{HT} = 0.3\,mm;$$

$$h_{S1} = 0.424\,mm;$$

$$h_{HT+S2a} = 0.75\,mm;$$

$$h_{\frac{1}{2}S2b} = 0.225\,mm;$$

$$W_1 = 0.635\,mm; \quad W_2 = 0.381\,mm; \quad L = 52.324\,mm.$$

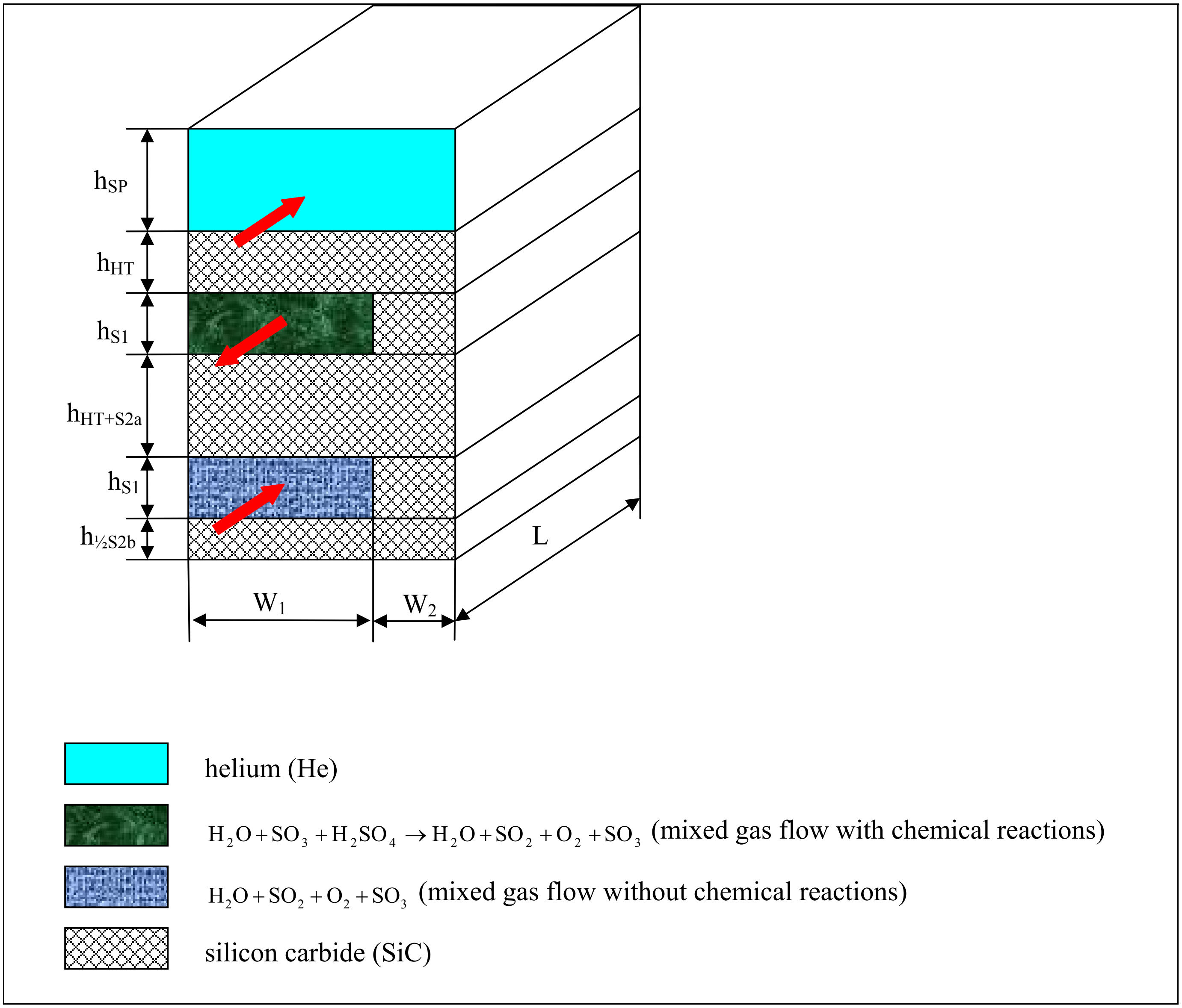


Figure 3. Sketch of the single channel model of high temperature heat exchanger.

The geometry and computational mesh of heat exchanger was created using the commercial mesh generator Gambit. A Gambit journal file was programmed in order to study the optimization of geometry. The programmed journal file is very useful and helpful without restarting from the beginning to draw the new geometry and computational mesh when user changes any dimensions or values in the geometry section.

Parametric studies using the simple single channel model were performed. The changed dimensions and flow rate parameters are shown in Table 1.

Constant material properties which are independent of temperature and chemical reactions (except thermal conductivity of SiC (shown in Figure 4)) were used. Other inputs include the following:

- SI flow rate per plate = 159/70 = 2.27 kg/hr.
- He flow rate per plate = 83/70 = 1.19 kg/hr.
- $T_{\text{He inlet}}$=1223.15 K (950°C).
- $T_{\text{feed SI inlet}}$= 974.9 K (701.75°C).
- $T_{\text{product SI inlet}}$=1223.15 K (950°C).
- Uniform velocity for He inlet: V=4.9458 m/sec.
- Uniform inlet velocity for flow with chemical reactions V=3.9935 m/sec.
- Uniform inlet velocity for flow without chemical reactions V=4.3429 m/sec.

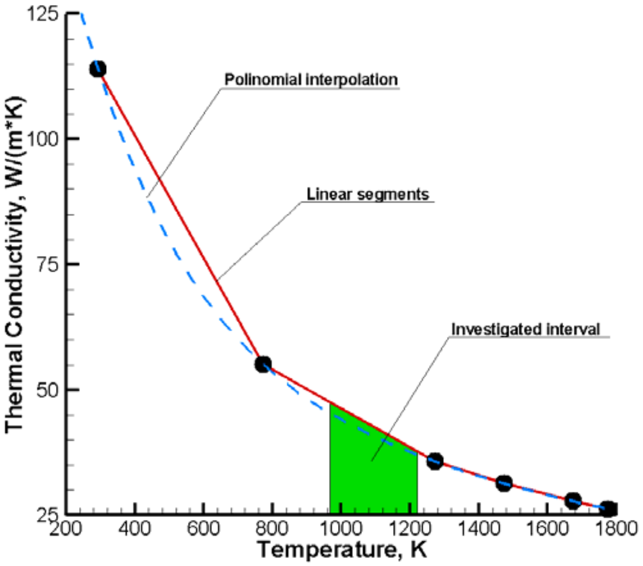


Figure 4. Thermal conductivity of SiC vs. temperature (values supplied by Ceramatec, Inc.).

Table 1 Various parameters of numerical simulations.

Simulation No.	Variable parameter	Numerical value	Min or max of varied parameter
Base case	-	-	-
1	h_{SP}	h_{SP}=0.25 mm	Min
2	h_{SP}	h_{SP} =1 mm	max
3	h_{HT}	h_{HT}=0.05 mm h_{HT+S2a}=0.5 mm	min
4	h_{HT}	h_{HT}=0.5 mm h_{HT+S2a}=0.95 mm	max
5	h_{S1}	h_{S1}=0.05 mm	min
6	h_{S1}	h_{S1}=0.75 mm	max
7	h_{S2a} h_{S2b}	h_{S2a}=0.05 mm h_{S2b}=0.05 mm h_{HT+S2a}=0.35 mm $h_{½S2b}$=0.025 mm	min
8	h_{S2a} h_{S2b}	h_{S2a}=1 mm h_{S2b}=1 mm h_{HT+S2a}=1.3 mm $h_{½S2b}$=0.5 mm	max
9	W_1	W_1=0.25 mm	min
10	W_1	W_1=1.25 mm	max
11	W_2	W_2=0.1 mm	min
12	W_2	W_2=1 mm	max
13	L	L=35 mm	min
14	L	L=100 mm	max
15	SI flow rate per plate	SI flow rate per plate =1 kg/hr	min
16	SI flow rate per plate	SI flow rate per plate =10 kg/hr	max
17	He flow rate per plate	He flow rate per plate =0.6 kg/hr	min
18	He flow rate per plate	He flow rate per plate =5 kg/hr	max

A summary of the results of the parametric studies are:

- The temperature difference for S-I (reacting flow) channel is about 225°C.
- Changes of dimensions do not have significant influence on temperature differences in each channel.
- Changes of flow rates in each channel have significant influence on temperature differences.
- Changes in geometrical parameters and flow rates have significant influence on pressure drops.

A single plate model was used for the study of flow distribution and pressure drop for the entire plate of the S-I decomposer. For the He channel the velocity distribution is nearly uniform as shown in Figure 5. For the S-I plates the current design of supply channel configuration is not appropriate because the flow distributions among the internal channels are not uniform as illustrated in Figure 6.

A new geometry for the S-I plates was proposed that includes a diffuser plate at the inlet manifold. The numerical results of velocity and pressure distribution calculations in the new proposed geometry is shown in Figure 7.

Sulfuric Acid Decomposition Heat Exchanger Design:

The grid independency study was initiated. Six different types of grids are chosen for the grid independence study. The computational time is decreasing with decreasing the density of the mesh, at the same time the percentage of discrepancy in the results is increasing with decreasing the mesh density.

Percentage decomposition of sulfur trioxide in a reactor tube depends on different factors including wall surface temperature, operating pressure, inlet temperature of the reacting mixture, mass/volumetric flow rate of the reacting mixture, diameter of the reactor tube, and length of the reactor tube. Variation in the percentage decomposition of sulfur trioxide is studied for the above mentioned parameters for the catalyst ALFA-4. In previous work, the decomposition of sulfur trioxide is analyzed for a 12.7 mm diameter reactor tube. Presently, the analysis is being carried out for different diameters of the reactor tube ranging from 1 to 12.7 mm with a constant length of the reactor tube at 500 mm. Percentage decomposition of sulfur trioxide gas for different reactor tube diameter is shown in Figure 8.

The percentage decomposition of sulfur trioxide is increasing with decreasing diameter of the reactor tube. At the same time the pressure drop is increasing with decreasing the reactor tube. The pressure drop values for different diameters of the reactor tubes, 1 to 4 mm, are shown in Figure 9 and the numerical values are tabulated in. There should be a trade-off between the pressure drop and percentage decomposition of sulfur trioxide.

The variations in percentage decomposition of sulfur trioxide with the variation in the length of reactor tube keeping wall surface temperature constant at 870^{o}C have been studied. Different simulation cases have been run for different diameters of the reactor tubes 4, 3, 2, 1.5 and 1mm. As an example, the values of percentage decomposition of sulfur trioxide for a 2 mm diameter reactor tube are shown in Figure 10.

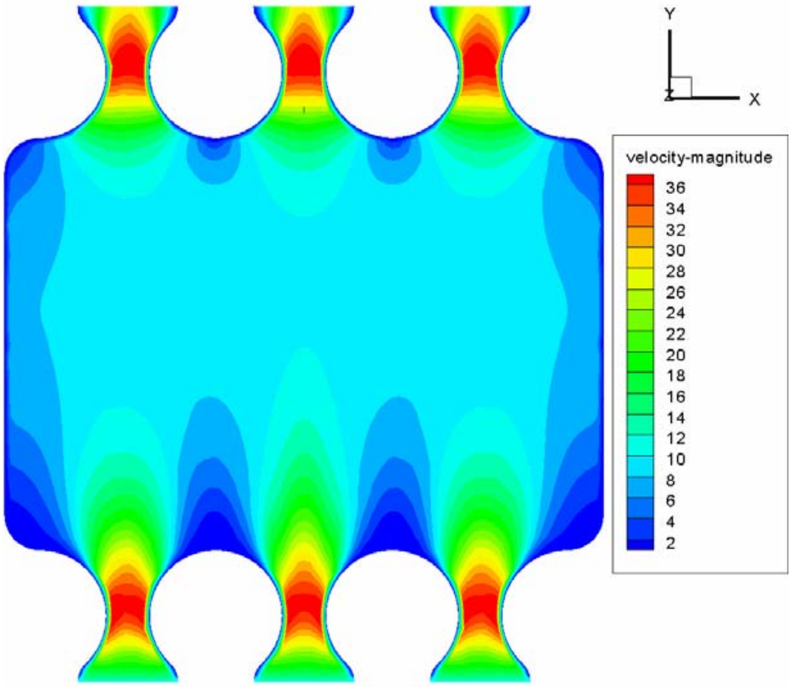


Figure 5. Velocity magnitude, m/sec (on the middle of the SP-opt a plate).

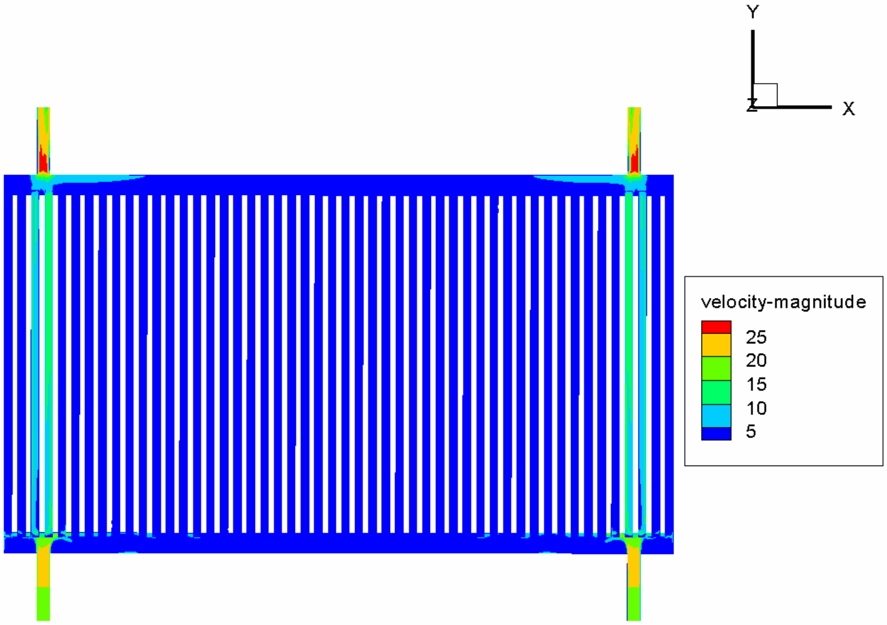
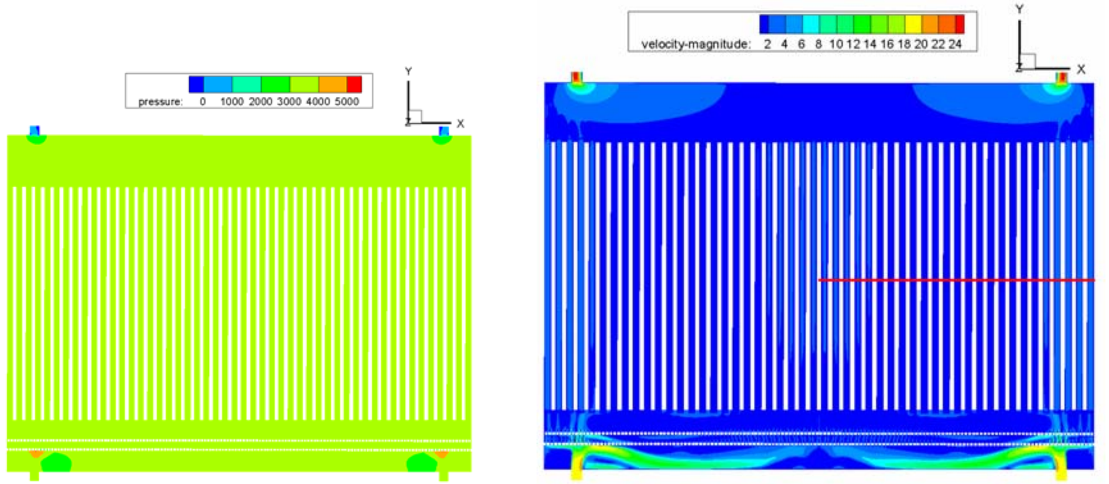
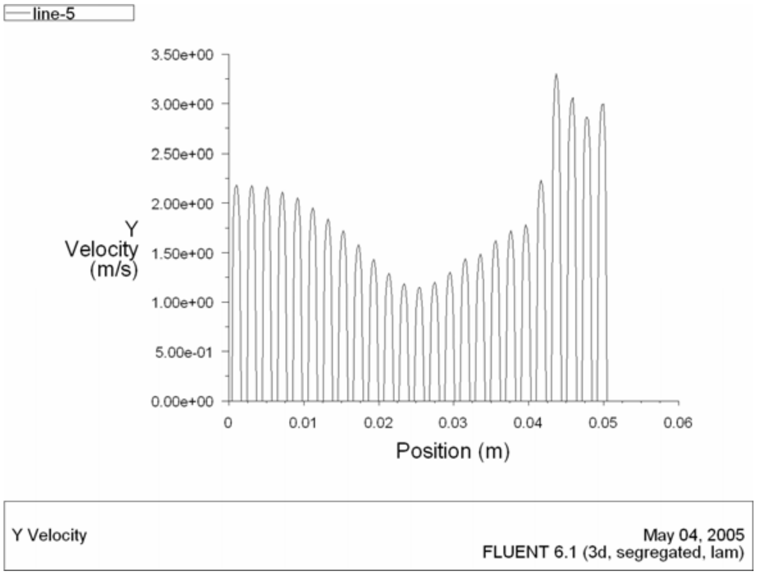


Figure 6. Velocity magnitude, m/sec (on the middle of the S1 and S2c plates).



Pressure distribution in the S1 and S2 layers, Pa *Velocity magnitude distribution in the S1 and S2 layers, m/s*



Y- Velocity distribution in the channel centers (on the red line)

Figure 7. Simulation results for the new proposed geometry design.

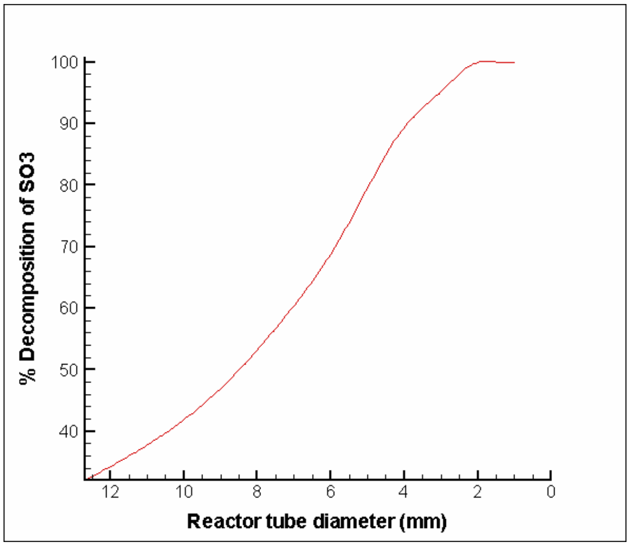


Figure 8. Percentage decomposition of sulfur trioxide for different diameters of the reactor tubes.

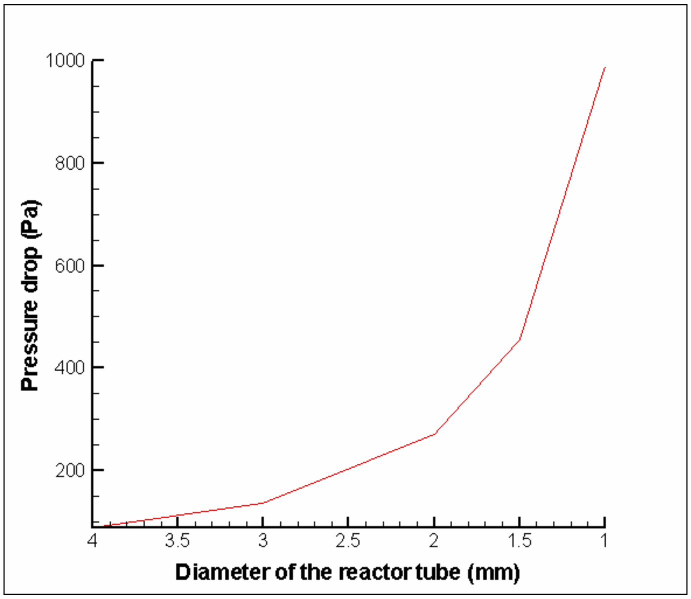


Figure 9. Pressure drop for different diameter of the reactor tube.

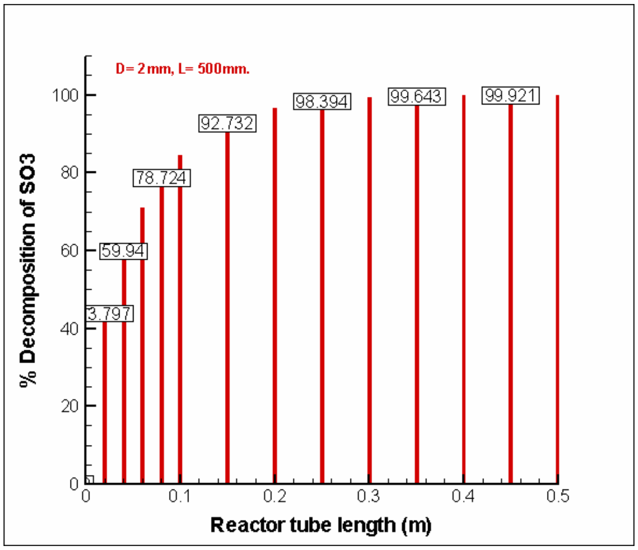


Figure 10. Percent SO_3 decomposition as a function of reactor tube length.

A few different simulation cases have been studied from 500 to 1000°C with an interval of 50°C to find out the percentage decomposition of sulfur trioxide variation with the variation of the reactor tube along with the variation of wall surface temperature. The diameters selected for this analysis are 4, 3, 2 and 1 mm and the length of the reactor tube is kept constant at 500 mm. A total of 44 cases have been run and the percentage decomposition of sulfur trioxide for all the cases are shown in Figure 11.

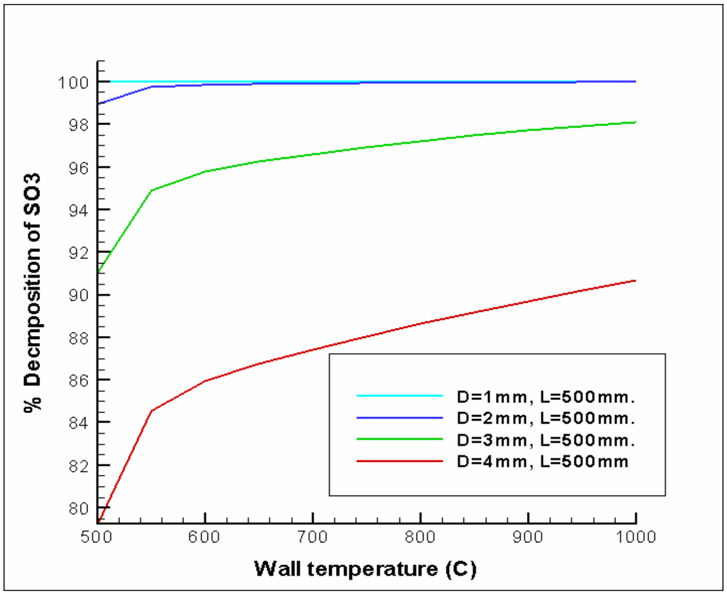


Figure 11. Percentage decomposition of sulfur trioxide for different diameters of the reactor tube at different wall surface temperatures keeping the length of the tubes constant at L=500mm

The decompositions of sulfur trioxide varies with the variation in the mole flow rate have also been studied. Different simulation cases have been studied for different mole flow rates of the sulfuric acid in the decomposer. All the cases are being carried out on a reactor tube of diameter 4 mm and length of 500 mm for different wall surface temperature ranging from 600 to 1000°C.

In previous work, there was no available data on some of the Arrhenius rate parameters for the platinum catalyst, such as activation energy and pre-exponential factors. After contacting several persons working in related areas some useful information was obtained from the Idaho National Laboratories (INL). The information is the following:

- At 800°C, reaction rate was 0.116 mol/hr with a corresponding SO2 yield of 23%
- At 850°C, reaction rate was 0.180 mol/hr with a corresponding SO2 yield of 36%.
- Catalyst used: 1.00 g of catalyst composed of 0.1 wt% Pt on TiO2 support.
- The Pt surface area was 0.032 square meters per gram of total catalyst weight (Pt + TiO2).
- The exponential factor (A_r) = 0.6218 mol/s^{-1} and Activation Energy (E_r) = 8.8034e^{+07} J/kg-mol

2.2 Scaled HTHX Tests (PI: Samir Moujaes, UNLV)

2.2.1 Scaled HTHX Tests Objective and Scope

The Scaled HTHX Tests have the following objectives and scope:

- It is proposed that an experimental facility be constructed at UNLV. This facility would provide needed experimental validation results to the numerical simulation effort going on within the UNLV Research Foundation consortium. The effort at UNLV will be geared towards the design, testing, and optimization of a High Temperature Heat Exchanger (HTHX) Experimental Facility which will be used as part of the effort by DOE to investigate the possibility of generating hydrogen by thermo-chemical means at high temperatures using heat from a nuclear reactor as the heat source.
- The experimental set up will be a prototype of the actual HTHX. Initially experiment will be run at lower temperatures and with different candidate fluids but with the same flow properties. In final stage the experiment will be run with actual candidate fluids.
- Determining the thermal properties of some of the fluids and solids used in the HTHX.
- Comparing the experimental results with CFD model.

2.2.2 Scaled HTHX Tests Highlights

- **Heat Exchanger Work Package**. The National Technical Director and DOE approved the work package for this new project. It was posted on the PICS system for June reporting.
- **Apparatus Design**. The heat exchanger experimental apparatus was designed and pressure drops and heat losses in the system were calculated. Heating and cooling elements, liquid pump, temperature measurements, and piping were chosen. 1:3 is the prototype length scale ratio for flow channels. The Reynolds numbers are matched, while the Prandtl numbers and Nusselt numbers are similar. The working fluids are Dow Corning 200 5 cSt silicone oil (hot side) and elevated pressure Helium (cold side). The silicone oil will serve as a fluid analog for molten salts. Alloy 6061 was chosen as the frame material.

2.2.3 Scaled HTHX Tests Technical Summary

Apparatus Materials and Working Fluids

General purpose aluminum (Alloy 6061) is chosen as the structural material for the experimental heat exchanger. It is rated good in corrosion resistance and welding, fair in machinability. The thermal conductivity is about 170 W/mK.

Helium is chosen as the cold side fluid because of its high heat capacity. Helium is treated as an ideal gas. Elevated pressure (4 atm) is used to get reasonable heat exchanger power. The minimum inlet Helium temperature is set at 30ºC to efficiently remove the thermal energy after it goes through the heat exchanger.

Dow Corning 200 Fluid, 5.0 cSt Silicone oil with well known physical and thermal properties is chosen as the hot side fluid, although its Prandtl number is higher than molten salts (i.e. Fliniak). It is non-toxic, convenient to handle, and environmentally kind. The maximum working temperature for silicone oil is set less than 90ºC because its flash point is 127 ºC.

Apparatus Design

The first Solid Works generated drawing was finished according to the machine shop requirement. The dimensions of the heat exchanger are confined by the ability of CNC and materials. 1:3 is the prototype to model dimension scale ratio for the cells. The overall size of the heat exchanger is 930 mm × 220 mm × 33 mm. It has two channels for hot and cold fluids that will be tested separately. There are 23 cells in the flow direction and 22 cells transverse to the flow direction in each side.

Apparatus Operation and Instrumentation

The working conditions are preset according to the scaling analysis and working availability. The hot channel will be always on the top to avoid the natural convection because of the high Raleigh number of the silicone oil. The hypothetical maximum heat exchanger power will be 880 W. Flow meters (to be decided) are mounted to measure the flow rates. Twenty-five pairs of T type thermocouples will be inserted in the base wall to measure the temperature distribution along the flow direction. The inlets and outlets temperature will be measured by four pairs of T type thermocouples. The power will be calculated and compared.

Differential pressure transmitters are used to measure the pressure drops across the heat exchanger. The flows in the channels are combinations of entrance flow instead of fully developed flow because of the offset strip fin structure. The pressure drops in the flow channels were carefully compared and calculated to choose the right meters.

Apparatus Auxiliary Components

A refrigerated bath (cooling capacity of 2850 W at 20°C) is needed to cool the Helium flow. Mechanical Convection Oven 1200 W is needed to heat the silicone oil. Different size alloy 6061 pipes will be used to transport the fluids. Coils made of copper tubes are needed to heat/cool the fluids. The pressure drops in the loops, the driving powers and the heat loss from the system are calculated. Glass Fiber is chosen as the insulation material for its reasonable price and thermal properties.

Auxiliary equipment for the experiments and laboratory and a partial budget have been determined.

Concerns

- The hydraulic simulation is satisfied between prototype and model with the same Reynolds number and the Prandtl numbers can be matched on the gas side. The liquid salt Prandtl number (≈10) however is smaller than the silicone oil (30 – 50). Although the Nusselt numbers can be matched on both sides, the low conductivity and larger dimensions make the heat transfer coefficient much lower.
- The heat transfer surface components are different. The fin heat transfer coefficient for the prototype is 0.5 $W/m^2 \cdot K$, while it is 1.0 $W/m^2 \cdot K$ for the model, although the geometry similarity is kept. The experimental setup only permits the heating channel to be on the top to avoid the natural convection.
- The higher thermal conductivity of Alloy 6061 makes the fin very efficient for the heat transfer, while the low thermal conductivity of the composite ceramic (20 $W/m \cdot K$) makes the fin less efficient.
- The radiation heat transfer is negligible in the liquid at low temperature, while it will be significant at high temperature in the liquid salt. The radiation heat transfer augmentation will not be available for the low temperature tests.

3.0 UNLV Materials Selection and Characterization Group (PI: Ajit Roy, UNLV)

3.1 Accomplishments

- Selection of structural metallic materials and alloys for high-temperature heat exchangers (HTHX) to generate hydrogen using nuclear power source poses a major challenge to scientific and engineering communities. These materials must possess excellent resistance to numerous environment-induced degradation and superior high-temperature metallurgical properties.
- Tensile properties of Alloys C-22, C-276, 800H, and Waspaloy have been evaluated at temperatures ranging between ambient and 600^{o}C. The susceptibility of all four alloys to stress-corrosion-cracking (SCC) has been determined in an aqueous solution containing sulfuric acid and sodium iodide (S-I) using both constant-load and slow-strain-rate (SSR) testing techniques. The localized corrosion behavior of all four alloys has also been evaluated in a similar environment at 30, 60 and 90^{o}C using cyclic potentiodynamic polarization (CPP) method. Zr-705, a candidate structural material for use in the HIx decomposition process, has also been tested for evaluation of its tensile properties and SCC resistance using similar testing techniques. Metallographic and fractographic evaluations of the tested specimens using optical microscopy and scanning electron microscopy, respectively are also in progress.
- Evaluations of the surface characteristics of coupons tested at the General Atomics (GA) Laboratory by SEM have also been performed. Based on the results of the screening tests performed at GA, several materials have been selected for investigation at UNLV. These materials include Niobium (Nb)-1 Zirconium (Zr) and Nb-7.5 Tantalum (Ta). Sample preparation using these two alloys has been initiated.
- The autoclave for high-temperature corrosion studies involving all candidate structural materials has just been installed in the Materials Performance Laboratory (MPL). Testing using coupons and self-loaded specimens (C-ring and U-bend) has also been initiated at elevated temperatures. The Instron testing machine, capable of evaluating the tensile properties, toughness and crack-growth of structural materials at elevated temperatures, has also recently been installed in MPL.

3.2 Recent Results

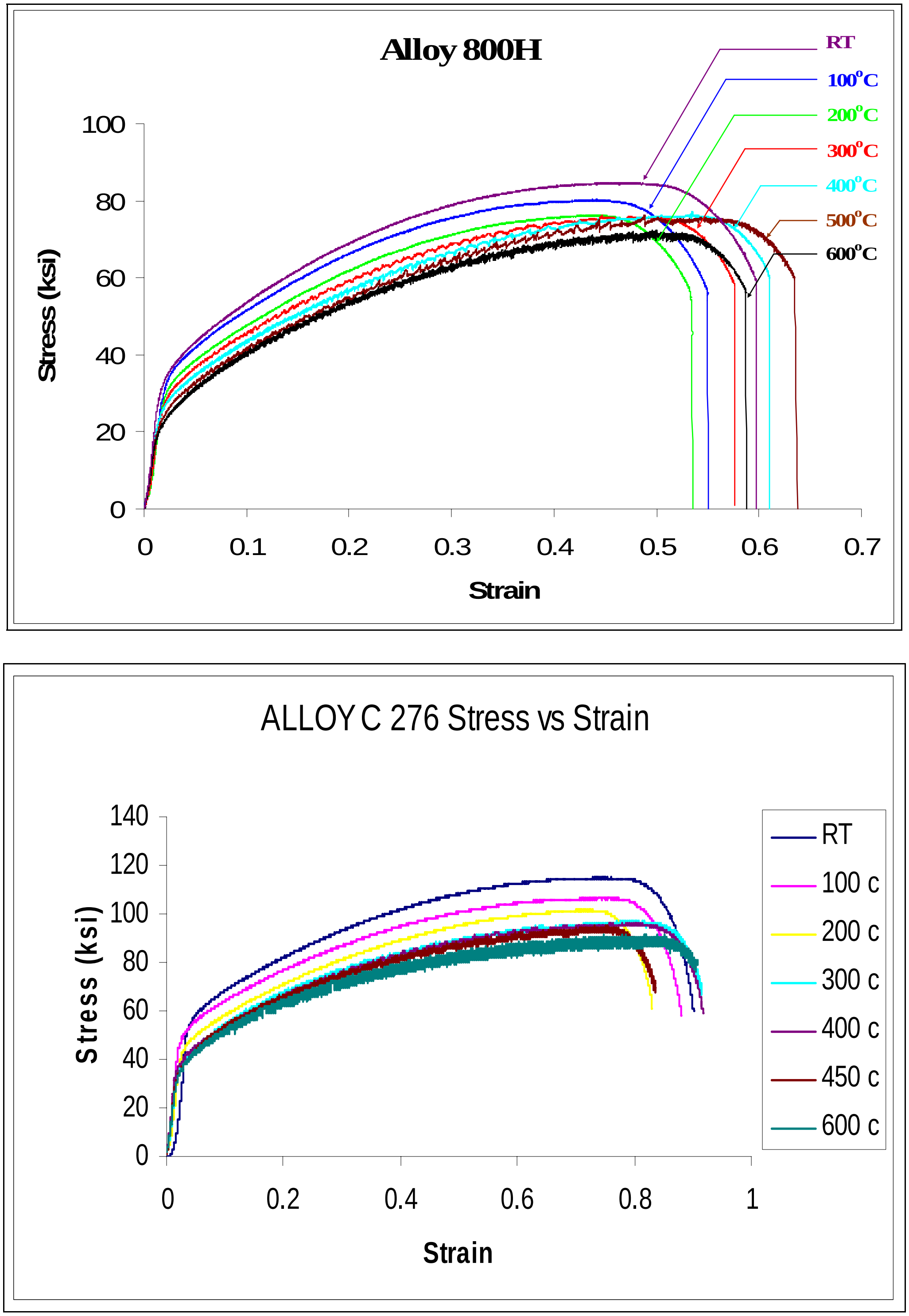


Figure 12. Comparison of Stress-Strain Diagrams at Different Temperatures.

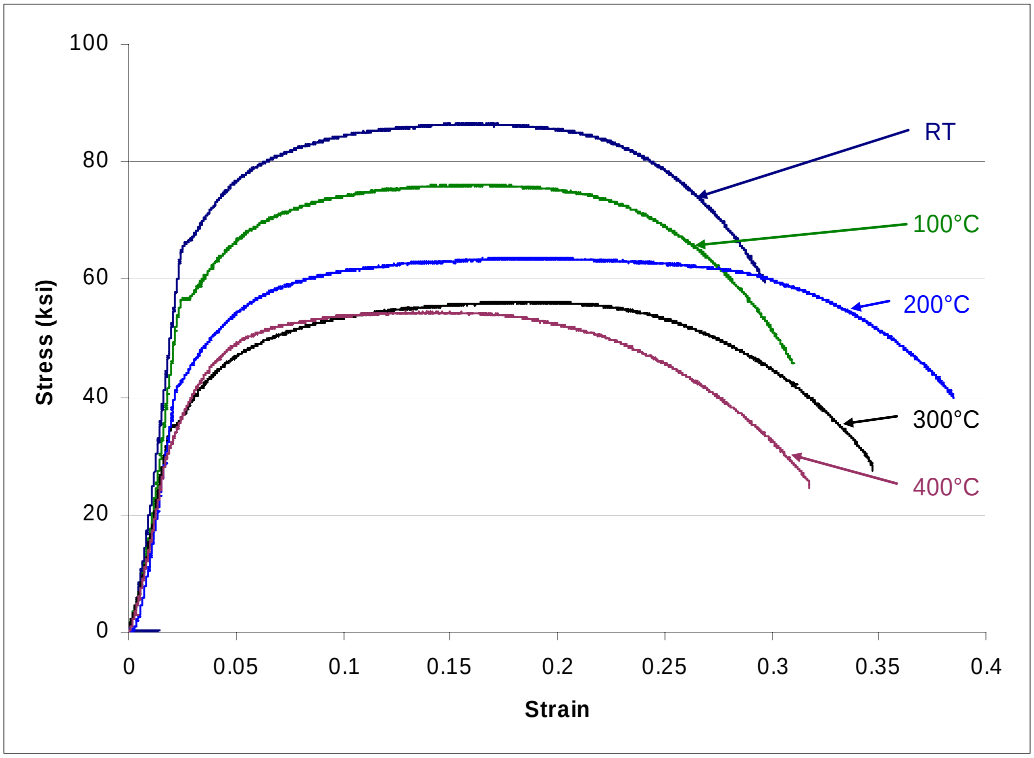


Figure 13. Comparison of Stress-Strain Diagram of Zr705 vs. Temperature.

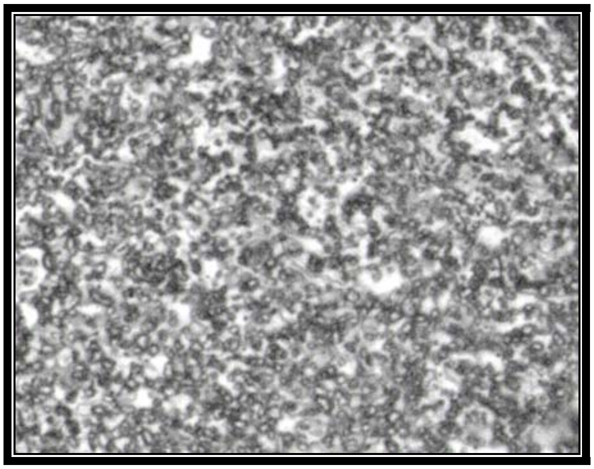


Figure 14. Optical Micrograph of Zr705, Etched, 1000X.

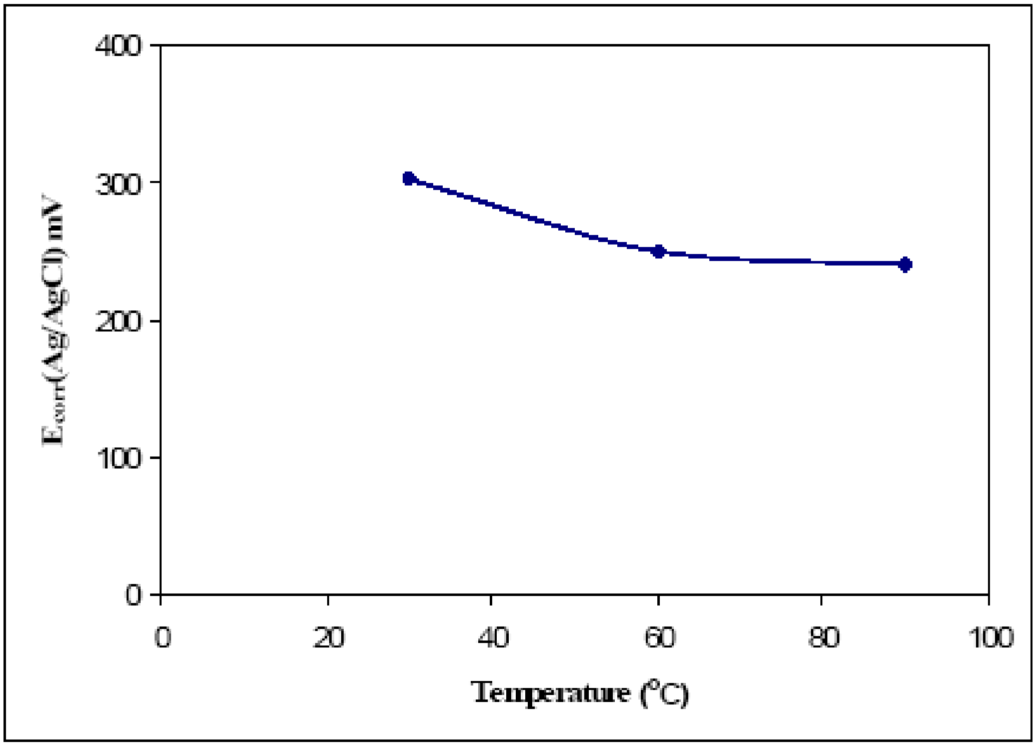


Figure 15. Polarization Test Results E_{corr} vs. Temperature for Alloy 800H.

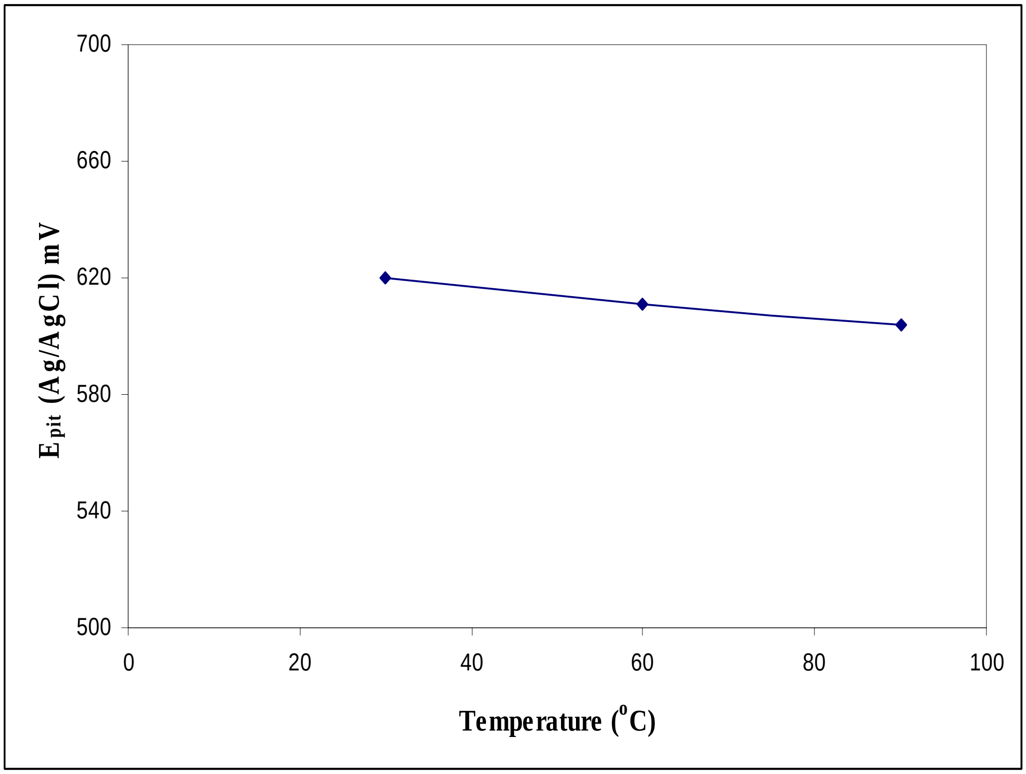


Figure 16. Polarization Test Results E_{pit} vs. Temperature for Alloy 800H.

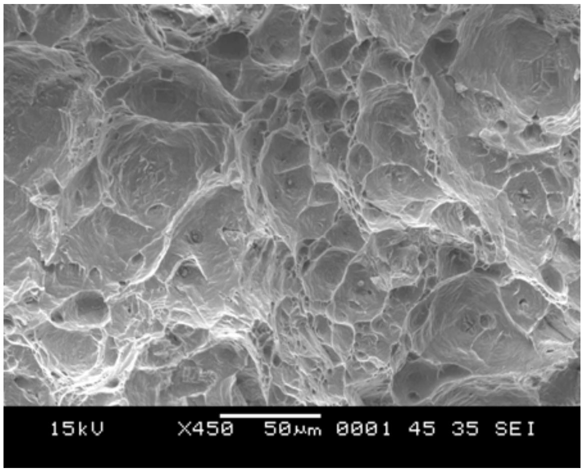


Figure 17. SEM Micrograph of Alloy 800H, 450X.

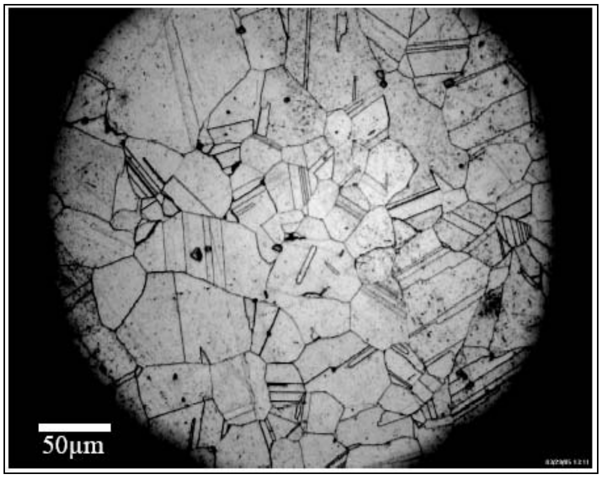


Figure 18. Optical Micrograph of Alloy 800H, Etched, 200X.

3.3 Plans for Next Quarter

- Continue planned experimental work both at UNLV and GA.
- Calibrate the newly-installed Instron testing machine.
- Prepare additional specimens to perform experiments according to the planned matrices.
- Continue literature search.

4.0 University of California, Berkeley (PI: Per Peterson, UCB)

4.1 Objectives and Scope

UCB's role in the HTHX project is to develop ceramic compact heat exchangers for use in NGNP intermediate loop and hydrogen production loops. The work scope includes: identification and characterization of candidate ceramic heat exchanger materials and processes, identification and demonstration of candidate ceramic heat exchanger fabrication methods, and, design and modeling of high temperature heat exchangers.

4.2 Highlights

- Test coupons made of SB-SiSiC and BioKer were sent to SNL for H_2SO_4 decomposition corrosion tests.
- An initial survey of liquid fluoride salt additives that react with and consume sulfuric acid to permit the safe use of liquid salts for high-temperature heat transport without double-wall S-I process heat exchangers was completed.
- The $50k sub-award to COI was put in place to provide ceramic vendor support and the work is going well.
- A preliminary thermal analysis for the core heat transfer region unit cell was finished.

4.3 Technical Progress Summary

LSI C-C/Si-C composite and other composite material study

The $50k sub-award to COI was put in place to provide ceramic vendor support and the work is going well. There are three tasks for COI to finish with the help of UCB:

- **TASK 1 -** COI will perform a survey of polymer and fiber materials, and recommend and procure a subset of candidate materials for actual testing. The options initially considered, and the final selections and justification, will be summarized in a short letter report. During this same period, UCB will provide engineering drawings for molds to COI for review and approval, and then will fabricate molds from materials recommended by COI (and potentially supplied by COI) for the Task 2 coupon fabrication work.
- **TASK 2 -** The primary work for Task 2 will be the determination of the minimum fin feature size that can be reliably produced by die embossing. For this purpose, UCB will fabricate a set of 120 mm x 120 mm molds. COI will then work to produce a set of plates using this mold, to determine the minimum feature size that can be reliably produced. The best-quality plate will be quartered to study the lamination process. Using the same process used to fabricate the embossed plate, a flat 3-mm thick test plate will be fabricated and will be cut into four 25-mm diameter disks. These disks, and the laminated test sample, will then be processed through the number of PIP stages needed to obtain final density. Four discs can be carbon coated prior to mechanical testing at UCB.
- **TASK 3** - UCB will provide a single 200 mm x 200 mm mold, with embossing features more representative of an actual heat exchanger, and with minimum feature sizes selected based on

COI experience from Task 2. This single plate will be designed to be sectioned into eight 50 mm x 100 mm plates for lamination and PIP processing. UCB will consult with Hypertherm to select a flow-channel geometry that can permit CVD coating of the interior flow channels. If Task 2 is not successful (for example, if is determined that a different mold design/approach is needed), Task 3 will be omitted to increase the resources available for more work on Task 2.

COI has provided UCB the letter report for Task 1 summarizing the selection criteria for the materials and processes that will be used to demonstrate the fabrication of chopped carbon fiber reinforced silicon carbide matrix die embossed plates using the COI Ceramics (COIC) polymer infiltration and pyrolysis (PIP) process. The design of mold for Task 2 is finished and the graphite molds are being fabricated.

Thermal design study and review

A preliminary thermal analysis for the core heat transfer region unit cell was finished. The test is used to get an idea of how much stress is added due to temperature difference between each layer. The maximum pure mechanical compressive stress is 95 MPa, and the pure thermal stress is 70 MPa. The combined mechanical and thermal compressive stress is 120 MPa. Due to the boundary setting, the thermal stresses are largest possible values. In later global thermal stress analysis, the thermal stresses will be lower than these values. These stress values were taken from the root of the molten salt fin. Tensile stresses are around 40 MPa, with or without the thermal loading. It looks like, the stress difference between each plate will add to compressive stress but not tensile stress. Figures 19 shows the comparison of stresses distributions in the unit cell due to pure mechanical effect, pure thermal effect, and the combination of both effects.

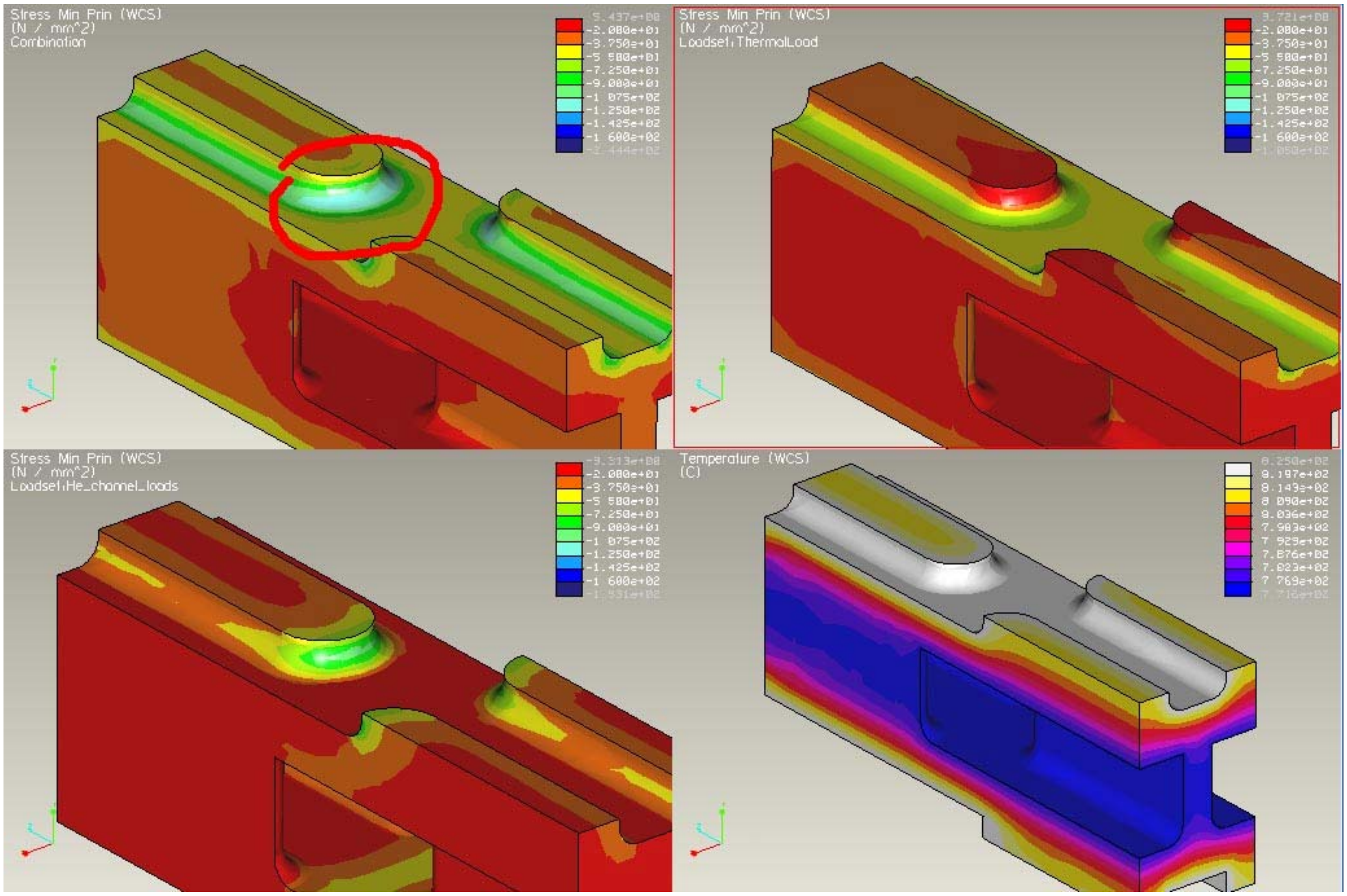


Figure 19. Stresses distribution in a unit cell due to thermal, mechanical effects. The top left figure is combined thermal and mechanical results, the top right one is thermal only result, the bottom left one is mechanical only result, and the bottom right one is the temperature distribution.

5.0 Corrosion Studies of Candidate Structural Materials in HI_x Environment as Functions of Metallurgical Variables (PI: Bunsen Wong, General Atomics)

5.1 Research Progress and Accomplishments

The level 2 milestone for Task 1 “Complete Immersion Corrosion Coupon Testing – Materials of Construction Screening” has been reached and the associated report will be submitted by 7/15/05.

Task 1: Construction Materials Screening

Milestone 1: **on track**

Si-SiC samples were tested last quarter. Analysis showed the Bioker 29 and Splint specimens performed well in HI_x (Figs. 20 and 21) whereas the Fiber specimen showed signs of dissolution and exhibited a weight loss of about 0.6% after 120 h of testing (Fig. 22). Thus, Si-SiC based materials can offer an economical means to manufacture heat exchangers for HI decomposition once the joining and connection issues are resolved. Long term testing on these specimens has been planned.

Since the first generation of heat exchanger will be fabricated with metals, long term immersion coupon testing of three qualified materials was conducted. The materials chosen are Ta-10W, Nb-1Zr and Nb-10Hf. Their selection was based both on corrosion performance and availability. The goal is to conduct testing up to 1000 h or until there is no visible change in the coupon passivation.

Figure 23 shows the progression of the Ta-10W sample from the immersion test. The sample shows no sign of corrosion and change in passivation is relatively minor. There is no obvious weight change in the specimen (Table 2).

The Nb-1Zr coupon shows good performance up to 120 h at the boiler condition. However, extensive corrosion was observed after 450 h (Fig. 24). The circumstance surrounding the experiment was unusual since the glass wool used to minimize HI_x vaporization was found inside the HI_x liquid. It was suspected that contamination from the glass wool had caused the corrosion. The corrosion product has been saved for analysis and detailed characterization of the coupon will be conducted at UNLV.

An experiment was conducted by wrapping a new coupon with glass wool and submerged in HI_x for testing (Fig. 25). Figure 26 shows the resultant coupon in which no corrosion can be observed. The reason behind the unexpected corrosion is still under investigation.

Long term testing of Nb-10Hf shows that the alloy is stable in HI_x as the coupon does not exhibit any sign of corrosion (Fig. 27). Results show that the passivation is still undergoing changes even after 790 h. From the long term testing conducted up to date, Ta-10W and Nb-10Hf are leading materials of construction candidates for HI decomposition whereas the use of Nb-1Zr will need to be examined carefully.

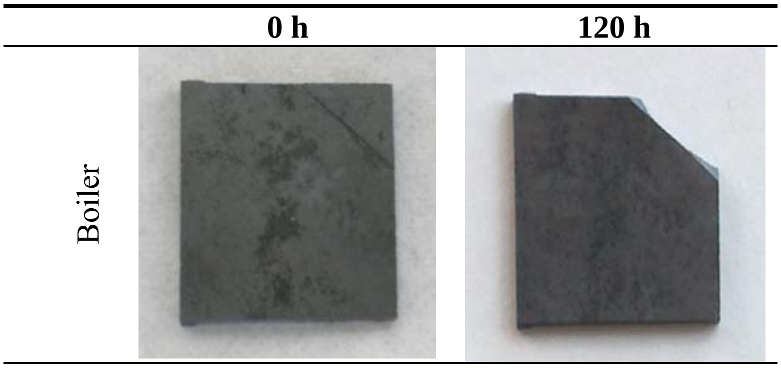


Figure. 20. Bioker 29 Si-SiC coupon after a 120 h test in HI_X at the boiler condition. The solution dissolved the glue which held the upper right hand corner piece.

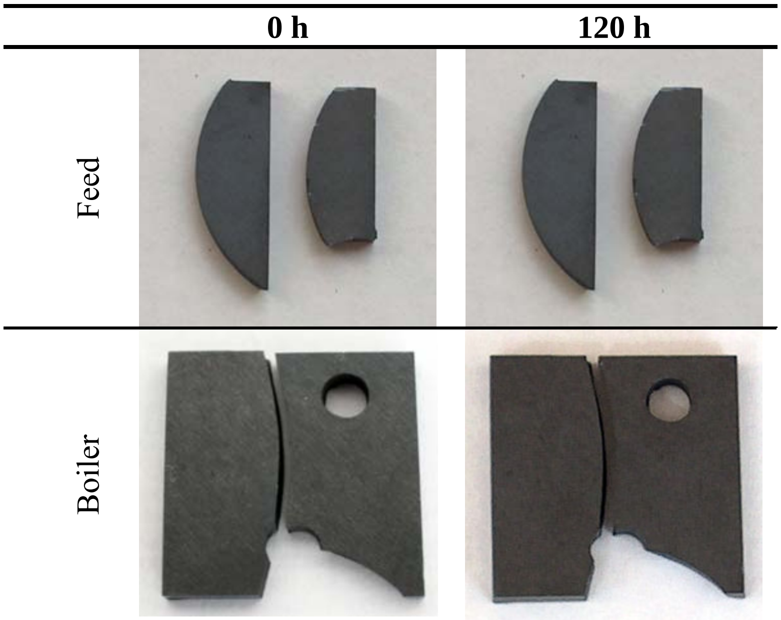


Figure 21. Splint Si-SiC coupon tested in HI_X for 120 h at both the feed and boiler condition.

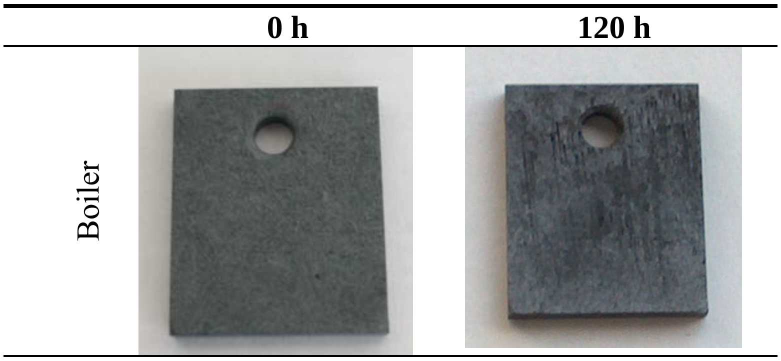


Figure 22. Fiber Si-SiC coupon test in HI_x at the boiler condition for 120 h. Dissolution of material can be observed in the coupon.

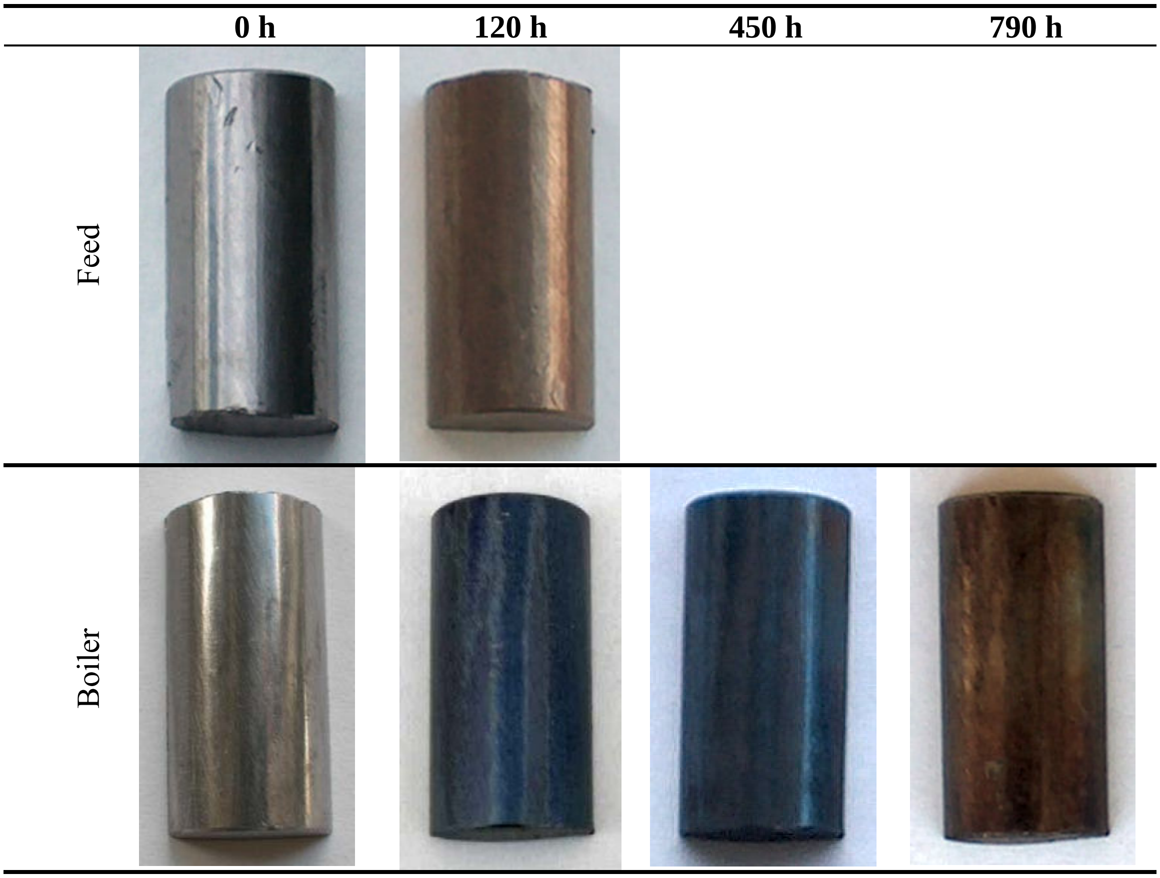


Figure 23. Ta-10W samples tested in HI_X at both the boiler and feed condition up to 790 h.

Table 2. Weight change in Ta-10W, Nb-1Zr and Nb-10Hf samples tested in HI_x.

Hours	Ta-10W (g)	Nb-1Zr (g)	Nb-10Hf (g)
0	21.354	37.302	21.181
120	21.353	37.303	21.181
450	21.356	19.700	21.183
790	21.355	-	21.184

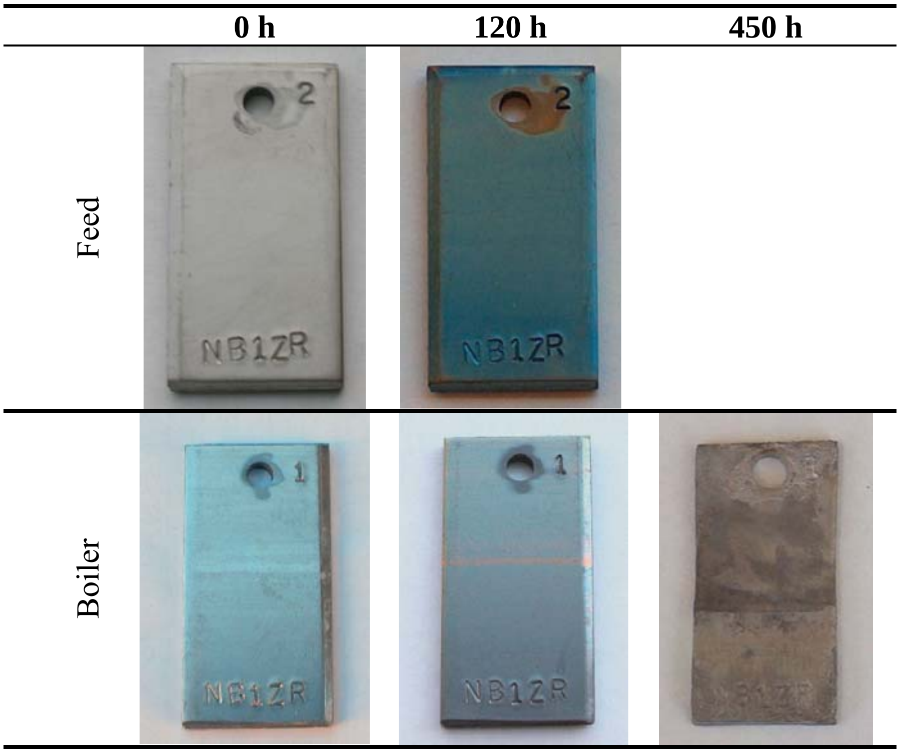


Figure 24. Nb-1Zr coupons tested in HI_X. at both the feed and boiler conditions.

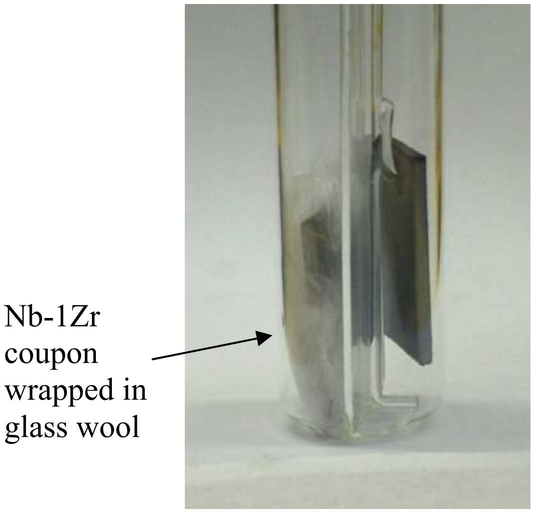


Figure 25. Immersion coupon testing with a Nb-1Zr coupon wrapped in glass wool. Another coupon was also tested simultaneously as a reference.

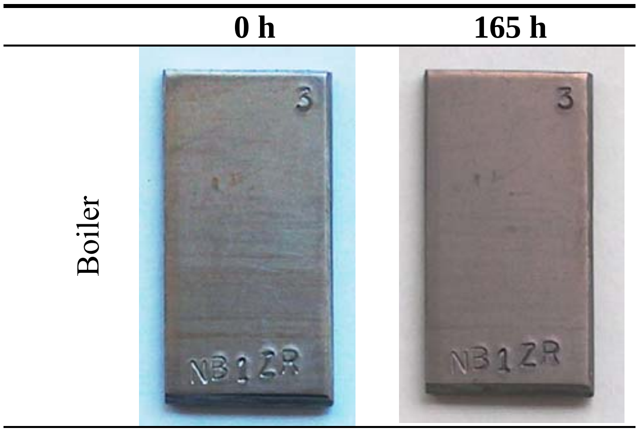


Figure 26. Nb-1Zr coupon wrapped in glass wool and tested in HI_X.

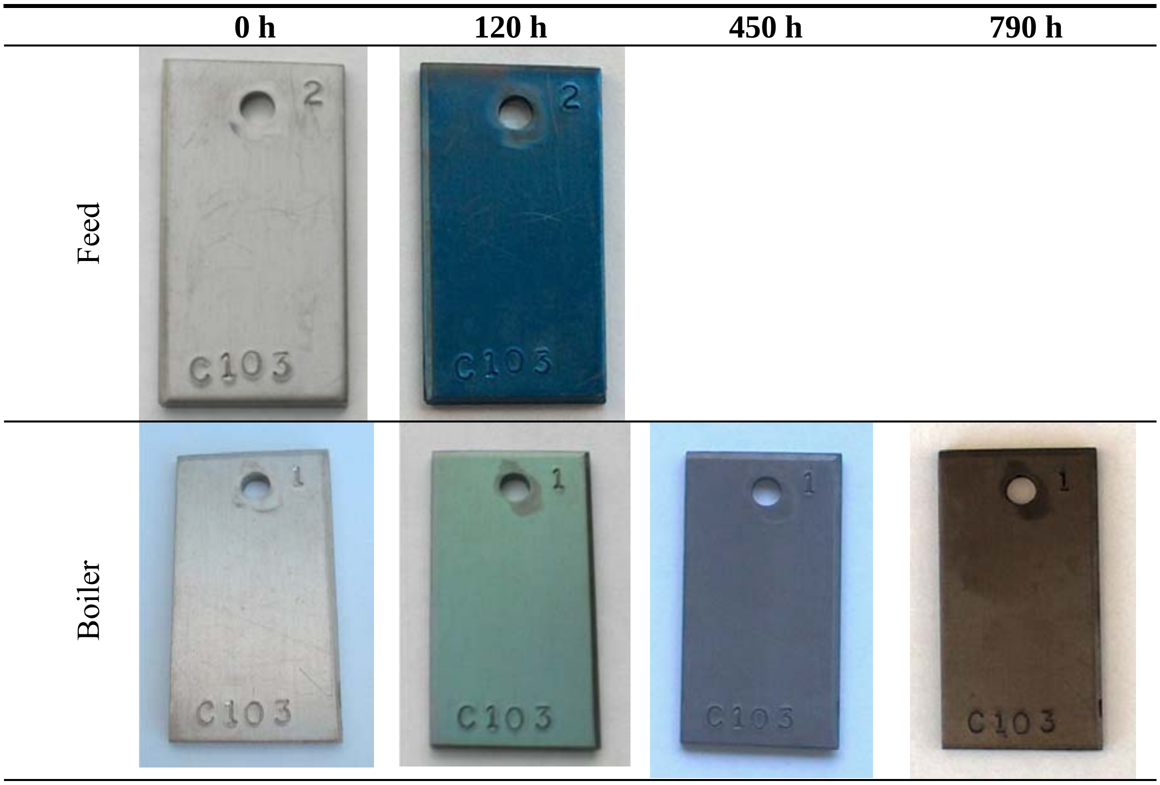


Figure 27. Nb-10Hf coupons tested in HI_X at both the boiler and feed condition up to 790 h.

Due to the excellent performance of Ta-10W, Ta-2.5W coupons have been screened at the boiler condition to determine the material's corrosion performance in HI_X. The availability of this material is better than Ta-10W and vendors have more experience in dealing with it. Figure 28 shows the coupon that has been tested for 330 h. The surface of the material is clean and and the e-beam weld does not show any sign of corrosion except a purplish tint. More long term testing on this material will be performed.

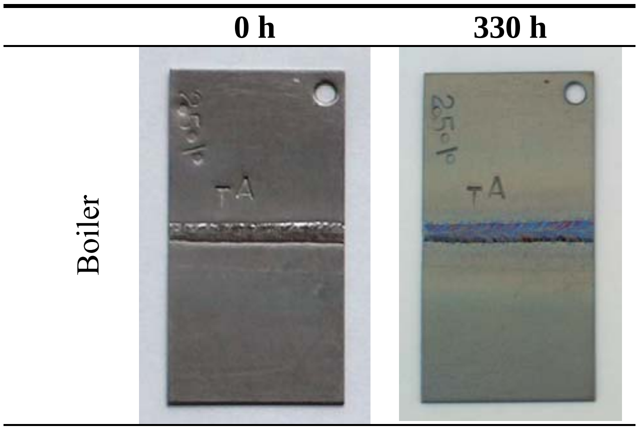


Figure 28. Ta-2.5W coupon with e-beam weld tested for 330 h in HI_X.

Task 2: Processing Effects on Corrosion Properties

Milestone 2: **completed**

The first experiment using Zr-705 tensile specimens has been performed in the test system that was installed last quarter. The 3.25" diameter of the vessel can accommodate not only coupons but larger specimens such as tensile and Double Cantilever Beam (DCB). Figures 29 and 30 show the Zr705 tensile specimens before and after treatment in HI_X. Extensive dissolution, similar to what was observed in the coupon, was found. It is interesting to note that the dissolution is more severe at the bottom of the specimen. This indicates a possible concentration gradient with the HI_X test medium.

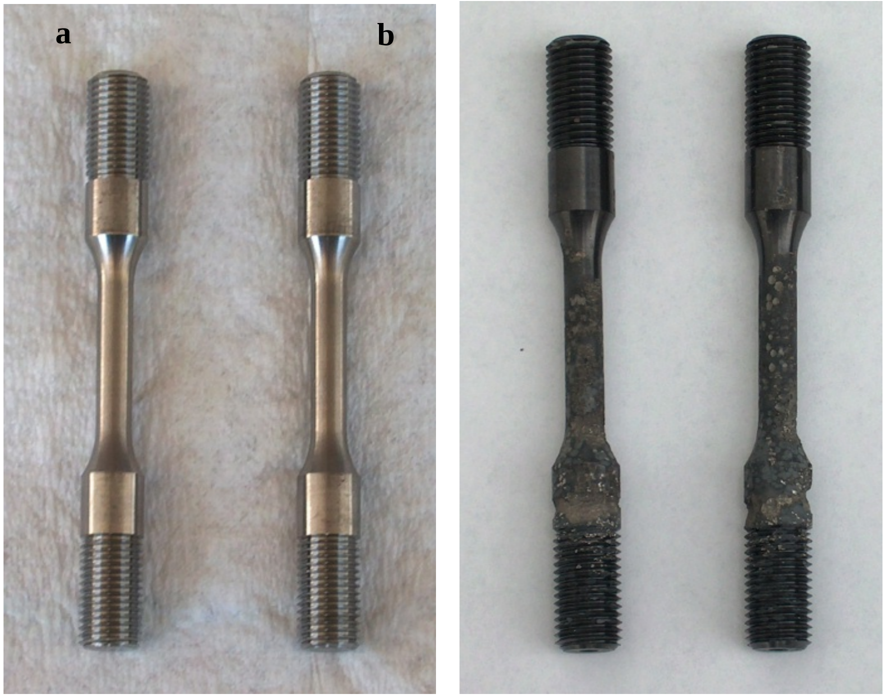


Figure 29. Zr705 tensile specimens: (a) before and (b) after a 120 hour test in HI_X at the boiler condition.

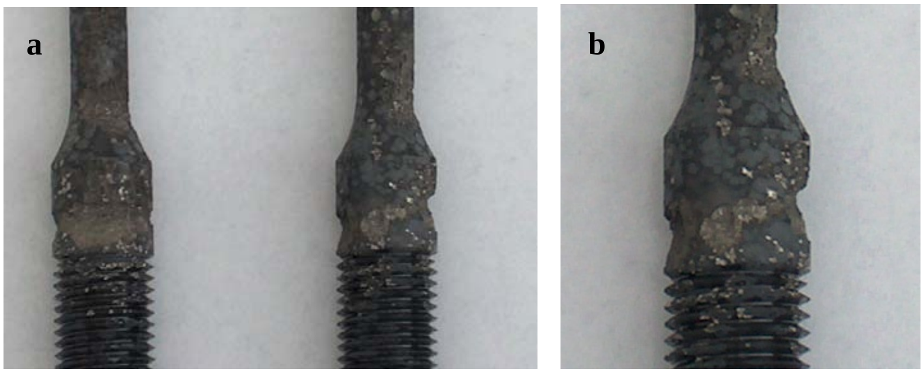


Figure 30. (a) and (b) Dissolution in Zr705 tensile specimens after testing in HI_X.

6.0 The Development of Self Catalytic Materials for Thermochemical Water Splitting Using the Sulfur-Iodine Process (PI: Ronald Ballinger, MIT)

6.1 Introduction

The Sulfur-Iodine process, as it is currently envisioned, will require that an H_2SO_4 decomposition reaction be accomplished over the temperature range from 450-850°C. After decomposition the reaction:

$$SO_3 \Rightarrow SO_2 + \frac{1}{2} O_2$$

must be promoted using a suitable catalyst. The higher temperature will push existing materials to the limits of their capability. In the temperature range of interest the catalyst is normally a noble metal such as platinum. In most cases the reactions are performed in some form of packed bed in which the structural material is separated from the catalyst. In the case of the Next Generation Nuclear Plant concepts, however, the heat source will be either helium or a molten salt which will be delivered through a heat exchanger arrangement. Designs that have been proposed include classical shell and tube designs as well as compact plate-fin and printed circuit designs. Materials of construction will include metallic materials in the short and intermediate term with the potential for ceramic material based designs in the longer term. With respect to the heat exchanger configuration, due to the amount of energy that must be transferred-in excess of 150MW-compact configurations will be mandated. Additionally, there is the potential for a significant reduction in overall system size if the functions of the heat exchanger can be combined with the catalyst. The purpose of this program is to develop a material that can act as both the structural material for the heat exchanger and the catalyst for the acid decomposition reaction.

The general approach for the development process is to focus on an alloy system that would normally be considered for the acid decomposition reaction and to modify this chemistry via the addition of a catalytic element. The program is focusing on the alloy-800HT and alloy systems with the incorporation of Platinum as an added element to the base chemistry. Several alloy chemistries will be produced, first in small "button" quantity form, and then in larger small heat size form that can be fabricated into useful shapes for characterization and analysis-both metallurgically/mechanically and for catalyst effectiveness. Lastly, depending on the results of the initial development process, material will be used to fabricate a small heat exchanger for actual testing.

This task will be performed in 4 subtasks: (1) Material chemistry identification, procurement and metallurgical characterization, (2) Catalyst effectiveness determination, (3) mechanical properties determination and (4) prototypic shape fabrication and testing. In this report tasks are indexed to the larger consortium proposal in which the catalyst work is identified as Task 3.

6.2 Progress

In this document, results of the program are reported for the Quarter April 1-June 30, 2005. Reporting will be by subtask as identified in the master proposal for the program.

Note: During the period April 22nd-June 27th 2005 the program was not allowed to expend funds. The suspension of funding occurred while a resolution of issues related to the use of "earmarked" funds for the program were resolved. Resolution was achieved by the transfer of the FY05 program to funding through a contract with the Sandia National Laboratory (SNL). The SNL contract was effective as of June 27th. However, no funds could be expended during the period April 22-June 27th which, in effect, encompasses the entire quarter. None-the-less, work has continued at the maximum level possible during this period. The student support during this period was provided by Nuclear Science and Engineering Department emergency funds. However, no laboratory work could be performed due to a lack of M&S resources.

Subtask 3.1: Material Chemistry Identification, Alloy Procurement and Metallurgical Characterization

Subtask 3.1.1: Initial Chemistry Identification& Characterization

This subtask has been completed during this quarter. A series of alloy 800HT plus Pt and alloy 617 plus Pt alloys in "button" form have been characterized during this quarter. The results of this characterization have been written up in an SM thesis which is in the process of being converted to a topical report. As a result of this characterization, the chemistry of the larger heats have been defined. The larger heat chemistries will consist of 2 wt% or less Pt added to base chemistries for alloys 800 and 617.

Alloy Development

Subtask 3.1.2: Larger Size Quantity Production

As mentioned above, the chemistries of the larger heats have been defined and cost estimates for their production have been developed. The cost for the production of two 50kg heats of material, one based on alloy 800 and the other based on alloy 617, is estimated to be $30,000. These heats will be produced in FY06 using funds from the FY06 budget for the project.

Subtask 3.1.3: Powder Production

No progress was made on this task during this reporting period.

Subtask 3.2: Catalyst Effectiveness Determination

Subtask 3.2.1: Facility Construction

The catalyst effectiveness system has been designed and procurement is in progress for the major components. During this quarter the major components have been finalized and will be ordered in the month of July. The HP 6890 Gas Chromatograph, the centerpiece of the system, is currently in house and being installed.

Subtask 3.2.2: Catalyst Proof of Principal

No progress was made on this task during this reporting period.

Subtask 3.2.3: Catalyst Effectiveness

Subtask 3.3 Mechanical Properties Determination

No progress was made on this task during this reporting period.

Subtask 3.4 Prototypic Shape Fabrication and Testing

No progress was made on this task during this reporting period.

Subtask 3.4.1: Compact Heat Exchanger Application

Discussions are ongoing with the Heatric Company regarding the manufacture of a small heat exchanger module using one or more of the alloys being developed in the program. The Heatric Company was provided with the requirements for the test modules and are finalizing the design. The exact product form required for the heat exchanger fabrication has been defined. The Special Metals Company, the supplier of the larger heats of material, have been included in the design process and will provide the proper product form to Heatric for the heat exchanger fabrication. Heat exchanger fabrication will take place as a part of the FY07 work.

Subtask 3.4.2: Shell & Tube Application

No progress was made on this task during this reporting period.

6.3 Effect of Funding Suspension on Program Progress

6.3.1 Short Term

As was discussed above, the suspension of program funding for the period 4/22/05-6/27/05 (actually, spending authorization was not granted until July 15, 2005) has resulted in a delay of the program by approximately 3 calendar months. Additionally, the suspension of work required that student support be terminated which has resulted in the student leaving the program. As a result of this it will be impossible to replace the student on the project until September 2005. Lastly, the training of a new student will take approximately 3 months to bring everything up to speed. As a result of the above events the program is approximately (or will be by the time the new student is up to speed) approximately 6 months behind schedule. As a result of this, the program schedule will need to be re-baselined in the near term. In the long term, the project is expected to be able to catch up and complete the original SOW by the end of year 3 in the project. Thus, the project would like to request an adjustment of the following items in the FY05 Work Package:

Work Package Items 7A, 8M3, 9D3: Related to Catalyst System Design & Construction, Original Completion Date: 5/1/05.

Change completion date to 9/1/05

Work package Items 10A, 11A, M2: Related to Catalyst Effectiveness Determination, Original Completion Date: 8/1/05

Change completion date to 12/1/05

6.3.2 Longer Term

It is proposed that the longer term effect on the project delay be evaluated during December 2005 to determine any additional adjustments that may be required.

7.0 Development of an Efficient Ceramic High Temperature Heat Exchanger (PI: Merrill Wilson, Ceramatec, Inc.)

7.1 Program Scope and Objectives

The objective of this research is to *assess the technical feasibility and economic viability of using ceramic and/or ceramic composite based materials* for high temperature heat exchangers. The technical feasibility will be addressed through:

- Materials design, wherein the corrosion, mechanical and thermal properties of preferred materials will be evaluated, and
- Heat exchanger design, wherein the heat, mass and mechanical design issues are numerically modeled and validated through empirical testing.

The economic viability will be assessed through cost models based on the above designs and common ceramic manufacturing practices.

7.2 Program Highlights

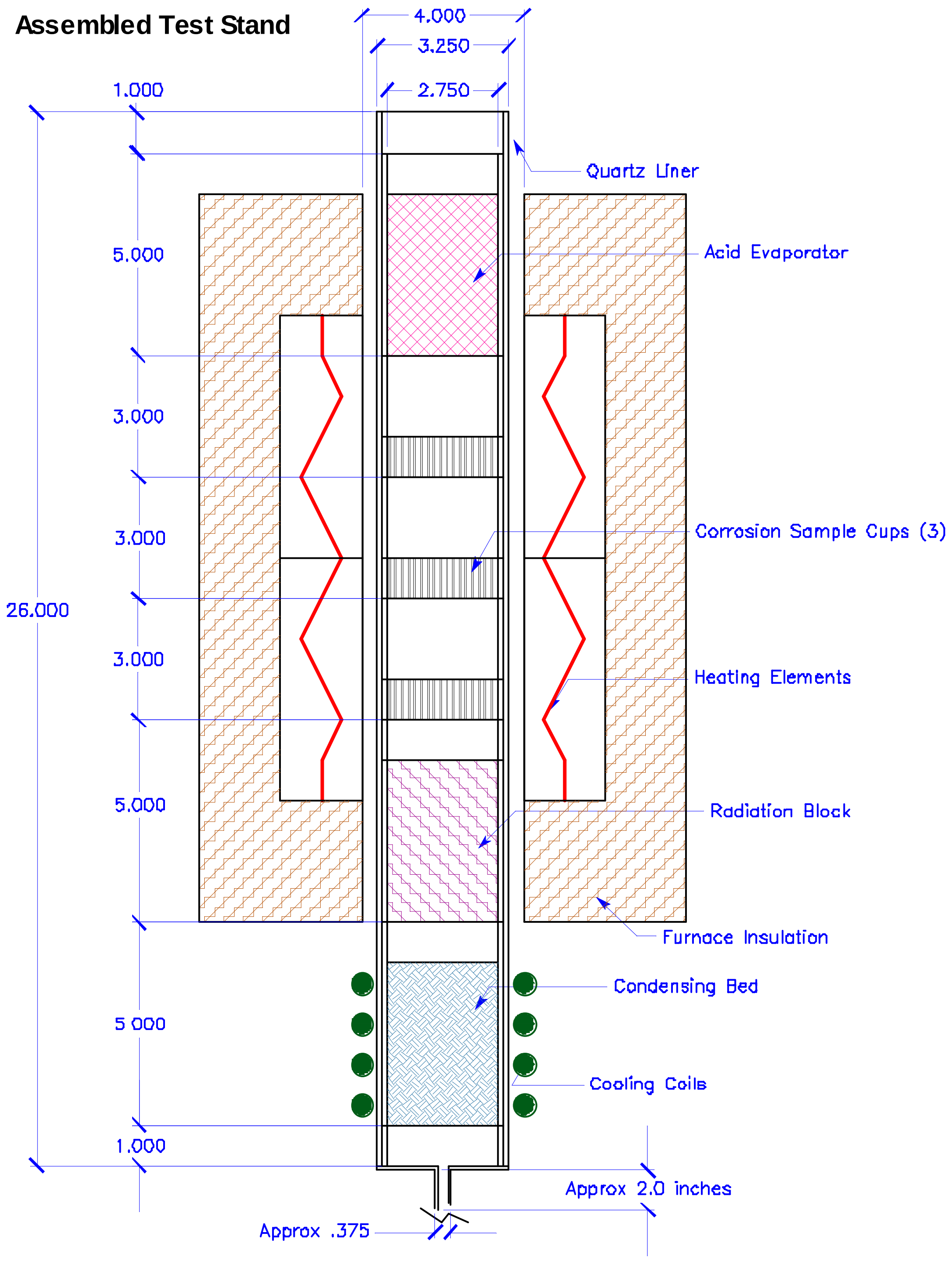
- Two high temperature exposure test rigs have been designed, equipment ordered and are being assembled. The first test rig is designed to expose ceramic samples to steam/oxygen atmospheres such that their baseline corrosion rates can be measured and compared to literature data. The second test rig will be capable of introducing sulfuric acid and thus quantify the enhanced corrosion rates due to the acid. Each test rig is capable of testing about fifty 4 point bend bars samples simultaneously to temperatures of about 1000°C at one atmosphere pressure.
- The collaborative design and analysis efforts of Ceramatec, Inc. and UNLV are progressing well. The parametric analyses have indicated which design variables are the most significant and can be used for design optimization.
- A thermal/flow test coupon has been established with design flexibility to parametrically test and validate the analyses and design performance experimentally. Several experimental test methods have been identified to map out the pressure distribution and thermal distribution of these tests.

7.3 Research Accomplishments

Task 1 Materials Design Workplan

Currently, a literature search is being done such that the design issues (corrosion resistance, thermal conductivity, thermal shock resistance, creep resistance, strength and reliability) for the candidate materials (SiC, $MoSi_2$, Ti_3SiC_2, Si_3N_4, Al_2O_3, SiAlON, Cordierite) can be quantified and ranked. The corrosion properties of these materials are likely the life limiting factor for the high temperature heat exchanger/decomposer. We have also found that there are limited corrosion data for these materials, especially with vaporized acids. Thus as part of the materials effort, Ceramatec, Inc. has designed, purchased equipment and is now building 2 High Temperature Exposure Test Rigs. The first test rig is designed to expose samples to steam/oxygen and inert gases. This rig will obtain baseline corrosion data similar to that reported in the literature. The second test rig has additional safety features enabling the addition of gaseous sulfuric acid. Between the two test rigs we will be able to compare our materials with literature data and to assess the detrimental effects of the acid.

The design of these exposure rigs is found in Figure 31. The design incorporates a quartz tube to isolate gas species in the exposure rig. This tube has multiple quartz cups stacked inside. Cups that are located near the top and bottom of the furnace are used to vaporize or condense the liquids and act as a radiation block to prevent excess heat loss and thermal gradients. The central cups are used to hold the corrosion specimens at the test temperatures. The specimens are loosely stacked in a structured manner to allow for nearly complete exposure to the corrosive atmosphere.



a) Schematic of High Temperature Corrosion Test Rig

b) Steam Exposure Test Rig

c) Quartz Liner w/ Evaporator, Condenser and Specimen Cups.

Figure 31. High Temperature Corrosion Test Rig.

For safety concerns, the sulfuric acid exposure rig will be installed into an enclosure such that if gases were to leak, they would be swept out of the room through a fume hood. Schematically, this is shown in Figure 32. Additional interlocks will also be included to prevent liquids from shocking the quartz test system. It is anticipated that the preliminary concentration within this rig will be: 60% steam, 30% H_2SO_4 and 10% oxygen. Although these concentrations are not expected to ever occur simultaneously, it represents the near peak concentrations of these species throughout the decomposition process. The Early stages will have a high concentration of S_2SO_4 (30%) and later stages would have a higher oxygen concentration (10% - after decomposition).

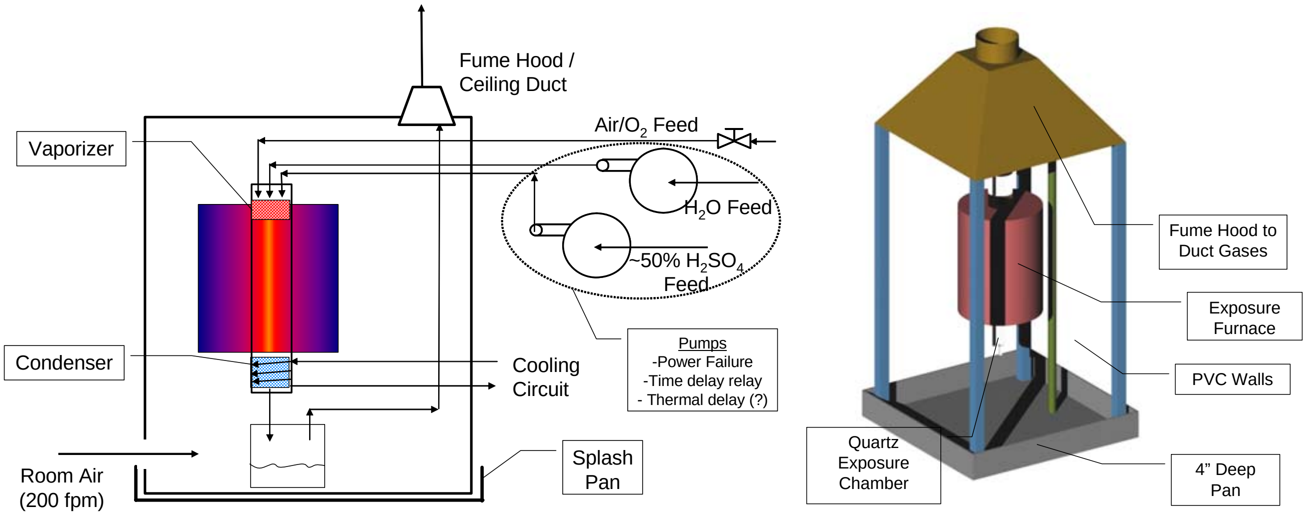


Figure 32. a) Safety Systems for H_2SO_4 *b) Safety Enclosure for H_2SO_4*

This test apparatus will be assembled and go through a final design and safety review within the next several weeks. That will enable the preliminary exposure tests to begin mid-August.

Task 2 High Temperature Heat Exchanger Design and Validation

Heat Exchanger Design and Analysis – The design of the sulfuric acid decomposer was described in the previous quarterly and is shown in Figure 33. This overall design is considered a "shell and plate" heat exchanger. It is similar to a shell and tube heat exchanger except the primary surfaces are generated from a stack of plates verses a bundle of tubes.

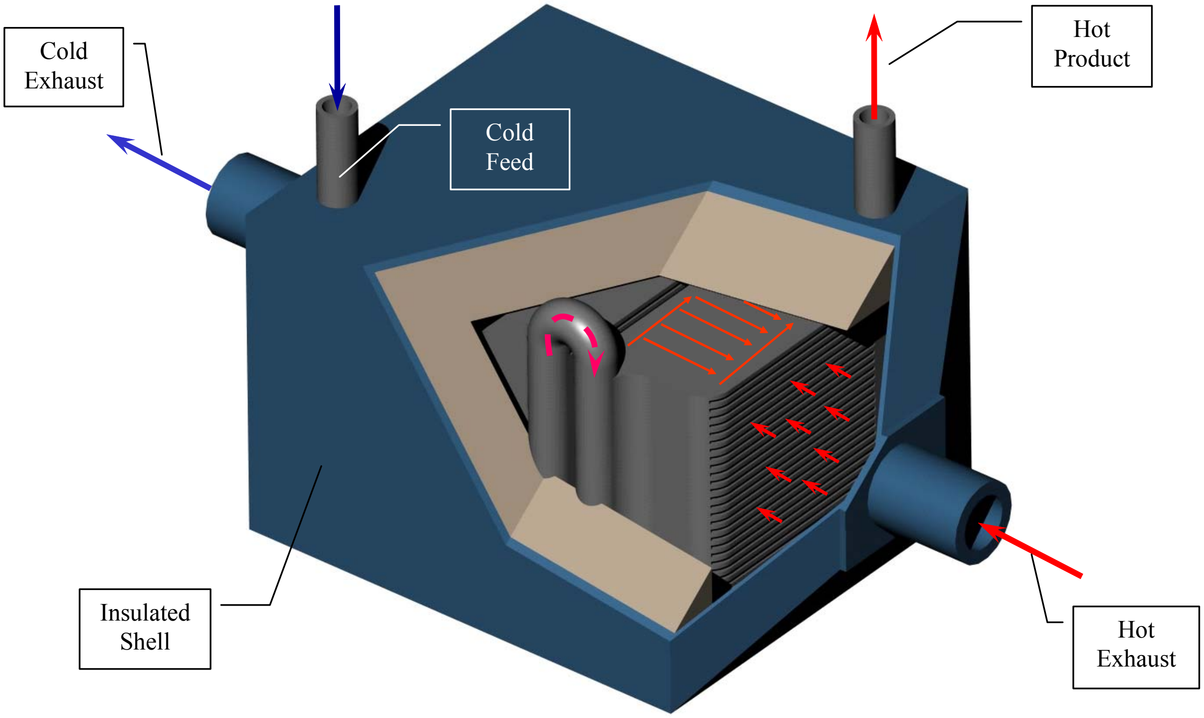


Figure 33. Multi-Stage Shell and Plate Compact Heat Exchanger.

Given this overall concept, the Revision 1.0 design of the plates and the modular stacks has been completed (Figure 34). Each of the plates incorporates micro-channels to enhance the heat transfer from the hot helium to the decomposing sulfuric acid. Critical design features include flow distribution, gas-solid-gas heat exchange efficiency and the thermo-mechanical durability of the structure. These design issues are being addressed through analysis and modeling in a collaborative effort of Ceramatec, Inc. and UNLV.

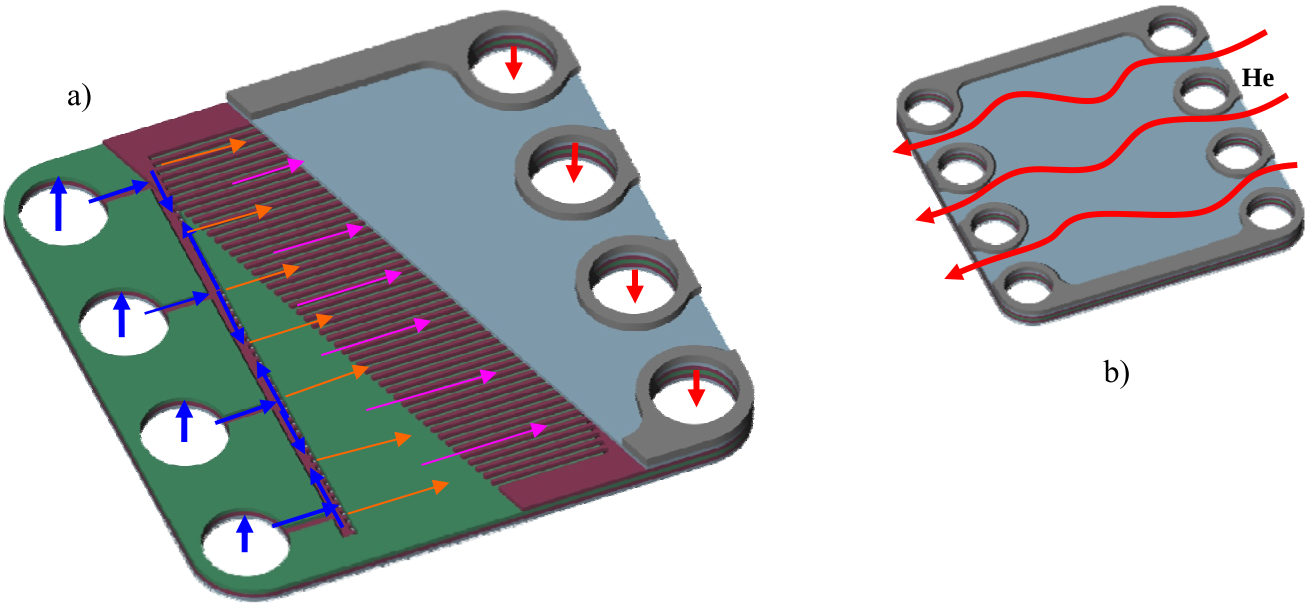
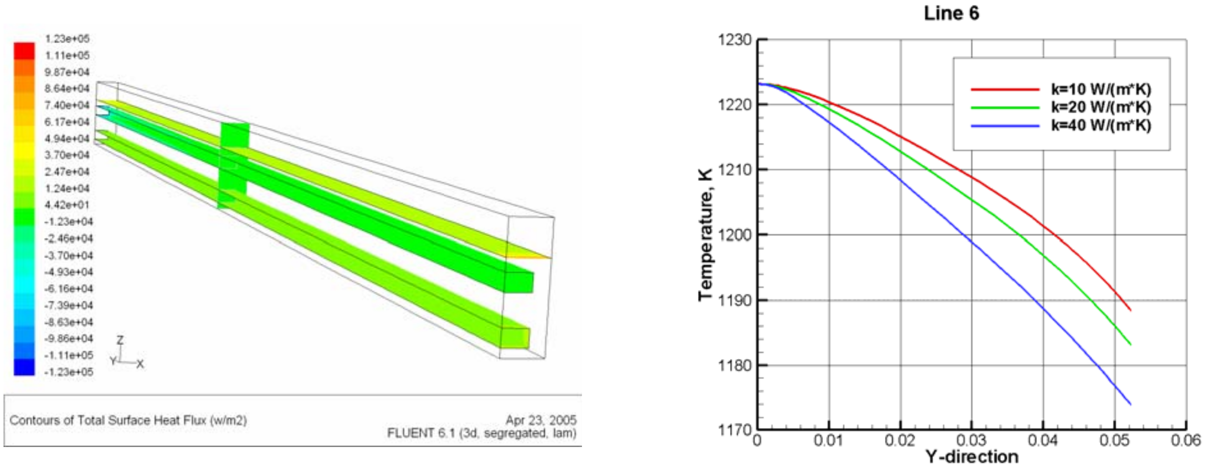


Figure 34. Revision 1.0 Design of the Heat Exchanger Plate for the Shell and Plate Decomposer a) Internal Sulfuric Acid Channel Flow, b) External He Heat Transfer Fluid Flow.

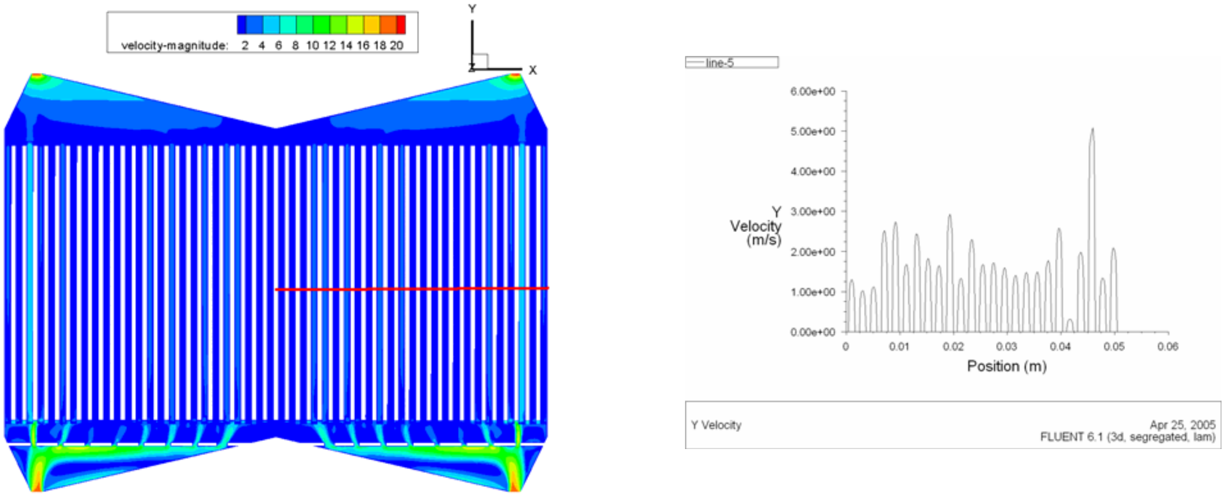
To date the modeling has focused on the flow and heat transfer in the micro-channels and the flow distribution within each heat exchanger plate.

As a parallel network of micro-channels, a common repeat unit (single micro-channel with its associated flows and surfaces) has been modeled parametrically in order to optimize its heat transfer capability with a minimal pressure drop. The design parameters being investigated are the micro-channel dimensions and the flow rate in these channels. The design metrics include the amount of heat transferred for the helium to the sulfuric acid, the average and local heat transfer coefficients, pressure drop and the relative axial heat conduction losses. Although this work is not complete, we have found that a significant amount of heat is transferred near the entrance of the micro-channels, that axial conduction losses must be considered and minimized, and that the uniformity of flow may control the overall effectiveness of the heat exchanger.

Non-uniform flow in the micro-channels decreases the overall effectiveness of the heat exchanger by 1) not fully preheating the high flow streams, 2) increasing the overall pressure drop (mechanical work), and 3) encourages thermal dispersion in both the axial and lateral directions. Thus, it is important to model the flow through the internal gas manifolds to assess the degree of non-uniformity and to optimize these manifolds to minimize these differences. As mentioned previously, UNLV is developing these models and providing analytical support for this design effort. They are performing conjugate flow and heat transfer analyses and use Fluent as their modeling tool. Some of the typical results are shown in Figure 35.



a) Heat Flux in Micro-Channels *b) Temperatures Along Length of Micro-Channel*



c) Velocity Distribution with Modified Manifold *d) Velocity Magnitude in Micro-Channels*

Figure 35. Typical Analytical Results from UNLV Conjugate Flow and Heat Transfer Modeling.

Heat Exchanger Design and Validation – The analytical results provide great insight to the performance of the heat exchanger; however, these tools and the actual design must be validated through experimental testing. Through the parametric analyses, one can come to understand the significance of various design parameters. Thus, in a parallel effort a thermal/flow test coupon was developed that can be easily modified to parametrically implement these variables into testable hardware that will be used to calibrate models and validate designs. This test coupon represents a slice of the full-size design, thus including multiple channels yet eliminating the need for flow distribution headers. In this manner, the pressure in and along the channels and the temperature gradient down the axis of the flow channels will be able to be measured. This design has sufficient flexibility to modify the height, width and number of channels. It is also large enough to address flow distribution within the manifolds. The design of the thermal/flow coupon is found in Figure 36.

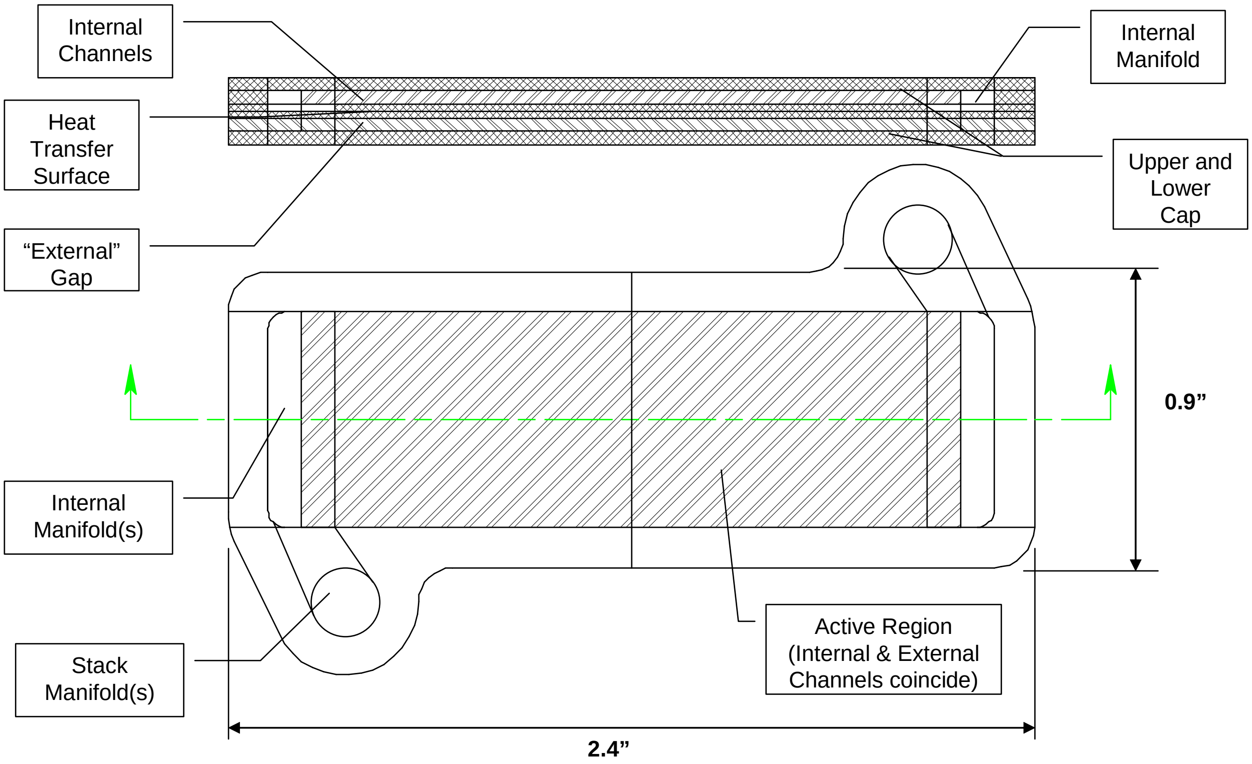
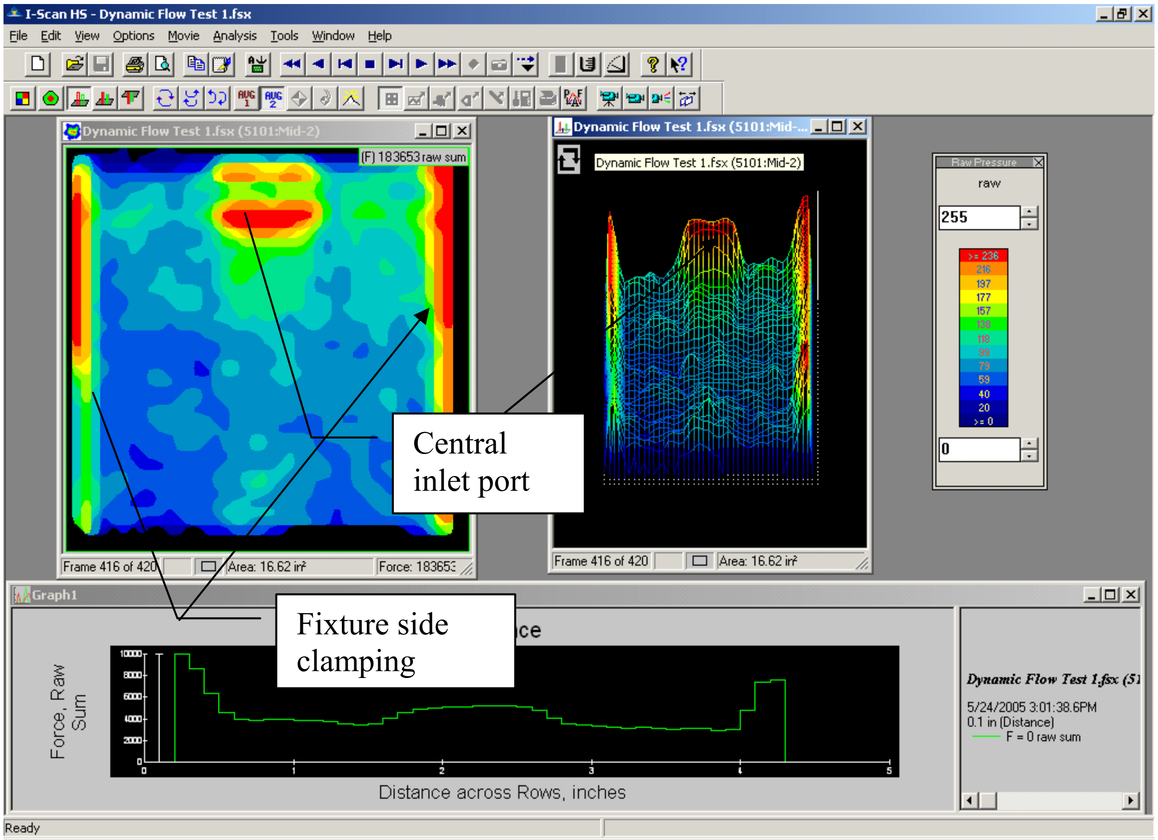


Figure 36. Thermal/Flow Test Coupon (Details of Flow Channels dependent on design Parameters).

Validation of the design features (micro-channels and manifolds) will be determined by measuring the pressure drop, pressure distribution, flow rates and thermal profile during testing. As a counter-flow heat exchanger the inlet and exit conditions (temperatures and pressures) such that the overall performance can be calculated. However, as a relatively small and singular part, the edge effects and surrounding boundary conditions may be significant. Thus by measuring the pressure and thermal profiles, the local properties can be measured to determine localized performance (entrance effects, surface conditions, heat transfer). In order to measure the pressure distribution within the micro-channels, Ceramatec will make flow coupons following the usual fabrication processes, except it will leave off the outer dense layer. This will leave the channels exposed so that one can cover/cap them with a pressure sensitive mat and be able to digitally measure and record the dynamic pressure distribution within the channels. Measurements of the thermal field will be done on normal thermal/flow coupons using infra-red thermometry. And although this will only measure the temperatures of the external surfaces, the amount of this information should allow us to accurately model the internal behavior of the gases and the solid. The pressure mat is fabricated by Tekscan of Boston. It has a special resolution of about 0.05 inches and a pressure resolution of about 0.10 psi. Using this tool and parametrically scaling flow rates, reliable qualifications can be achieved. Infra-red thermometry is further developed, giving better spatial and thermal resolution. Figure 37 is a sample test wherein exposed micro-channels were capped with the pressure sensitive mat and a variation in pressure field was measured dynamically. (Note that the high pressures diffuse from the high pressure upper central port).



Central inlet port

Fixture side clamping

Figure 37. Pressure Distribution as Measured with Tekscan's Pressure Sensitive Mat.