High Temperature Heat Exchanger Development

Anthony Hechanova
UNLV Research Foundation

May 2005

PD30

Overview

Timeline

- Project start date: 9/03
- Project end date: 9/08
- Percent complete: 25%

Budget

- Total project funding
  - DOE/NE: $5,280k
- Funding received in FY04: $1,900k
- Funding for FY05: $2,630k

Barriers

- Barriers addressed
  - NHI R&D Plan – material performance and component design and testing for: intermediate heat exchanger, H_2SO_4 decomposition, and HI decomposition

Partners

- UNLV, UC Berkeley, MIT, General Atomics, Ceramatec, Sandia National Lab

Objectives

To assist DOE-NE in the development of hydrogen production from nuclear energy through:

- Identification and testing of candidate materials for heat exchanger components.
- Design of critical components in the interface and sulfur iodine thermochemical process.
- Fabrication and testing of prototypical components.

Approach: ID05SS12
(PI: Prof. Ajit Roy, UNLV)

Identification and testing of candidate metallic materials for heat exchanger components.

- Materials: Alloy C-22, Alloy C-276, Waspaloy, Incoloy 800H, Niobium-1 Zirconium, Niobium-7.5 Tantalum, and Zr 705.
- Techniques: tensile properties, stress corrosion cracking (constant load and slow-strain-rate), fractographic evaluations, surface analysis using spectroscopy.

Technical Accomplishments/ Progress/Results

- Stress corrosion cracking studies of Alloy C-22, C-276, and Waspaloy in sulfuric acid and sodium iodide at 90 C completed. Developing a mechanistic understanding of their failure.
- High-temperature instruments (autoclave up to 600 C and mechanical testing up to 1200 C) being installed this summer.
- Coupons tested at GA are being evaluated.

Approach: ID05SS16 -- Identify the materials of construction for HI Decomposition. (PI: Dr. Bunsen Wong, GA)

Screening → **Development** → **Prototype**

- Screening: Immersion Coupons
- Development: Crack Initiation & Growth, Long Term Testing, Cladding
- Prototype: S-I Loop/Pilot Plant Testing

Zr705

new

tested

Nb-1Zr

new

tested

Technical Accomplishments/ Progress/Results

- 22 coupons from four classes of materials: refractory and reactive metals, superalloys and ceramics, have been screened for 100 hours or more each in liquid HI_x.
- A list of suitable development , including Nb-1Zr, Ta-7.5Nb and SiC are among candidates.
- Long term corrosion performance of coupons has started.

Technical Accomplishments/ Progress/Results

Excellent	Good	Fair	Poor
Ta-40Nb, Nb-1Zr, Nb-10Hf, SiC(CVD), SiC(Ceramatec sintered), Mullite	Ta, Ta-10W, Nb, Nb-7.5Ta, SiC (sintered)	Mo-47Re, Alumina	Mo, C-276, Haynes 188, graphite*, Zr702, Zr705

* structurally sound but absorbed HIx

Excellent: very minor change in color due to passivation
Good: distinguish color change due to passivation
Fair: mild corrosion- localized oxidation, uneven passivation and minor weight loss
Poor: severe corrosion - dissolution and pitting

Future Work

Reminder of FY05 and FY06

- Continue long term coupon testing
- Conduct tests to study the effect of HIx on stress corrosion behavior of materials will begin at GA in 4/05.
- Evaluate material cost reduction through cladding.

Approach: ID05SS15 – self-catalytic materials (PI: Prof. Ron Ballinger, MIT)

- Select “Model” Structural Alloys
  - Alloy 800HT
  - Alloy 617
- Make Additions of Platinum to base Alloy Composition
  - 2, 5, 15, 30 wt%
- Evaluate Resulting Structure & Mechanical Properties
  - Microstructure
  - Tensile, Creep
- Evaluate Catalytic Effectiveness
- Fabricate “Unit” Heat Exchanger Module and Test

Technical Accomplishments/ Progress/Results

- Model alloys have been fabricated in “button” (small heat) form
- Initial microstructural characterization of materials have been performed
- Initial electrochemical characterization has been accomplished
- Chemistry for larger heats has been established
- Heat exchanger design in initial stages
- Initial results indicate that the materials being developed will also be effective catalysts for the reduction of hydrogen-approaching that of platinum
- These results have implications for the potential use of these materials for high temperature electrolysis applications

Future Work

- Complete Characterization of Model Alloys
- Construct Catalyst Effectiveness Determination System
- Fabricate Larger Heats of Selected Alloys
  - 2 wt% Pt, Alloy 800HT, Alloy 617
- Characterize Larger Heats
  - Metallurgical
  - Electrochemical
  - Catalyst Effectiveness

Approach: ID05SS14 – Ceramic compact HX (PI: Prof. Per Peterson, UC Berkeley)

- UCB proposed that compact plate heat exchangers could be fabricated from inexpensive chopped-carbon-fiber based ceramic composites
- Individual plates can be formed by die-embossing flow channels using a mold -ORNL demonstrated fabrication of such plates
- Assembly, pyrolization, and infiltration can create complex, monolithic parts
  - Carbon fiber maintains dimensional stability during pyrolysis
  - Two possible inexpensive infiltration processes: silicon melt infiltration (MI) and polymer infiltration and pyrolysis (PIP)
- Various coatings to achieve helium hermeticity and corrosion resistance to heat transfer fluid such as molten salt and hydrogen production fluids such HI or H_2SO_4
  - Chemical vapor deposition (CVD) SiC coating, carbon coating, cordierite coating

Technical Accomplishments/ Progress/Results

- MI material high pressure helium permeation testing verified very good helium hermeticity of several types of MI composite materials:
  - MI SiC splint-based material (SB-SiSiC)
  - MI pitch based carbon fiber reinforced SiSiC (BioKer)
- CVD coating of C/SiC coupons was demonstrated, which can be applied to interior HX surfaces after fabrication is complete. The resulting coupons show very good helium hermeticity and high strength
- MI test coupons have been sent to GA for HI corrosion test and to SNL for sulfur gas corrosion test
- Preliminary corrosion testing with flinak salt underway

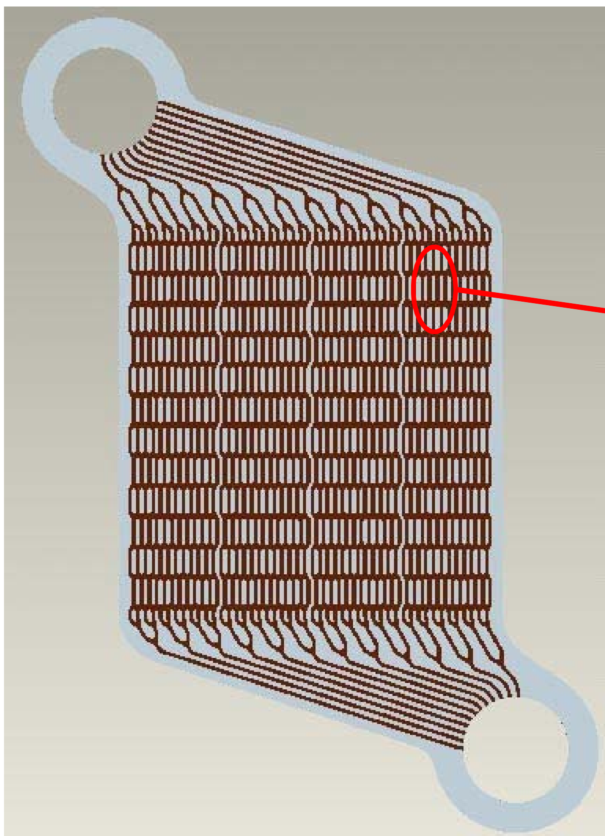
Technical Accomplishments/ Progress/Results

- MI material mechanical properties such as Young's modulus and failure stress were measured:

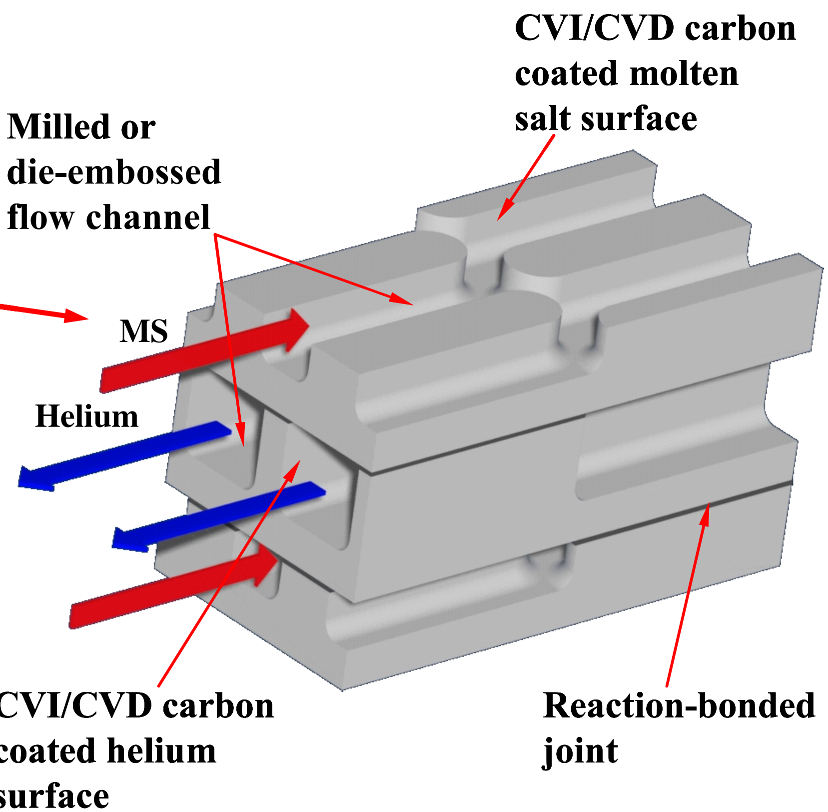
MI Material	Density kg/m^3	Young's modulus GPa	Failure stress MPa
Carbon fiber reinforced SiSiC with coating	2523	325	270
Splint based SiSiC	2932	450	224
Pitch based SiSiC	2600	298	200
Short fiber reinforced SiC	2000	60	90 - 140

Technical Accomplishments/ Progress/Results

- HX design and analysis
  - Approximate heat transfer/pressure loss analysis
  - Full plate and manifold design



Molten salt plate

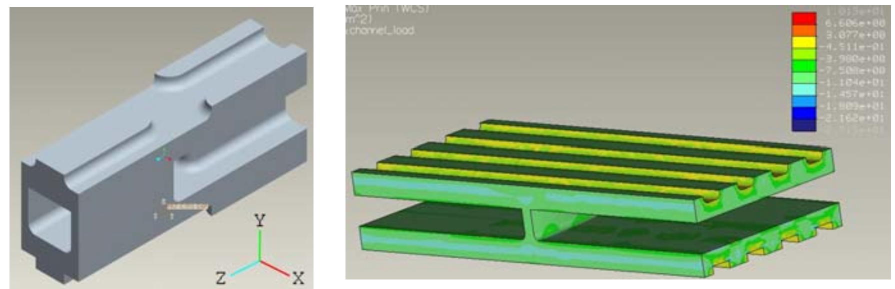


Unit Cell

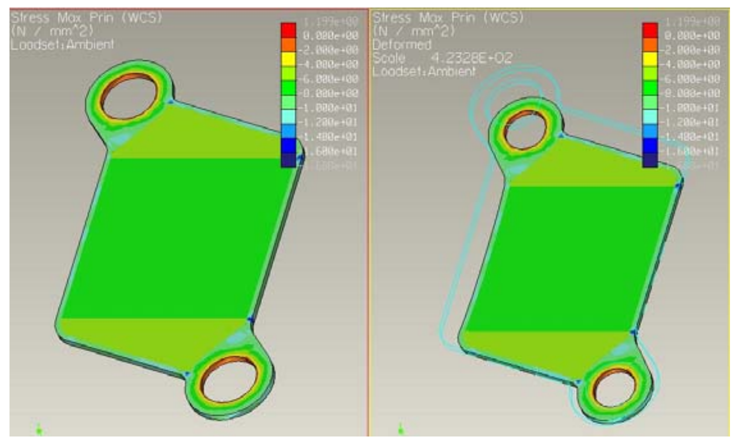
Technical Accomplishments/ Progress/Results

- **isothermal mechanical stress analysis with Pro/Engineer software**
  - **Finished unit-cell isothermal mechanical stress analysis and thermal stress analysis**
  - **Obtained equivalent mechanical properties from unit cells**
  - **Obtained whole HX mechanical average stress distribution**
  - **Obtained local max isothermal stresses basing on whole HX average stress**

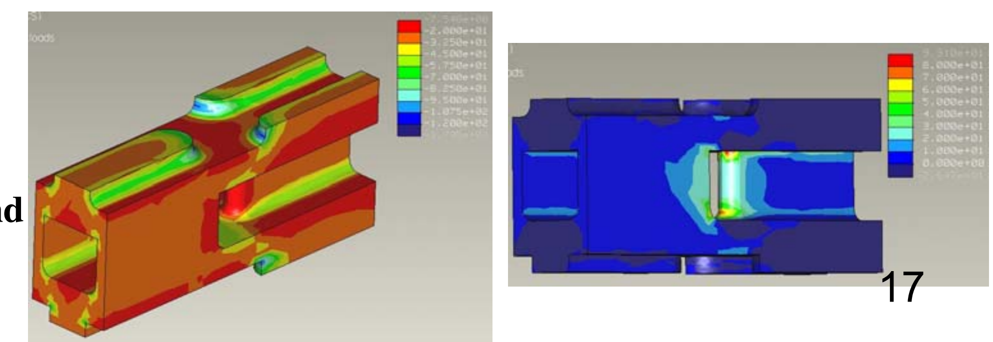
Unit cells



Whole HX average stress



Maximum compressive and tensile stresses

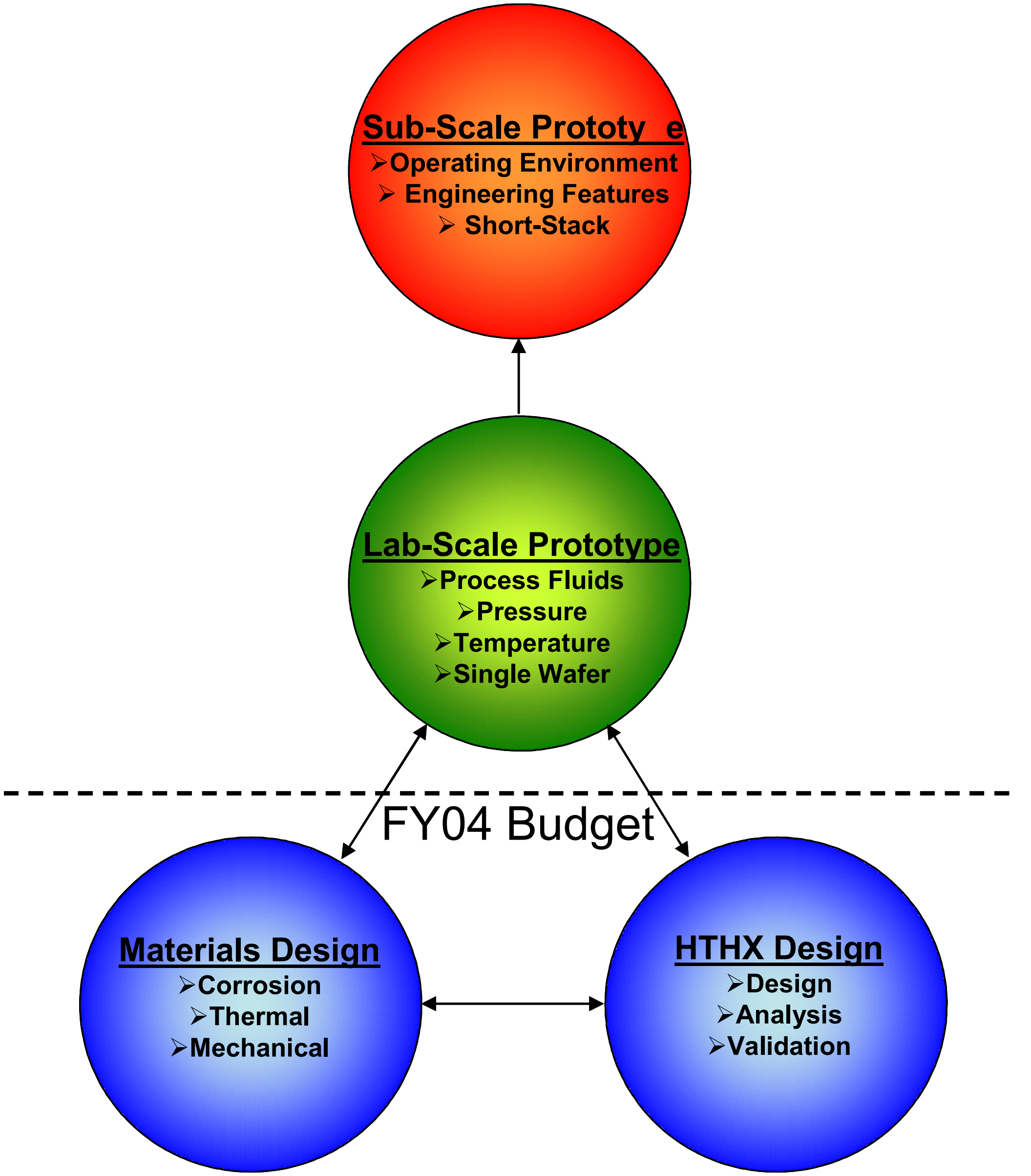


Future Work

- Demonstrate fabrication of small plate HX (vendor input)
  - Identify candidate fiber and matrix materials (vendor input)
  - Identify candidate MI and PIP approaches
  - Fabricate embossed plates with optimized flow channels
  - Demonstrate infiltration of plate assemblies (vendor input)
- Advance the analysis and design of chopped carbon fiber reinforced plate HXs
  - Transient mechanical/thermal stress analysis of complete HX (including manifolds)
  - Safety analysis for applications with S-I process fluids
  - Design flow-loop for testing with molten salts

Approach: ID05SS17 and ID05SS18 Ceramic HX (PI: Merrill Wilson, Ceramatec, Inc.)

- **Staged Development:** Iterative scale-up such that parallel developing technologies are integrated cohesively.
- **Collaboration:** Utilize team's expertise & infrastructure to increase knowledge base and minimize costs.
- **Walk the Walk:** Make prototypical parts and perform validation tests.



Technical Progress - Materials

- Identification of Material Design Parameters has been completed and narrowed down candidate materials

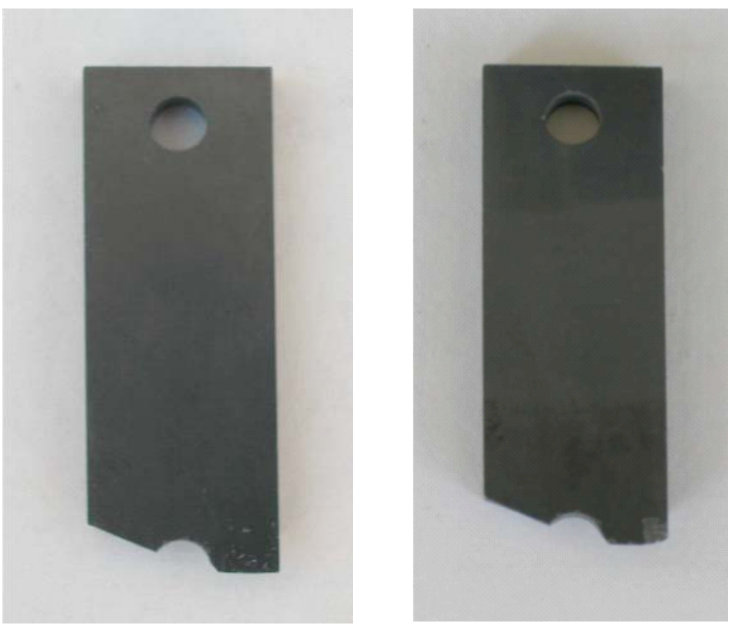
- **SiC**
- **Ti_3SiC_2**
- **Al_2O_3**
- **Cordierite**
- **$MoSi_2$**
- **Si_3N_4**
- **SiAlON**

Parameter	**Required value**
Thermal conductivity	< 30 W/m-K
Strength	Sufficient to provide 100 MPa allowable stress
Probability of Failure	1×10^{-6}
Corrosion rate	? 3.75×10^{-9} m/h
Thermal shock parameter	0.1 – 5 kW/m^2
Creep rate	< 3.1×10^{-11} m/min

Technical Progress - Materials

- Corrosion samples being fabricated and testing underway
  - HIx exposure w/ GA
  - SI Decomposition w/ SNL

new 120hours



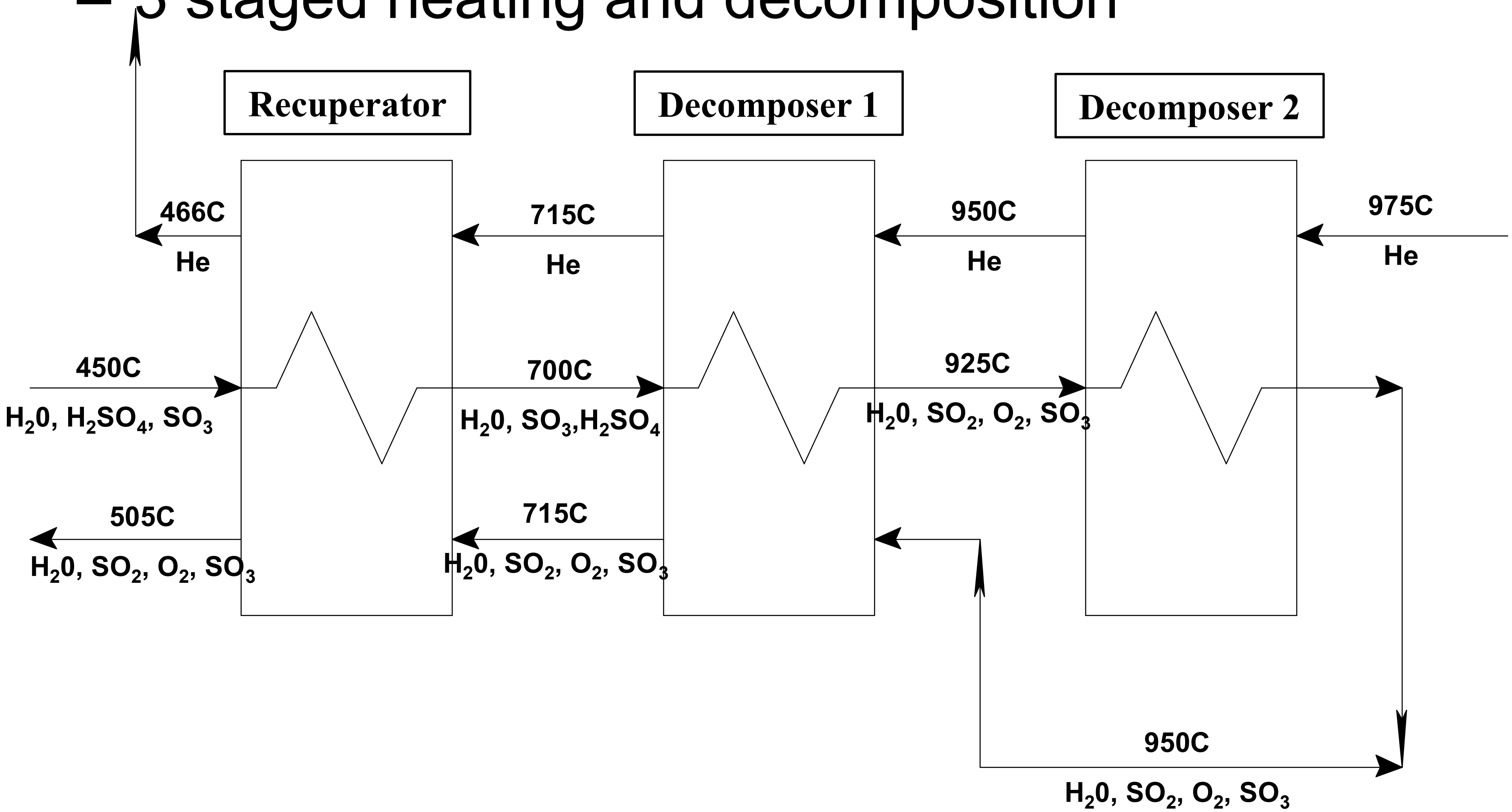
a) CVD Silicon Carbide

new 120hours

b) Ceramatec Sintered Silicon Carbide

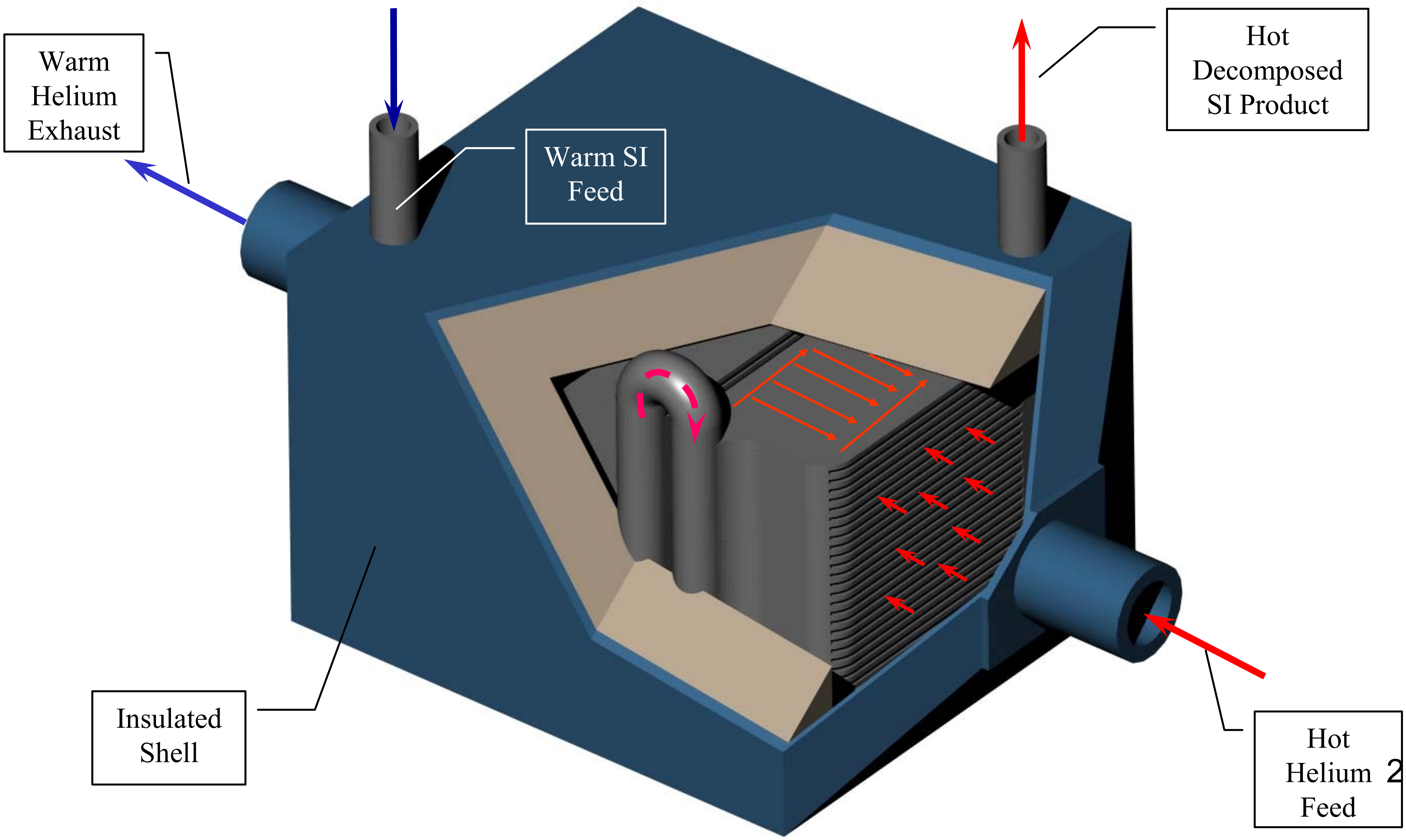
Technical Progress – HX Design

- Process conditions have been identified.
  - 3 staged heating and decomposition



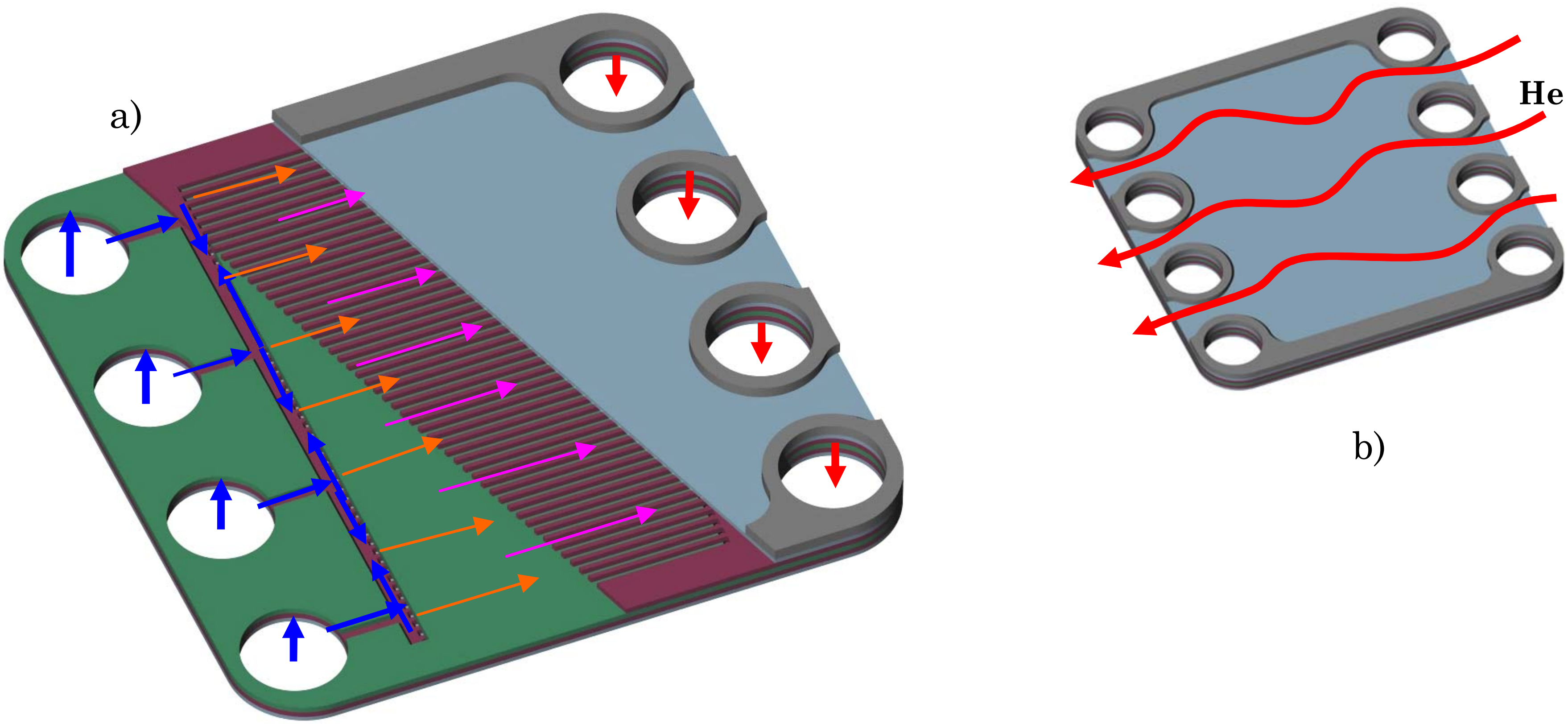
Technical Progress – HX Design

- Compact Shell and Plate Design.
  - High Performance Micro-Channels
  - Low Volume, Low Cost



Technical Progress – HX Design

- Micro-Channel Plate Design.
  - Helium and Sulfuric Acid Isolation
  - Capable of High Pressures



a) Internal Sulfuric Acid Channel Flow, b) External He Heat Transfer Fluid Flow.

Future Work

- FY04:
  - Materials: Complete round 1 of corrosion and mechanical testing for candidate materials.
  - Design: Optimize micro-channel and plate designs through FEA.
  - Validation: Fabricate and test flow coupons validating the performance expectations.
- FY05:
  - Integrate into lab-scale prototypes evaluating the thermo-fluid and thermo-mechanical performance and limits.

Approach: ID05SS13 – computational design support (PI: Prof. Yitung Chen, UNLV)

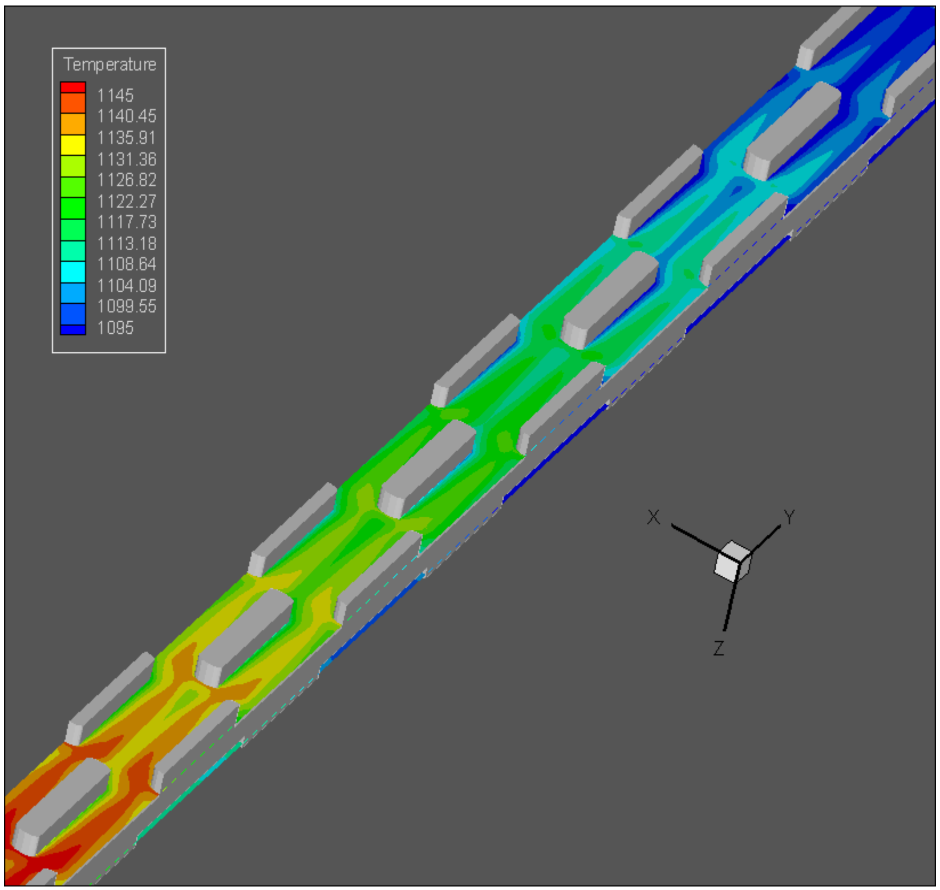
- Use Gambit to generate computational mesh for the UCB design (off-set strip-fin) and the Ceramatec design (micro-channel)
- Use FLUENT to model hydrodynamics and heat transfer using liquid salt and helium as working fluids
- Evaluate optimization concepts to the baseline design by modifying design parameters and re-running the codes
- Expand concepts to address specific components to be determined through discussions with national technical directors
- Collaborate with UC Berkeley and Ceramatec to develop structural analysis methodologies for HTHX concepts
- Collaborate with General Atomics to perform baseline design and calculations for the sulfuric acid decomposer heat exchanger

Technical Accomplishments/ Progress/Results

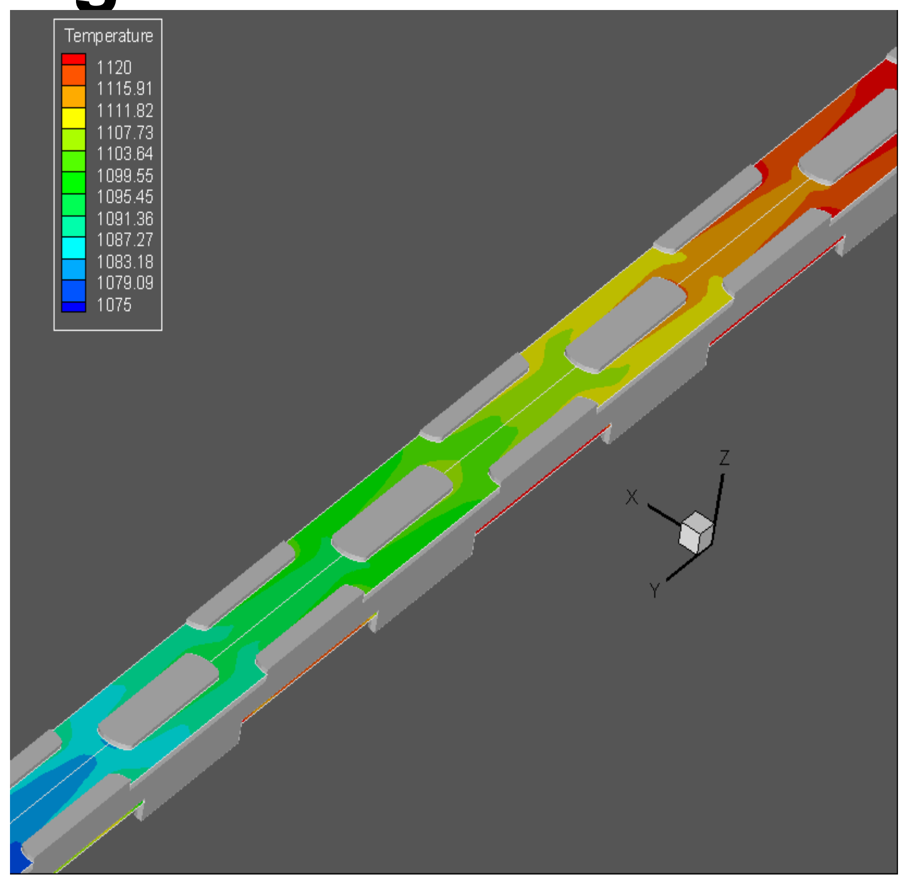
- Performed CFD analysis using variable material properties
- Performed grid independence studies
- Performed turbulence modeling
- Updated design to include manufacturing geometrical effects
- Completed CFD design evaluation of baseline compact off-set strip-fin HTHX
- Performing optimization studies of compact HTHX considering fin gap distance, length, thickness, pitch, and channel height
- Identified software and developed method for stress analysis
- Performing thermal and mechanical stress analysis
- Performing hydrodynamics modeling on the ceramic heat exchanger based on the Ceramatec design
- Performed literature review and determining baseline conditions for sulfuric acid decomposition reactions

Accomplishments/Progress/ Results

Temperature (K) contours on HX in the middle region



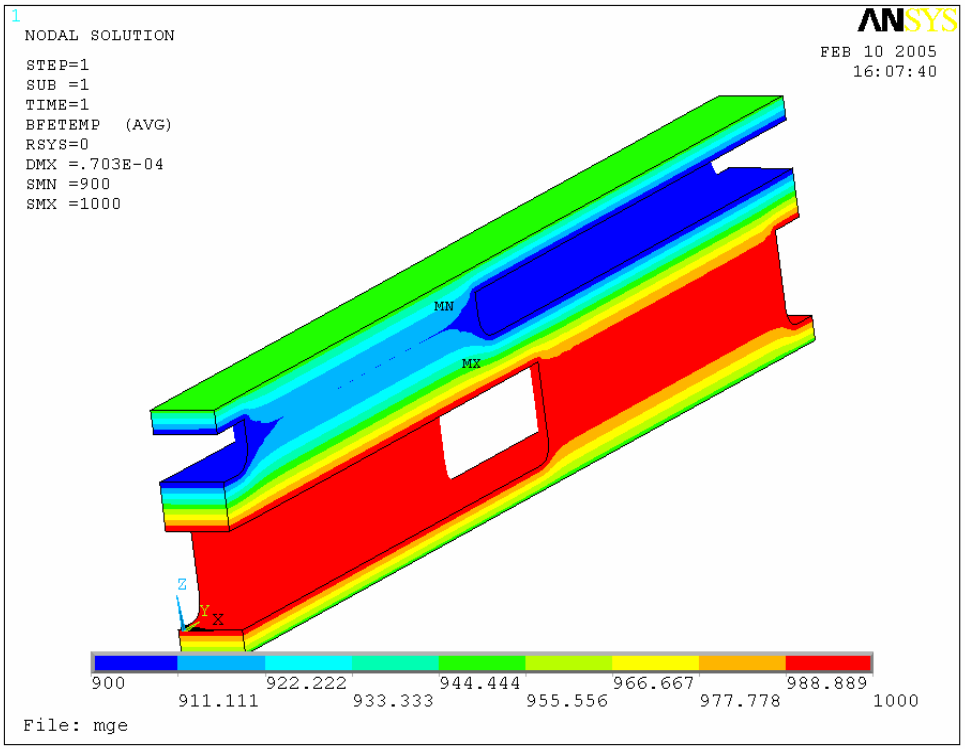
Helium side



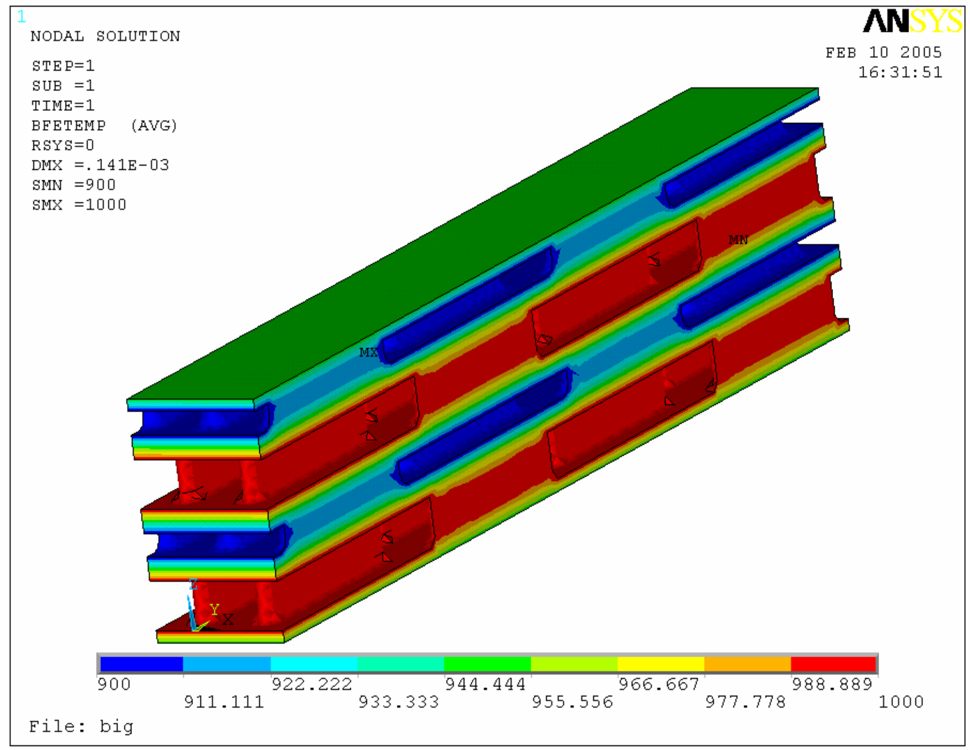
Liquid salt side

Accomplishments/Progress/ Results

Temperature Distributions (K)



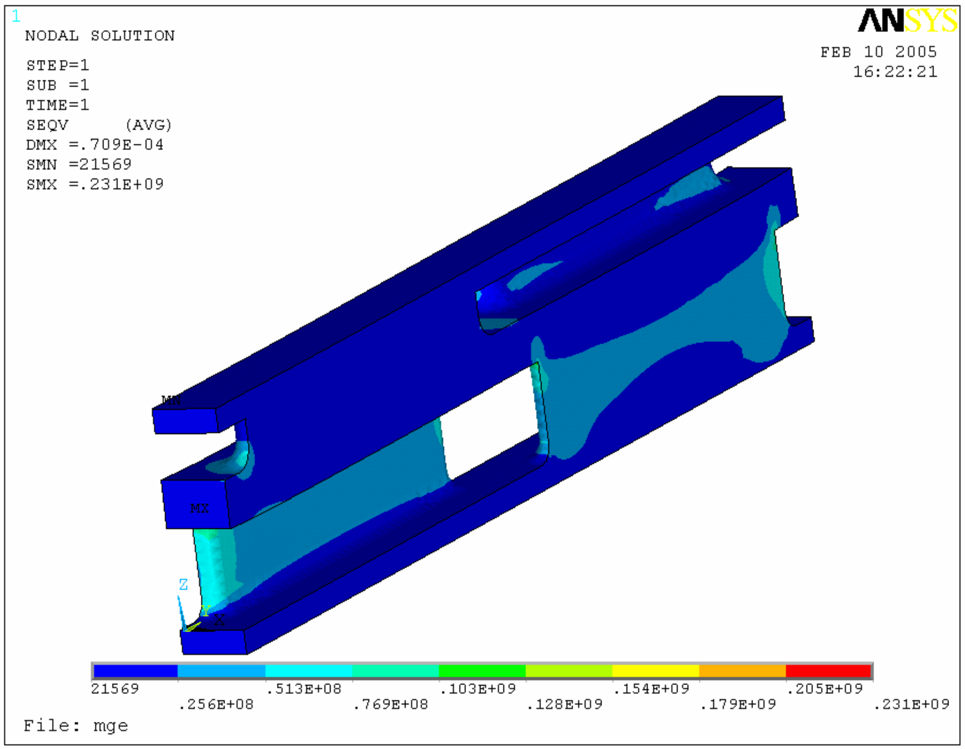
Rounded fins MGE
(1 module)



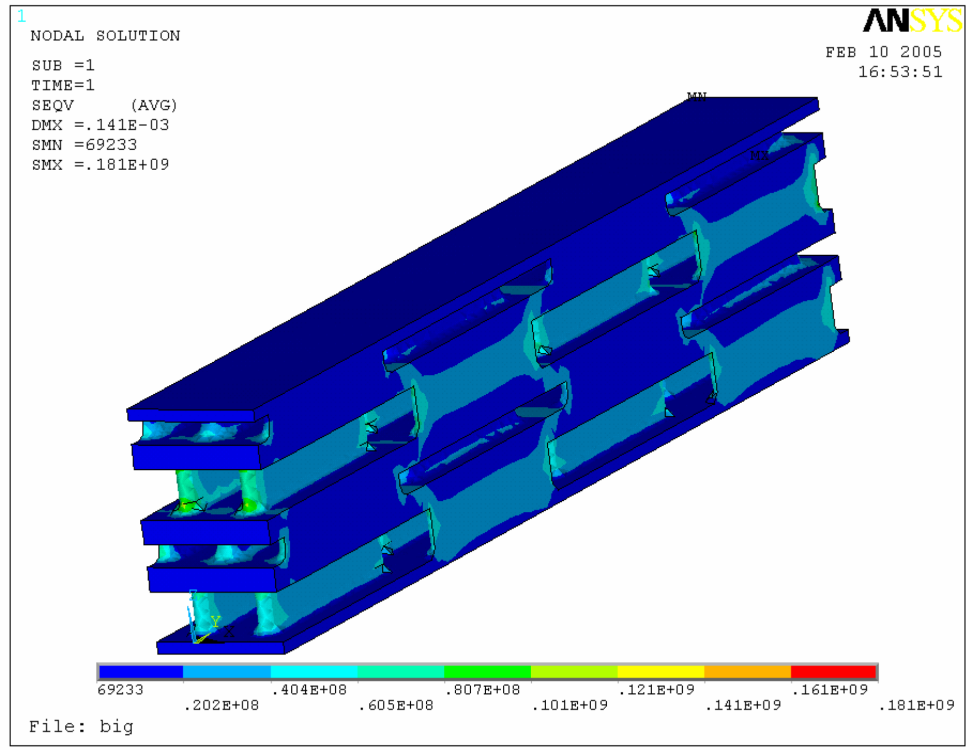
Rounded fins MGE
(16 modules)

Accomplishments/Progress/ Results

Von Mises Stress (Pa) (with pressure)



Rounded fins MGE
(1 module)

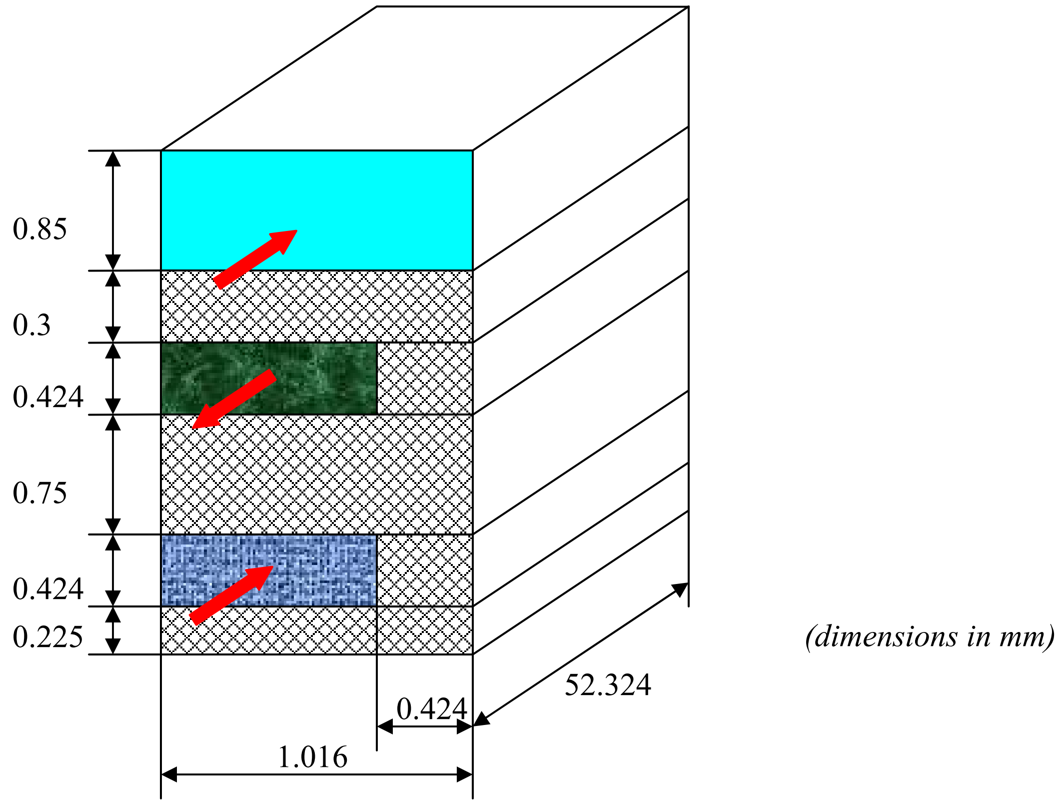


Rounded fins MGE
(16 modules)

Accomplishments/Progress/ Results

Modeling of Decomposer 1 (3 Fluids)

Single channel model: parametric study for dimensions and flow rate



helium (He)

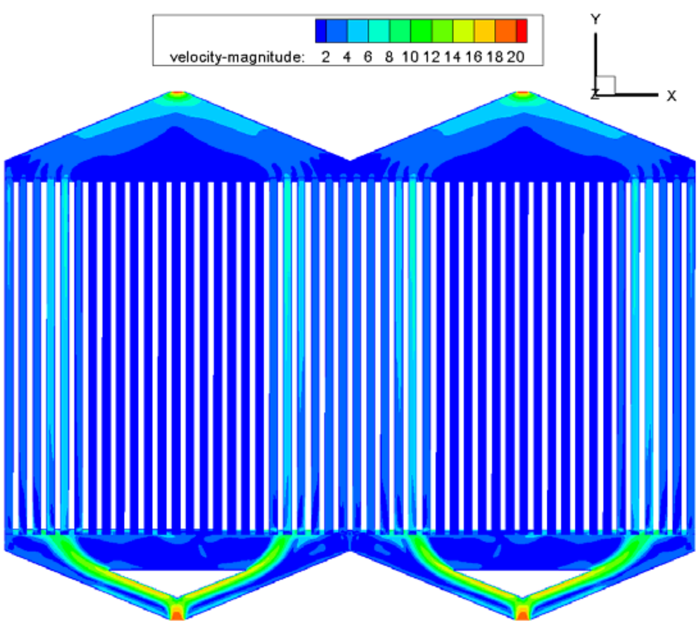
mixed gas flow with chemical reactions: $H_2O + SO_3 + H_2SO_4 \rightarrow H_2O + SO_2 + O_2 + SO_3$

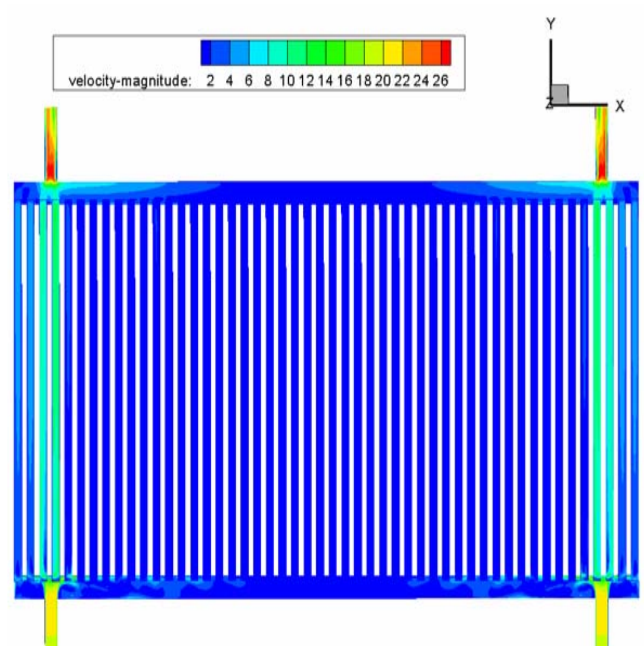
mixed gas flow without chemical reactions: $H_2O + SO_2 + O_2 + SO_3$

silicon carbide (SiC)

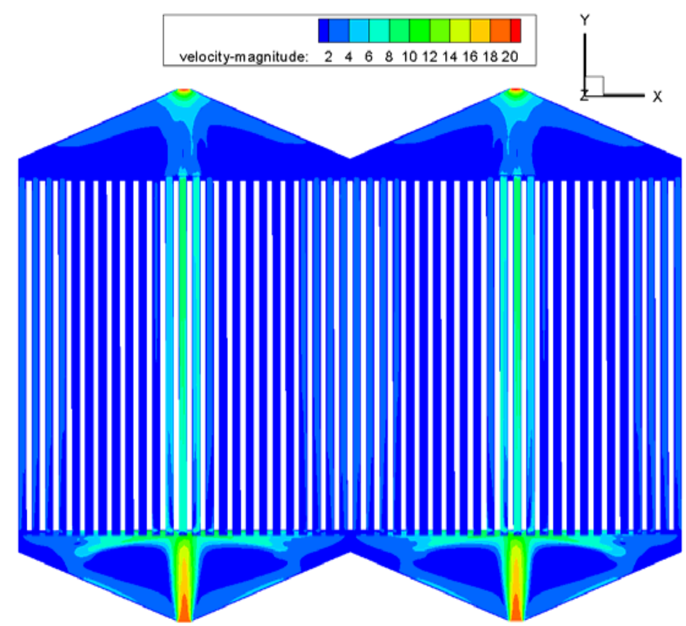
Accomplishments/Progress/ Results

Comparison of the Velocity Magnitude Distributions on the Middle of the S1 and S2c Plates for the 3 Different Entrance and Exit Channel Forms





Base geometry



Future Work

Reminder of FY05 and FY06

- Finish 3-D parametric study with different fin/channel dimensions
- Initiate the study of unsteady flow
- Perform numerical calculations on the the Ceramatec HTHX design
- Perform the thermo-structure analysis of the heat exchanger for different materials
- Complete sulfuric acid decomposition heat exchanger design
- Compare the results between numerical and experimental modeling of the heat exchanger
- Modify the numerical modeling and geometry of HTHX

Publications and Presentations

"Construction Material Development in Sulfur-Iodine Thermochemical Water-Splitting Process for Hydrogen Production" *by B. Wong, L. Brown, R. Buckingham, A. Kaiparambil, R. Santhanakrishnan, B. Russ, A. Roy, and G. Besenbruch, AIChE, 2005 Spring National Meeting, April 10-14, Hyatt Regency, Atlanta, GA*

"Materials Challenges in Sulfur-Iodine Thermochemical Water Splitting process for Hydrogen Production" *by Bunsen Wong, Bob Buckingham, Lloyd Brown, Jose Gomez, Ben Russ and Gottfried Besenbruch, ASM Conference, October 20, 2004, Columbus, OH*

Sundaresan Subramanian, Roald Akberov, Yitung Chen, and Anthony E. Hechanova, 2004, "*Development of an Advanced High Temperature Heat Exchanger Design for Hydrogen Production*," IMECE2004-59623, Proceedings of IMECE2004 ASME International Mechanical Engineering Congress, November 13–19, Anaheim, CA