High Temperature Heat Exchanger Development

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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

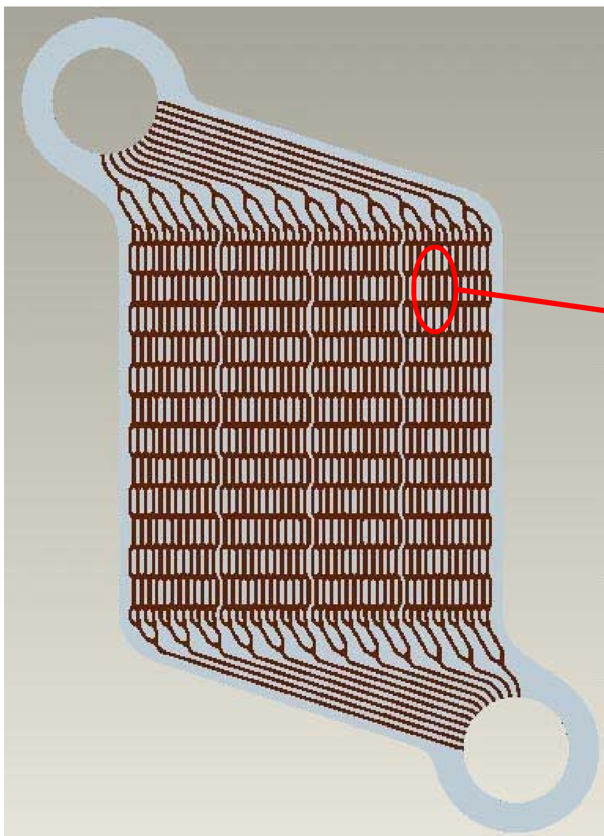
Technical Accomplishments/ Progress/Results

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

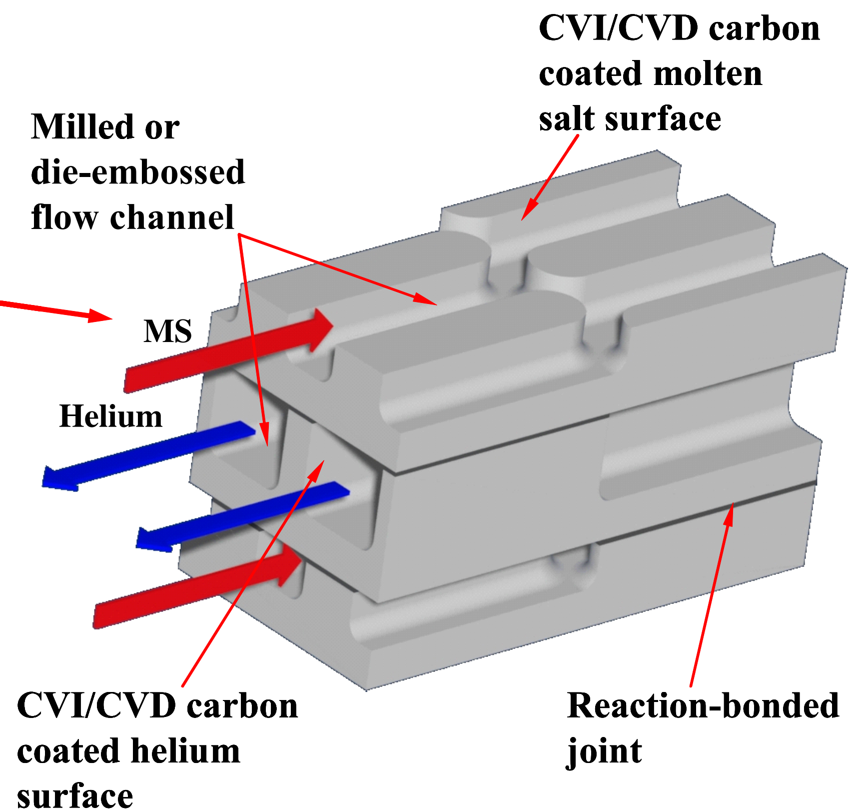
MI Material	**Density kg/m^3**	**Young's modulus GPa**	**Failure stress MPa**
Carbon fiber reinforced SiSiC with coating	**2523**	**325**	**270**
Splint based SiSiC	**2932**	**450**	**224**
Pitch based SiSiC	**2600**	**298**	**200**
Short fiber reinforced SiC	**2000**	**60**	**90 - 140**

Technical Accomplishments/ Progress/Results

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



Molten salt plate

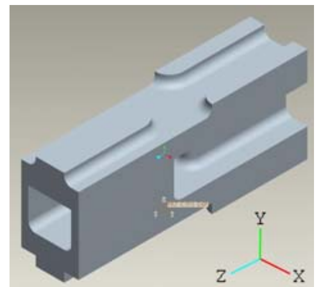


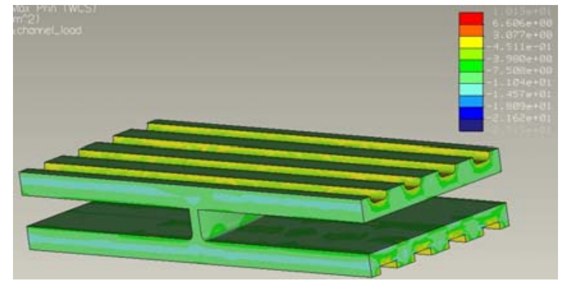
Unit Cell

Technical Accomplishments/ Progress/Results

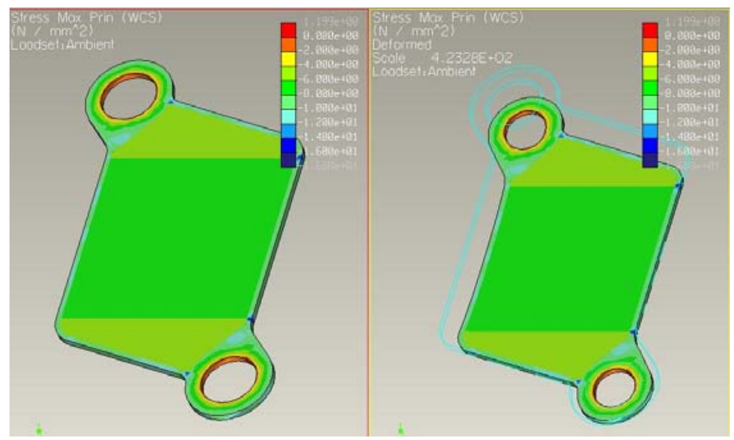
- **isothermal mechanical stress analysis with Pro/Engineer software**
  - **Finished unit-cell isothermal mechanical stress analysis and thermal stress analysis**
  - **Obtained equivalent mechanical properties from unit cells**
  - **Obtained whole HX mechanical average stress distribution**
  - **Obtained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

Unit cells

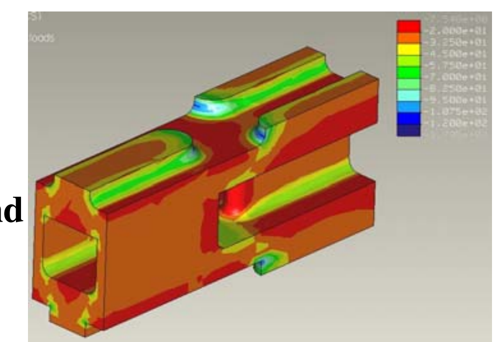


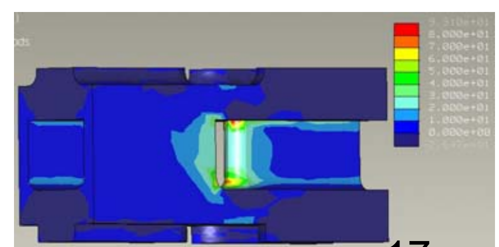


Whole HX average stress



Maximum compressive and tensile stresses



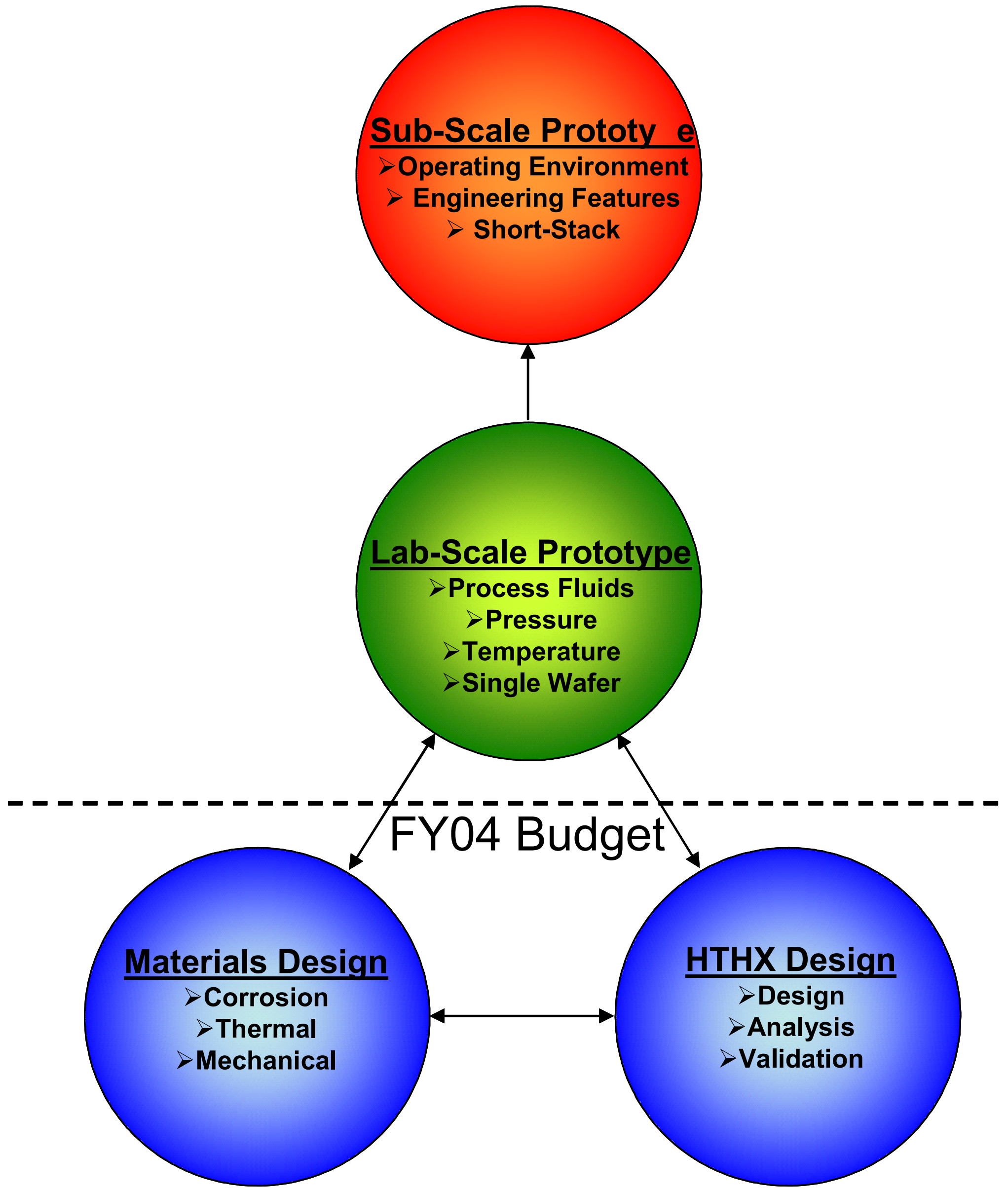


Future Work

- 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

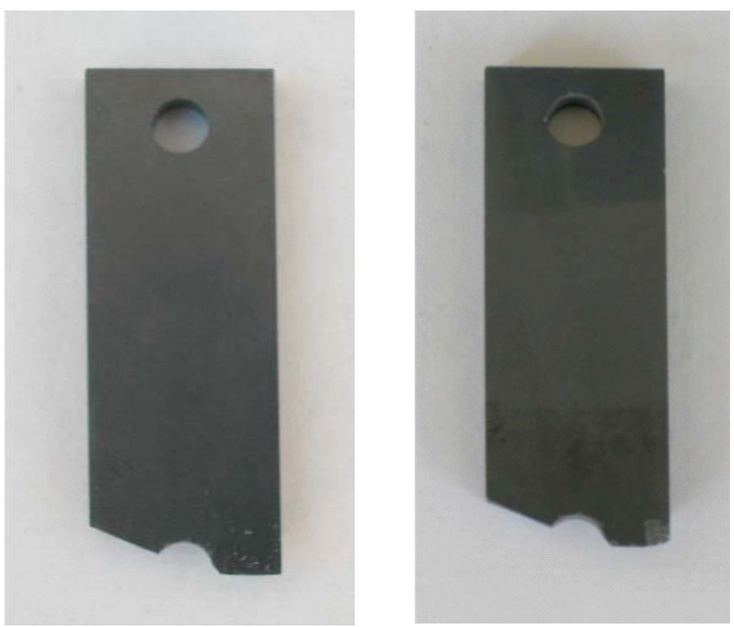
- Identification of Material Design Parameters has been completed and narrowed down candidate materials

- **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

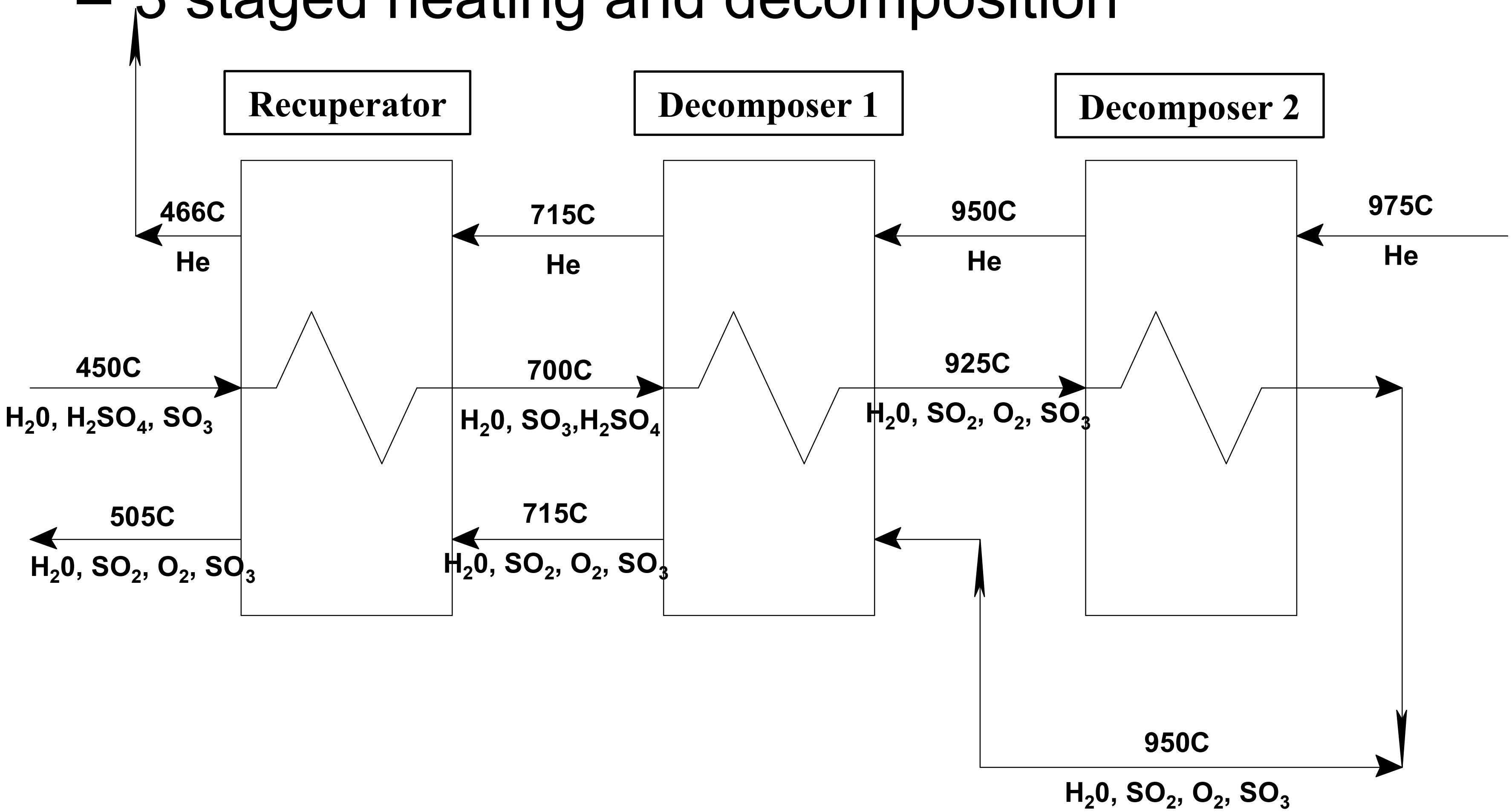


a) CVD Silicon Carbide

b) Ceramatec Sintered Silicon Carbide

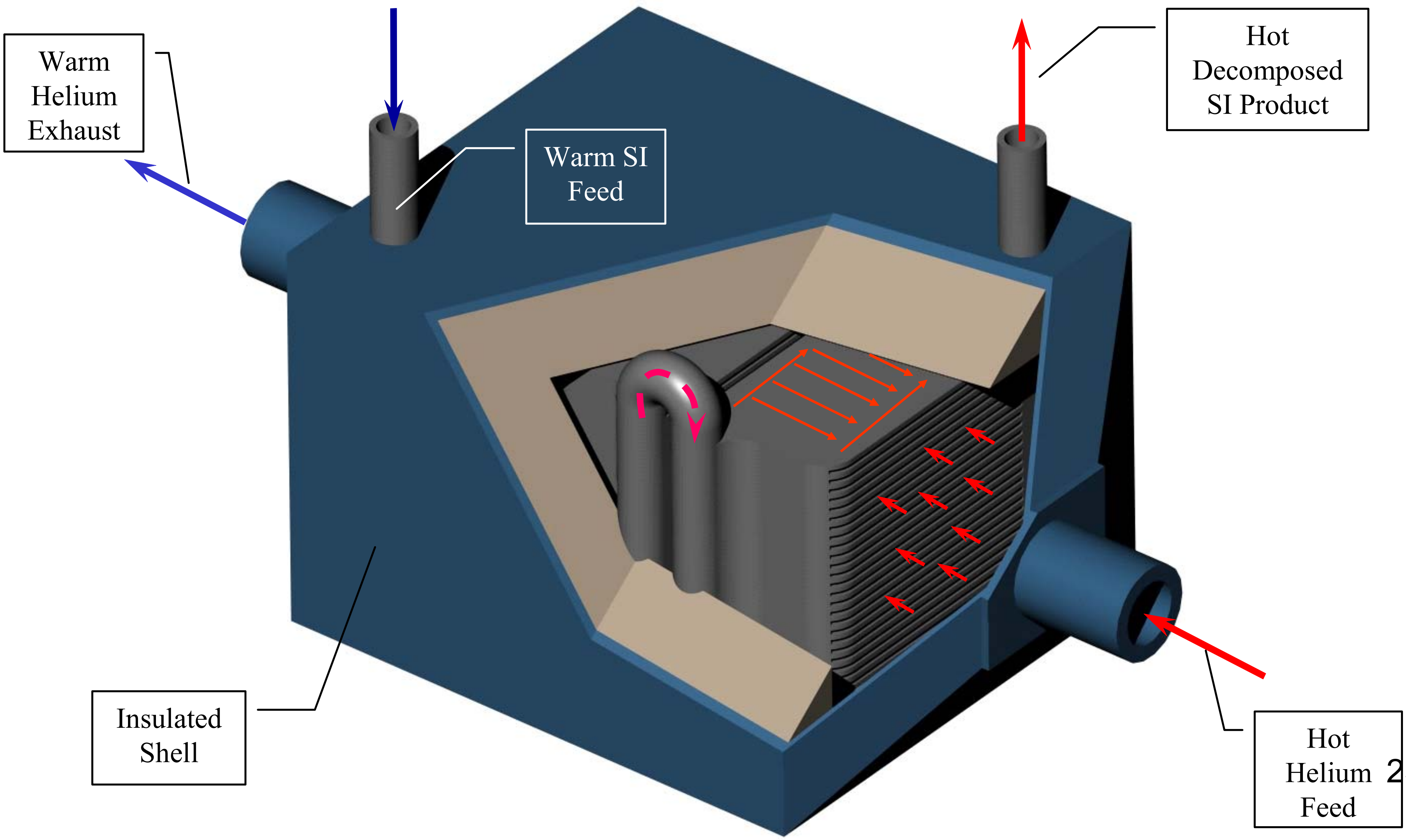
Technical Progress – HX Design

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



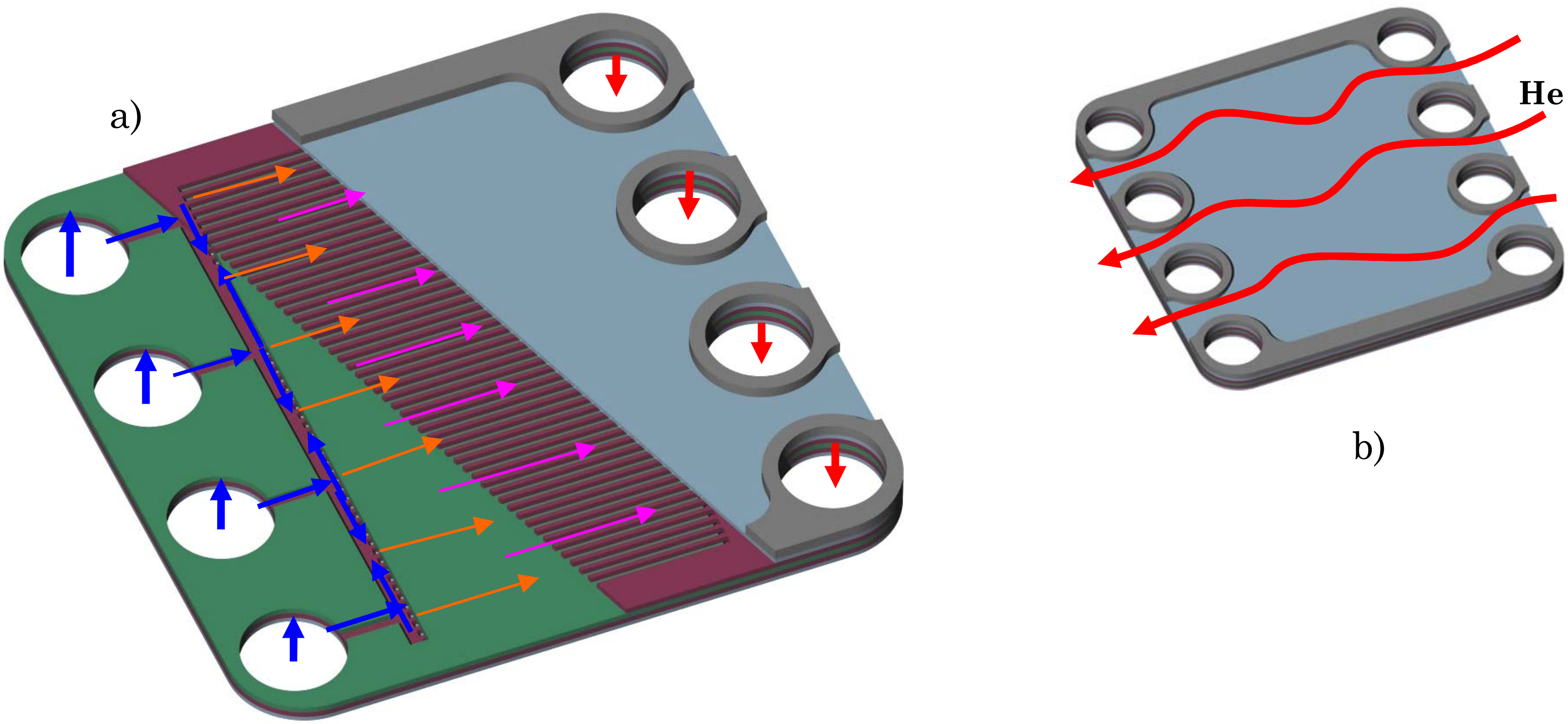
Technical Progress – HX Design

- 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)

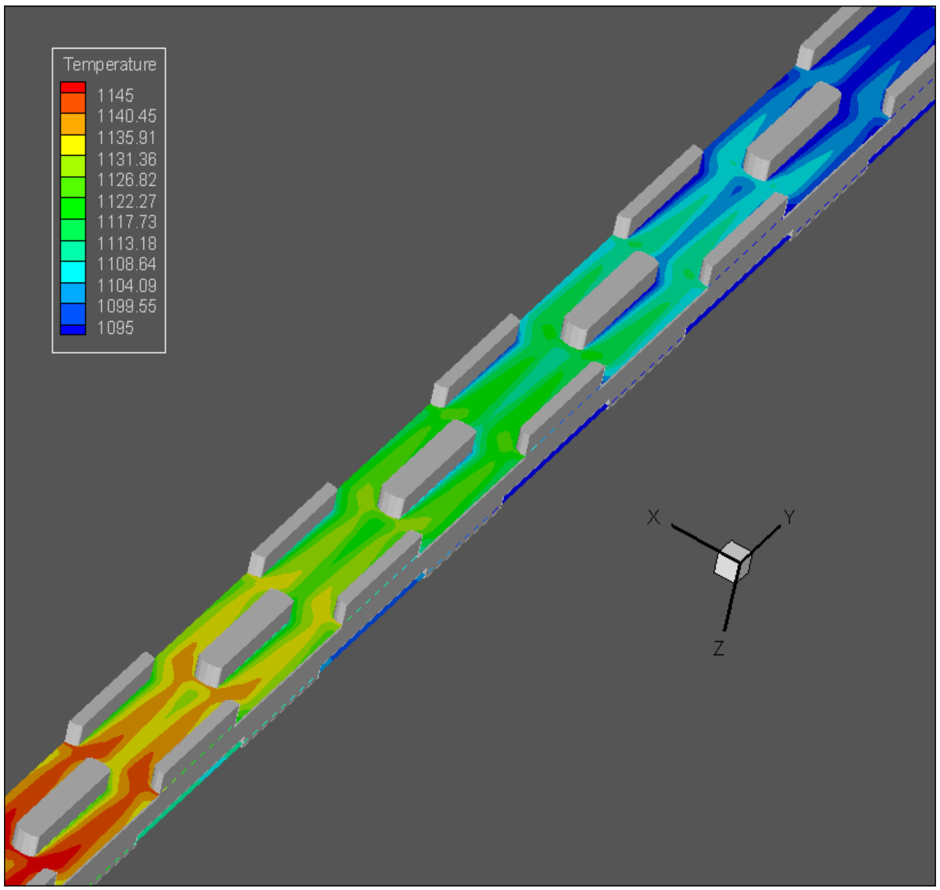
- Use Gambit to generate computational mesh for the UCB design (off-set strip-fin) and the Ceramatec design (micro-channel)
- Use FLUENT to model hydrodynamics and heat transfer using liquid salt and helium as working fluids
- Evaluate optimization concepts to the baseline design by modifying design 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

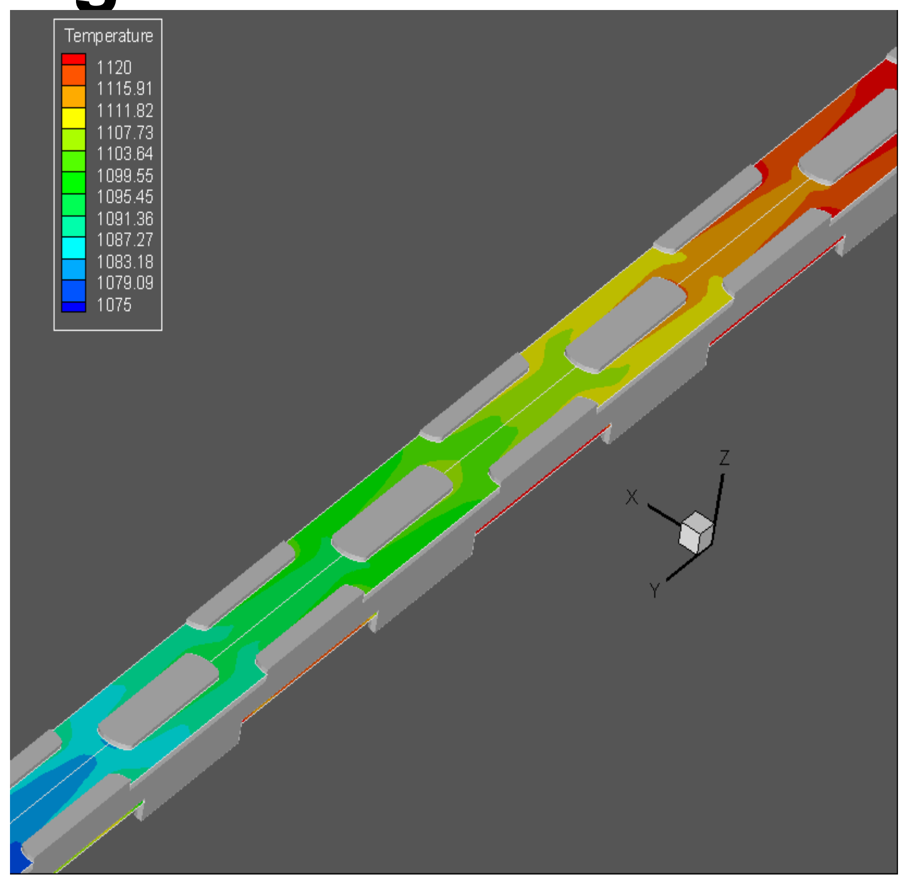
- Performed CFD analysis using variable material properties
- Performed grid independence studies
- Performed turbulence modeling
- Updated design to include manufacturing geometrical effects
- Completed CFD design evaluation of baseline compact off-set strip-fin HTHX
- Performing optimization studies 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



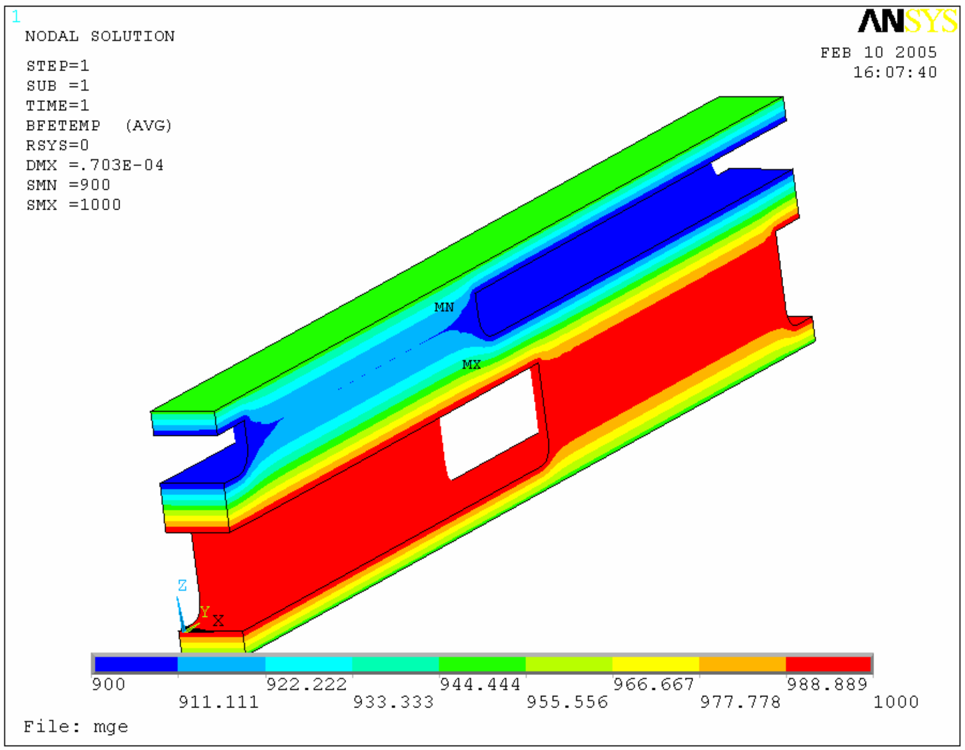
Helium side



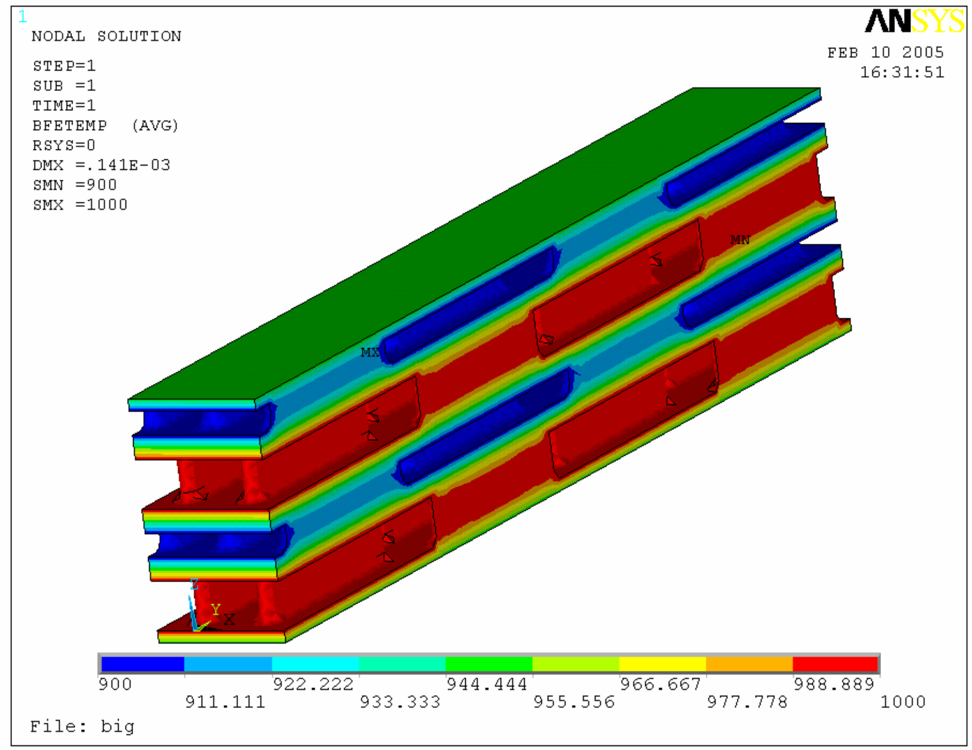
Liquid salt side

Accomplishments/Progress/ Results

Temperature Distributions (K)



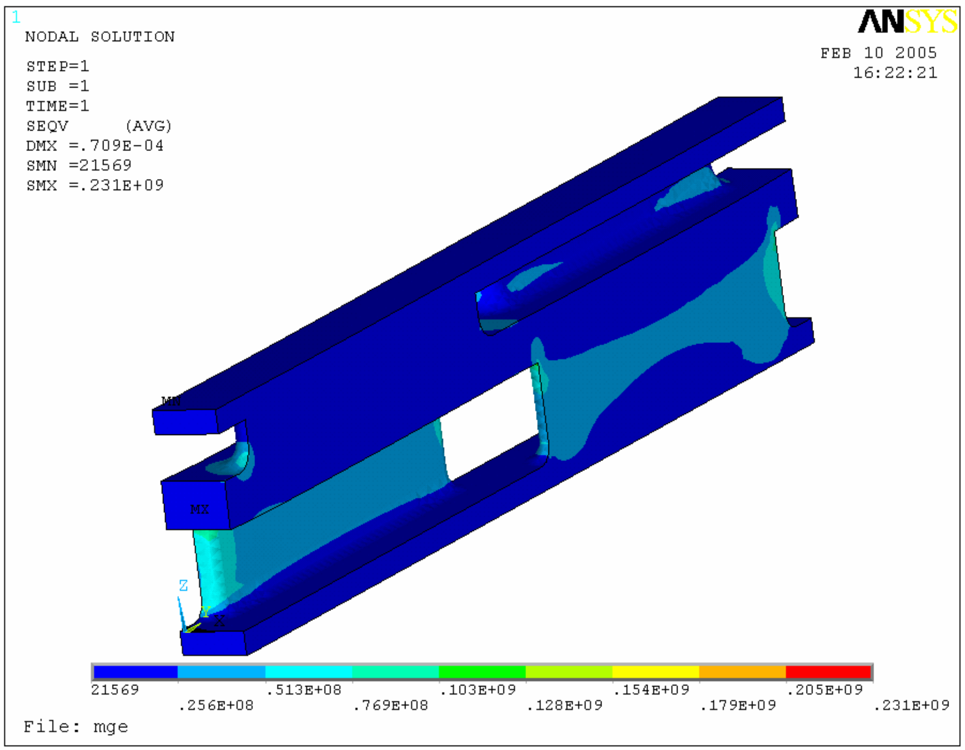
Rounded fins MGE
(1 module)



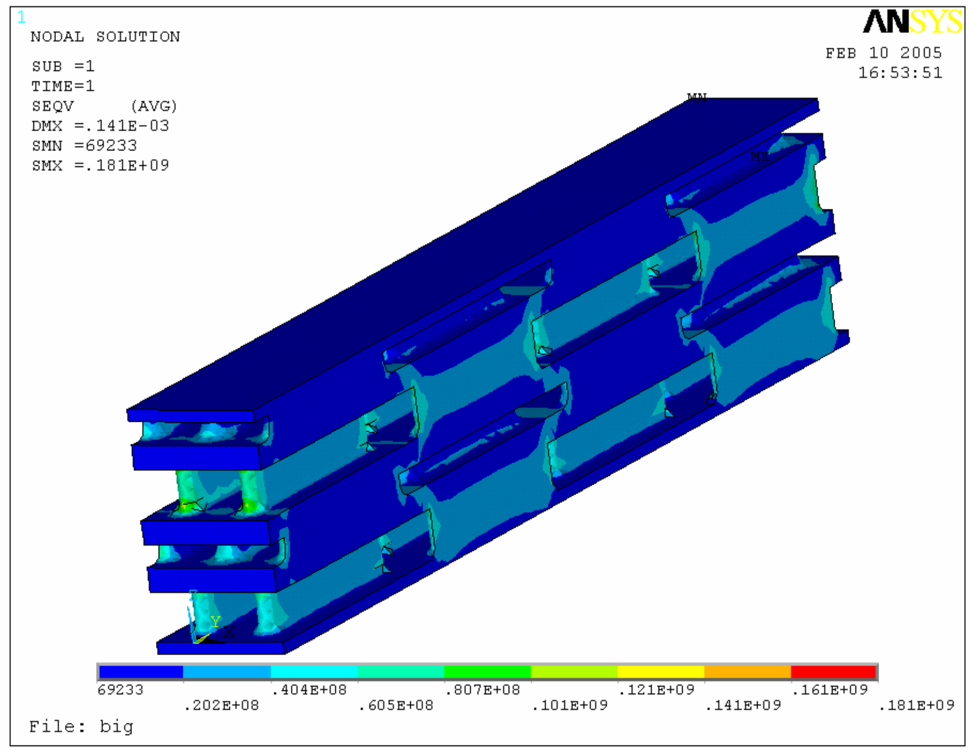
Rounded fins MGE
(16 modules)

Accomplishments/Progress/ Results

Von Mises Stress (Pa) (with pressure)



Rounded fins MGE
(1 module)

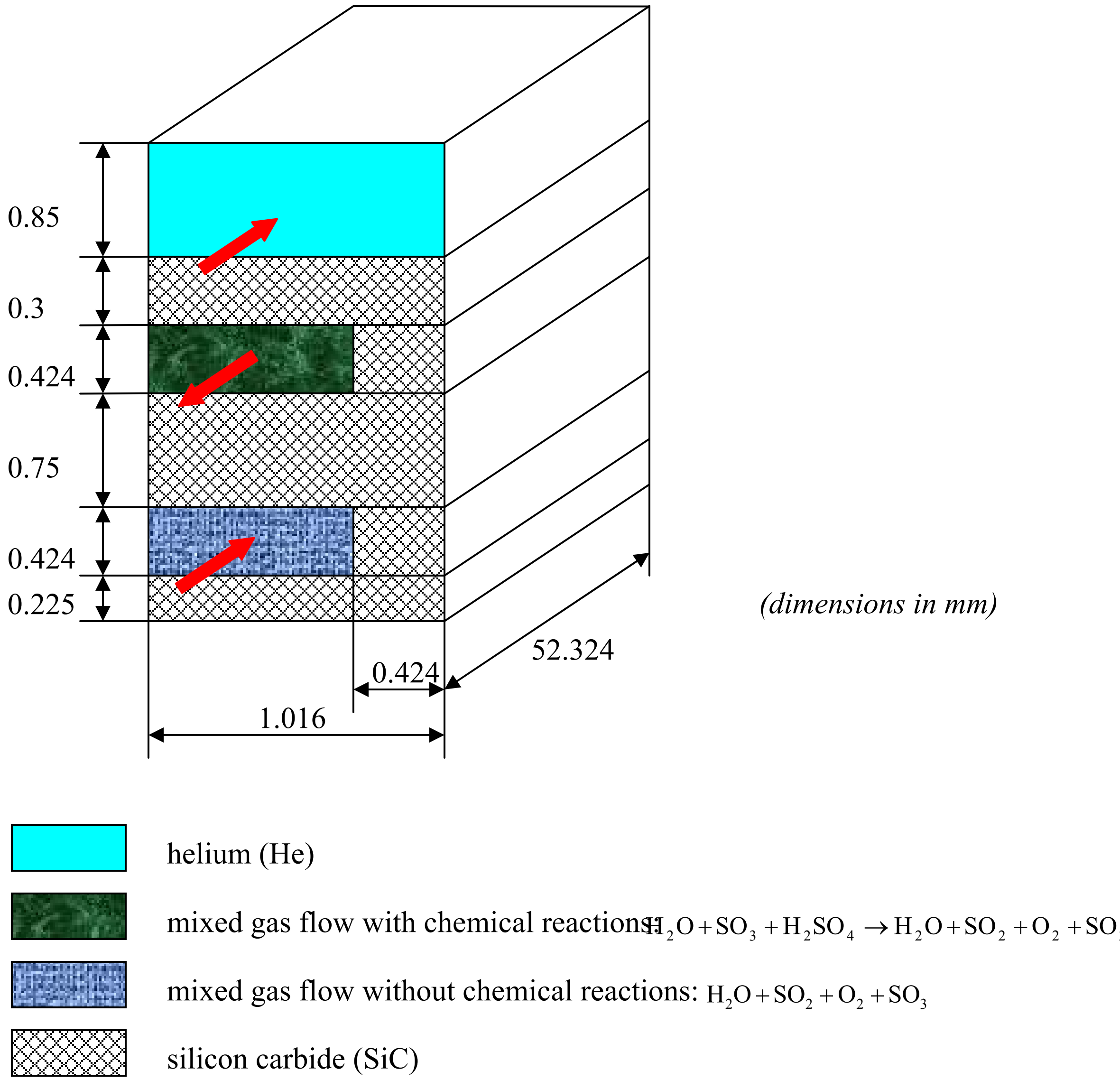


Rounded fins MGE
(16 modules)

Accomplishments/Progress/ Results

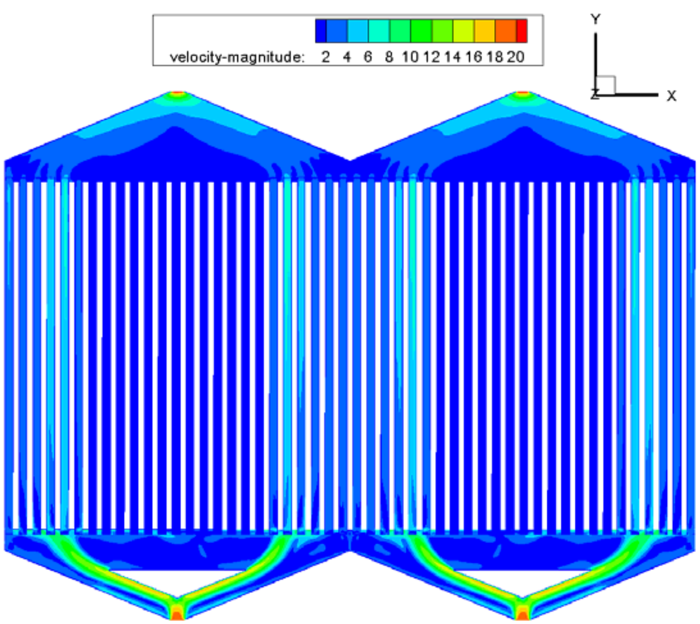
Modeling of Decomposer 1 (3 Fluids)

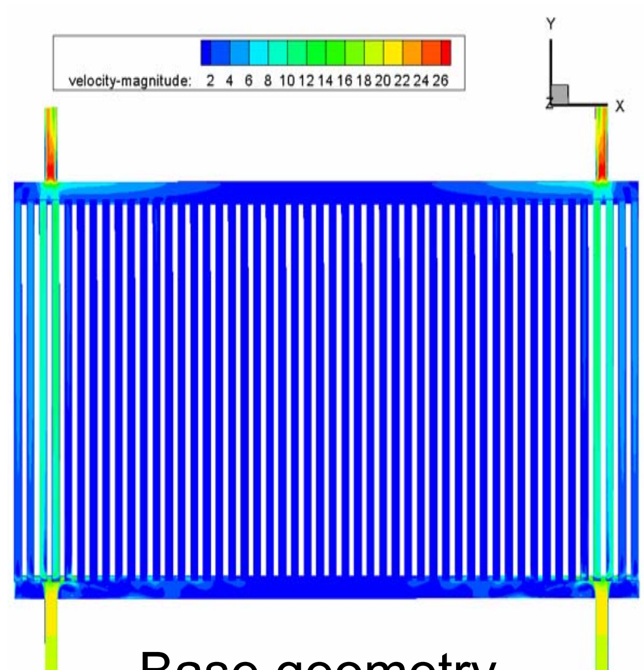
Single channel model: parametric study for dimensions and flow rate



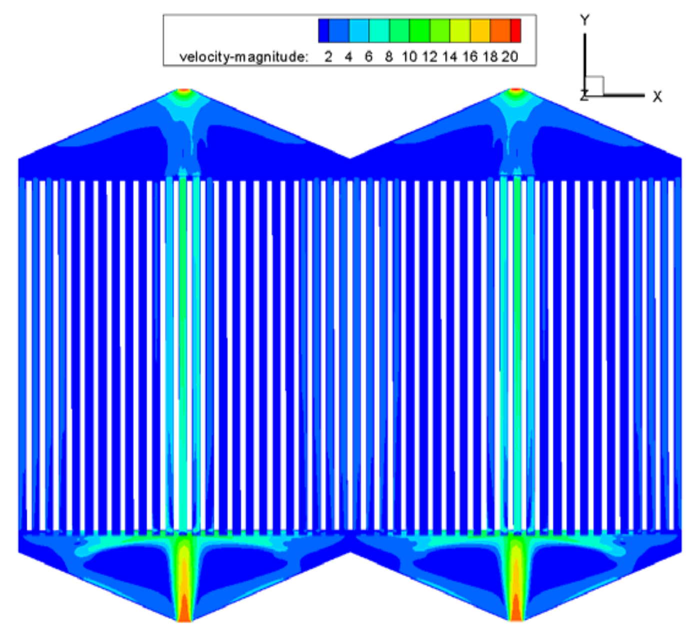
Accomplishments/Progress/ Results

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