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HIGH TEMPERATURE HEAT EXCHANGE DESIGN AND FABRICATION FOR SYSTEMS WITH LARGE PRESSURE DIFFERENTIALS

Kick-off Meeting

DE-FE0024012

November 7, 2014

Outline

- Participants
- Technical Overview
  - Temperature, pressure demands of a Brayton cycle
  - Microchannel heat exchangers
- Scope of Work
  - Objective
  - Tasks
- Project Management

Part 1

PARTICIPANTS

Systems for fuel production, power generation and geothermal heating and cooling

Supercritical fluid process design and toll extractions from organic feedstocks

***Core competencies*:**

- **25+ years commercializing "Green" supercritical fluid technologies (SCF)**
- **Designer and developer of supercritical fluid processes, systems & major components**
- **Industrial scale 24/7/365 installations, world wide:**
  - **Food**
  - **Chemicals**
  - **Nutraceutical**
  - **Pharmaceutical**
  - **Chemical**
- **Heat exchangers for high pressure, high temperature application**

SunShot microchannel heat exchanger – container

- 2,500 psi code stamped
- End caps not shown

Manifold

Southwest Research Institute

- Independent, nonprofit applied research and development organization founded in 1947
- Eleven technical divisions
  - Aerospace Electronics, Systems Engineering & Training
  - Applied Physics
  - Applied Power
  - Automation & Data Systems
  - Chemistry & Chemical Engineering
  - Engine, Emissions & Vehicle Research
  - Fuels & Lubricants Research
  - Geosciences & Engineering
  - Mechanical Engineering
  - Signal Exploitation & Geolocation
  - Space Science & Engineering
- Total 2013 revenue of $592 million
  - 38% Industry, 36% Govt., 26% Govt. Sub
  - $6.7 million was reinvested for internal research and development
- Over 2,800 staff
  - 275 PhD's / 499 Master's / 762 Bachelor's

- Over 1,200 acres facility in San Antonio, Texas
  - 200+ buildings, 2.2 million sq. ft of laboratories & offices
  - Pressurized Closed Flow Loops
  - Subsea and High Altitude Test Chambers
  - Race Oval and Crash Test Track
  - Explosives and Ballistics Ranges
  - Radar and Antenna Ranges
  - Fire testing buildings
  - Turbomachinery labs

Part 2

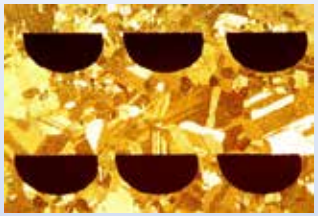
TECHNICAL OVERVIEW

Background – competing technologies

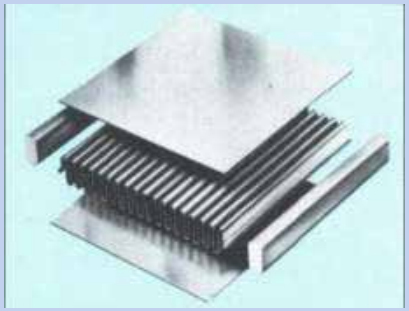
Microchannel designs

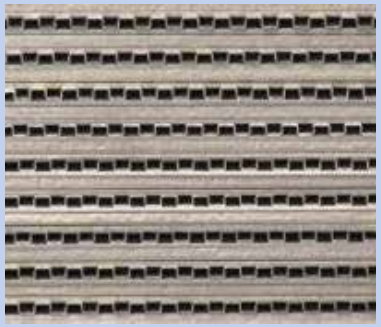
Heatric

Printed Circuit (PCHX)

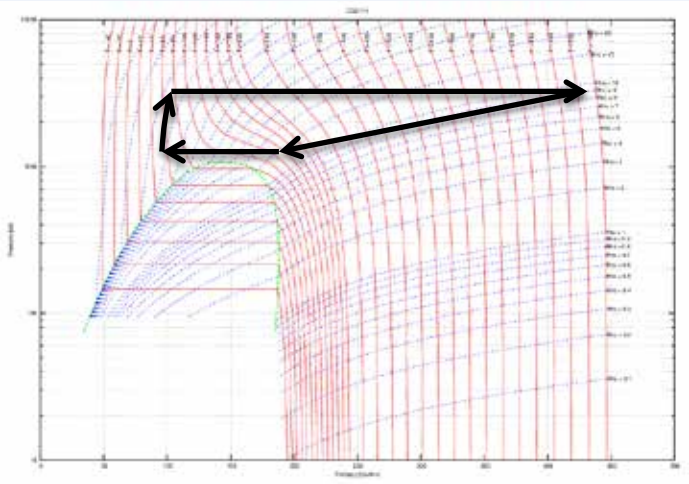


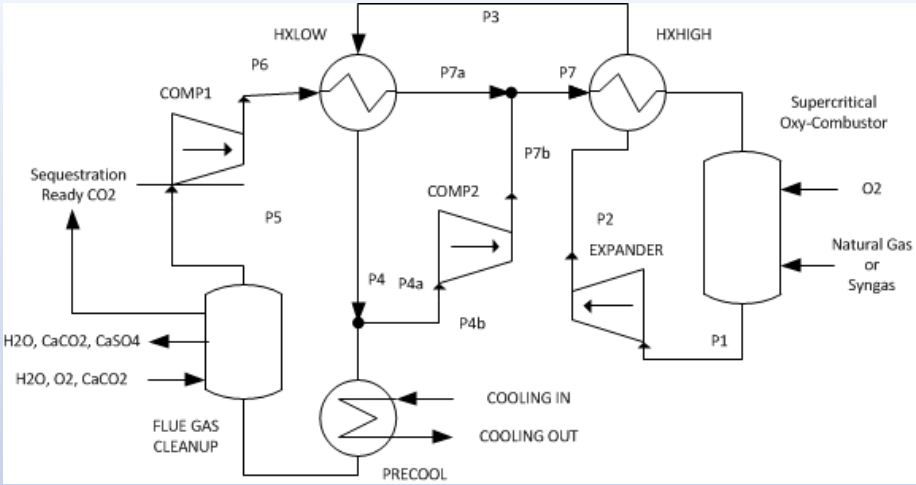
Formed Plate (FPHE)

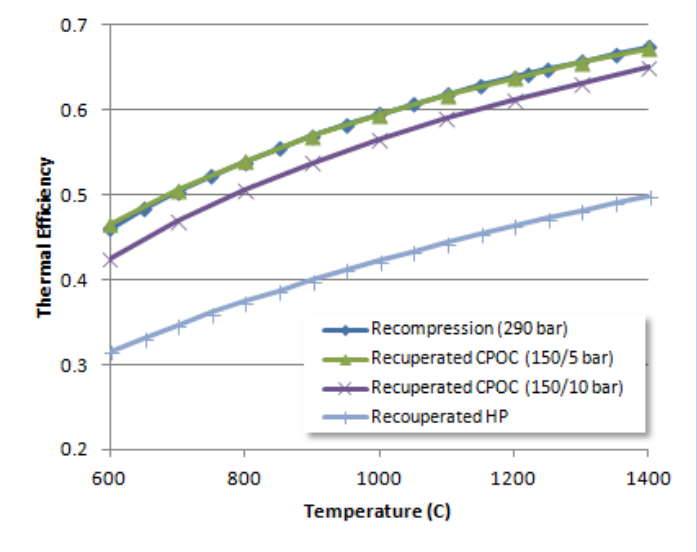




Recompression cycle

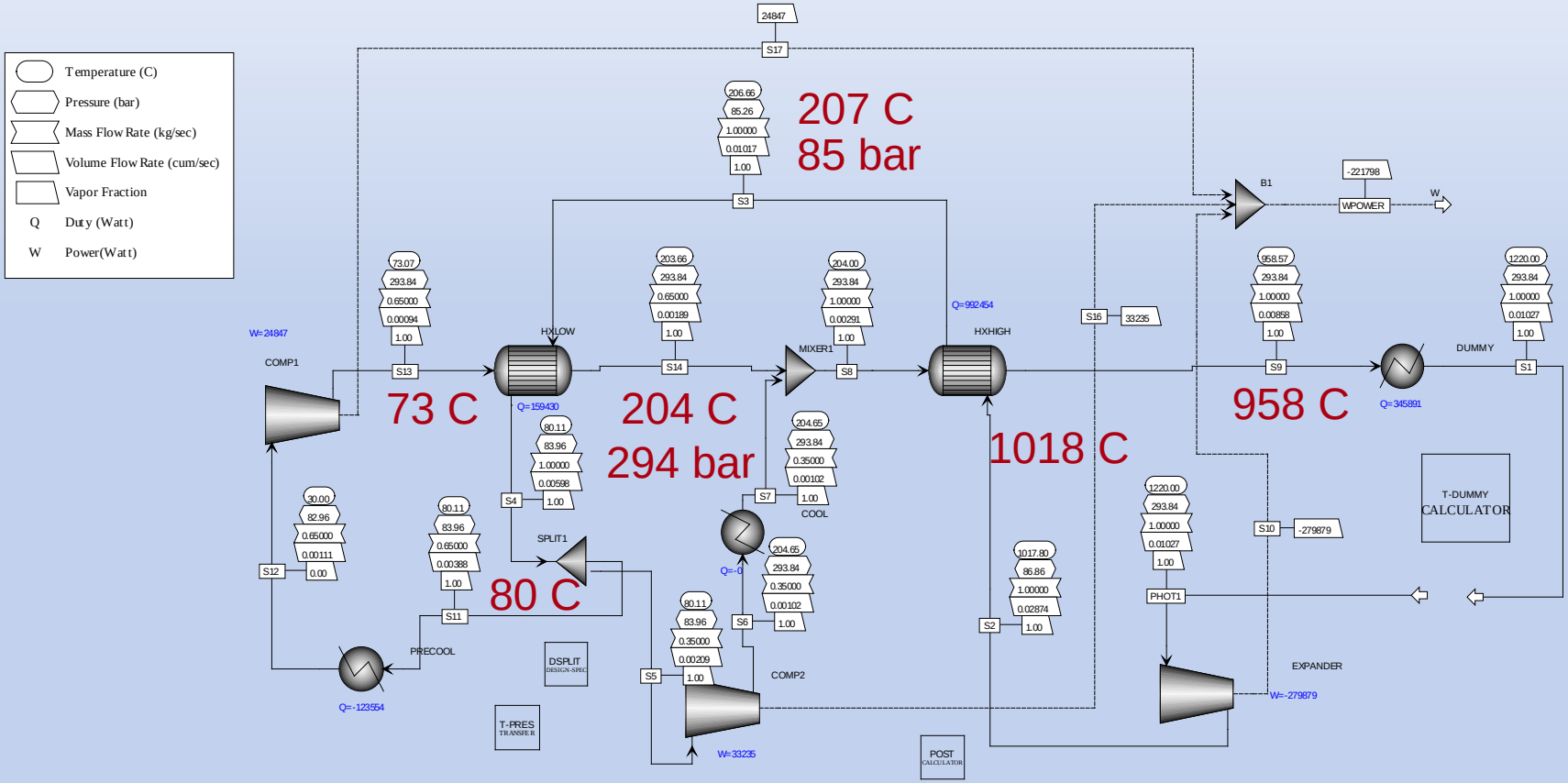






	CPOC	Recompression
Efficiency	63.85%	64.00%
Combustor Inlet Temp (C)	184	950
Turbine Inlet Temp (C)	1200	1200
Turbine Inlet Pressure (bar)	150	290
Turbine Outlet Pressure (bar)	1	100
Mass flow (kg/s)	1.00	1.00
W net (MW)	0.830	0.221
Q in (MW)	1.300	0.345
HX high (MW)	0.451	0.992
HX low (MW)	0.010	0.154
Total Recuperation (MW)	0.461	1.146

Recompression cycle



Alloy review

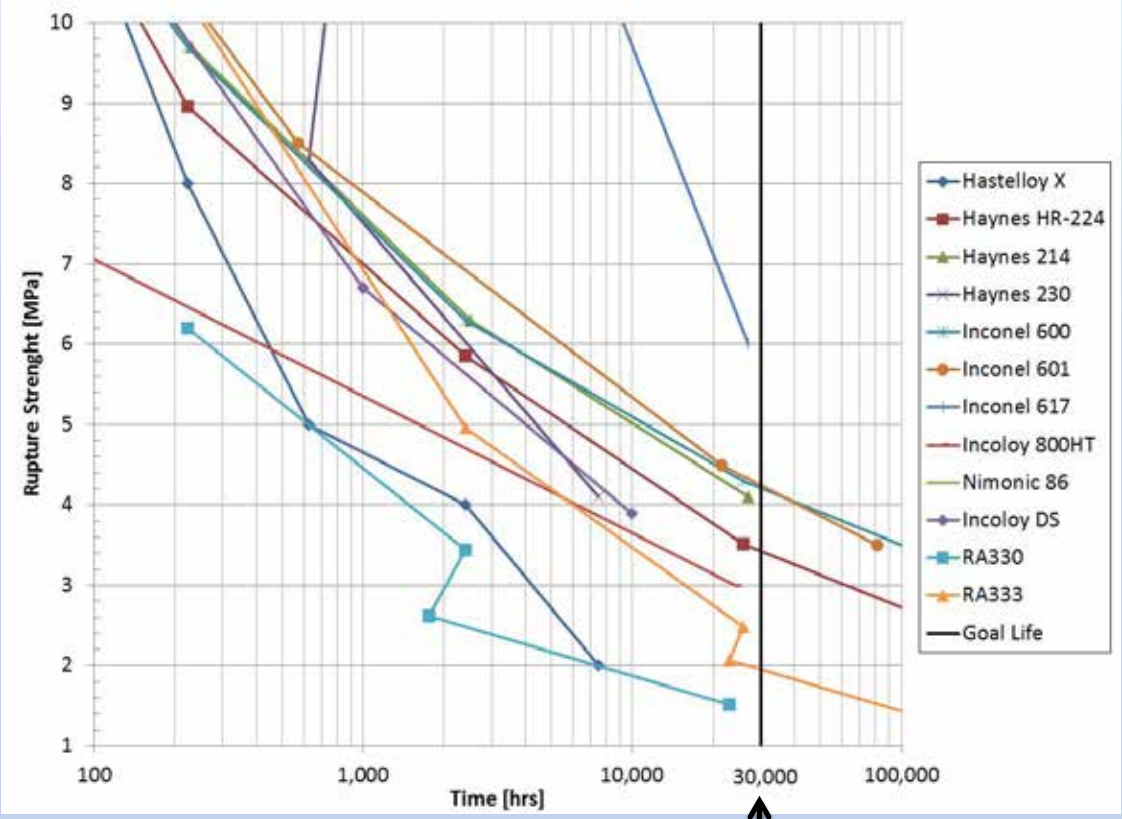
Alloy	UNS No.	Corrosion resistance	Allowable strength, psi @ 700 C	ASTM Spec	Spec description
Inconel 718	N07718	Good	42,000		Not found in ASME listings
Incoloy 909	N19909	Poor	33,000		Not found in ASME listings
Inconel 740			35,000		Not found in ASME listings
Brightray C	N06003	Unknown	15,000		Not found in ASME listings
Haynes 230	N06320	Good	10,000	SB-564	Forgings, Ni alloy
Inconel 625	N06625	Good	10,000	SB-564	Forgings, Ni alloy

Alloys of 10,000+ psi allowable tensile strength at 700 C

- Top 3 alloys have not been listed in ASME2010 Sect. II Tables for allowable stresses at elevated temperatures.
  - Data comes from vendor data for tensile strength, divided by 3.5 safety factor
  - Not considered as candidate materials for this study
- ASTM spec indicates the application.
  - Most are forgings
- Stress v.s. temperature plots follow

Alloy choices – creep rupture

Creep Rupture Strength for Various Metals at 1050°C



Possible life requirement

Key design problems

- Manifold:
  - Minimize pressure drop
  - Ensure even distribution of flow
- Heat transfer efficiency
  - Novel methods of turbulation so as to:
    - Increase the heat transfer coefficient
    - Manage variability in coefficient as a function of channel length
    - Balance hot and cold sides
- Seals and pressure containment
- Materials of construction
  - Tensile strength at high temperature
  - Creep
  - Corrosion considerations

Research and design path

Research

Global Thermodynamics Model
Tool: Excel, REFPROP
Input: Heat Exchanger Operating Conditions
Output: Required flow rates and discharge temperatures

Heat Transfer Coefficient Study
Tool: Literature
Input: Flow Rate, tube geometry
Output: Heat transfer coefficient correlations

Conjugate Heat Transfer Model
Tool: ANSYS CFX
Input: Heat Exchanger geometry, fluid properties, operating conditions
Output: Fluid conditions, metal temperatures

CHT Model Validation Study
Tool: ANSYS CFX and Mechanical
Input: HTC study results, CHT model results
Output: Validated CHT model parameters

Design

Parametric CHT Simulation
Tool: ANSYS CFX
Output: Heat Exchanger Performance

Pressure Containment Design
Tool: ANSYS Mechanical
Output: Sizing of heat exchanger flanges and shell

Structural Design Simulation
Tool: ANSYS Mechanical
Output: Stress, fatigue and creep extrema of tube bundle, manifolds and pressure vessel.

Three design studies will initially be decoupled, but may be performed iteratively or become fully coupled if needed.

Part 3

SCOPE OF WORK

Objectives

- Develop preliminary heat exchanger design concepts:
  - Operation at high temperature
    - Peak temperatures to 750 C
  - Operation at high pressure
    - Peak differential pressures (between low- and high-pressure streams) of 2,500 psi
    - Maximum high-pressure side of 4,000 psi.
  - Assess expected service life and corrosion effects at operational conditions
    - Special attention to products of combustion and supercritical carbon dioxide
- Build prototype and test

Task 1: Project management

- Biweekly team meetings
- Preparation of Project Management Plan, updated in event of:
  - Policy or procedural changes
  - Changes to cost or timeline
  - Changes to scope or methodology
- Risk assessment
- Quarterly reports to DOE
- Responsibility: **Thar Energy LLC**

Task 2: Technology gap analysis

- Assess and describe state-of-the-art
- Identify major design challenges
- Review of candidate materials, emphasizing
  - Corrosion characteristics
  - Creep rupture
  - ASME status
  - Availability and manufacturability
- Develop design criteria to meet objectives
  - Heat transfer per unit volume
  - Approach temperatures
  - ASME pressure vessel code requirements
- Responsibility: **Thar Energy LLC**

Task 3: Preliminary design studies

For each heat exchanger configuration studied:

- Task 3.1: Thermal hydraulic performances
  - 1D heat transfer correlations
  - 1D flow network modeling
- Task 3.2: Pressure containment
  - Design pressure containment solutions
  - Take seals and thermal expansion into account
- Responsibility: **SwRI**

Include flow passages, flow-stream manifolds and heat exchanger flow connections

Task 3: Preliminary design studies

- Task 3.3: Materials
  - Determine materials as identified in tech gap as appropriate to:
    - Heat transfer surfaces
    - Manifolds
    - Pressure containment
  - Choose sealing materials and design
- Task 3.4: Manufacturing technique
  - Evaluate additive and subtractive joining methods
  - Assess automation techniques
    - Include jig design where appropriate
- Responsibility: **Thar LLC**

Task 4: Detailed design

- 4.1: Detailed thermal hydraulic analysis
  - Coupled heat transfer and flow analysis, 1D & 3D
    - 3D analysis assesses conjugate heat transfer within a CFD framework
  - Derive system leve thermal, fluid and mechanical behavior (e.g., Del-P, mass flowrate, metal and fluid temperatures throughout the heat exchanger)
- 4.2: Detailed pressure containment design
  - Solid modeling of: Container, manifolds, flow passages and connections
  - Determine tolerances for machining methods chosen

Task 4: Detailed design

- 4.3: Detailed stress analysis
  - FEA modeling of thermal stresses, pressure loading, connection loads and cyclic startup/shutdown effects
  - Benchmark against allowable ASME limits
  - Consideration to fatigue and creep
- Responsibility, 4.1-4.3: **SwRI**

Task 4: Detailed design

- 4.4: Component material selections
  - Choose for: pressure containment, manifolds, connections, flow passages
  - Choose on basis of: cost, availability, form and method of manufacturing*
    - *For example, welded or seamless tubing
- 4.5: Manufacturing process analysis
  - Automated flow-passage fabrication and assembly in a single process
  - Methods for bundle insertion and removal from separate pressure container
- Responsibility, 4.4-4.5: **Thar Energy**

Task 5: Prototype fabrication

- 100 kW size
- Bench-top scaled automated methods
  - Used to extent possible to:
    - Facilitate fabrication
    - Understand manufacturing processes
- Fabrication in Pittsburgh
  - Hydrostatic testing performed there
- Responsibility: **Thar Energy**

Task 6: Prototype test

- 6.1: Hydrostatic pressure test
  - Representative pressures at low temperature
- 6.2: Pressurized flow test at operating temperatures
  - At minimum and maximum operating conditions
    - KAPL at max 275 C
    - Thar at 500 to 700 C
  - Steady state and transient data collected
  - Compare/calibrate to design calculations
  - Experimental error analysis included
- Responsibility: **Thar and KAPL**

Part 4

PROJECT MANAGEMENT

Risk analysis and mitigation

Description of Risk	Probability	Impact	Mitigation and Response Strategies
Technical/Scope Risks:			
CHT results not agreeing with conventional HT analysis	High	Med	Tune CHT model parameters to match correlations
Desired resolution of model requires excessively fine mesh, long computation time	Med	Low	Utilize cluster computing resources at SwRI
Not able to reach operational temperature during prototype testing	High	Med	Scale experimental results based on computational analysis
Fabrication failure, e.g.: - braze wetting at center of bundle; - tube/hourglass plugging; voids in braze joint	High	High	Methodical development of sub-processes verified by testing prior to development of full process Rebuild and test small-scale HX
Limited inspection capability in fabrication process	Med	Low	Destructive inspection at end of program
Flow-induced vibration	Med	High	If catastrophic, re-design and re-build of prototype
Reliability of seals subject to thermal cycling	Med	Low	Continue program but confer with seal vendors of future remedies
Tube damage during assembly	Med	High	Hydrostatic test; repair or re-build if necessary
Tube/tube-sheet hole misalignment	Med	Med	Braze on two sides of tube sheet, if necessary
Prototype does not meet ASME code	Low	Med	Re-design
Escessive thermal stress indicated in design	Med	Med	Revise design
Excessive leakage	Med	High	Internal leaks: continue testing and measure leakage External: repair or change seals
Review of candidate materials proves negative	Low	High	Fabricate from available materials and test to reduced temperatures/pressures Subject of go/no-go decision

Risk mitigation

- Other risks tabulated with Backup slide
  - Resource risks, management risks, schedule and budgetary risks, environmental and external risks
- Mitigation methodology
  - List all perceived risks as below
  - Color code status as shown
  - Update/append new risks at least quarterly in team meeting

			Mitigation action -2	
Description -1	**Impact -1**	**Status -2**	**Planned**	**Taken**
Risk A	**High**	**Med**	*Describe*	*Describe*
Risk B	**Med**	**Low**		
Risk C	**Low**	**High**		

1- These items taken from PMP Fig. 1 - Risk Mitigation

2- Status and action plans are reviewed at least quarterly in team meeting

Milestones

				Dates of:			
Budget Period	**Milestone Number**	**Task/ Subtask Number**	**Description**	**Planned Start**	**Planned Completion**	**Actual Completion**	**Verification Method**
1-Q1	1	1.0	Submit Project Management Plan	10/14/2014	10/24/2014		PMP submission
1-Q1	2	1.0	Kickoff meeting	10/27/2015	11/7/2014		Meeting minutes
1-Q1	3	2.0	Convey Tech Gap analysis to team **Go/no-go**	10/15/2014	12/31/2014		Tech Gap report issued. Feasibility confirmed for: - Tensile strength at 700C of at least 10,000 psi - Acceptable corrosion loss rate and creep resistance
1-Q2	4	3.0	Complete preliminary design; team meeting on basic design rules	11/3/2014	1/16/2015		Meeting minutes
1-Q3	5	4.0	Detailed drawings completed; test plan formulated and submitted to DOE	1/2/2015	3/29/2015		Detailed drawings issued
1-Q4	6	5.0	Prototype delivery to Thar **Go/no-go**	3/1/2015	7/15/2015		Prior to delivery: - No exterior leakage - At test conditions, high pressure flow loss no more than 3% of full flow Delivery made
1-Q4	7	1.0	Final report	9/21/2015	9/30/2015		Report to DOE

Budgeting and funding

	Total Project 10/01/14 to 9/30/15	
Prime Recipient	Government Share	Cost Share
Thar Energy LLC	$500,000	$125,000
Percentage	80%	20%

	Total Budget 10/1/14 to 9/30/15				
	10/1/14-12/31/14	1/1/15-3/31/15	4/1/15-6/30/15	7/1/15-9/30/15	Total Budget
Baseline Cost Plan	Q1	Q2	Q3	Q4	Q1-Q4
Federal Share	$125,000	$125,000	$125,000	$125,000	$500,000
Non-federal Share	$31,250	$31,250	$31,250	$31,250	$125,000
Total Planned	$156,250	$156,250	$156,250	$156,250	$625,000

Budget Period	Fiscal Year	Performing Organization	Planned costs	
			Federal Share	Non-federal Share
1 (Total)	FY15	Thar Energy LLC	$300,000	$125,000
1 (Total)	FY15	Southwest Research Insitute	$200,000	$0

Budget topics for discussion

- Shift of equipment/design funding between SwRI and Thar Energy
  - If Thar undertakes testing instead of SwRI
- Slight modification to SwRI overall budget
  - $190K instead of $200K
- KAPL legal documentation

Gantt chart

● Milestone
● Go/No-go Milestone

	Tasks & Milestones	Start Date	End Date	Cost	Q1 10/1/14-12/31/14			Q2 1/1/15-3/31/15			Q3 4/1/15-6/30/15			Q4 7/1/15-9/30/15		
					Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
	Task 1.0 - Project management, planning and reporting	10/1/2014	9/30/2014	$25,000												
1.1	Project management and planning	10/1/2014	9/30/2014													
1.2	Quarterly reports	10/1/2014	9/30/2015													
	Milestones															
1	Submit Project Management Plan		10/24/2014		●											
2	Kickoff meeting		11/7/2014			●										
7	Final report		9/30/2015													●
	Task 2.0 - Technology gap analysis	10/15/2014	12/31/2014	$75,000												
2.1	Identify major design challenges	10/15/2014	12/31/2014													
2.2	Identify candidate materials	11/3/2014	12/31/2014													
2.3	Define ASME code requirements	11/3/2014	12/31/2014													
2.4	Establish metrics for design evaluation	12/1/2014	12/31/2014													
	Milestones															
3	Convey Tech Gap analysis to team		12/31/2014				●									
	Task 3.0 - Preliminary design studies	11/3/2014	1/30/2015	$75,000												
3.1	Thermal hydraulic performances	11/3/2014	12/31/2014													
3.2	Pressure containment	11/3/2014	12/31/2014													
3.3	Materials	11/3/2014	12/31/2014													
3.4	Manufacturing technique analysis	12/1/2014	1/30/2015													
	Milestones															
4	Team meeting to decide basic design precepts		1/16/2015					●								
	Task 4.0 - Detailed design of heat exchanger	1/19/2015	4/30/2015	$165,000												
4.1	Detailed thermal hydraulic analysis	1/19/2015	3/29/2015													
4.2	Detailed pressure containment design	1/19/2015	3/29/2015													
4.3	Detailed stress analysis	1/19/2015	3/29/2015													
4.4	Component material selections	1/19/2015	3/29/2015													
4.5	Detailed manufacturing process analysis	3/2/2015	4/30/2014													
	Milestones															
5	Detailed drawings completed; test plan formulated		3/29/2015							●						
	Task 5.0 - Prototype fabrication	3/2/2015	6/12/2015	$155,000												
5.1	Materials procurement and machining quotes	3/2/2015	5/29/2015													
5.2	Fabrication	4/1/2015	6/12/2015													
	Milestones															
6	Prototype delivery to SwRI		7/15/2015											●		
	Task 6.0 - Prototype hardware test	3/16/2015	9/18/2015	$130,000												
6.1	Test planning and set up	3/16/2015	6/12/2015													
6.2	Hydrostatic pressure test	6/15/2015	6/19/2015													
6.3	Pressurized flow test at operating temperatures	7/15/2015	8/31/2015													

BACKUP SLIDES

Risk analysis and mitigation

Description of Risk	Probability	Impact	Mitigation and Response Strategies
Resource Risks:			
Computational resource availability (SwRI Cluster)	Low	Med	Several clusters at SwRI to choose from
Work load of engineers becomes excessive	Low	Low	SwRI Machinery Program has >30 engineers and >1000 technical staff across SwRI
KAPL testing resources not available	Low	Low	Coordinate with KAPL to secure testing resources early in the program
Thar engineering manpower limited	Med	Med	Hire two new MEs (in progress)
Thar test stand set-up and operation gets delayed	Low	High	Borrow extra manpower and equipment resources from Thar sister company, Thar Process

Risk analysis and mitigation

Description of Risk	Probability	Impact	Mitigation and Response Strategies
Management Risks:			
Wide geographical separation of team	High	Low	Regular teleconference meetings, periodic face to face meetings
Definition of instrumentation suite and test procedures and conditions	Med	Low	Face to face coordination between design, analysis and test personnel
Schedule Risks:			
CHT model takes longer to develop than planned	Med	Med	Utilize SwRI subject experts
KAPL test facilities in use	Low	Low	Coordinate with KAPL to secure test time early in the program
Hydrostatic test failure	Low	High	Repair if possible. Rebuild if necessary.
Materials delivery delayed	Low	Med	Determine lead times for delivery during preliminary design; then place orders before end of detailed design, if necessary
Budgetary Risks:			
Thar test stand costs underestimated	Low	Low	Thar absorbs higher than anticipated cost share

Risk analysis and mitigation

Description of Risk	Probability	Impact	Mitigation and Response Strategies
Environmental, Safety and Health Risks:			
High temperature, high pressure gases	High	Low	Proper training of test personnel in safety protocols
Foreign gas exposure	Med	Med	Proper training and availability of monitoring equipment and PPE
DOE environmental issues not resolved - no testing at KAPL	Med	Med	Appeal to DOE to accept KAPL policies
External Influences Risks:			
Competitive IP discovered	Low	Low	Modify design to avoid interference