Innovative Hydrogen Liquefaction Cycle

Martin A Shimko

Gas Equipment Engineering Corporation

Project # PD21

2008 DOE Merit Review

June 11, 2008

This presentation does not contain any proprietary, confidential, or otherwise restricted information

HYDROGEN ENERGY SYSTEMS AVALENCE LLC™

H2 Liquefier Development Program

Timeline

Restart Date: Jan 2007
End Date: Sept 2011
Percent Complete: 30%

Barrier Addressed

High Cost and Low Efficiency of Hydrogen Liquefaction

Budget

Project Funding:		$2.52M
	DOE:	$2.00M
	Contractor:	$0.52M

$161K Received in FY06

$394K Received in FY07

$700K Allocated for FY08

Partners

GEECO:	*Detailed Design*
	Liquefier Fabrication
	System Testing
Avalence:	*System Integration*
MIT:	*Cycle Design*
	Catalytic HXC Design
R&D Dynamic:	*TBX Design and Fab*

Refined Project Objectives

- Design a Practical H2 Liquefaction Cycle That Significantly Increase Efficiencies Over Existing Technologies
- Produce a small-scale (100 – 500 kg/day) hardware demonstration of a hydrogen liquefaction plant
- Use Low/No Risk Development Components That Scale to 50,000 kg/day Plant Size
- Document a Significant Reduction in the Total Cost of H2 Liquefaction at the 50,000 kg/day Production Level

Overall Project Schedule

Revised to:

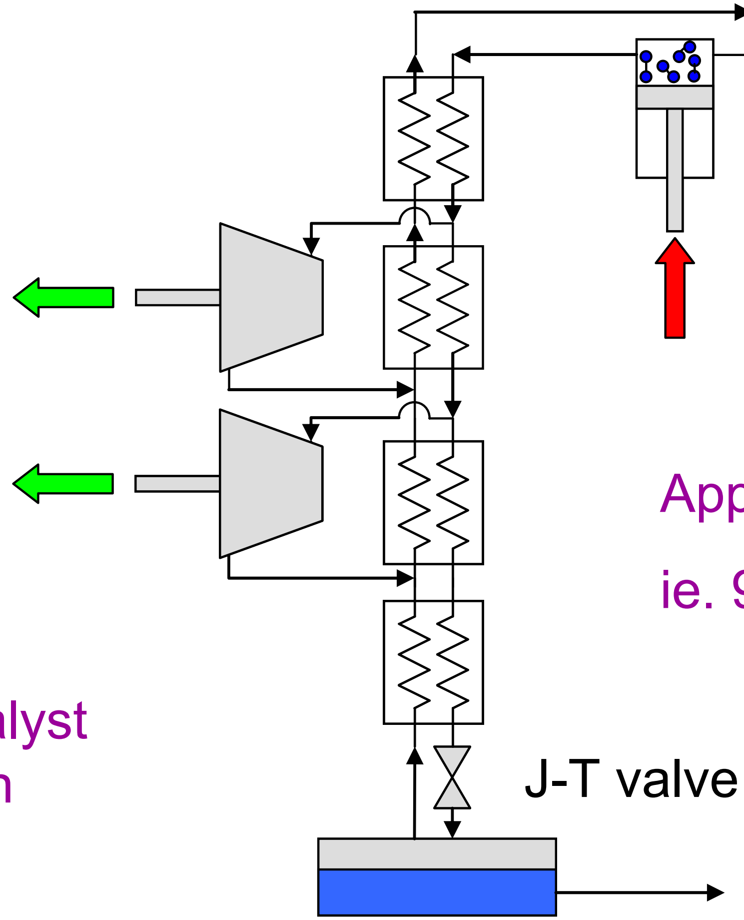
- Reflect Project Restart in Jan '07
- Limited Component Development and Demonstration Phase Consistent with FY '08 Funding
- Complete Component Development and Produce Full Pilot Plant Demonstration if Future Funds Allocated

PROJECT TIME LINE	Calendar Year Quarter																		
	Q1 07	Q2 07	Q3 07	Q4 07	Q1 08	Q2 08	Q3 08	Q4 08	Q1 09	Q2 09	Q3 09	Q4 09	Q1 10	Q2 10	Q3 10	Q4 10	Q1 11	Q2 11	Q3 11
Cycle Design	■	■	■																
Equipment Specification and System Design				■	■														
Develop Catalytic Heat Exchangers						■	■	■	■										
Develop Turbo Expanders								■	■	■	■								
Develop Hydraulic Expander								■	■	■	■								
Procure Major Components												■	■	■					
Build Demonstration Plant													■	■	■	■			
Test Demonstration Plant																	■	■	■

Technology Background

- Present "State of the Art" Operates at ~30 to 35% of Carnot Efficiency (Linde)
  - Achieve 9.7 kWh/kg Results (per H2A program)
  - Use Joule-Thompson Expansion Valves For Coldest Temperature Cooling Stage
- Work by Quack (2002) Claims a "Practical" Limit of About 60% of Carnot
  - Multiple Cooling Loops/Fluid → Very High Cost
- MIT Has He Liquefier Experience Using Hydraulic Expanders
  - Piston Driven Hydraulic Motor
- Efficient He Based Cryogenic Expanders Exist
- Developing H_2 Expanders For Lowest Temperature Stage Is Problematic

Present State of the Art
H_2 liquefaction - Claude cycle



Approximately 10% Yield

ie. 90% “Recycled” Flow

Ortho-Para Catalyst
Beds Not Shown

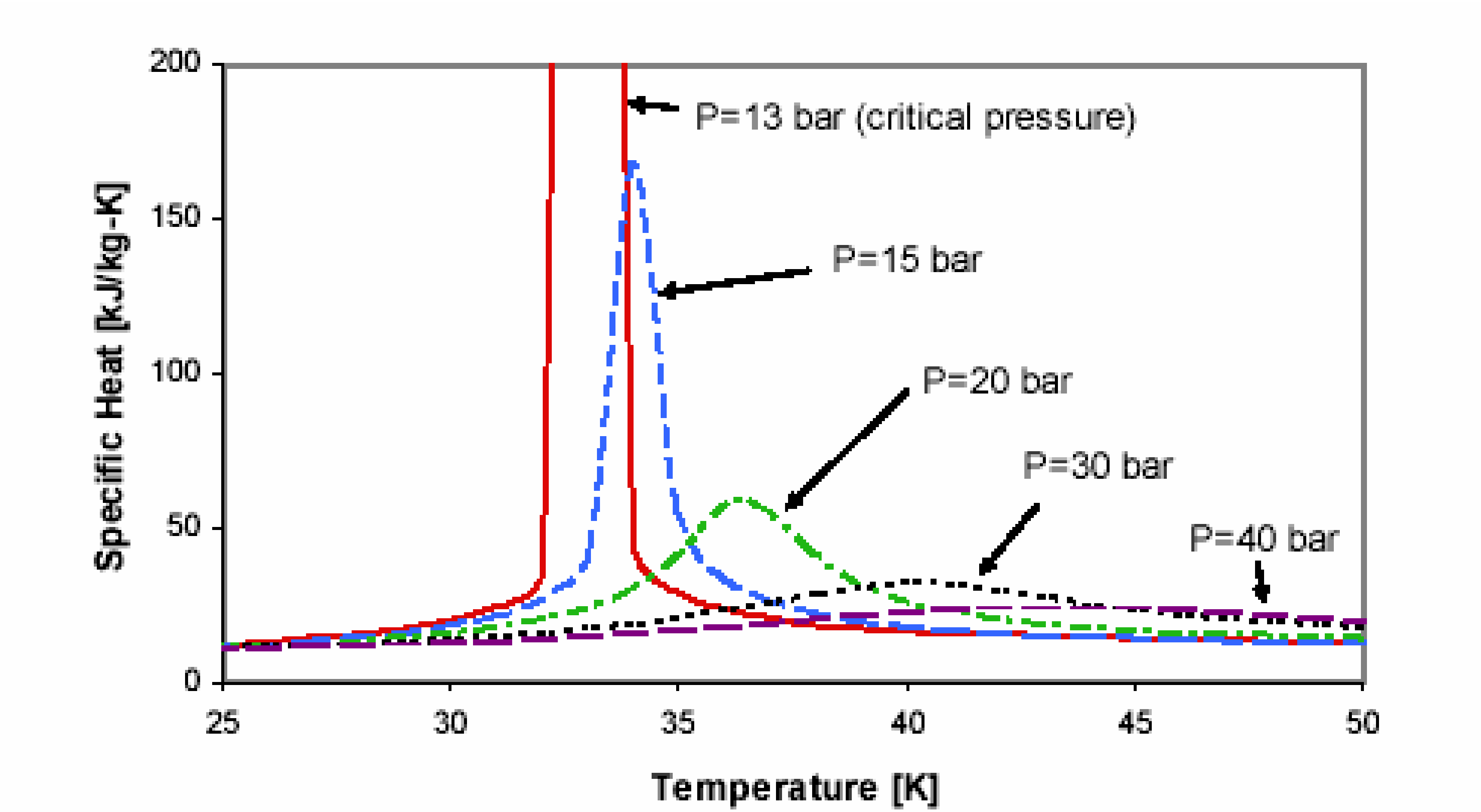
“First Year” Project Work

- Challenged Historical Technology “Wisdom”
- Found H2 Para/Ortho Equations of State
- Developed “Simple” Cycle Simulation Program
- Investigated Several Cycle Options
- Selected and “Optimized” Innovative Cycle
- Estimated System Efficiency and Cost
  - 500 kg/day Pilot Plant (hardware demonstration)
  - 50,000 kg/day Commercial Plant
- Identified Required Component Development

Cycle Simulation Program

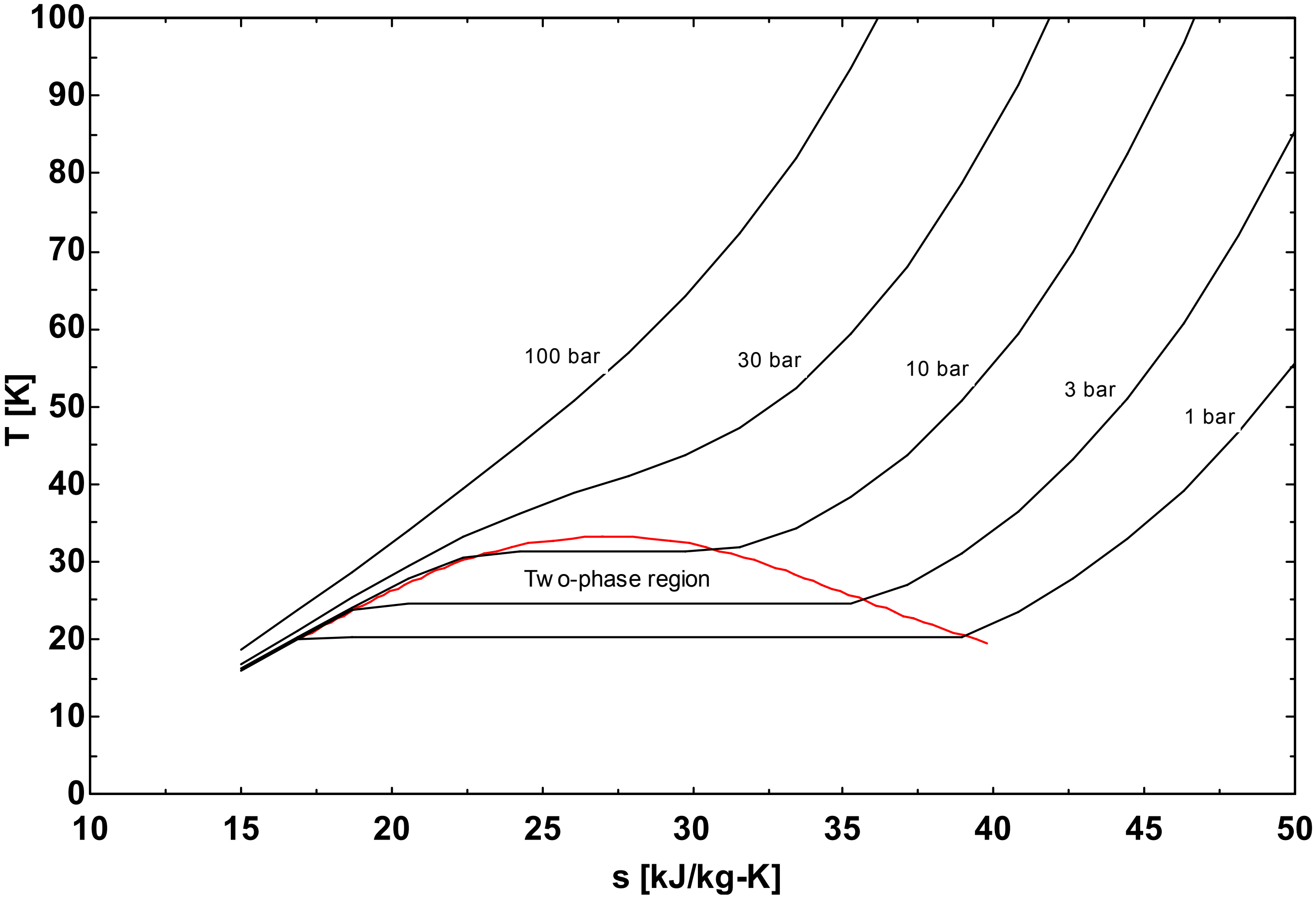
- Developed MATLAB Program with Excel Spreadsheet Utilizing the Latest H2 State Properties from NIST
- Cycle was Simulated with Combinations of the Following:
  - Turbine Adiabatic Efficiency: 80%, 90%
  - Heat Exchanger Pinch Point $\Delta T/T$: 1 to 5%
  - Hydrogen Pressure: 15 bar, 20 bar, 25 bar
  - Helium Pressure Ratio: 5, 6, 7
  - Compressor Efficiencies: 65 to 85%

Supercritical Hydrogen Isobars



Increasing Pressure Reduces the Cooling Load at Low Temperature

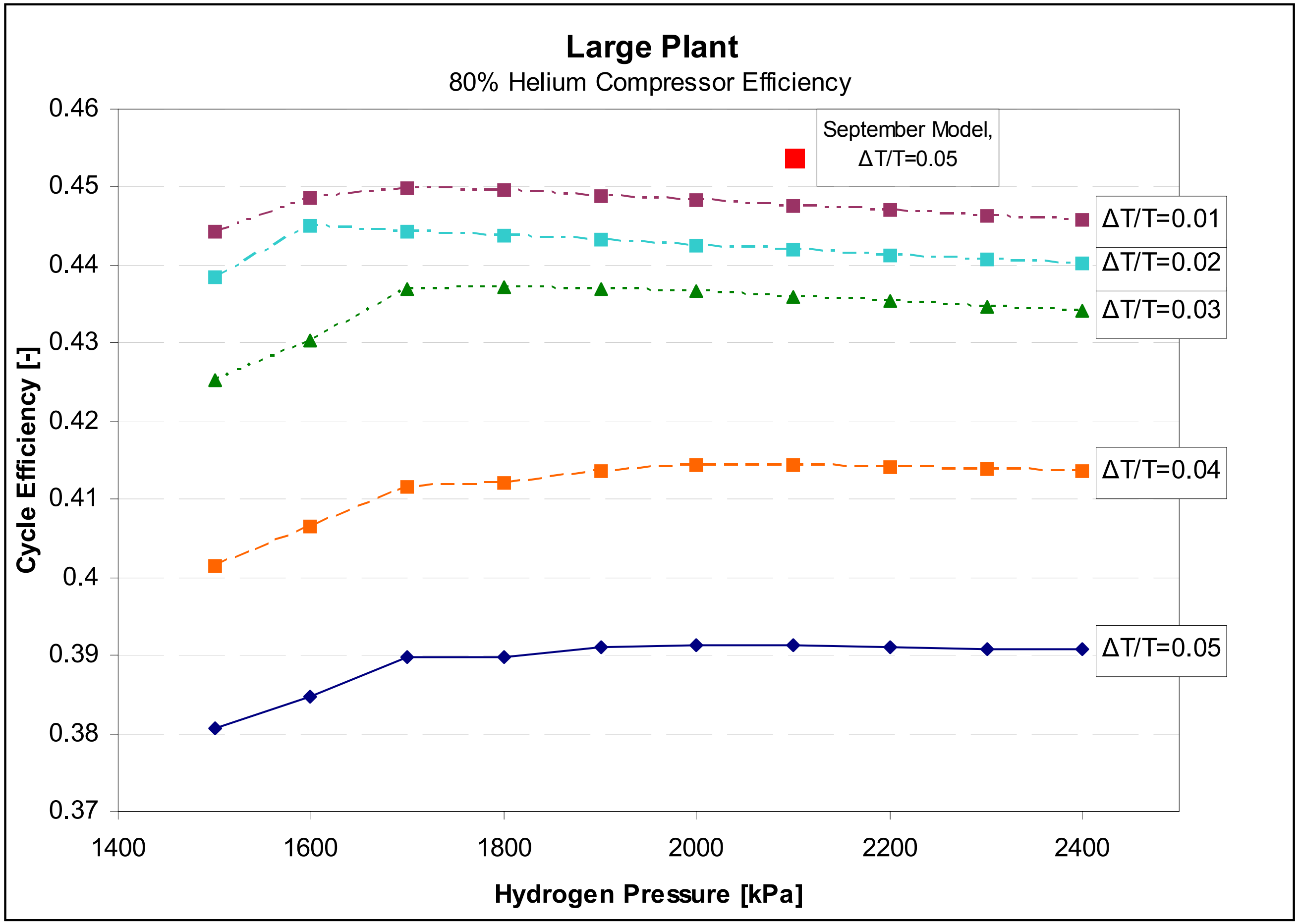
T-S Diagram For Normal Hydrogen



Pressures Above 15 bar Enable the Use of Wet Expander For 100% Liquefaction Conversion

Typical System Trade Study

Effect of Hydrogen Pressure



<u>Assumptions</u>

η for large plant:

expanders:

[η_{1a}=0.82, η_{1b}=0.83, η_2= 0.83, η_3=0.86, η_4=0.86]

He compressor:

η_{comp}= 0.80

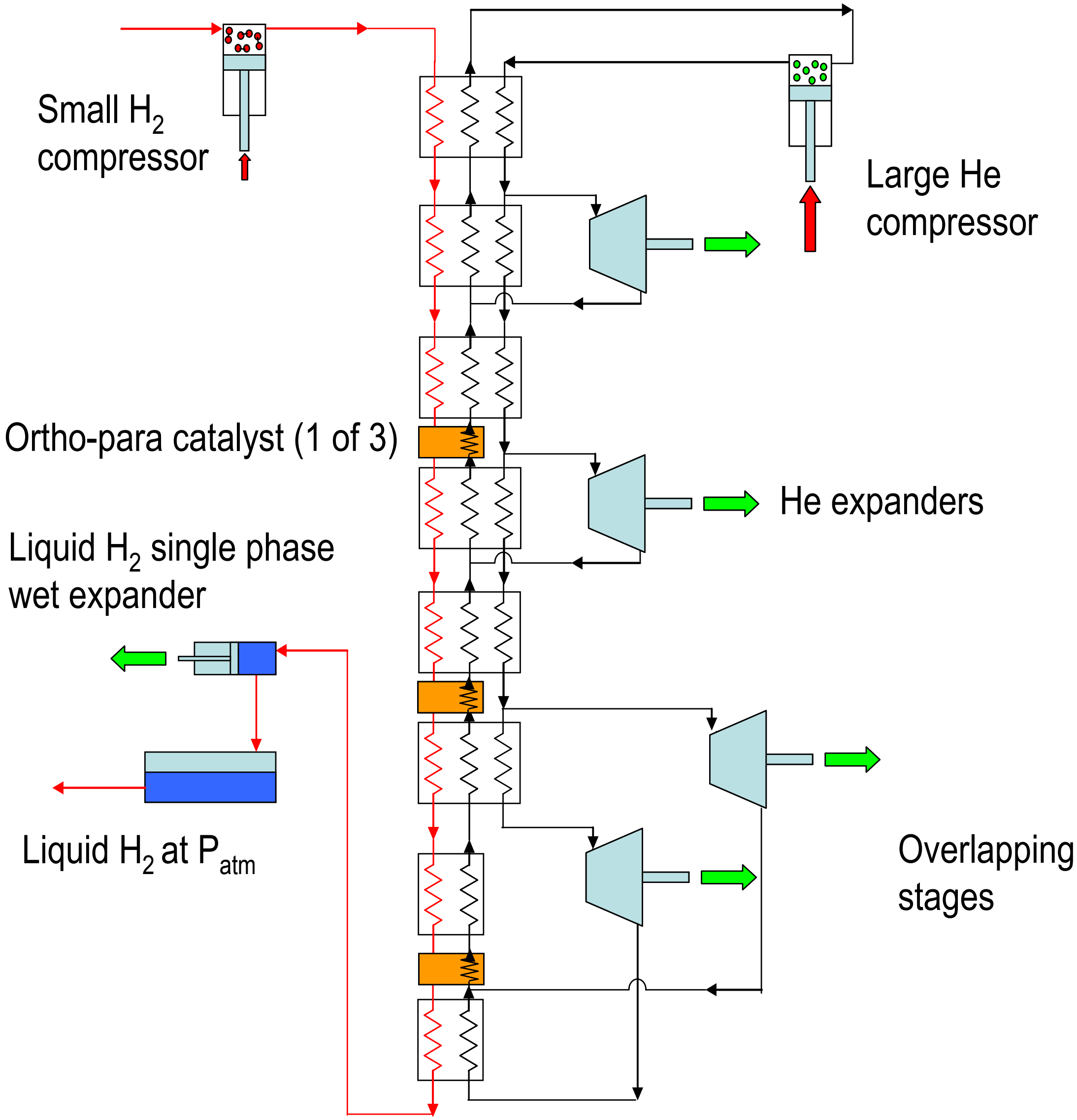
H_2 compressor:

η_{comp}= 0.60

Main Features of Selected Approach

- Once-Through H_2 Liquefaction – 100% Yield
- Collins-Style Cycle with He as Refrigeration Loop Working Fluid
- Constant, Supercritical Pressure in H_2
- Components Use Established Technology and Facilitate Scalability
- Efficiency Through Effective Staging of Expanders
- Development of Catalytic Heat Exchangers Would Further Increase Efficiency and Lower Cost

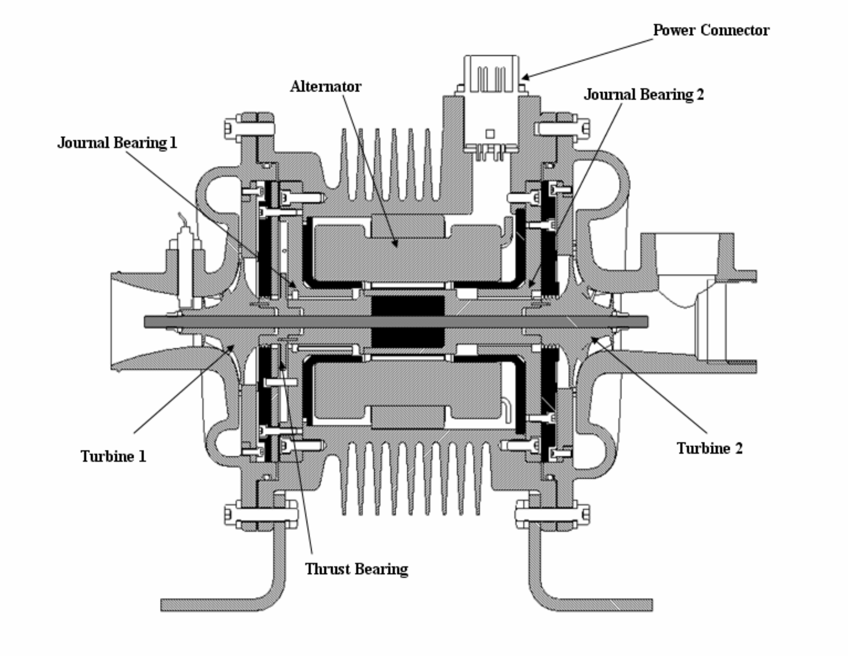
Final Design, Single Pass, High-Pressure H_2 Liquefaction

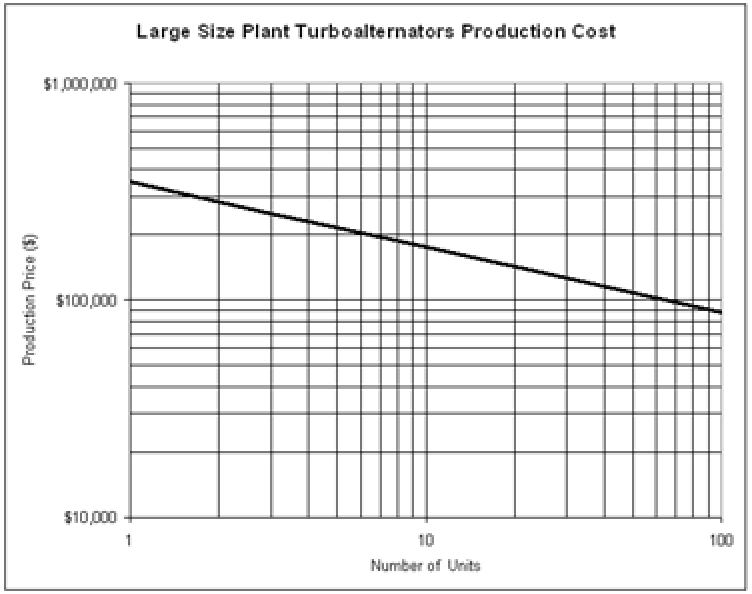


Liquefier Performance		Pilot	Large
System parameters	$\Delta T/T$	0.03	0.03
	η_{exp1}	0.6	0.85
	η_{exp2}	0.7	0.83
	η_{exp3}	0.75	0.86
	η_{exp4}	0.65	0.86
	$\eta_{comp,He}$	0.65	0.8
	$\eta_{comp,H2}$	0.6	0.8
	$\eta_{wet\_expander}$	0.9	0.9
	P_{H2} [bar]	21	21
	$P_{He,high}$ [bar]	15	15
	$P_{He,low}$ [bar]	2.5	2.5
Environmental and final properties	T_{atm} [K]	300	300
	P_{atm} [bar]	1	1
	$x_{para,in}$ [-]	0.25	0.25
	T_f [K]	20	20
	P_f [bar]	1	1
	$x_{para,f}$ [-]	0.95	0.95
Simulation result	η_{cycle}	0.2214	0.4455
	W_{ideal} [kWh/kg]	3.89	3.89
	W_{net} [kWh/kg]	17.57	8.73

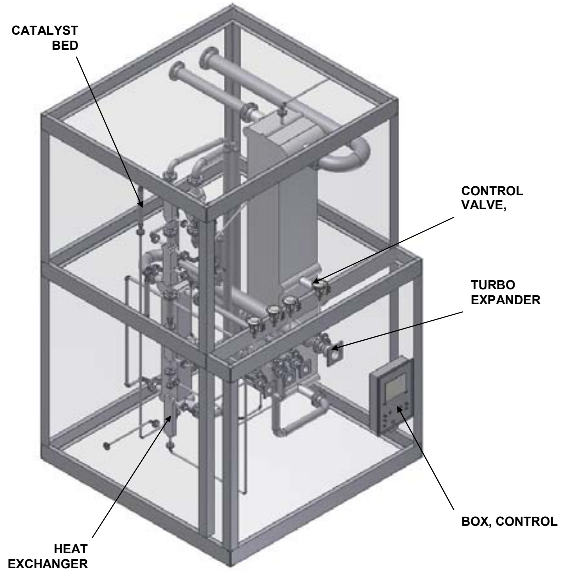
R & D Dynamics Phase I Work

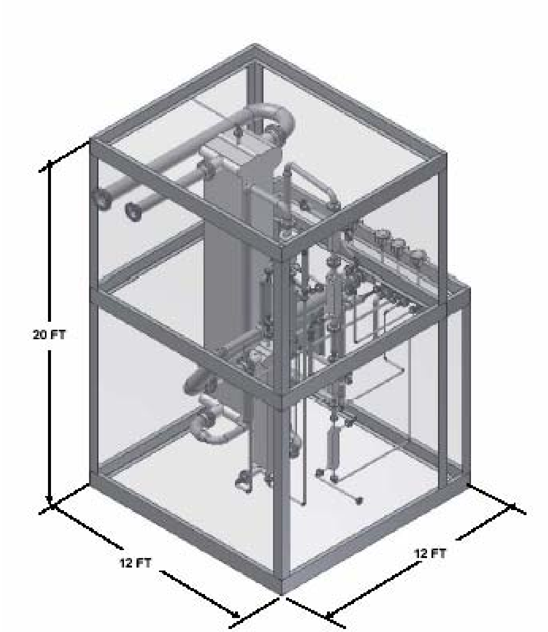
- Selection of Turbo-Alternators for Efficient Operation
- Preliminary Design of Turbo Equipment
  - Pilot Plant at 500 kg/day
  - Commercial Plant at 50,000 kg/day
- Pairings of Stage 1 and 3 and Stage 2 and 4 on Common Shafts
- Estimate Cost of the Commercial Sized Turbo Equipment

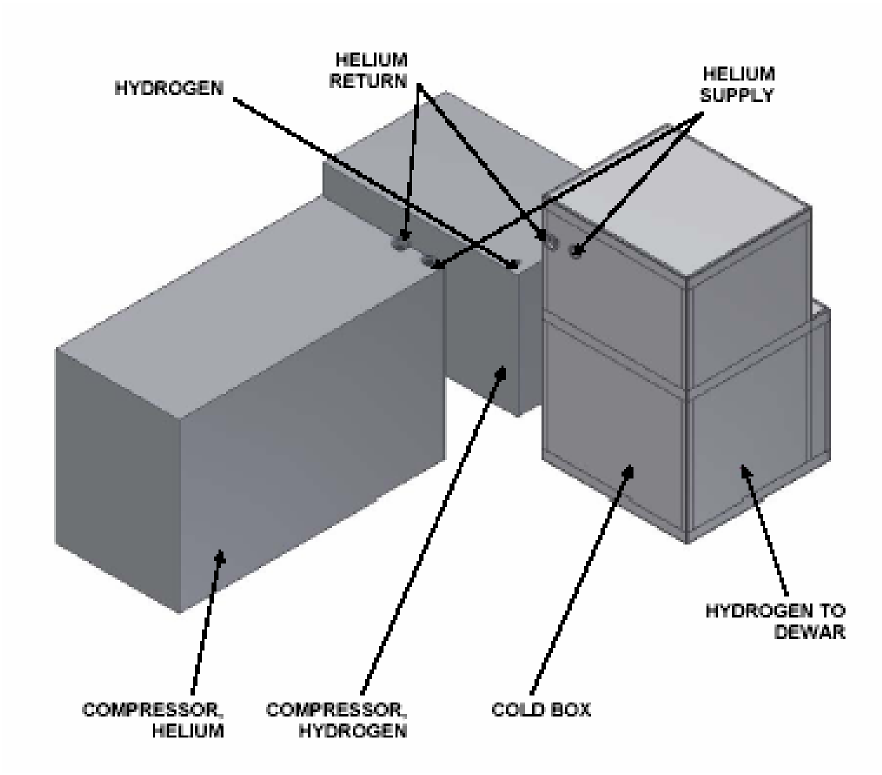




Pilot Plant Design







Equipment Cost Estimate

Compressor, He	1	$900,000.00	10	$24,000,000.00
HX 1-2-3	1	$160,000.00	10	$4,084,000.00
HX 3A	1	$37,000.00	1	$183,000.00
HX 4-5	1	$67,000.00	4	$1,322,000.00
HX 5A	1	$35,000.00	1	$130,000.00
HX 6-7	1	$45,000.00	1	$187,000.00
HX 7A	1	$33,000.00	1	$104,000.00
HX 8	1	$31,000.00	1	$136,000.00
Catalyst Bed	6	$6,000.00	6	$120,000.00
TBX 1	1	$150,000.00	1+1	$350,000.00
TBX 2	1	$150,000.00	1	$250,000.00
TBX 3	1	$150,000.00	1	$250,000.00
TBX 4	1	$150,000.00	1	$250,000.00
Control Valves	4	$6,000.00	5	$75,000.00
Check Valves	13	$25,000.00	13	$130,000.00
Control System	1	$75,000.00	1	$100,000.00
Instrument Air Supply	1	$5,000.00	1	$10,000.00
H2 Expander	1	$25,000.00	1	$125,000.00
Piping		$10,000.00		$250,000.00
Insulation		$10,000.00		$150,000.00
Structures		$10,000.00		$200,000.00
Electric Switchgear		$100,000.00		$500,000.00
Miscellaneous		$100,000.00		$500,000.00
TOTAL:		**$2,680,000.00**		**$39,106,000.00**

Already Meets 2012 DOE Goals For 30,000 kg/day Plant

Summary of Design Results

- **INCREASES EFFICIENCY BY 30% OVER PRESENT STATE-OF-THE-ART**
  - **From 30% TO 44% OF CARNOT, or**
  - **From 9.7 kWh/kg to 7.4 kWh/kg**
- **SYSTEM "EQUIPMENT" COST ~40% OF H2A ESTIMATE**
  - **TEC Could Be Significantly Higher, But Also Not Included In H2A Model**
  - **Largely Conventional Component Use**
  - **Development Risk and Cost Uncertainty Minimized**

Summary of Economic Estimates

Based on Liquefying 15.9M kg Annually and Amortizing CapEx Over 7 years

	DOE H2A Model Results	Project Estimates
Liquefier Capital Cost	$102.3M	$39.1M
Annual Energy Cost ($0.05/kWh)	$9.5M	$7.1M
O&M plus Misc Annual Costs	$5.1M	$5.1M
Capital Cost Contribution to the Liquefier Share of Real Levelized Delivered Hydrogen Cost ($(2005)/kg)	$1.08	$0.42
Energy/Fuel Cost Contribution to the Liquefier Share of Real Levelized Delivered Hydrogen Cost ($(2005)/kg)	$0.60	$0.45
Other Cost Contribution to the Liquefier Share of Real Levelized Delivered Hydrogen Cost ($(2005)/kg)	$0.32	$0.32
Liquefier Portion of Real Levelized Delivered Hydrogen Cost ($(2005)/kg)	$2.00	$1.19

Key Components Identified

Requiring Some Level of Development

- Catalytic Heat Exchangers
  - Increased Cycle Efficiency
  - Reduced Equipment Cost
- Centrifugal H2 Wet Expander
  - Achieve “Commercial” Reliability
- He Turbo-Alternator
  - Detailed Design and Testing to Achieve High Efficiency and Low Cost

Next Steps in Project Work

Consistent With Available Funding For Project and Specifically The Next 18 Months

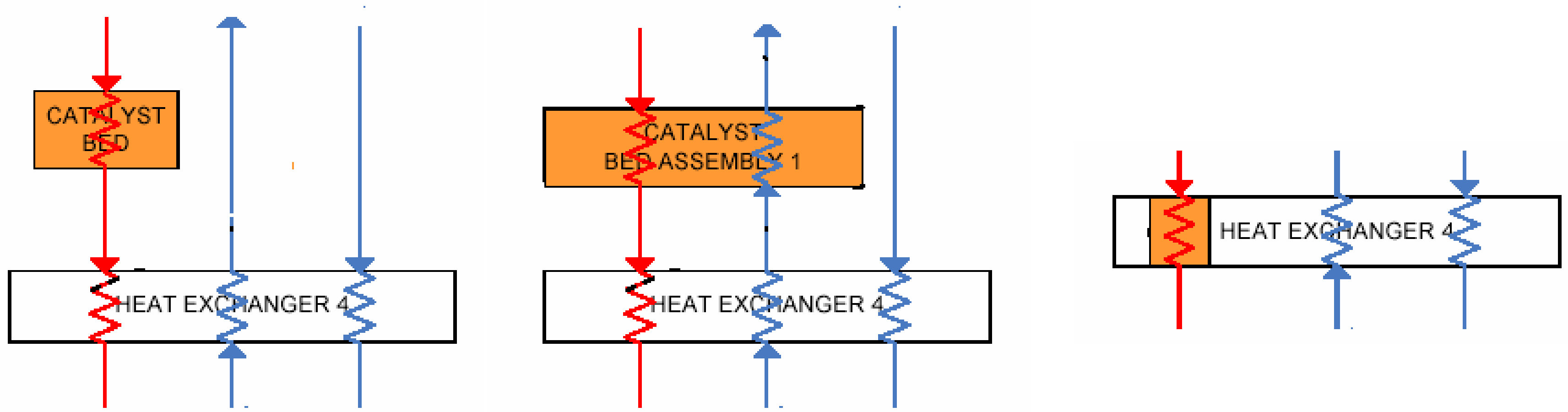
Full Pilot Plant Fabrication and Testing — $4.5M

- **Far Exceeds Initial Proposal Estimate**

Key Component Development — $545K

- **Develop and Demonstrate a Catalytic Heat Exchanger**

Catalytic Heat Exchanger Evolution



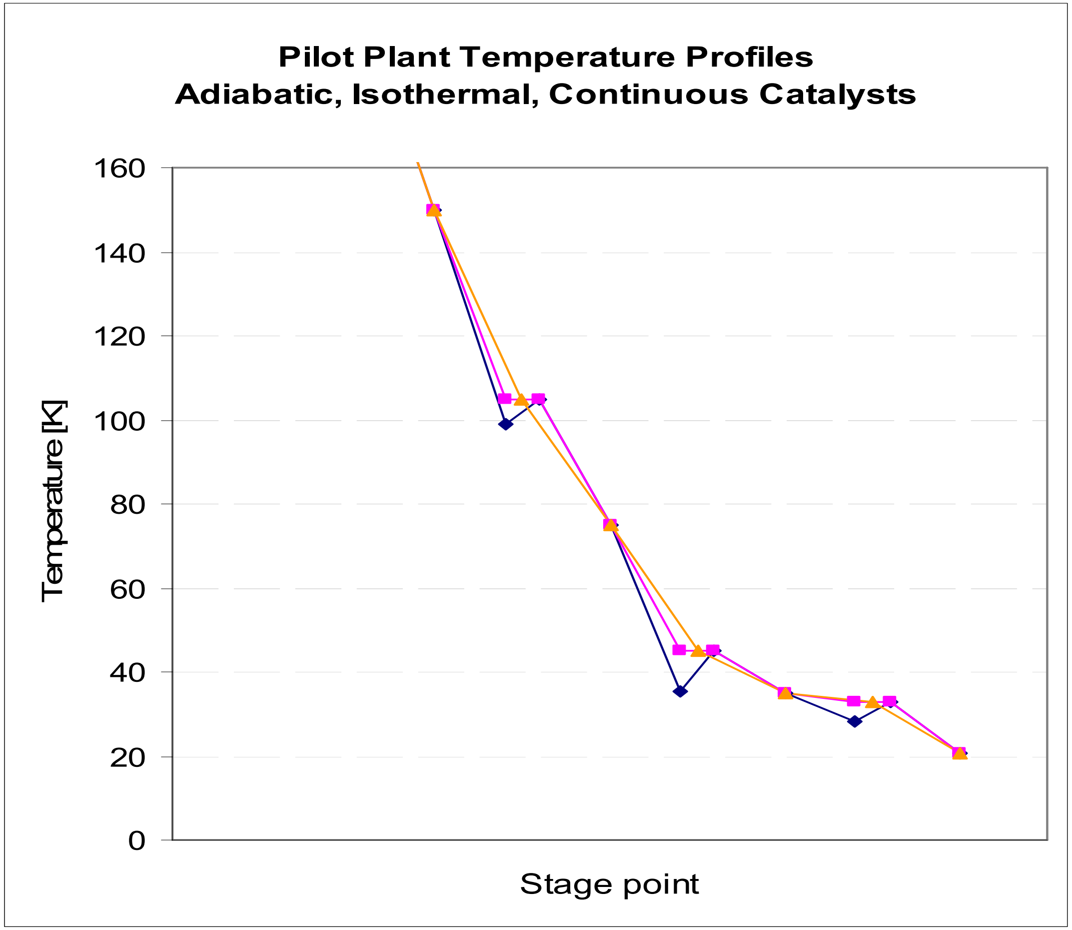
Adiabatic Catalyst Beds

Isothermal Catalyst Bed (Used in Performance Model)

Continuous Catalytic Heat Exchanger

Catalyst Characteristic's Effect on Temperature Profile and Efficiency

Pilot Plant Performance Simuation	η cycle	W net (kWh/kg)
Adiabatic Catalyst Beds	19.76	19.69
Isothermal Catalyst Beds	22.14	17.57
Continuous Catalytic Heat Exchangers	23.33	16.67

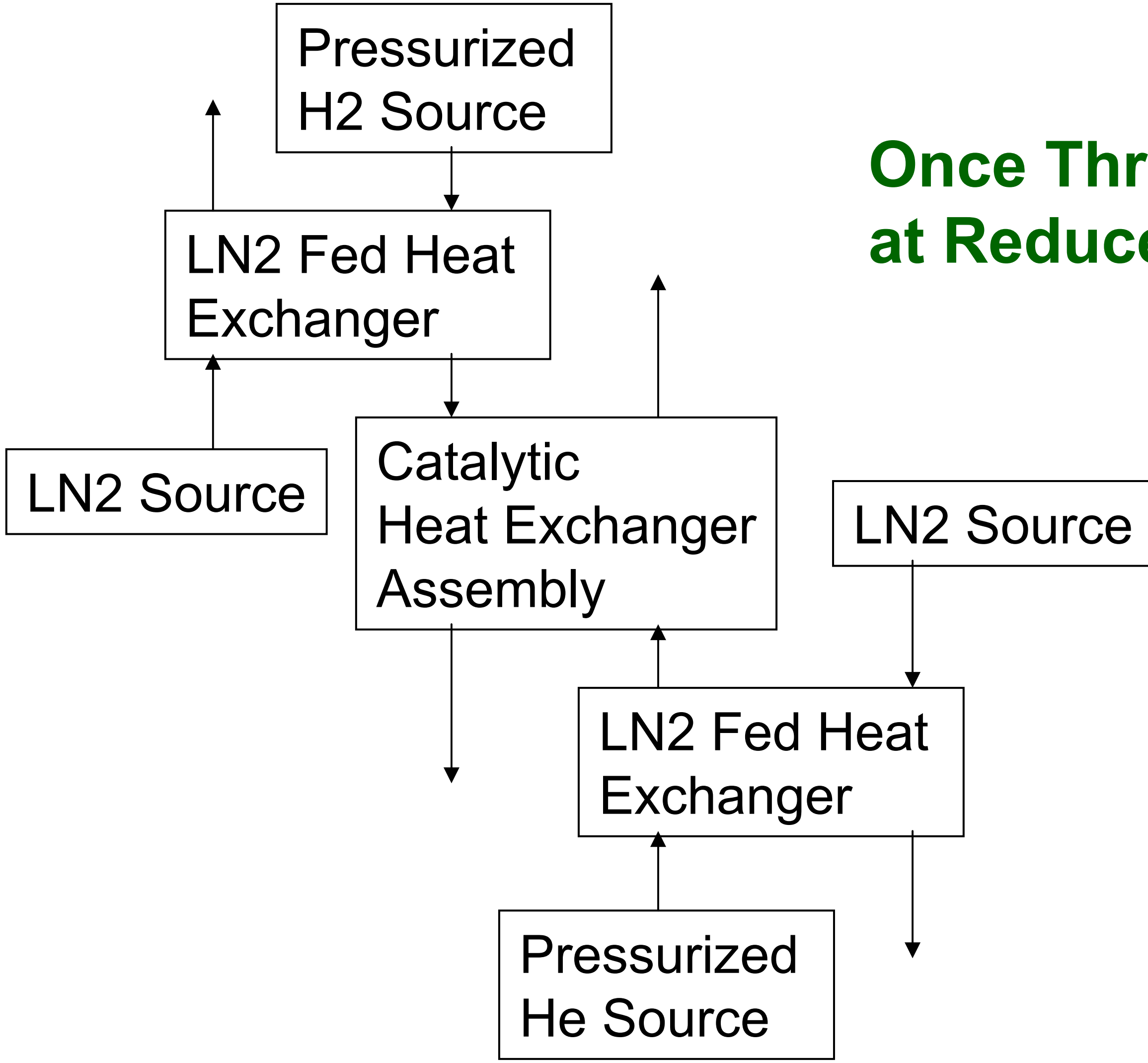


Year II

Develop and Demonstrate a Catalytic Heat Exchanger

- **MIT**
  - **Develop Catalytic Heat Exchanger Design**
  - **Bench Top Testing**
- **GEECO**
  - **Heat Exchanger Fabrication**
  - **Test Facility Fabrication**
  - **Prototype Testing**

Possible Test Loop for Catalytic Heat Exchanger Demonstration Testing



Once Through Testing at Reduced Scale