Innovative Hydrogen Liquefaction Cycle

Gas Equipment Engineering Corporation

May 15, 2007

Presentation at DOE 2007 Merit Review

LIQUEFIER DEVELOPMENT PROGRAM

US DOE R&D Grant - Hydrogen Production and Delivery

Program Topic - Hydrogen Delivery
Subtopic – Hydrogen Liquefaction

Budget

$2.518 M for Pilot Plant Design, Fabrication, and Testing

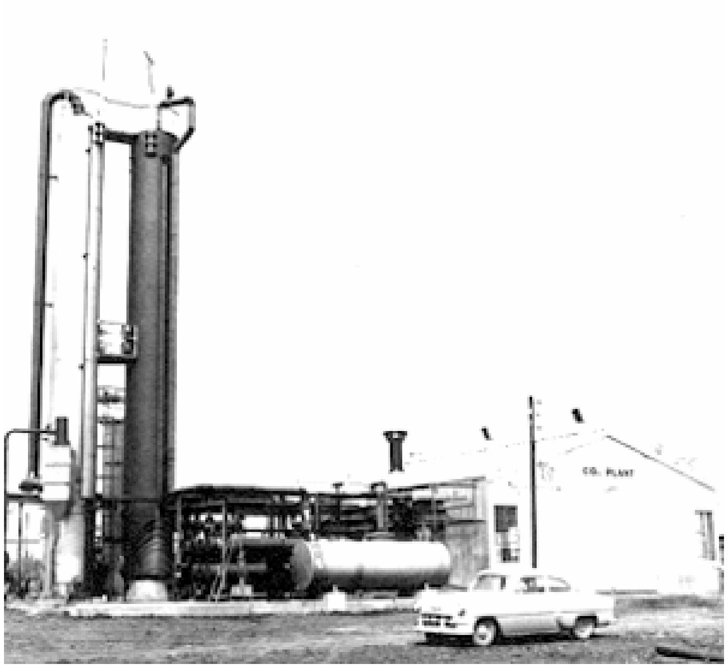
- Cost Share
  - $2.0 M from DOE
  - $0.518 M from Contractor
- $161K Received in FY06
- $500K Planned for FY07

Timeline

- Project restart date – Jan ‘07
- Project end date – Dec ‘09
- Percent complete – 8%

GAS EQUIPMENT ENGINEERING CORPORATION

Founded in 1921 as a manufacturer of industrial gas production equipment



Early GEECO CO_2 Plant

GEECO Produces O2 and N2 Generators for US Navy

- **CV 14 in 1962, through**
- **CVN 78 in 2007**

USS Nimitz and USS Independence

The O2/N2 Producer that GEECO supplied for the USS Nimitz (CVN68) in 1968 is still operating reliably today

Project Partners

Team Member	Responsibility
Gas Equipment Engineering Corp.	Contract Administration Detailed Design Liquefier Fabrication System Testing
Avālence	Project Coordination System Integration
R&D Dynamics Bloomfield, CT	Turbo-Expander Design and Fabrication
MIT Cambridge, MA	Cycle Evaluation & Modeling He Liquefier Experience

Proposed Project Approach

- Evaluate Alternative Cycle Approaches
  - Target High Efficiency/ Low Cost
  - Enable Unique Cycle Cost/Performance Trade-Offs
- Scaleable to >50,000 kg/day Systems
  - Present Capital Versus Operating Cost Trade-Off at 200, 2000, 20,000, 200,000 kg/day
- Target Cycle Performance Projections To Exceeding DOE Efficiency Target of 3.6 kWh/kg
- Build Small Scale Pilot Plant of ~ 200 kg/day

Overall Project Schedule

PROJECT TIME LINE											
	Q1 07	Q2 07	Q3 07	Q4 07	Q1 08	Q2 08	Q3 08	Q4 08	Q1 09	Q2 09	Q3 09
Cycle Design	■	■	■								
Detailed System Design			■	■							
Design and Build T/E		■	■	■	■	■	■				
Procure Major Components					■	■					
Build Pilot Plant						■	■	■			
Test Plant									■	■	■

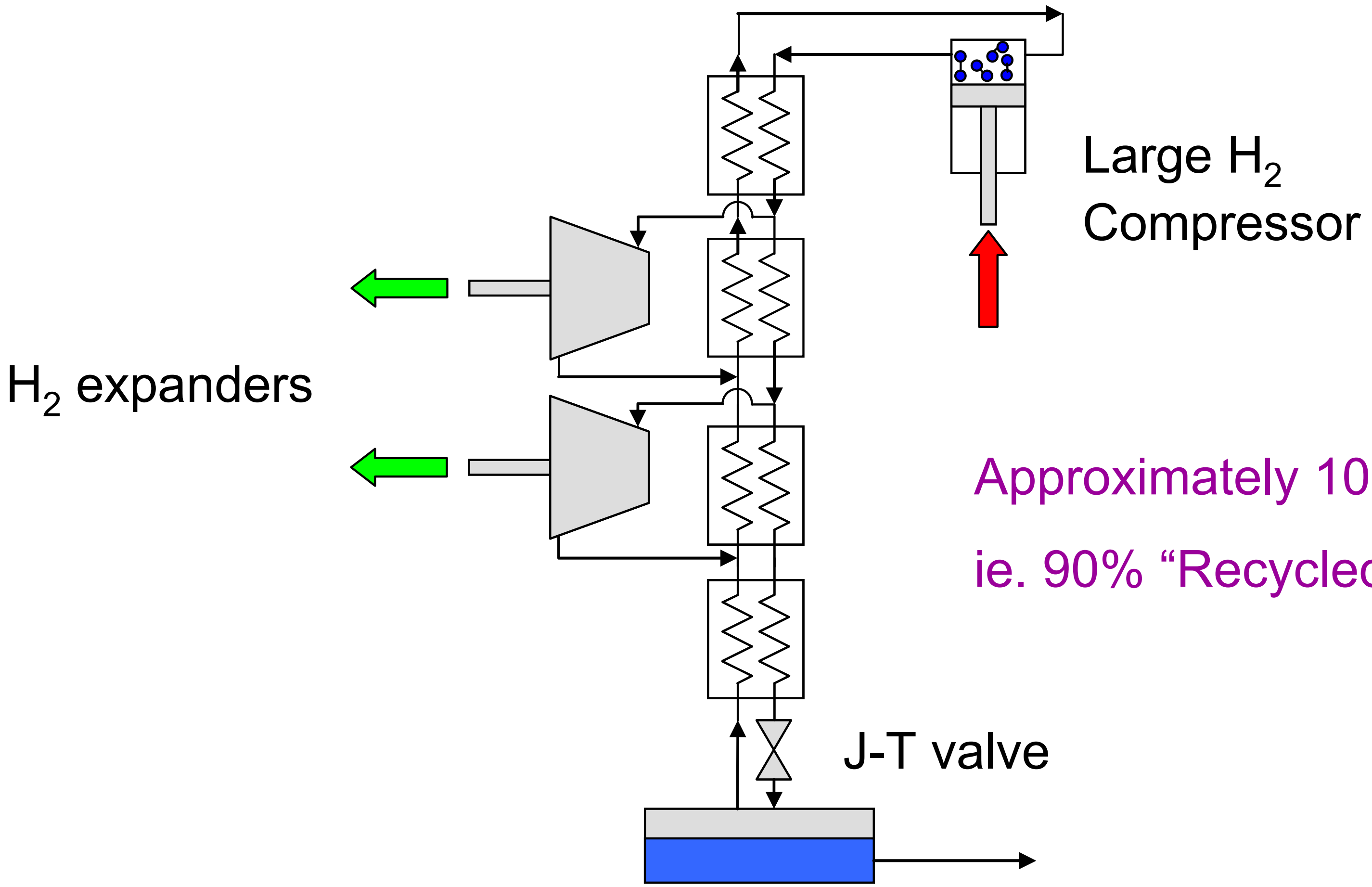
Initial Phase Schedule

PHASE I TIME LINE																		
	Jan		Feb		Mar		April		May		June		July		Aug		Sept	
Cycle Options Defined	■	■	■	■	■	■												
Peliminary Cycle Definitions					■	■	■	■	■	■	■	■	■					
Cycle Performance Modelling									■	■	■	■	■	■	■	■		
Cycle Economic Comparison															■	■	■	■
Specify Turbo Expander Requirements															■	■	■	■
Cycle Selection						*												
Quarterly Progress Report						*						*						*
Design Review																		*

First Year Project Challenges

- Challenge Historical Technology "Wisdom"
- Find H_2 Para/Ortho Equations of State
- Develop Simple and Scalable Economic Assessments of Potential Cycles
- "Optimize" the Design of Potential Cycles
- Restructure Project Due to Long Delays in Funding
  - Required Change in Technical Partner
- Produce Pilot Plant Design With Optimized Scale
  - System Size Versus Available Components

Present State of the Art
H_2 liquefaction - Claude cycle



Approximately 10% Yield

ie. 90% “Recycled” Flow

Technology Background

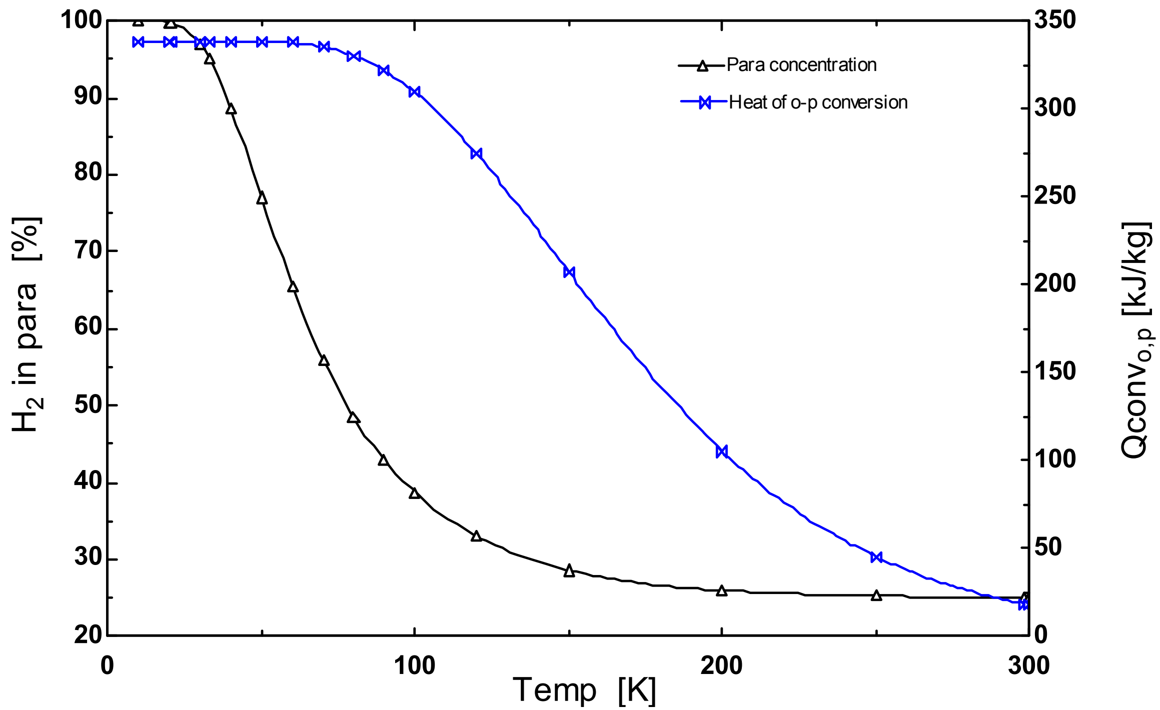
- Present "State of the Art" Operates at ~30 to 35% of Carnot Efficiency (Linde)
- Work by Quack (2002) Claims a Practical Limit of About 60%
  - To Achieve This a Very Elaborate and Expensive Set of Components was Required
- MIT He Liquefier Experience Using Hydraulic Motors Will Be Examined for H_2 Systems
- More Experience with He Cryogenic Expanders Exists
- Consider Acoustic Sterling Based on Recent Advances

Ideal Work Of Liquefaction

$$W_{ideal} = W_{cooling} + W_{conversion} + W_{condensation}$$

$W_{cooling}$	Reduce H_2 Gas Temperature
$W_{conversion}$	H_2 Conversion to Para State
$W_{condensation}$	Gas to Liquid Conversion

Para Concentration And Heat Of Conversion vs. Temperature

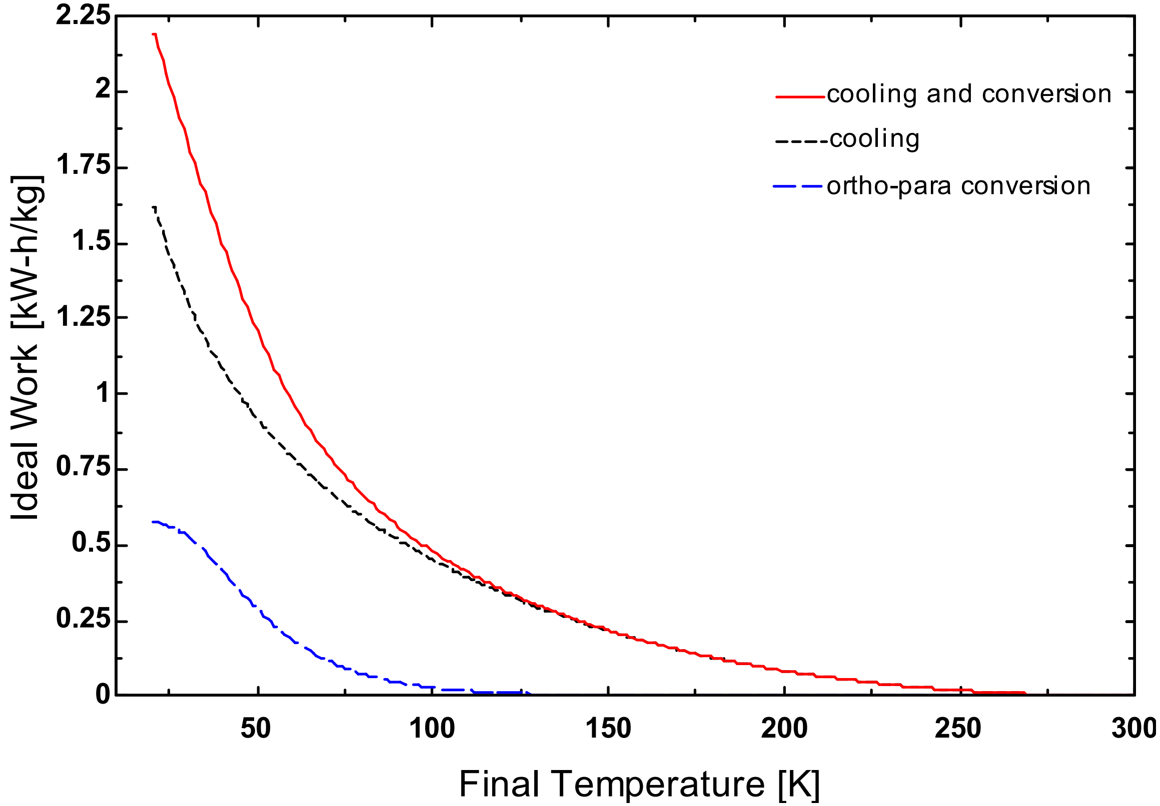


Initial Task was to Find Documented Equation of State (EOS) Information Useful for Ortho or Non-Equilibrium Ortho/Para H_2

Result:

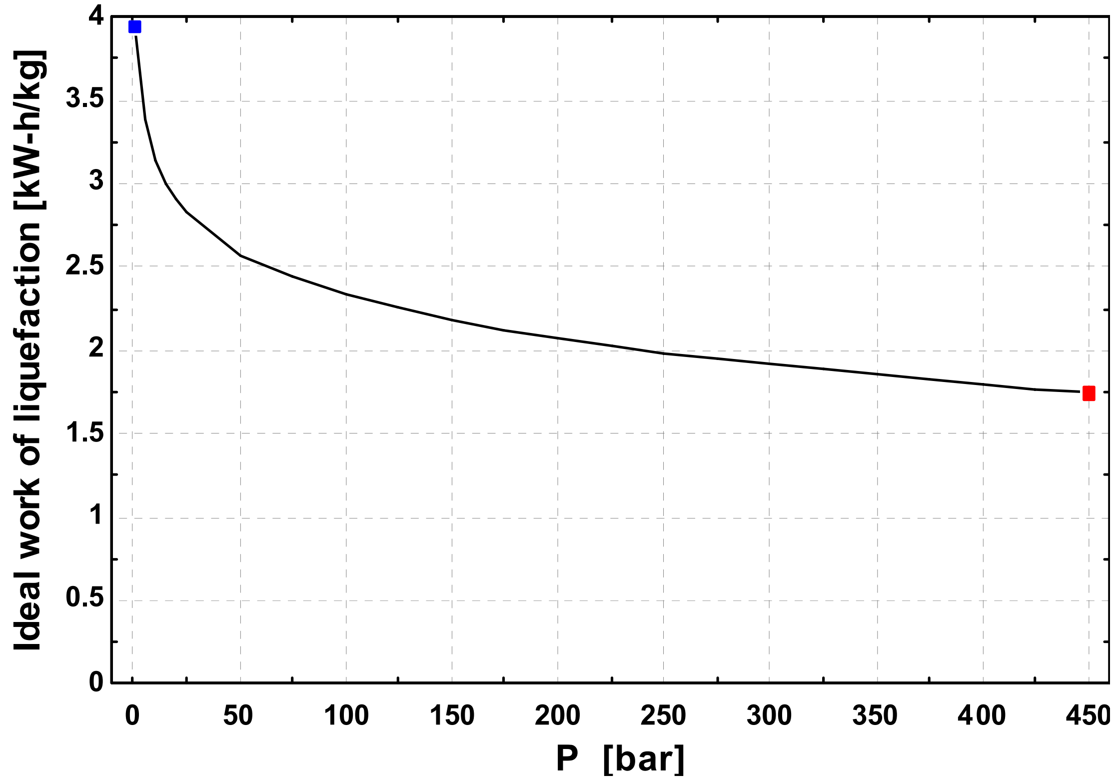
REFPROP 8.0 from NIST (Currently in Beta Testing)
New EOS (Leachman) for n-H_2 and p-H_2 Accurate at Higher Pressure Range and in Critical Region

Work Of Cooling And Conversion vs. Final Temperature



The Ortho-Para Conversion Load is a Significant Portion of the Total Liquefaction Load

Effect of Initial Pressure on Ideal Work of Liquefaction

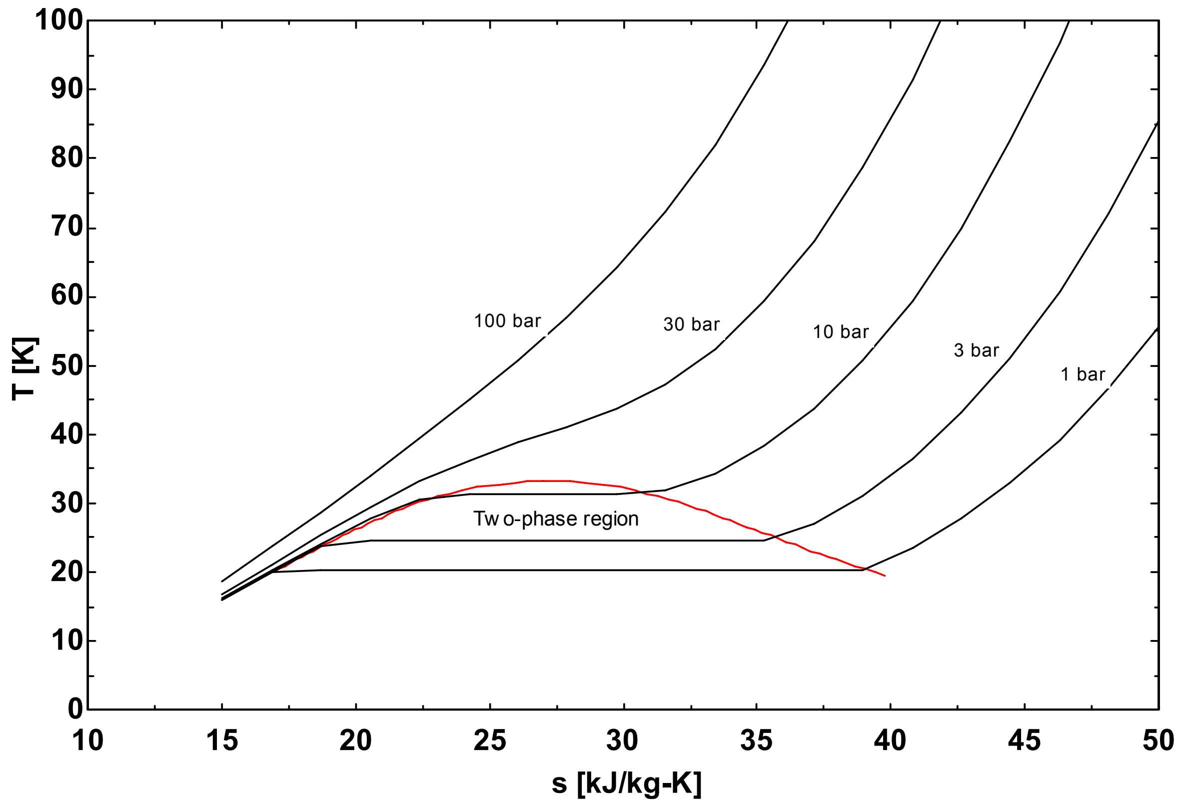


The "Correct" Initial Pressure Can Be Found to Optimize the Total Work Input

Potential Cycle Alternatives

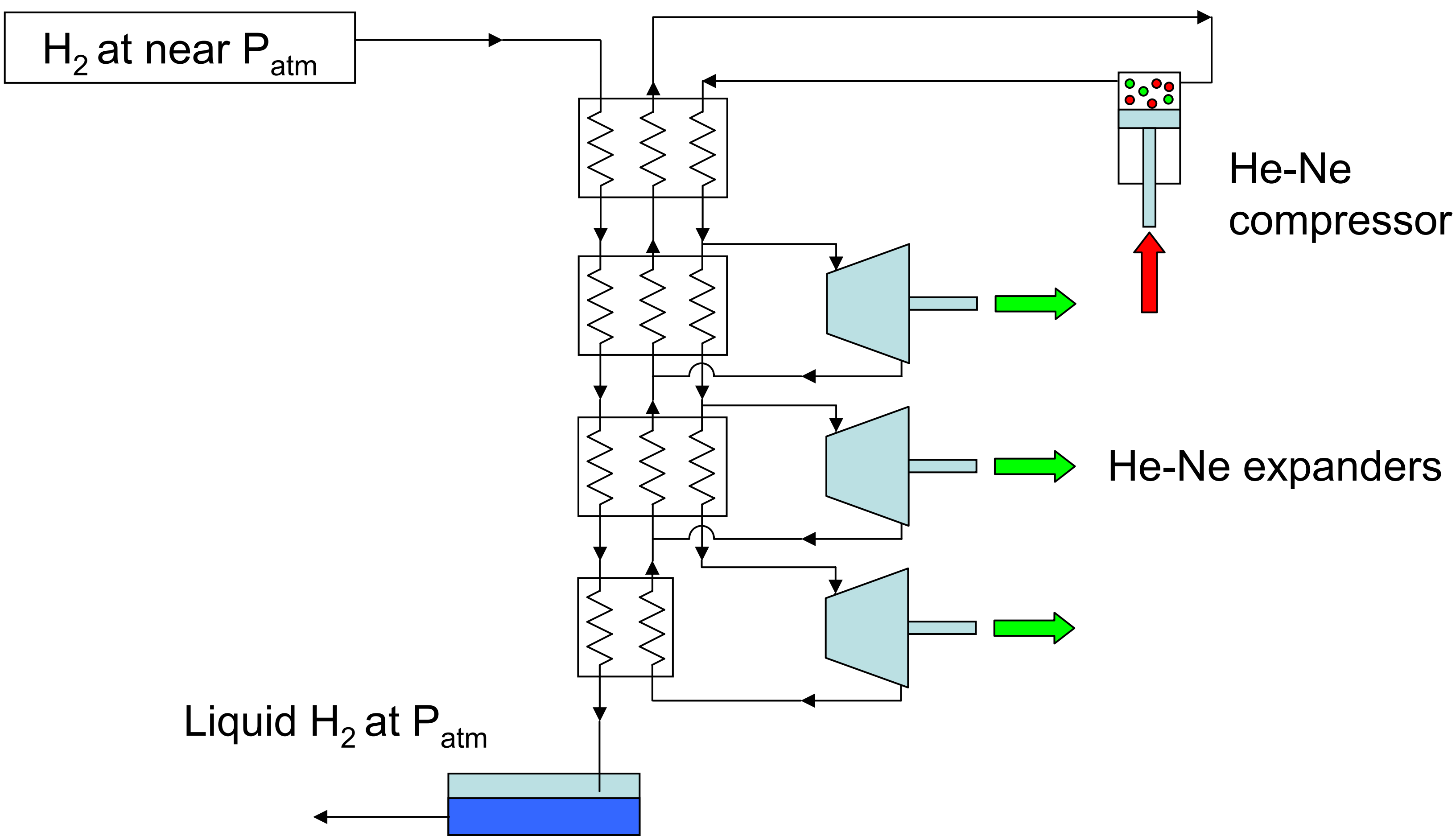
- Explore “Once Through” Cycle Design
  - Minimize H_2 Compressor Size
- Vary H_2 Pressure to System Advantage
  - Elevate System Pressure “Just Enough”
  - Replace JT Valve with Hydraulic Motor
    - Higher Efficiency Method to Reduce Pressure Back to Ambient
- Evaluate Performing Cooling “Work” In A Variety of Ways
  - Turbo-Machinery Directly on H_2 Flow
  - Turbo-Machinery in Separate Cooling Loops Via HXC
  - Acoustic Sterling for Higher Temp Stages

T-S Diagram For Normal Hydrogen

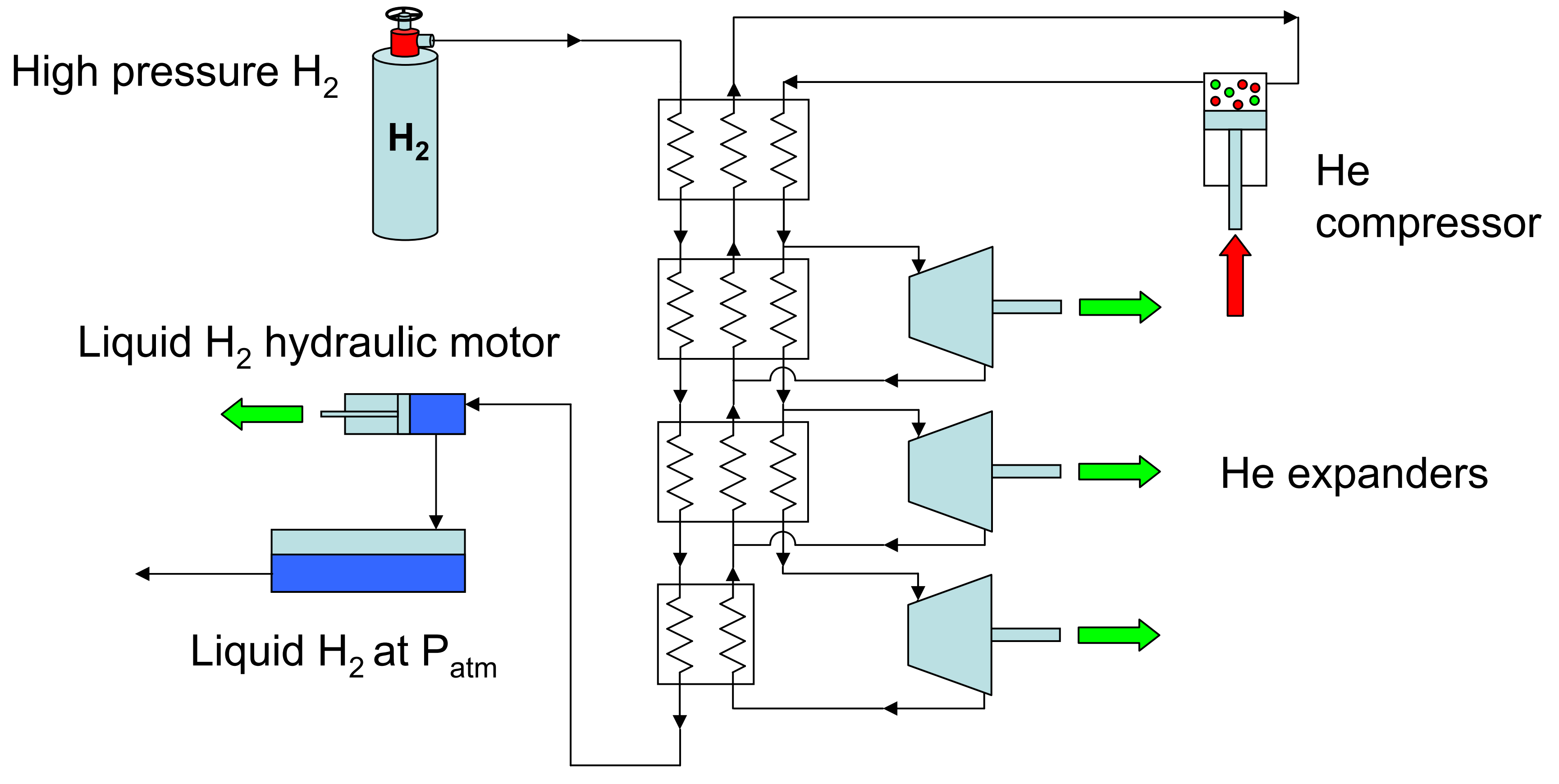


Pressures Above 20 bar Enable the Use of Hydraulic Motors For 100% Liquefaction Conversion

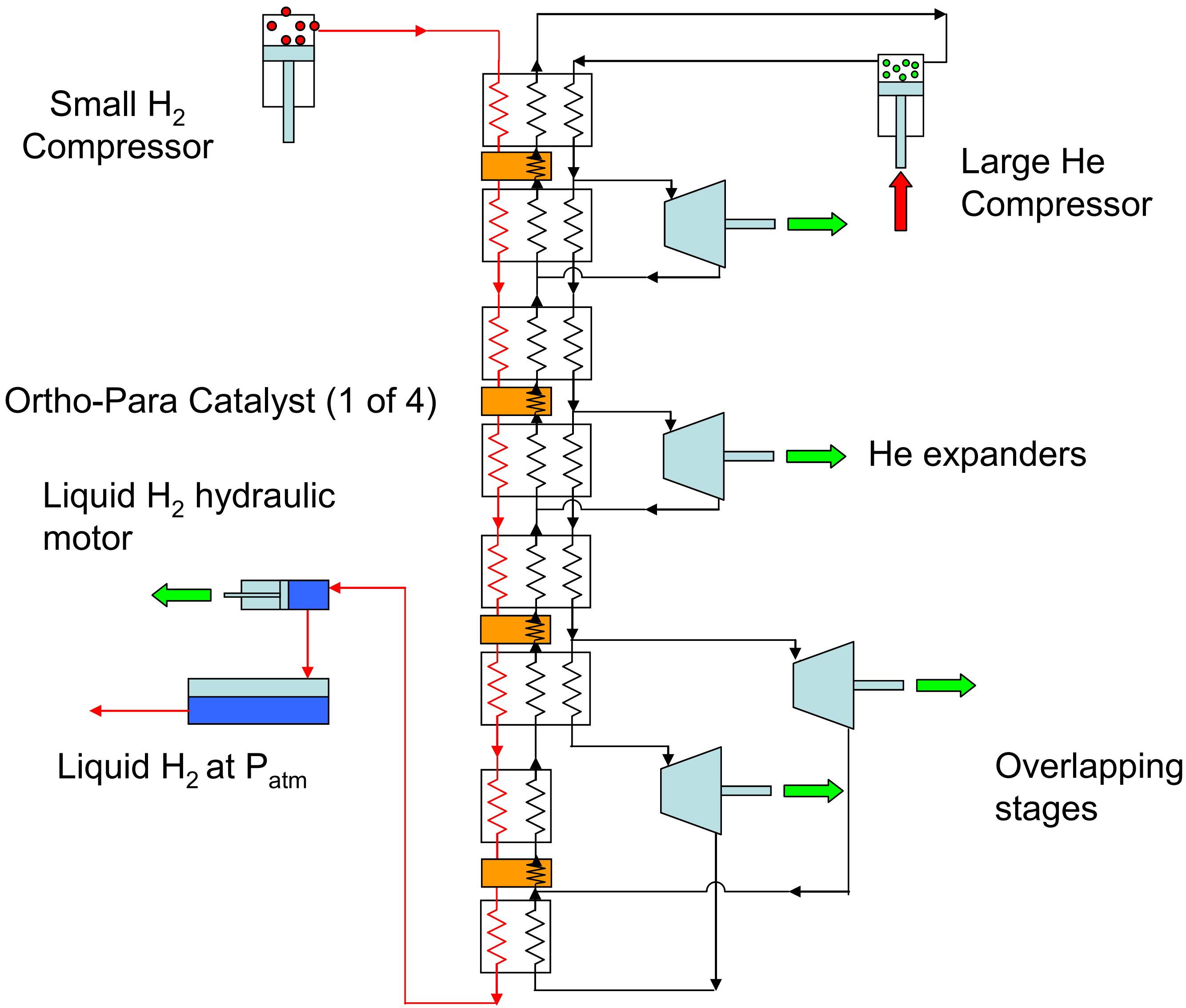
Possible Cycle Single Pass, Low-Pressure H_2 Liquefaction



Simple Design, Single Pass, High-Pressure H_2 Liquefaction



Final Design, Single Pass, High-Pressure H_2 Liquefaction



Cycle Simulations Using Excel

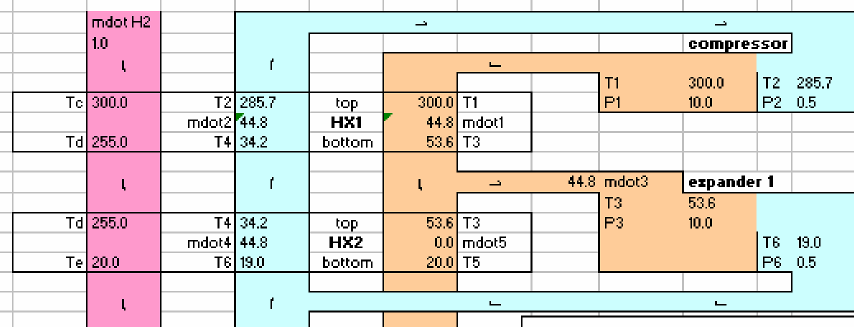
	T	P	h	s			xo	xp	hn	hp	sn	sp
	300	0.001					0.74928	0.25072	3958.889	4455.076	72.56237	75.83041
			4482.579	81.62769			0.74928	0.25072	4482.605	4455.076	81.62777	75.83041
						OFFSETS			523.7162	0	9.065407	0

hydrogen properties

State	T [K]	P [MPa]	h [kJ/kg]	s [kJ/kg-K]			xo	xp	hn	hp	sn	sp
c	300	40	4717.305	37.69595			0.74928	0.25072	4717.334	4687.396	37.69604	31.89437
d	254.987	40	4046.323	35.27267			0.747694	0.252307	4046.528	3979.762	35.2734	29.33731
e	20	40	408.7108	-3.3529			0.001693	0.998307	930.9276	407.5291	5.633563	-3.41965

Helium Cycle

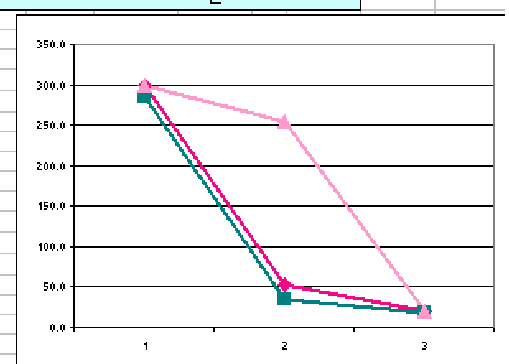
State	T [K]	P [MPa]	h [kJ/kg]	s [kJ/kg-K]	mdot [kg/s]
1	300	10	1595.408	18.47284	44.82672
2	285.7143	0.5	1490.565	24.43057	44.82672
3	53.64798	10	302.2011	9.360715	44.82672
4	34.185	0.5	182.3902	13.36715	44.82672
5	20	10	110.9957	3.755839	0
6	19.04762	0.5	101.2419	10.22593	44.82672
3i	62.74474	10	352.4409	10.22593	



Constraint Equations:		
HX1	3.37E-08	First law, HX1
HX2	1.83E-07	First law, HX2
equate dTi	0	

Variable Constraints			True if > 0
285.71	T2 <= T1	300.00	14.29
285.71	T2 <= Tc	300.00	14.29
34.19	T4 <= T3	53.65	19.46
34.19	T4 <= Td	254.99	220.80
34.19	T4 <= T2	285.71	251.53
19.05	T6 <= T5	20.00	0.95
19.05	T6 <= Te	20.00	0.95
19.05	T6 <= T4	34.19	15.14
1.00	x1 <= 1	1.00	0.00
254.99	Td <= Tc	300.00	45.01
20.00	Te <= Td	254.99	234.99
0	0 <= all T	1.00	1.00

Entropy Generation		these should be positive...
HX1	85.05	
HX2	102.19	
exp1	38.78	
sum	226.017	



H_2 Properties in Excel

- Lookup Table for o-p Concentration
- Offsets Calculated from Zero Pressure Properties (Haar et. al.)
- Properties of n-H2 and p-H2 Called from REFPROP 8.0 Using Leachman EOS

=Enthalpy("parahyd","TP","SI",E9,F9)

- Offsets Applied to n-H2 Enthalpies and Entropies
- Properties Combined Using Mixture Equations

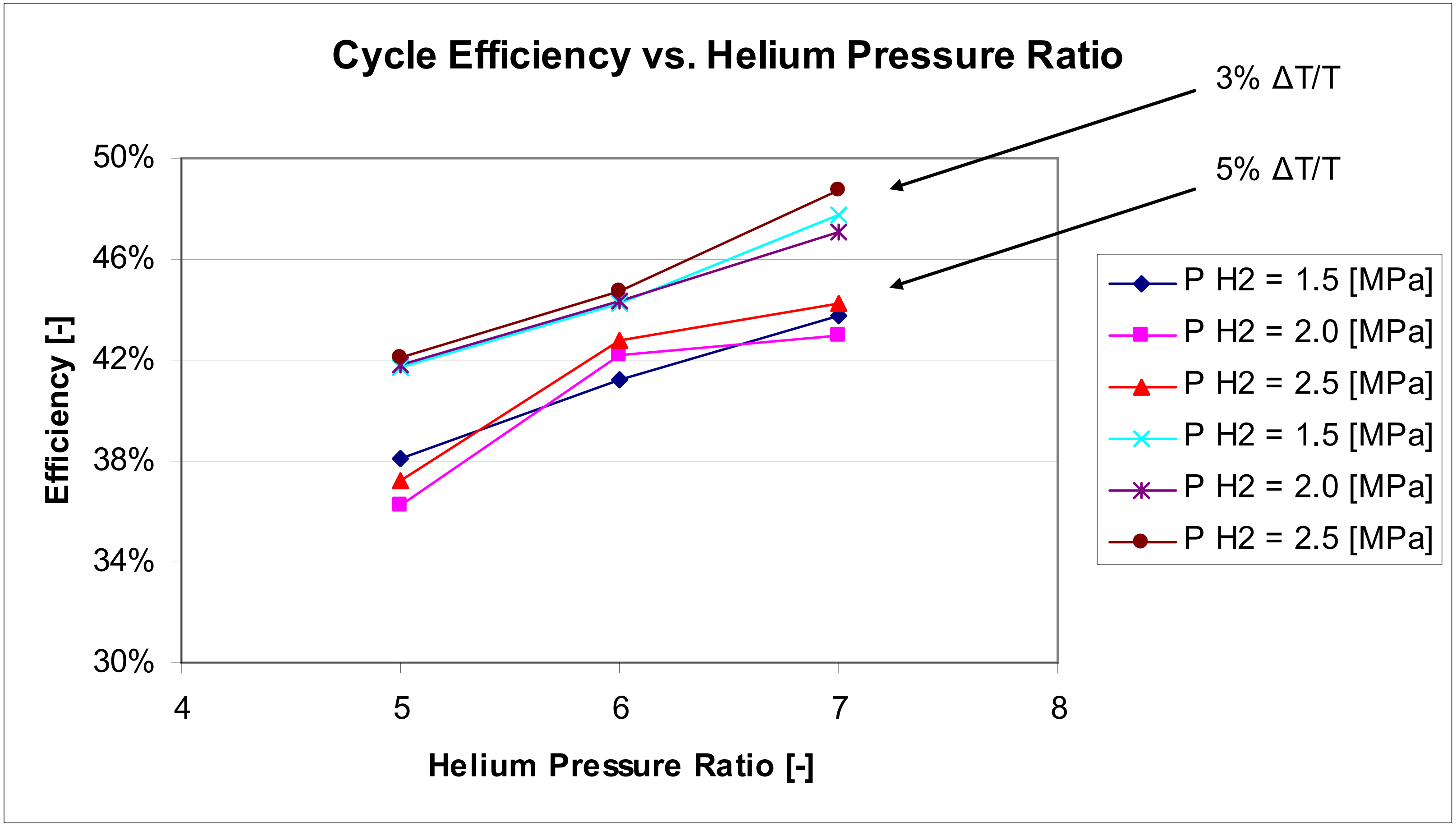
hydrogen properties

State	T [K]	P [MPa]	h [kJ/kg]	s [kJ/kg-K]	xo	xp	hn	hp	sn	sp
c	300	40	4717.305	37.695946	0.74928	0.25072	4717.334	4687.396	37.69604	31.89437
d	77	40	1340.734	16.801672	0.492654	0.507346	1517.508	1002.323	18.53103	9.600858
e	20	40	408.7108	-3.3529	0.001693	0.998307	930.9276	407.5291	5.633563	-3.419647

Cycle Simulation Parameters

- Cycle was Simulated with Combinations of the Following:
  - Turbine Adiabatic Efficiency: 80%, 90%
  - Heat Exchanger Pinch Point $\Delta T/T$: 5%, 3%
  - Hydrogen Pressure: 15 bar, 20 bar, 25 bar
  - Helium Pressure Ratio: 5, 6, 7
- Cycle Efficiency Ranged from 36% to 52%

Sample of Cycle Simulation Results



Main Features of Selected Approach

- Once-Through H_2 Liquefaction – 100% Yield
- Collins-Style cycle with He as Working Fluid
- Constant, Supercritical Pressure in H_2 Loop
- Components Use Established Technology and Facilitate Scalability
- Efficiency Through Effective Staging

- **POTENTIAL TO INCREASE EFFICIENCY BY 30% OVER PRESENT STATE-OF-THE-ART**

- **CONVENTIONAL COMPONENT USE AT REDUCED FLOW RATE PROMISES LOWER CAPITAL COST**

Next Steps in Project Work

- Integrate HX Model into Cycle Simulation
  - Determine Required Heat Exchanger UA and Hydrogen “View Factors” in Three Channel HX
- Gather Compressor and Expander Performance and Cost Data
- Simulate Several Additional Cycles
- Investigate Sensitivity of Various Parameters on Cycle Efficiency
- Get Feedback from Turbo-Expander Development Partner