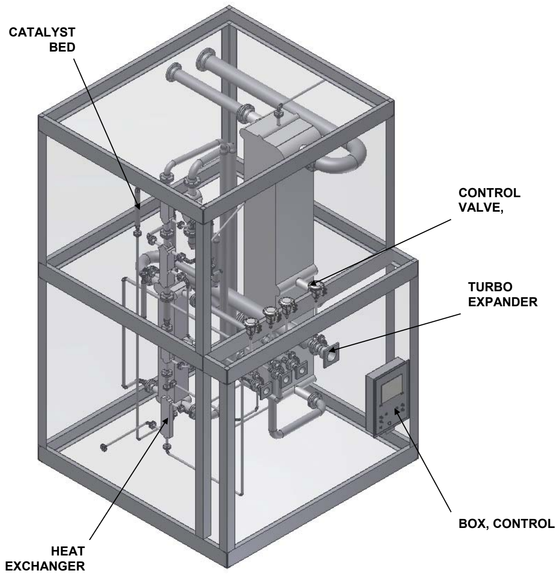
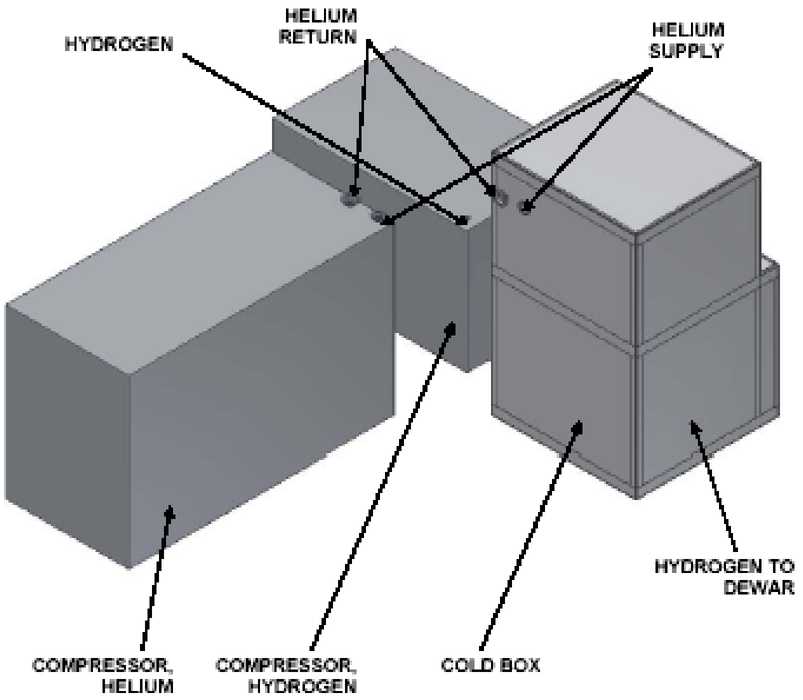
Innovative Hydrogen Liquefaction Cycle (Final Review)





Vadim Zykin
Gas Equipment Engineering Corporation

Project # PD026

2011 DOE Merit Review
May 10, 2011 (Poster)

H2 Liquefier Development Program

Timeline

Restart Date: Jan 2007
End Date: Sept 2011
Percent Complete: 80%

Budget

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

All DOE Funds Received (FY06-FY10)

FY11 Efforts Cost Share to finish project (scope reduced)

Barrier Addressed

High Cost and Low Efficiency of Hydrogen Liquefaction

Partners

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

Project History

- 2007 Proposal
- Started out as an effort to design an innovative liquefaction cycle AND build a pilot plant
  - Design successful, substantially more efficient
  - Pilot plant not affordable given the budget (500 kg/day –more than 100% of budget, by itself)
- Most of the effort spent on the design
- Project de-scoped to demonstrate a key component – the combined Heat Exchanger and Catalyst

Refined Project Objectives

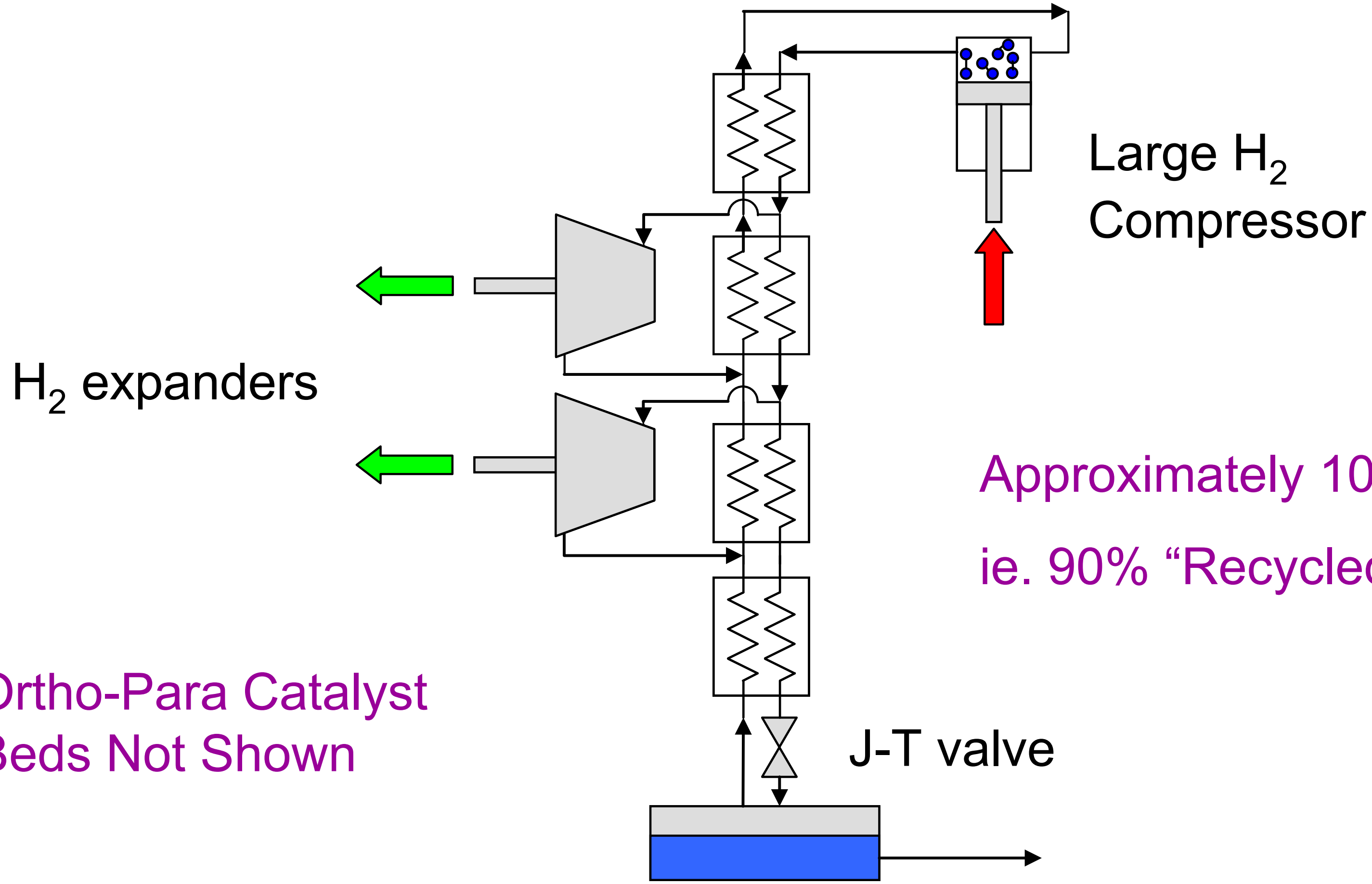
- Design a Practical H2 Liquefaction Cycle That Significantly Increase Efficiencies Over Existing Technologies — Complete

- Design a 50,000 kg/day Plant Using Low/No Risk Development Components — Complete

- Document a Significant Reduction in the Total Cost of H2 Liquefaction at the 50,000 kg/day Production Level — Complete

- Identify, Design, and Test the Key Component – Continuous Catalytic Heat Exchanger — In-Process

Present State of the Art
H_2 liquefaction - Claude cycle



Approximately 10% Yield

ie. 90% “Recycled” Flow

Ortho-Para Catalyst
Beds Not Shown

Design Process (Previously Briefed)

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 ΔT/T: 1 to 5%
  - Hydrogen Pressure: 15 bar, 20 bar, 25 bar
  - Helium Pressure Ratio: 5, 6, 7
  - Compressor Efficiencies: 65 to 85%

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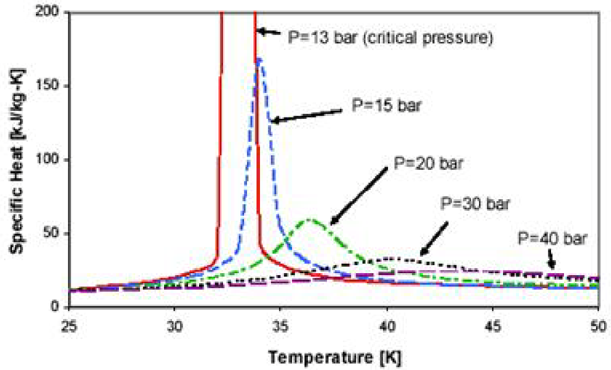
Supercritical Hydrogen Isobars



Increasing Pressure Reduces the Cooling Load at Low Temperature

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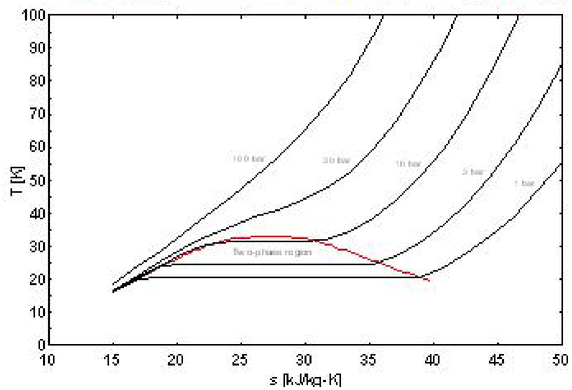
T-S Diagram For Normal Hydrogen



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

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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

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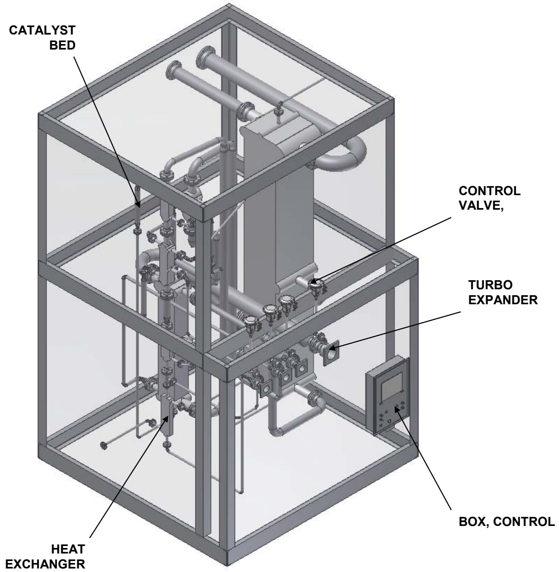
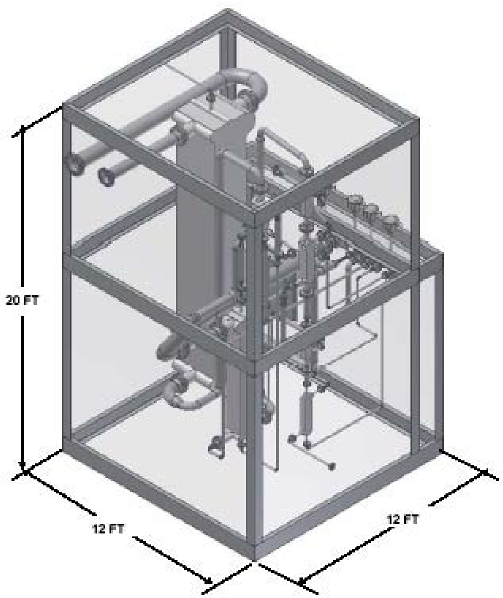
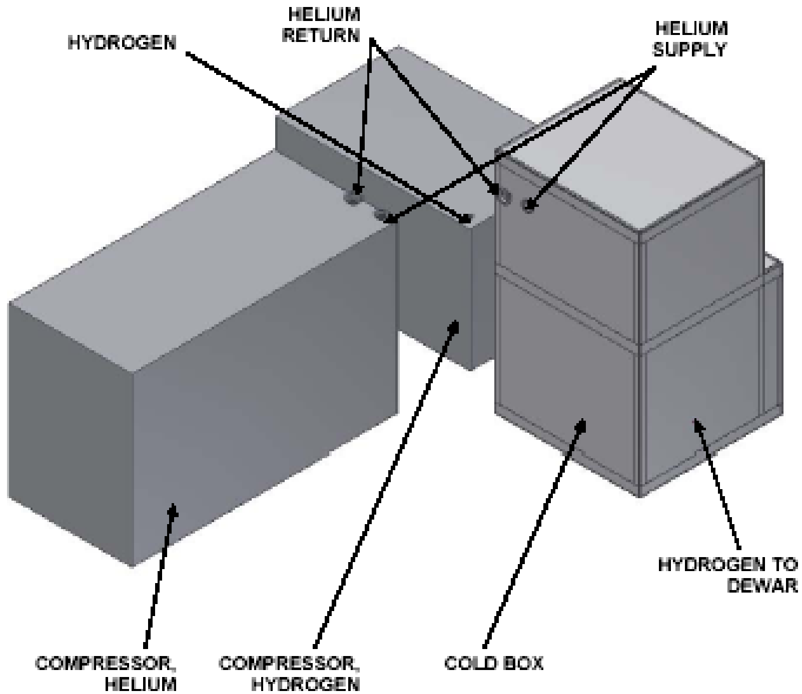
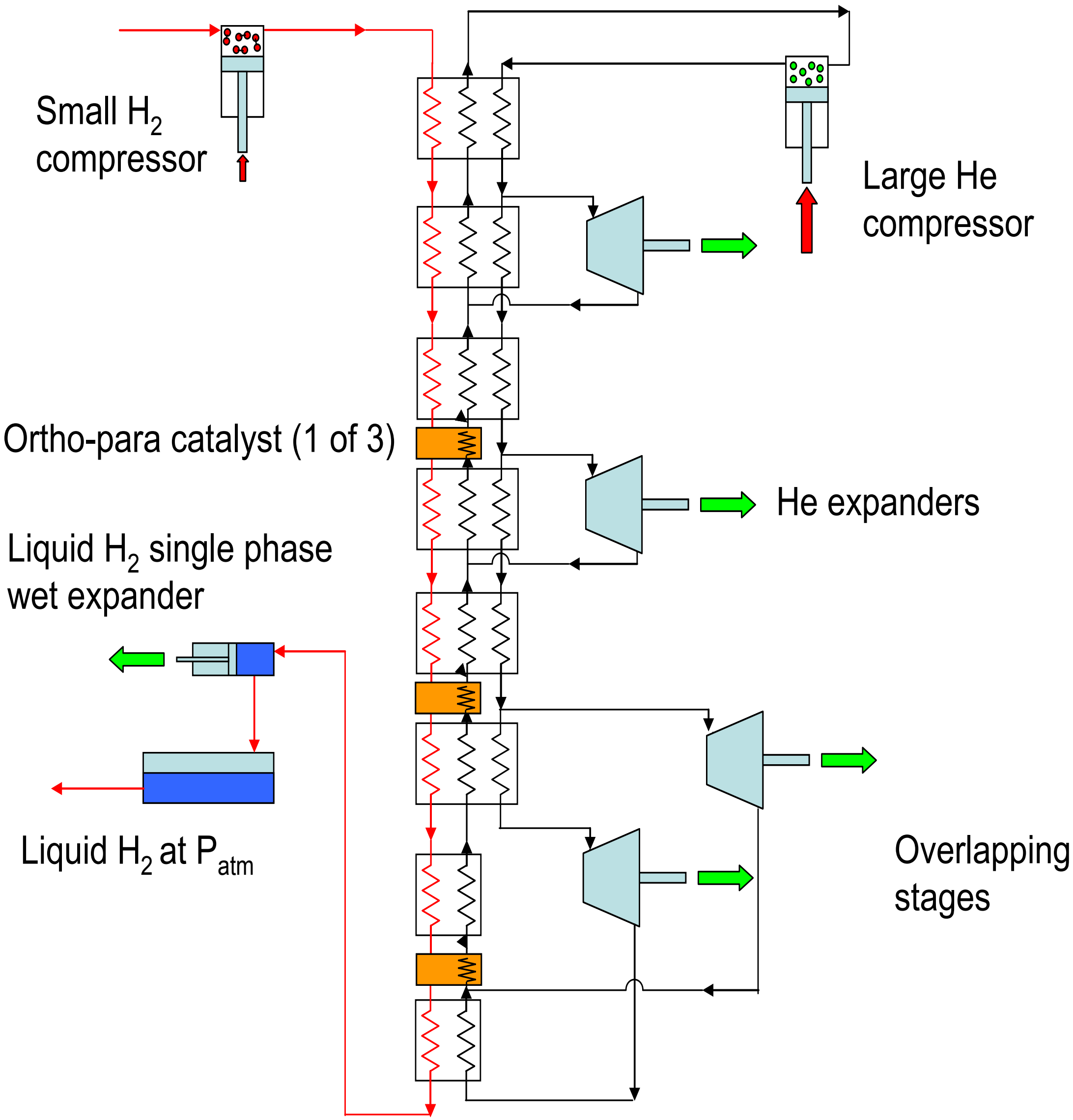
Pilot Plant Design







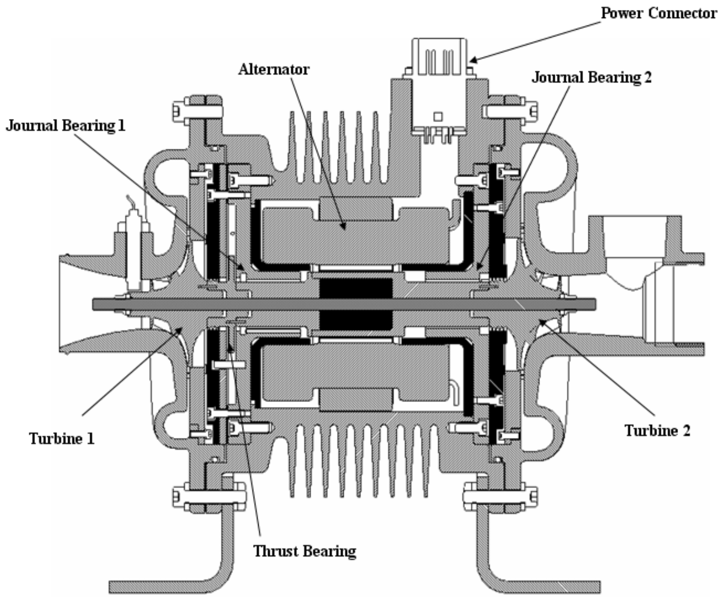
Final Design, Single Pass, High-Pressure H_2 Liquefaction

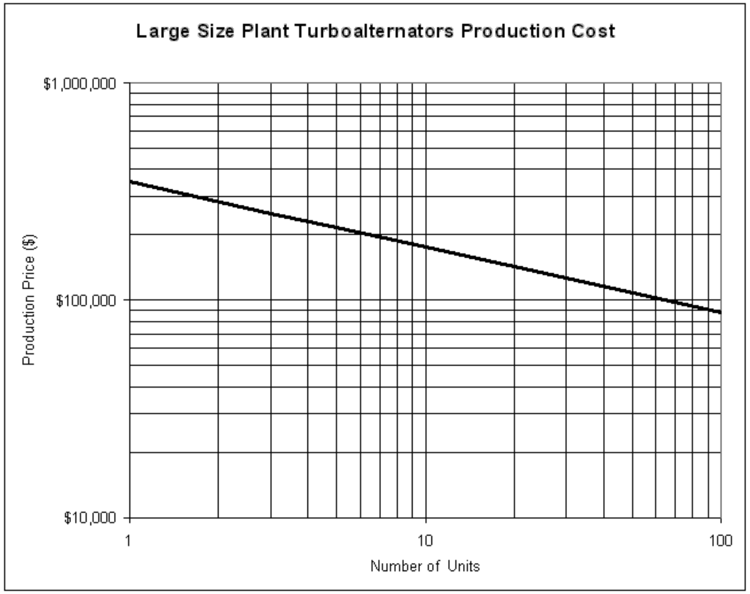


Liquefier Performance		Pilot	Large
System parameters	$\Delta T/T$	0.03	0.03
	η_{exp1}	0.6	0.85
	η_{exp2}	0.7	0.83
	η_{exp3}	0.75	0.86
	η_{exp4}	0.65	0.86
	$\eta_{comp,He}$	0.65	0.8
	$\eta_{comp,H2}$	0.6	0.8
	$\eta_{wet\_expander}$	0.9	0.9
	P_{H2} [bar]	21	21
	$P_{He,high}$ [bar]	15	15
	$P_{He,low}$ [bar]	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 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





Equipment Cost Estimate Completed

Major Equipment	Qty	Pilot (500kg/day)	Qty	50,000 kg/day
Compressor, H2	1	$400,000.00	3	$5,700,000.00
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**

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

**** 2008 Estimate ~20% low for 2011**

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**

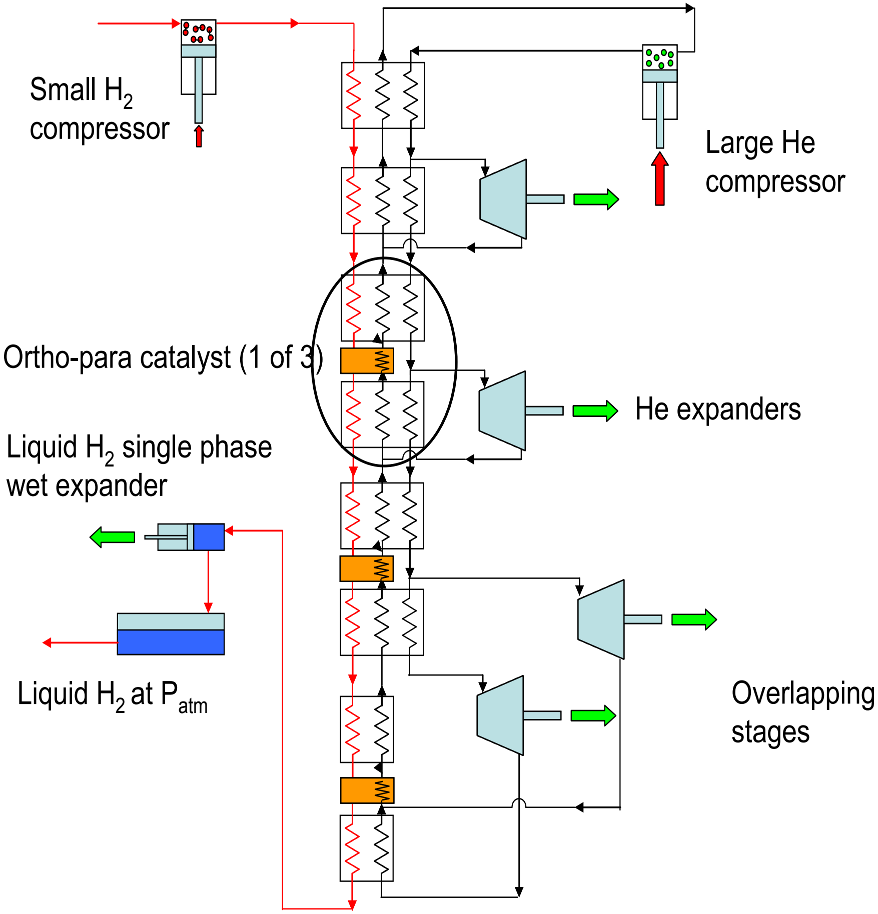
Key Components Identified

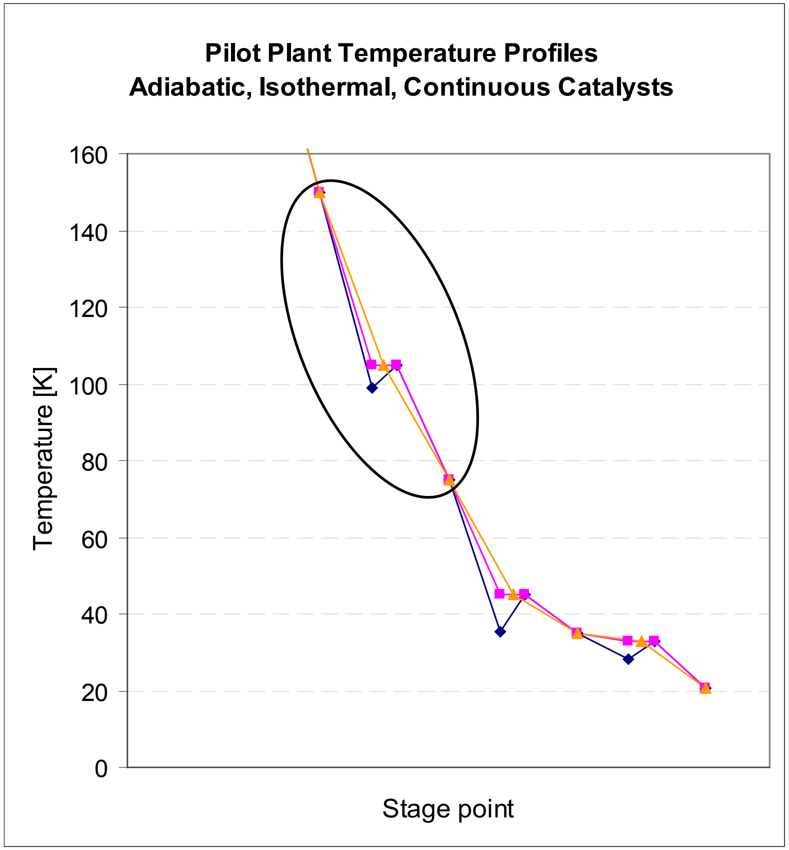
Requiring Some Level of Development

- **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

CHEX Selected For Demonstration Testing

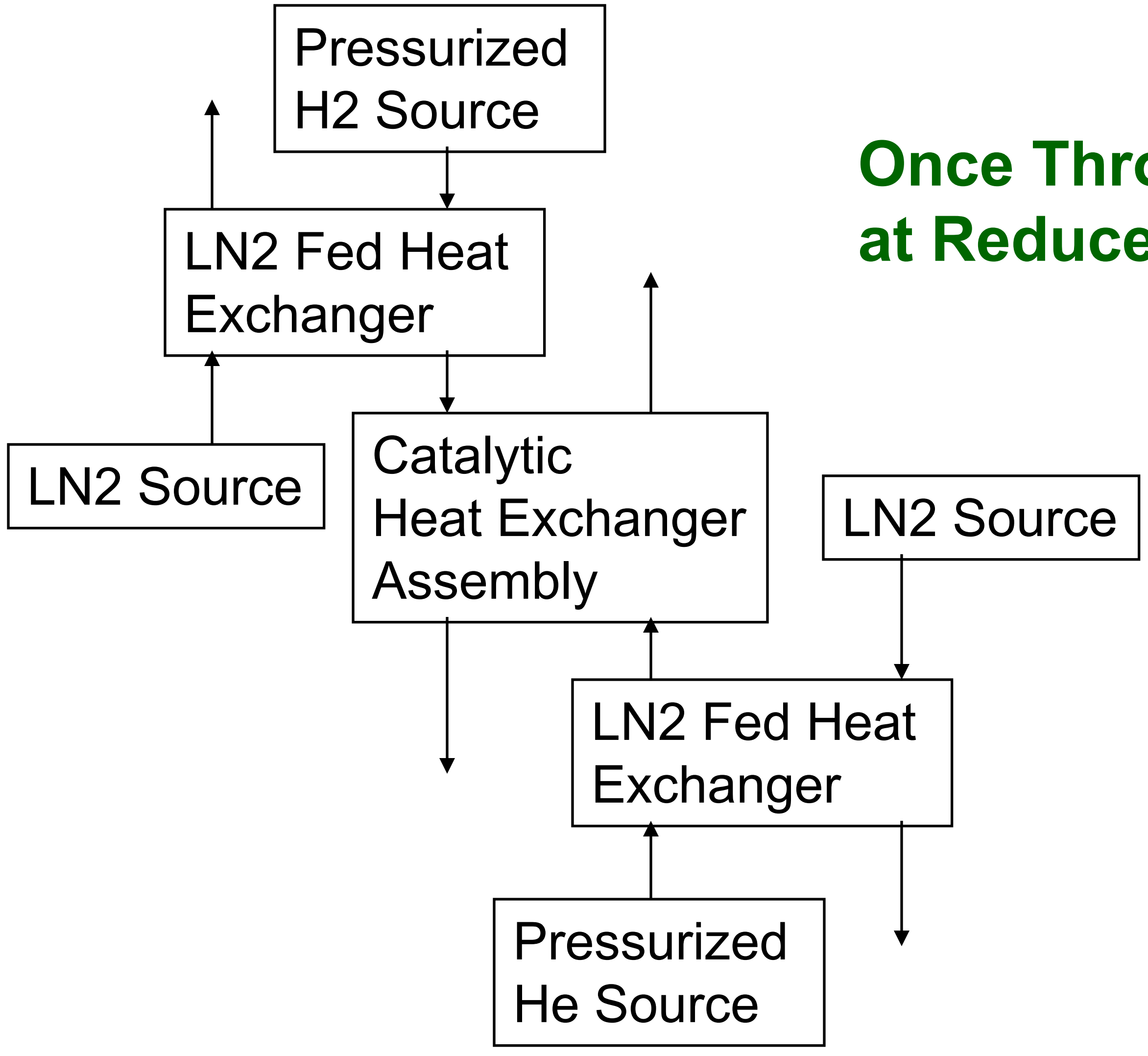
Once-Through, H2 Liquefaction Cycle





Selection Enables Cost Effective Testing at Cryogenic Temperatures Using LN2 Cooling

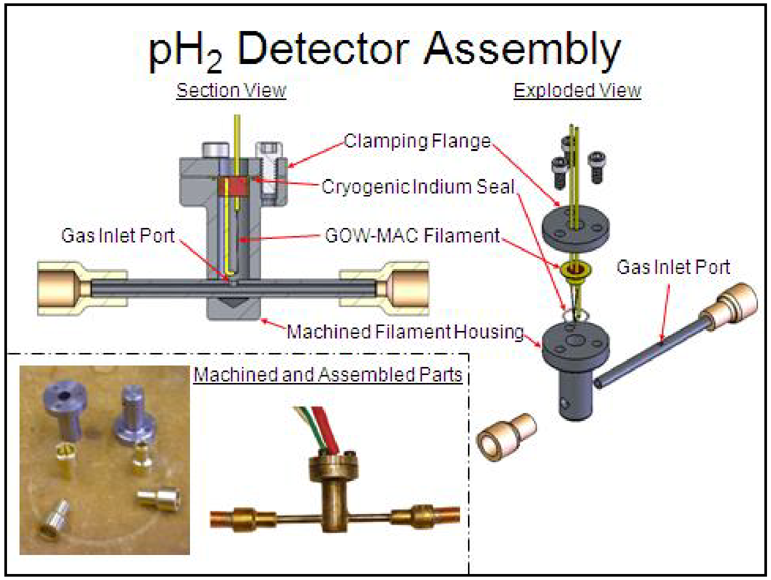
Concept of Test Loop for Catalytic Heat Exchanger Demonstration Testing

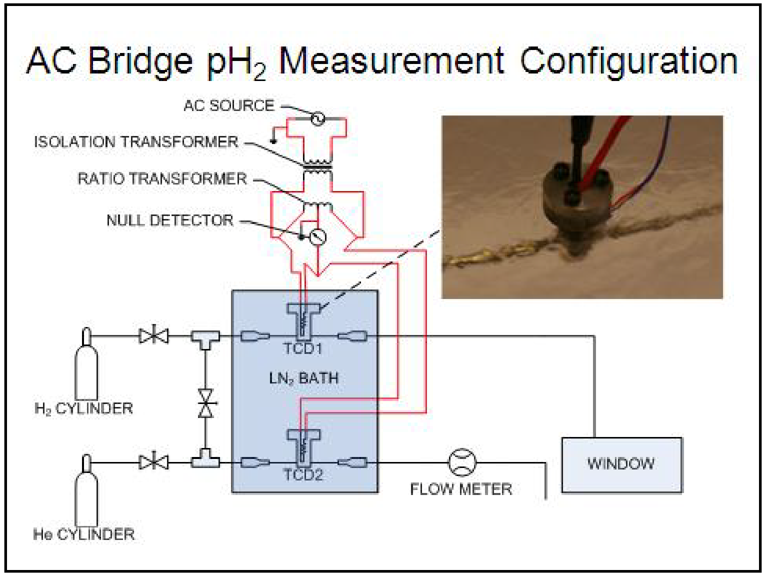


Once Through Testing at Reduced Scale

CHEX Testing Goals

- **Perform Testing of CHEX at Cryogenic Temperatures**
  - **Produce a Para-Ortho Measurement Device For These Temperatures (Completed)**
- **Build and Test Sub-Scale CHEX**
  - **Adiabatic Test Article**
  - **Continuous CHEX**
- **Validate Model Results**
- **Demonstrate Practical, Scalable CHEX Design**





The CHEX Test Article Design Was Completed

Problems with parallel plates…

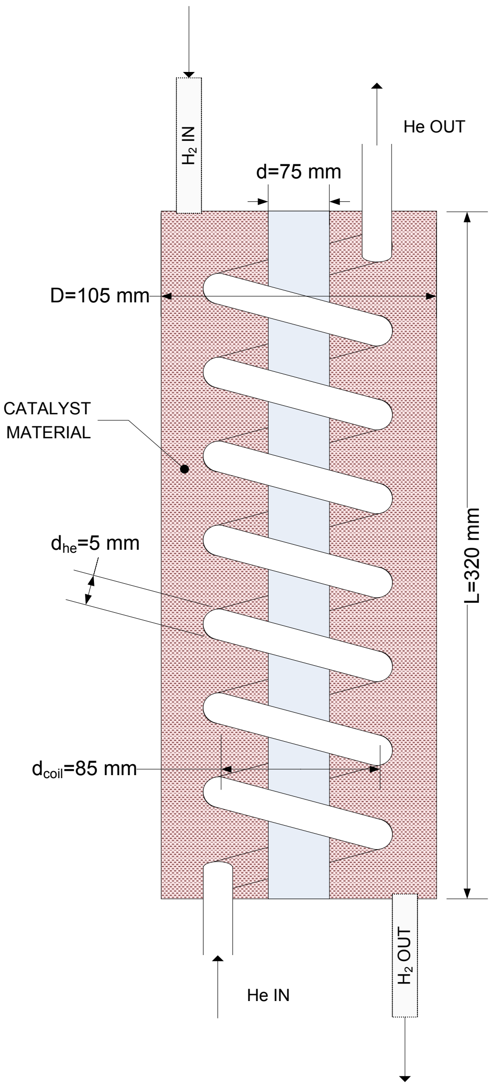
- Difficult to manufacture reliable seals between H2 and He passages
- Maldistribution due to variation in duct width
- Large flat surfaces with large ΔP
- Parallel pathways do not communicate with each other

Solution: Develop tubular design

- equal catalyst volume,
- stream-to-stream surface area, and
- helium stream cross-sectional area

Basic design

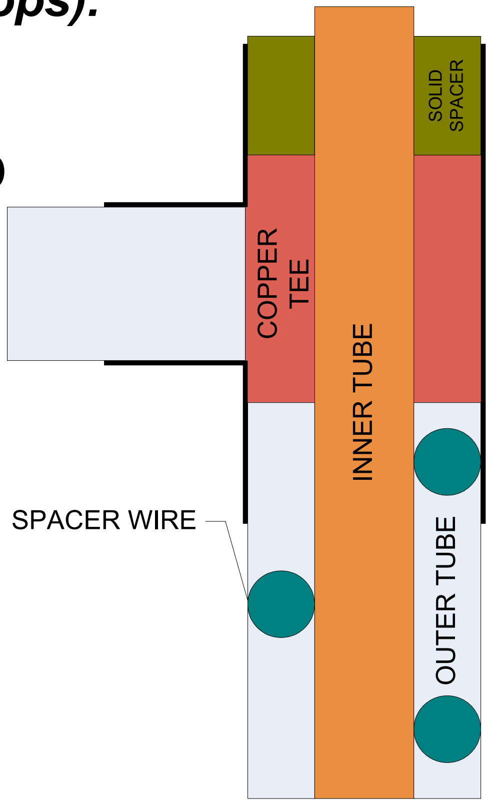
- Annular space filled with catalyst
- 8 parallel, helical counter-flow cooling passages (8-start helix)
- Characteristic dimension in catalyst approximately equal to parallel plate design



The Auxiliary Heat Exchangers for the Test Apparatus Were Sized

Sizing the Auxiliary Heat Exchangers
(recuperators for the independent H2 and He loops).

- Choose a desired HX effectiveness
- Calculate required NTU
- Choose an acceptable ΔP/P and determine L and D



Geometry:

Coiled concentric tubes (to fit Dewar)

Results :

<u>H2 Recuperator</u>

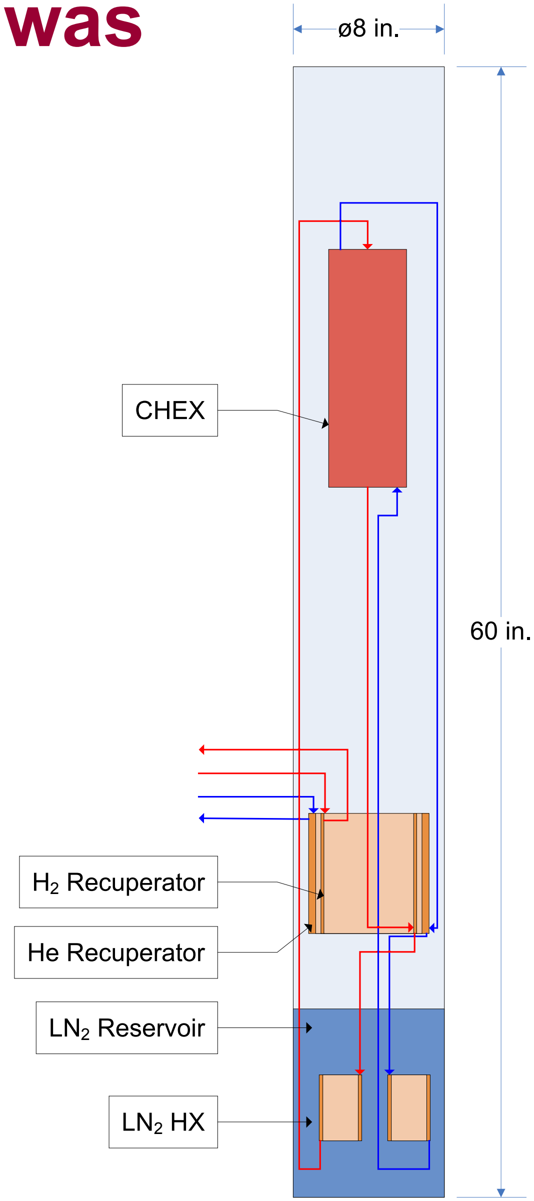
ε=0.85, NTU=4.96, UA=37.9 W/K, ΔP/P=0.01
Din=3.5 mm, Dout=5 mm, L=2.7 m

<u>He Recuperator</u>

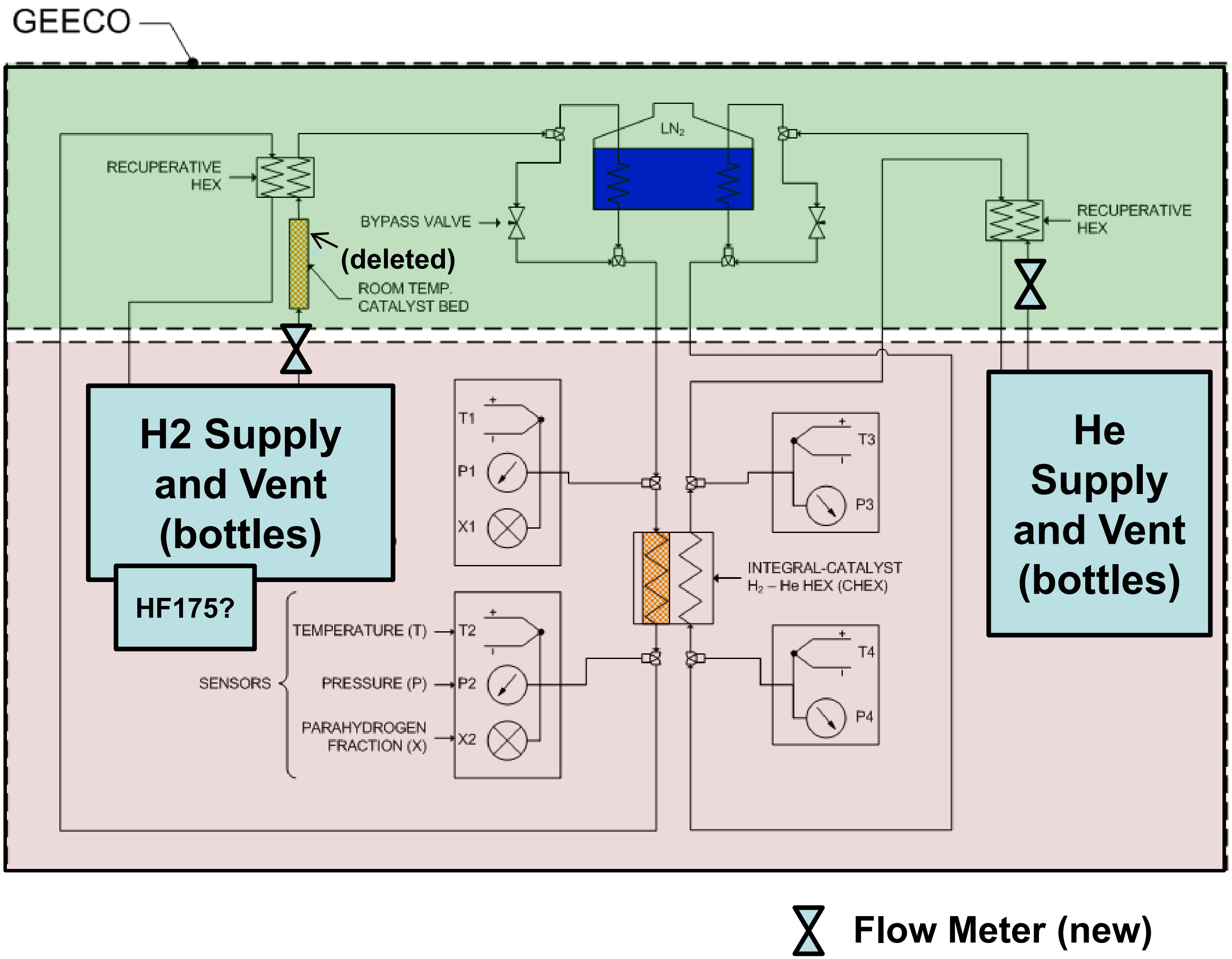
ε=0.75, NTU=3, UA=27.4 W/K, ΔP/P=0.05
Din= 7.4 mm, Dout=10.5 mm, L=3 m

The Test Article "Cold Box" was Designed

- Use Existing Cryostat
- Sized to Accept Cryogenic Recuperators and Heat Exchangers
- Tubing and Instrumentation Will Pass Thru Cryostat Upper Lid



CHEX Test Apparatus (GEECO Facility Variant)



Summary

- Design developed that 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
- Equipment cost also acceptable
  - ~40% OF H2A ESTIMATE (2008 Number)
  - Development Risk and Cost Uncertainty Minimized
- Program testing a key component of the system, the CHEX, in 2011 – Project ends this September
- GEECO would like to acknowledge the efforts of our partners in this project, R&D Dynamics, and MIT