Active Magnetic Regenerative Liquefier

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Heracles Energy Corporation d.b.a. Prometheus Energy

May 10, 2011

PD019

Overview

Timeline

- Start date: June 2008
- Project end date: May 2012[*]
- ~75 % of authorized spent as of March 31, 2011
- ~56 % of total award spent[*]

[*](due to ~ 9 months of delays)

Budget

- $2.5 MM total award
  - DOE: $2.0 MM
  - Prometheus: $0.5 MM
- Total Funding FY10: $0.4 MM
- Planned Funding FY11: $0.25 MM

Barriers

- Barriers addressed
  - High capital cost and low energy efficiency of current hydrogen liquefaction
  - Delivery cost of <$1.00/gge
  - 30 te/day: $40 MM; 75% η_{DOE}

Partners

- Prometheus Energy is project lead
  - UW, UVic, UQTR collaborations
  - Special vendors; eg CryoMagnetic
  - Visitors for GO/NO GO included BMW, LLNL, PNNL, ANL

Relevance: Develop a More Efficient H_2 Liquefier

- LH_2 is a potential pathway for large-scale H_2 transport, but currently relies on the costly, low efficiency Claude expansion cycle. There is a need to reduce both the capital and O/M cost for LH_2 to become economically viable for large-scale utilization.

$$\dot{W}_{ideal} = \dot{m}\,[T_H(S_H - S_f) + (h_f - h_H)]$$

$$\dot{W}_{Real} = \dot{W}_{ideal} + T_H\,\dot{S}_{Irrev\,Total}$$

$$\dot{S}_{Irrev\,Total}\,(magnetic) \ll \dot{S}_{Irrev\,Total}\,(gas)$$

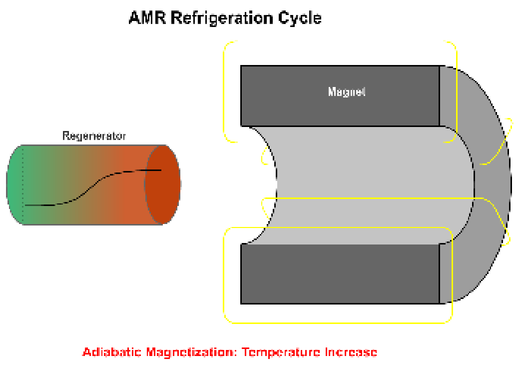
$$FOM = \dot{W}_{Ideal}/\dot{W}_{Real} \quad so \quad FOM\,(magnetic) \gg FOM\,(gas)$$

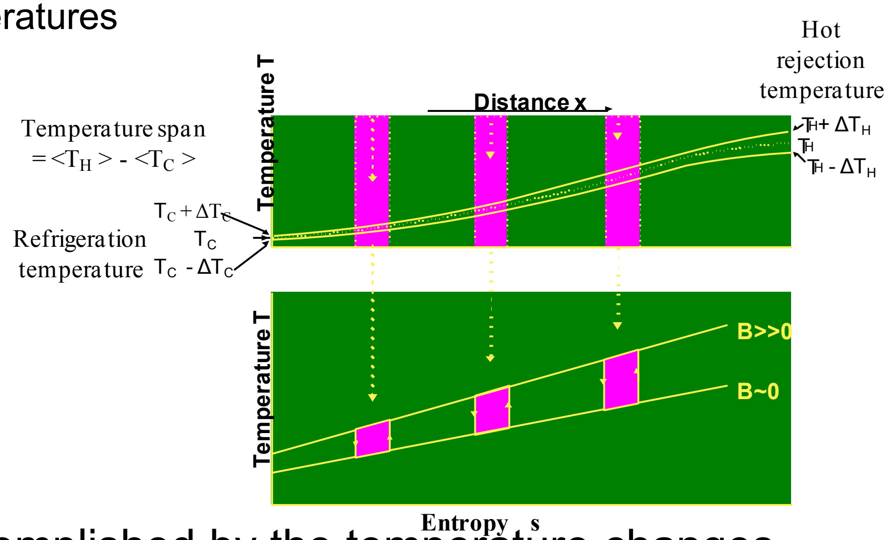
- The objective of this project is to analyze, design, fabricate, and test two liquefier prototypes based on magnetocaloric technology to help meet DOE’s targets for capital cost and energy efficiency for LH_2 delivery.

- DOE’s efficiency target is 75 % @ 30 te/day [~113,229 gpd] with $40 MM for a ‘turn key facility’ [~$353/gpd].
  - FOM (magnetic cycle) ~ 0.6 ; FOM (best gas cycle) ~ 0.35

What is an Active Magnetic Regenerative Liquefier (AMRL)?

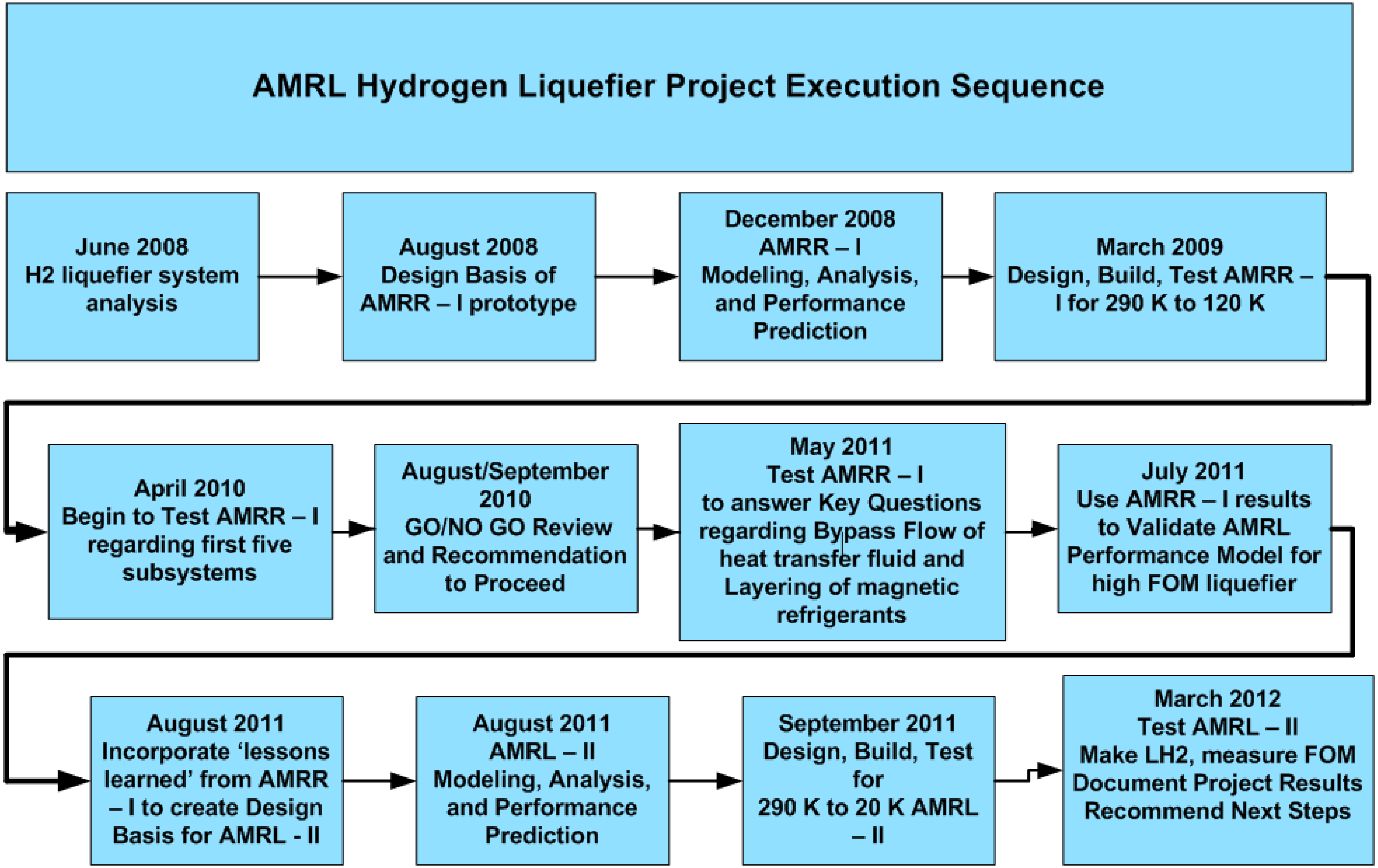
- In magnetic cycles, the “refrigerants” are solid magnetic materials whose entropy can be manipulated by an external magnetic field
  - Use ferromagnets near their Curie temperatures
  - Basic process is semi-reversible





- Rejection & absorption of heat are accomplished by the temperature changes upon magnetization/demagnetization, respectively
  - Heat transfer fluid required to couple solid refrigerant to heat source/sink
  - Solid refrigerants in porous beds offer excellent heat transfer; i.e., small temperature approach
- Adiabatic temperature changes of magnetic refrigerants depend on:
  - On ratio of initial temperatures to magnetic ordering temperature;
  - On ratio of initial and final magnetic field;
  - Typical changes are ~10-15 K for a 7 T field change
- Limited temperature spans of individual magnetic refrigerants overcome with regenerative cycles that use several layers of refrigerants in a porous bed

Project Approach



AMRL Hydrogen Liquefier Project Execution Sequence

June 2008
H2 liquefier system analysis

August 2008
Design Basis of AMRR – I prototype

December 2008
AMRR – I
Modeling, Analysis, and Performance Prediction

March 2009
Design, Build, Test AMRR – I for 290 K to 120 K

April 2010
Begin to Test AMRR – I regarding first five subsystems

August/September 2010
GO/NO GO Review and Recommendation to Proceed

May 2011
Test AMRR – I
to answer Key Questions regarding Bypass Flow of heat transfer fluid and Layering of magnetic refrigerants

July 2011
Use AMRR – I results to Validate AMRL Performance Model for high FOM liquefier

August 2011
Incorporate ‘lessons learned’ from AMRR – I to create Design Basis for AMRL - II

August 2011
AMRL – II
Modeling, Analysis, and Performance Prediction

September 2011
Design, Build, Test for
290 K to 20 K AMRL – II

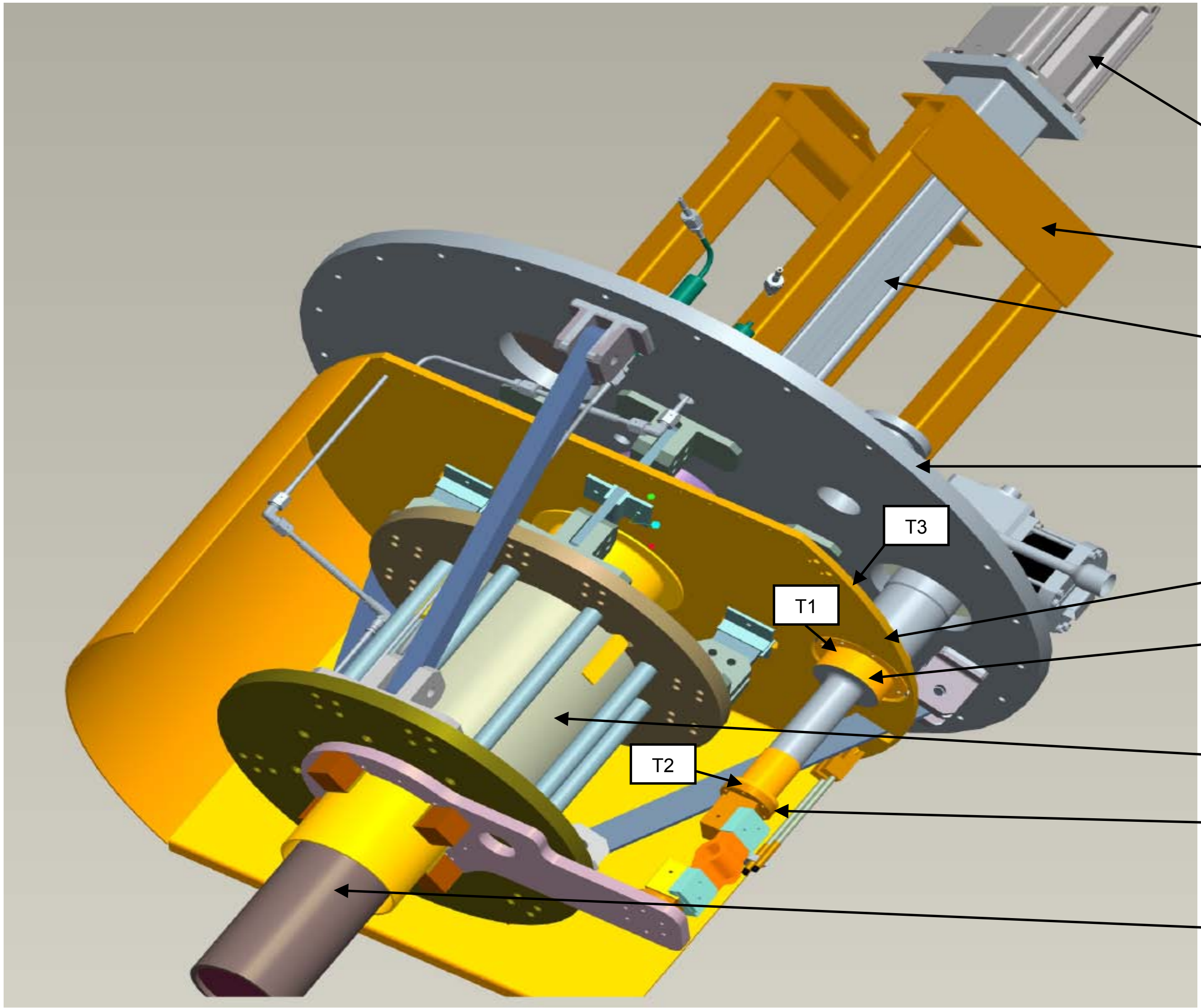
March 2012
Test AMRL – II
Make LH2, measure FOM
Document Project Results
Recommend Next Steps

Project Effort/Milestones Over the Past Year

- Complete the design, fabrication, and test of the magnetic regenerators, the drive, and the heat transfer fluid subsystems of our reciprocating active magnetic regenerative refrigerator (AMRR) prototype
- Test the integrated eight subsystems of our first AMRR prototype
- Experimentally measure the cooling power, work input, and efficiency of an AMRR prototype using Gd spheres and a 7 T magnetic field as a function of the amount of bypass flow of the heat transfer fluid for ~290 K to ~240 K temperature span
- Compare measured performance data against our numerical process simulation calculations of this specific reciprocating dual regenerator AMRR prototype.
- Measure temperature span, cooling power, work input of a multi-layer regenerator
- Incorporate lessons learned from first prototype into the design of a rotary AMRL prototype to span from ~290 K to ~20 K and produce LH_2 with a FOM of ~0.5.

Milestone	Planned	Actual	Comment
Go/No Go meeting and decision to move to Phase II of this project.	8/23/2010	9/15/2010	Progress & promise of AMRL → GO decision
Completing assembly of final 3 of 8 subsystems of 1st reciprocating AMRR prototype.	12/31/2010	3/31/2011	Changed heat transfer fluid subsystem design from He to liquid to He.
Initial testing of integrated AMRR prototype	4/30/2011	5/9/2011	Latest test results at AMR poster session

Technical Accomplishment – Reciprocating AMRR Prototype Design Completed



Actuator drive motor

Actuator mechanical support

Linear actuator

Lid for high vacuum cold box

Heat Shield

Cryocooler 1st Stage

Superconducting Magnet

Cryocooler 2nd Stage

Warm bore: encloses regenerators, fluid (heat transfer) subsystems and instrumentation

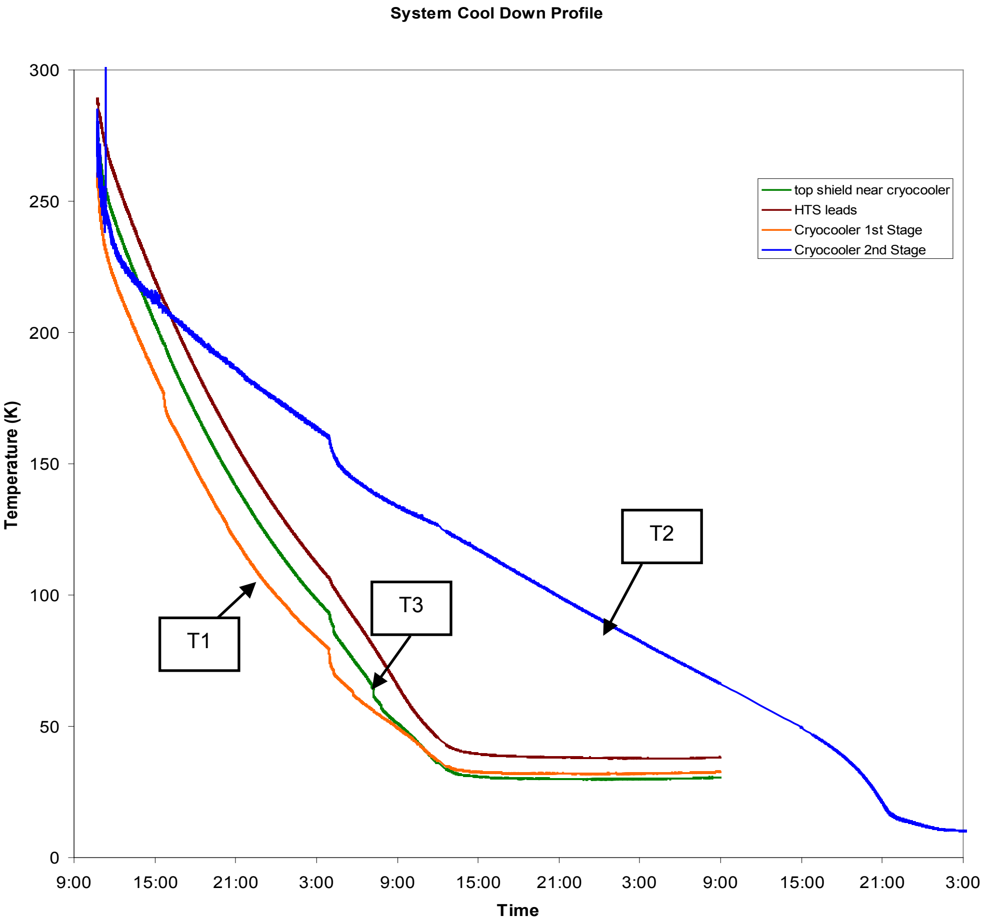
Technical Accomplishment –
Gd Magneto-caloric Effect Verified

- Validated the magnetocaloric behavior of Gd refrigerant material with respect to the published literature (ΔT vs. B)

Gd inserted into 3T field (temperature increases)

Gd removed from 3T field (temperature decreases)

Technical Accomplishment - First Five AMRR Subsystems Successfully Integrated & Tested



- Reduced conductive heat leaks from support structure and instrumentation while reducing heat leaks form radiation and convection to very low values.
- Central bore of AMRR where dual reciprocating magnetic regenerators remain between ~290 K and ~120 K while superconducting magnet is ~ 4K.
- Measured heat leaks to magnet are ~0.3W compared to 1.5W design value.
- Magnet has been cycled on and off and the field profile has been measured and corresponds to design parameters.
- Cryocooler works very well; slightly exceeding vendor specifications.

Technical Accomplishment – Optimized Magnetic Regenerators Designed for the AMRR

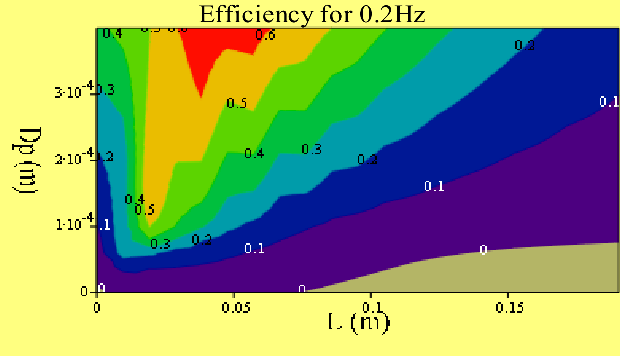
- A irreversible entropy minimization MathCad model was written to calculate comparative thermodynamic performance of different regenerators. Efficiency and cooling power were simultaneously optimized simultaneously with respect to:
  - T_{cold} ; regenerator length; Gd particle diameter; drive actuator frequency
- Regenerator diameter, drive actuator cycle, and heat transfer fluid (HTF) can also be changed. HTF mass flow rate is optimized for actuator frequency and adiabatic temperature change (ΔT_{cold}) data for Gd and total cooling power can be maximized.
- This regenerator design model considers tens of thousands of configurations in minutes and is used to guide more advanced simulations. Our advanced Fortran AMRR performance simulation model takes 1-2 days for each design point.

$$\dot{S}_{total} = \dot{S}_{heat\,transfer} + \dot{S}_{conduction} + \dot{S}_{pressure\,drop} + \dot{S}_{no-flow} + \dot{S}_{eddy\,currents}$$

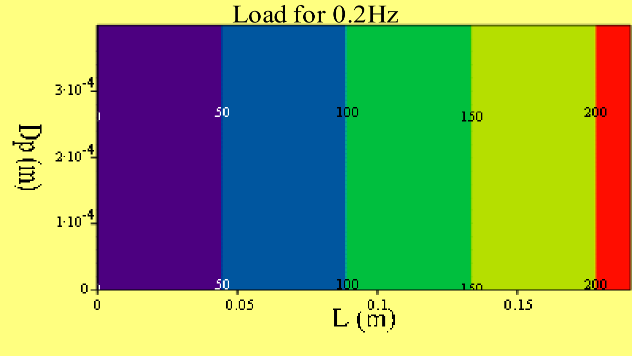
$$\eta = \frac{\dot{W}_{reversible}}{\dot{W}_{actual}} = \frac{\dot{Q}_C\left(\frac{T_H}{T_C} - 1\right)}{\dot{Q}_C\left(\frac{T_H}{T_C} - 1\right) + T_H\,\dot{S}_{total}}$$

Technical Accomplishment - Results of optimized regenerator design parameters

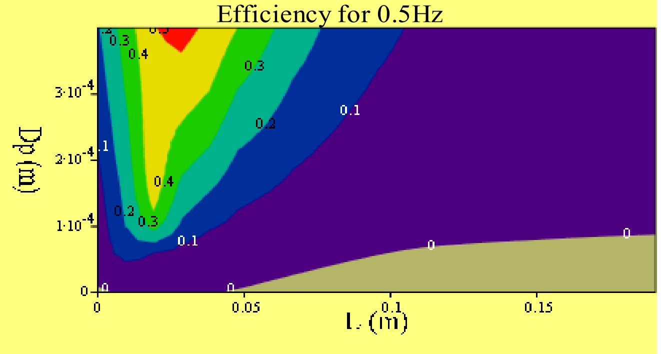
- Results for COPs from irreversible entropy calculations for cylindrical Gd magnetic regenerator geometries with $T_H = 295$ K, $T_C = 250$ K; maximum helium heat transfer fluid flow rate at 19 atm for various cycle frequency, but with no bypass flow.



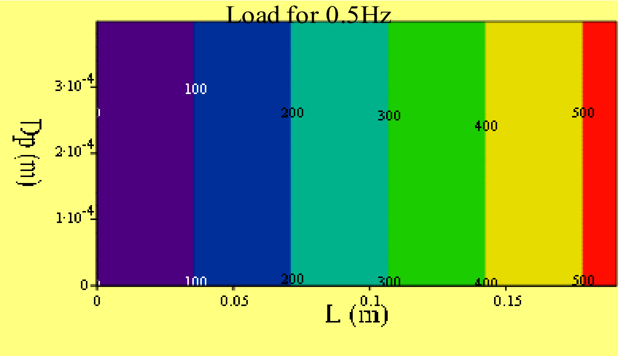
$$\left[\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.2\right)\right)^{\langle 2\rangle},\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.2\right)\right)^{\langle 4\rangle},\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.2\right)\right)^{\langle 15\rangle}\right]$$



$$\left[\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.2\right)\right)^{\langle 2\rangle},\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.2\right)\right)^{\langle 4\rangle},\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.2\right)\right)^{\langle 9\rangle}\right]$$



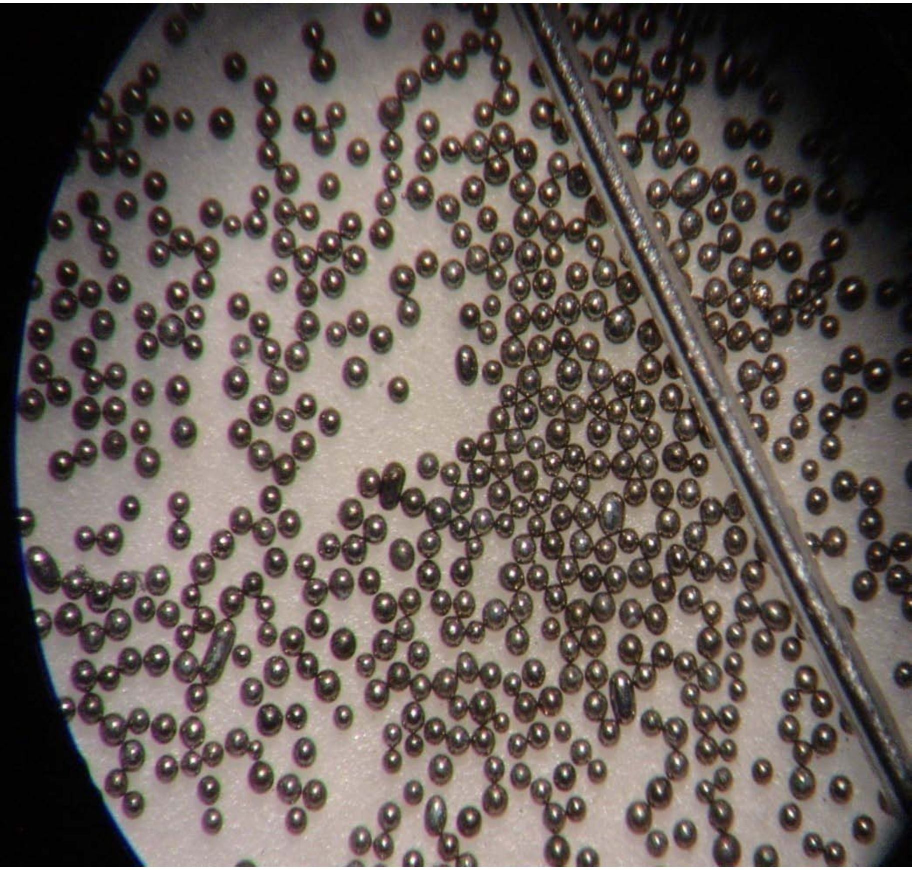
$$\left[\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.5\right)\right)^{\langle 2\rangle},\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.5\right)\right)^{\langle 4\rangle},\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.5\right)\right)^{\langle 15\rangle}\right]$$



$$\left[\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.5\right)\right)^{\langle 2\rangle},\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.5\right)\right)^{\langle 4\rangle},\left(\mathrm{Selfun}\left(\mathrm{Xcut},T_g,0.5\right)\right)^{\langle 9\rangle}\right]$$

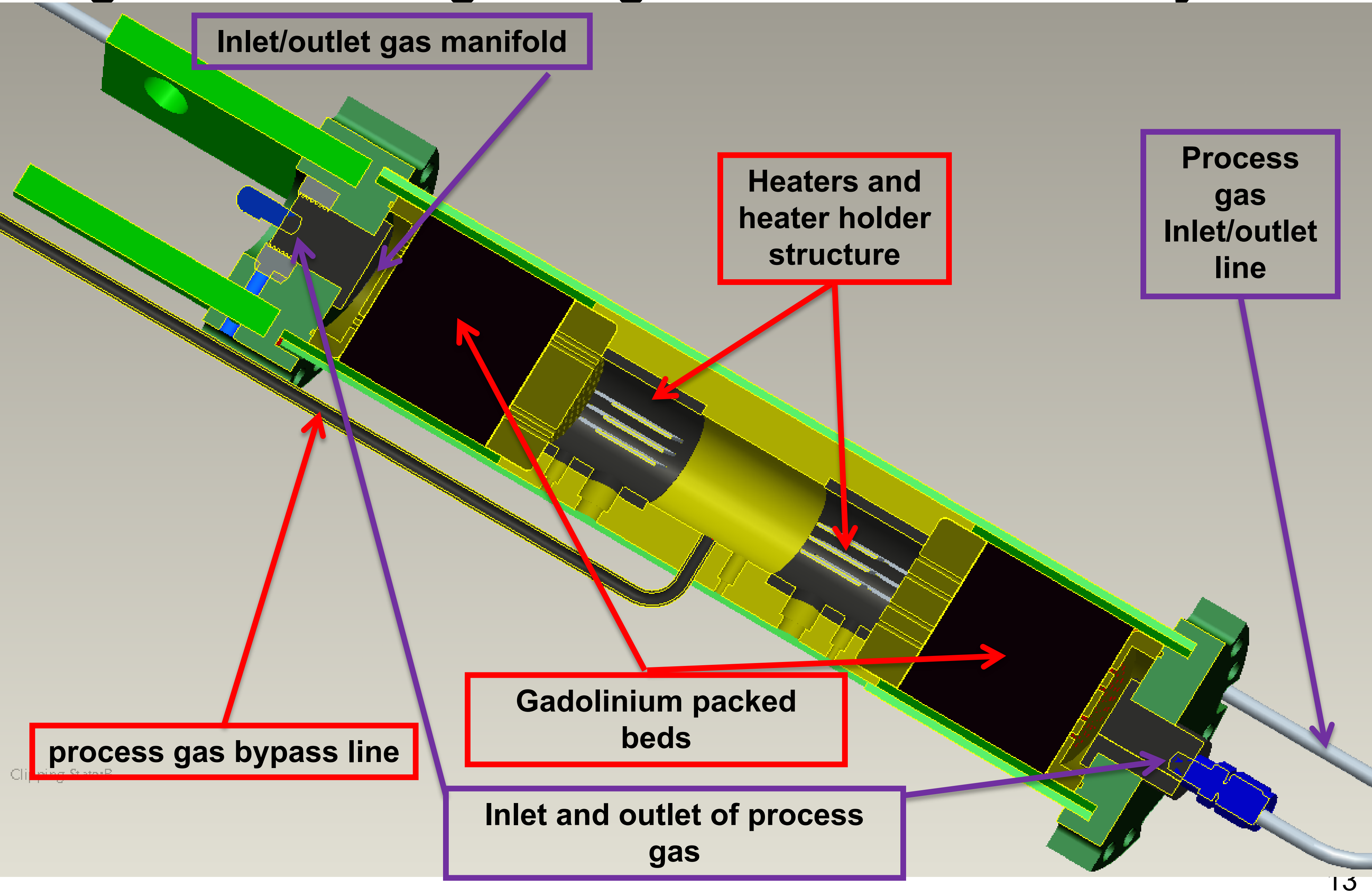
Technical Accomplishment – Spherical magnetic refrigerants substantially reduce fabrication costs and improve heat transfer fluid flow mechanics for regenerators

New spherical particles are ~100-200 microns



Regenerator materials are machined into ~200 - 250 micron chips for monolithic beds

Technical Accomplishment – Dual Magnetic Regenerator Design integrates numerous Subsystems



Inlet/outlet gas manifold

Heaters and heater holder structure

Process gas Inlet/outlet line

Gadolinium packed beds

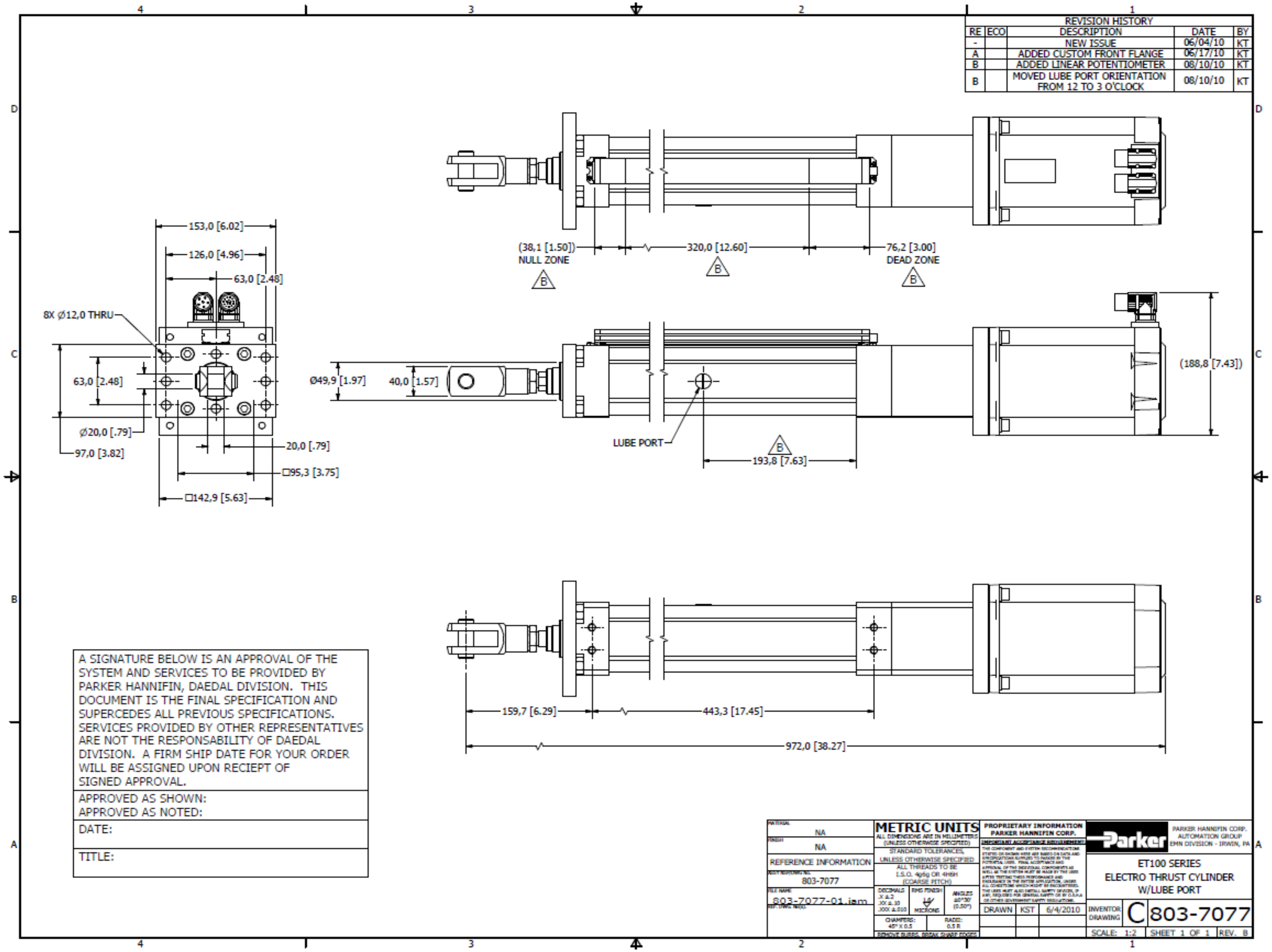
process gas bypass line

Inlet and outlet of process gas

Technical Accomplishment – Monolith Fabrication to eliminate motion of Gd particles during AMRR cycle

- **Gd spheres are being fabricated into identical monolithic dual reciprocating regenerators with support/drive/HTF**

Technical accomplishment – AMRR drive actuator was a challenge due to timing and net forces



REVISION HISTORY				
RE	ECO	DESCRIPTION	DATE	BY
-		NEW ISSUE	06/04/10	KT
A		ADDED CUSTOM FRONT FLANGE	06/17/10	KT
B		ADDED LINEAR POTENTIOMETER	08/10/10	KT
B		MOVED LUBE PORT ORIENTATION FROM 12 TO 3 O'CLOCK	08/10/10	KT

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APPROVED AS SHOWN:
APPROVED AS NOTED:

DATE:

TITLE:

MATERIAL: NA
FINISH: NA
REFERENCE INFORMATION
ASSY NUMBER/DWG No.: 803-7077
FILE NAME: 803-7077-01.iam
REF. DWG. No(s).

METRIC UNITS
ALL DIMENSIONS ARE IN MILLIMETERS
(UNLESS OTHERWISE SPECIFIED)
STANDARD TOLERANCES, UNLESS OTHERWISE SPECIFIED
ALL THREADS TO BE I.S.O. 4g6g OR 4H6H (COARSE PITCH)
DECIMALS .X ±.2 .XX ±.10 .XXX ±.010
RMS FINISH 1.6 MICRONS
ANGLES ±0°30' (0.50°)
CHAMFERS: 45° X 0.5
RADII: 0.5 R
REMOVE BURRS, BREAK SHARP EDGES

PROPRIETARY INFORMATION
PARKER HANNIFIN CORP.
IMPORTANT ACCEPTANCE REQUIREMENT

DRAWN KST 6/4/2010

Parker
PARKER HANNIFIN CORP.
AUTOMATION GROUP
EMN DIVISION - IRWIN, PA

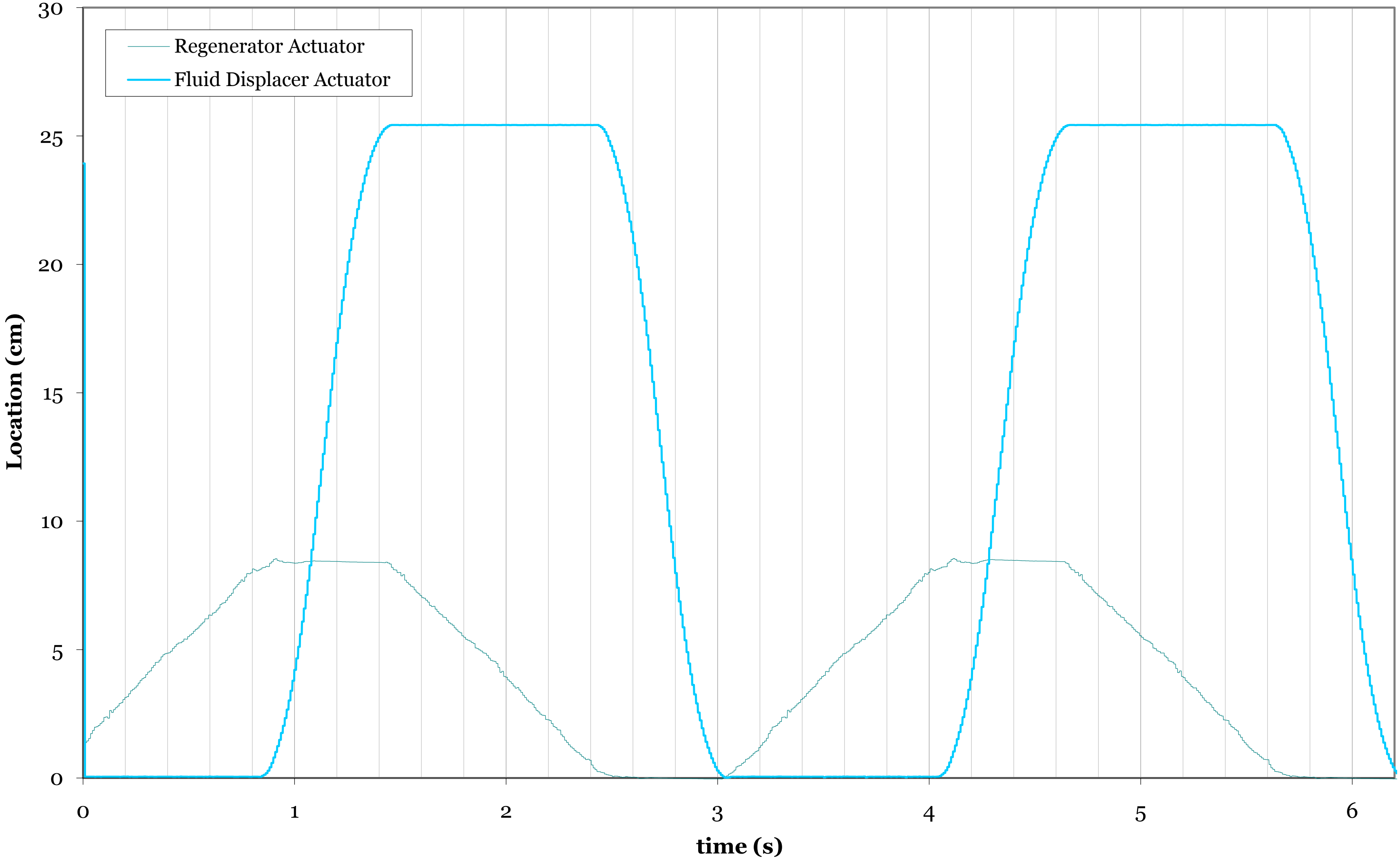
ET100 SERIES
ELECTRO THRUST CYLINDER
W/LUBE PORT

INVENTOR DRAWING C 803-7077
SCALE: 1:2 SHEET 1 OF 1 REV. B

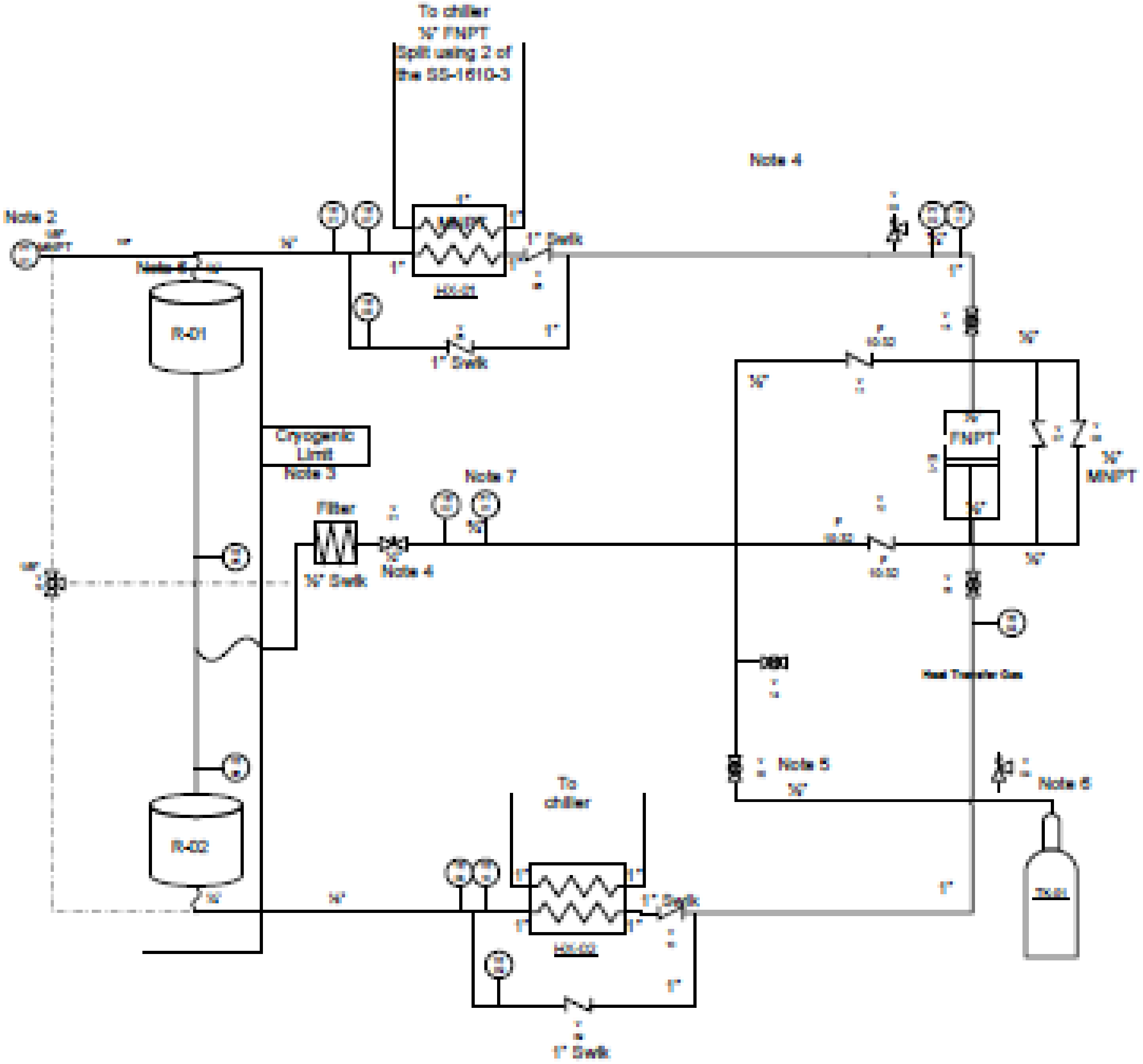
Technical accomplishment – AMRR drive actuator was purchased, assembled, & interfaced to LabVIEW

Technical accomplishment – The heat transfer fluid flow and regenerator drive motions for AMRR cycle

Measured Actuator Synchronization Test results using LabVIEW DAQ program
AMRR cycle requires no flow during regenerator movement in/out of magnetic field
AMRR cycle requires constant flow of HTF when regenerator is stationary



Technical accomplishment – The Heat Transfer Fluid subsystem is illustrated on this simplified P&ID

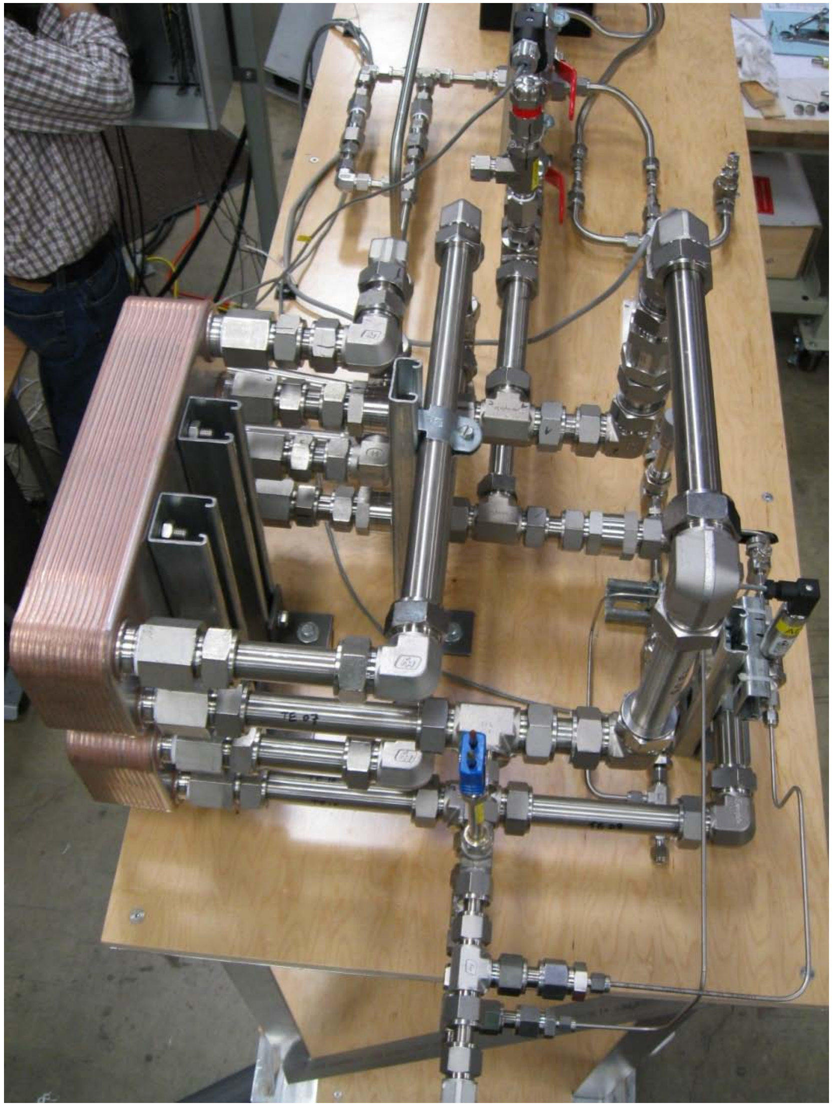


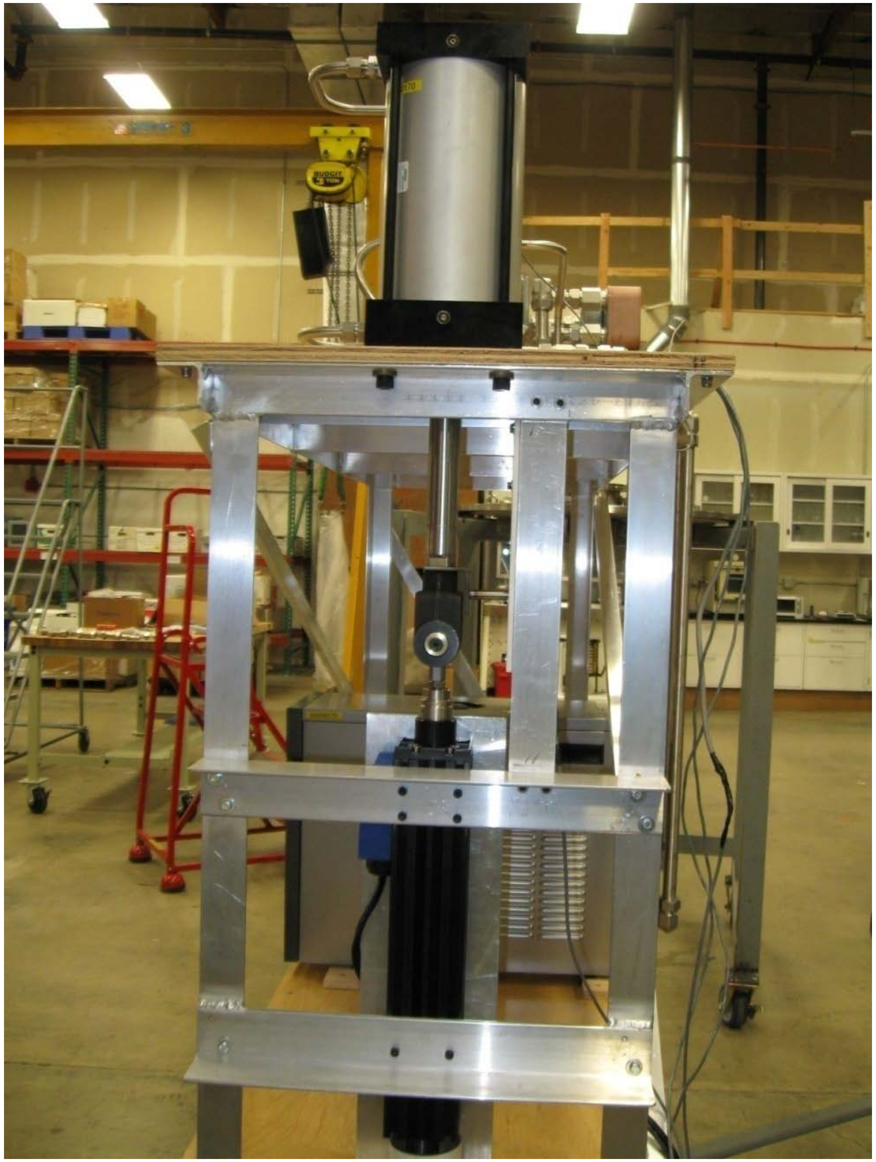
The He HTF flows in a reciprocating motion from hot to cold and cold to hot through the dual magnetic regenerators as they are moved in/out of the magnetic field.

The chiller insures that T_H is constant during the hot to cold blow period.

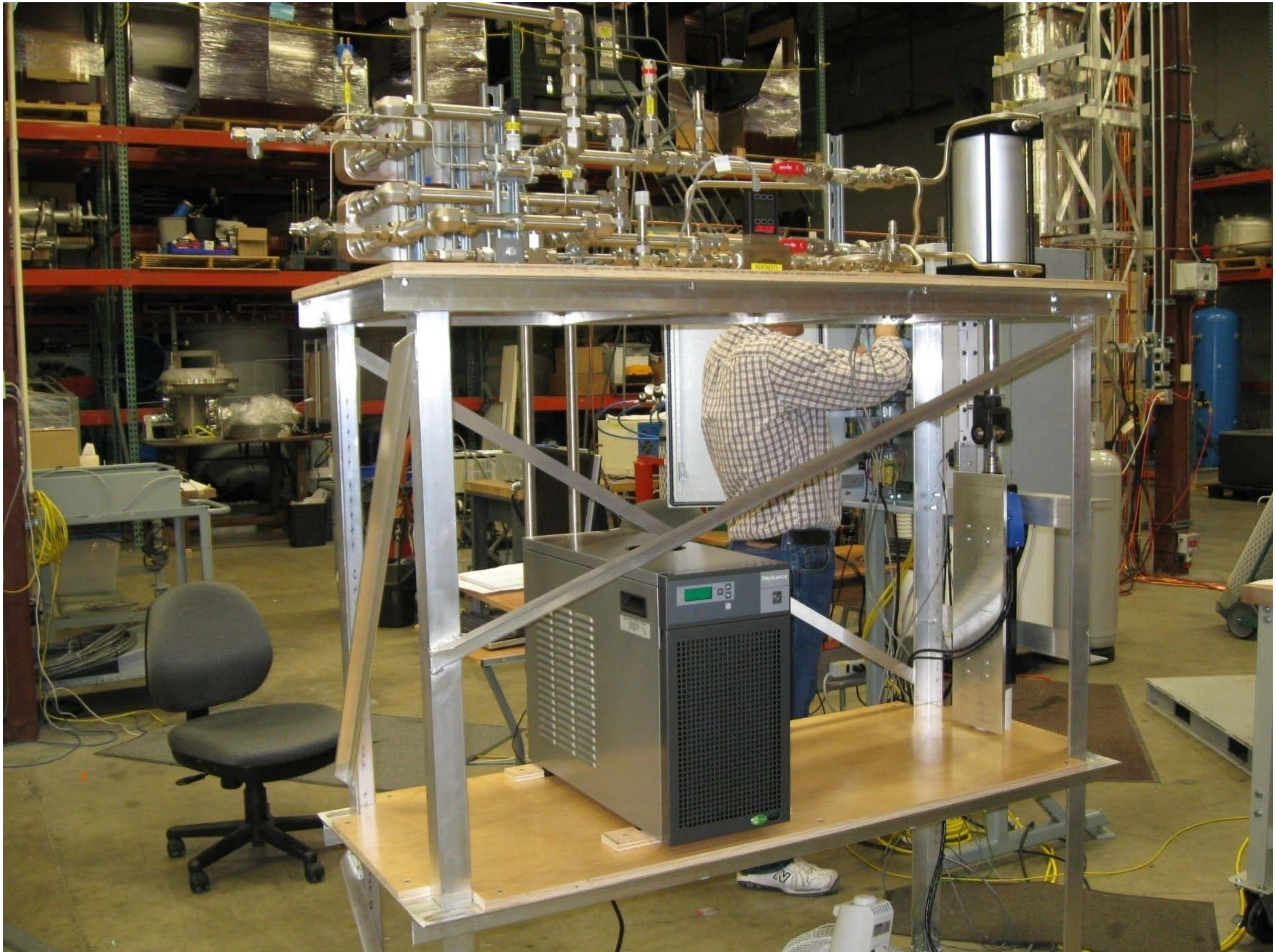
The cold thermal load HEX between regenerators is not shown although the bypass flow path is illustrated as coming out of the cold region.

Technical accomplishment – AMRR fluid actuator with coupling to HTF positive displacement pump

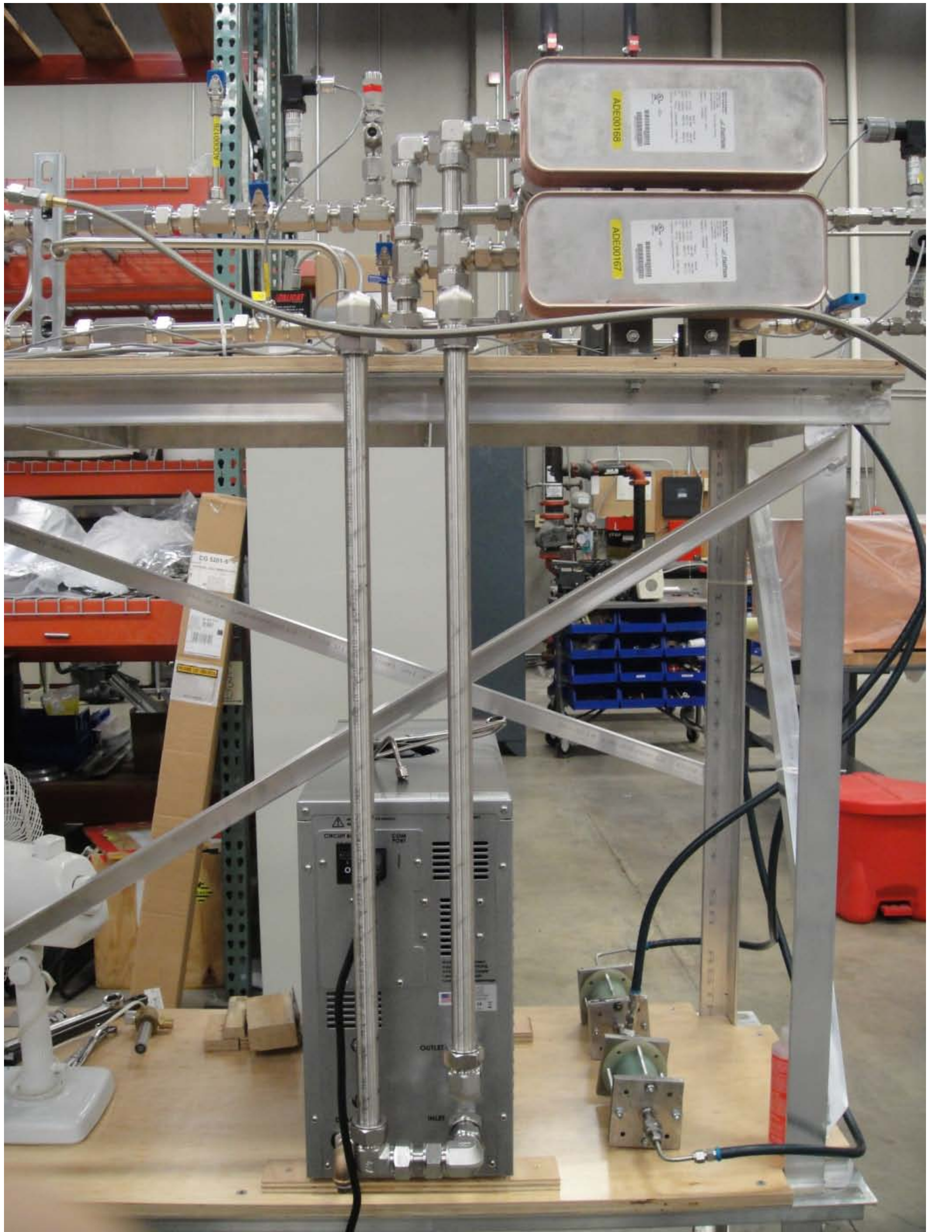




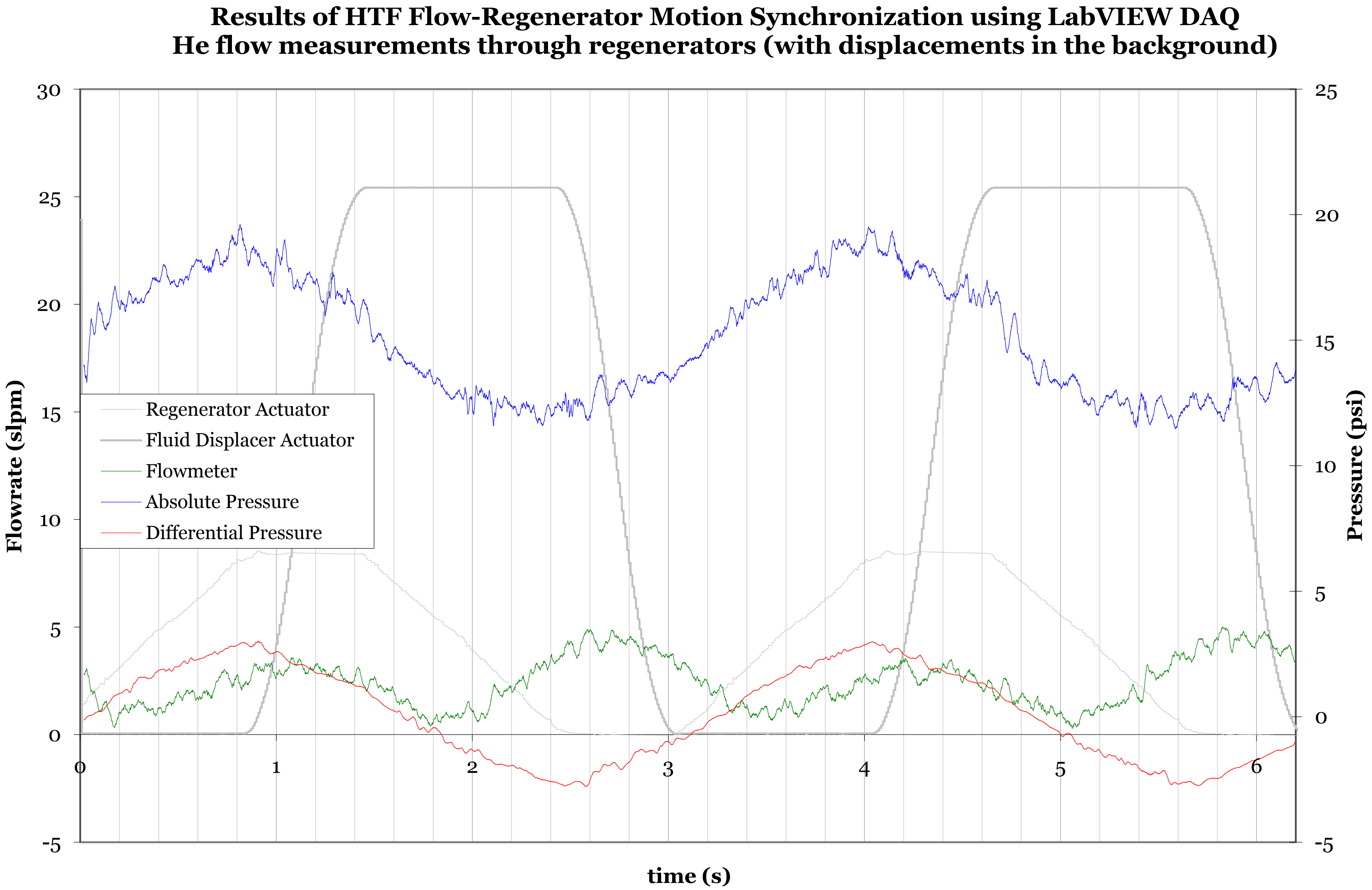
Technical accomplishment – Heat Transfer Fluid components are shown in this photograph



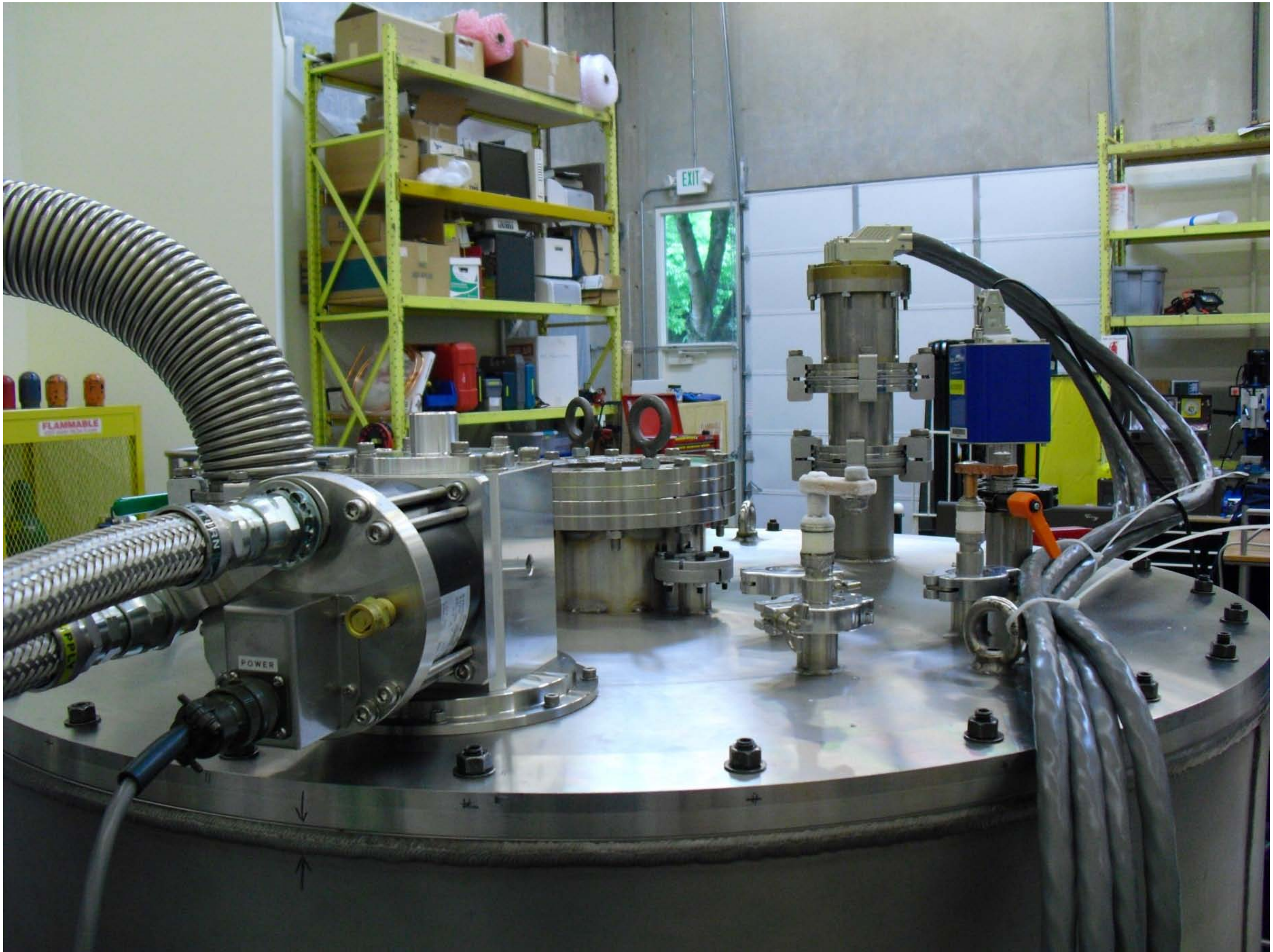
Technical accomplishment – the chiller coupling to HTF circuit allows controllable T_H fluid temperature



Technical accomplishment – The heat transfer fluid flow and regenerator drive motions for AMRR cycle



Technical accomplishment – All subsystems of the AMRR are being integrated together onto Cold Box

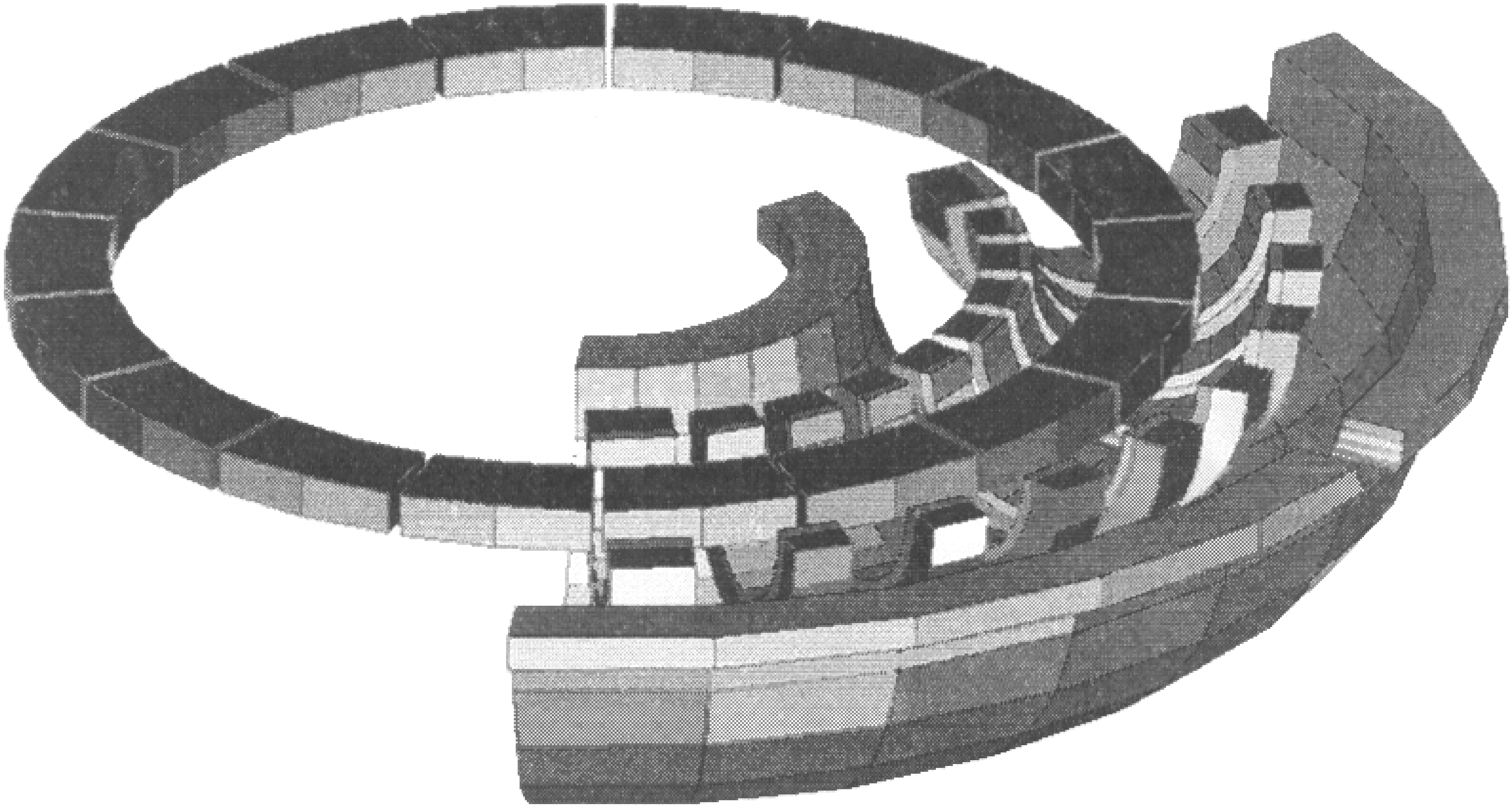


Technical Accomplishment - 1st AMRR Prototype Provides Excellent Insight for 25 kg/day LH_2 Design

- Large magnetic forces in reciprocating dual-regenerator configuration are very difficult to react against each other
- Several existing alternative design options considered with present bias toward rotary wheel geometry using s/c magnets configured into a partial tokamak
- Magnetic regenerator subsystem is a split rotary wheel & housing
- Magnetic materials are the same choices for layering as tested in reciprocating AMRR prototype
- Bypass flow of HTF is achievable with HEXs outside of tokamak region
- Continuous rotational motion and flow housing executes the HTF flow timing of the AMR cycle
- Wheel geometry is close to optimal aspect ratio
- Seal between HTF housing and rotating magnetic wheel is solvable
- Force balance is readily accomplished

Technical accomplishment – Tokamak Configuration Developed

- **Partial tokamak s/c magnet configuration with split, rotating wheel regenerator (HTF, housing, drive, etc not shown)**



Collaborations

- Dr. Andrew Rowe; Department of Mechanical Engineering; U. of Victoria.
  - Participant as magnetic refrigeration expert during Go/No Go review in Aug 2010
  - Discussed potential of bypass heat transfer fluid flow in high efficiency AMRLs;
  - Shared measured results of temperature span of small cylindrical magnetic regenerators in a reciprocating cycle with a hot sink temperature of ~300 K.
- Dr. Richard Chahine; Hydrogen Research Institute; U. of Quebec a Trois Rivières.
  - Expert resource to discuss various issues associated with hydrogen and natural gas purification and liquefaction.
- Dr. Kannan Krishan; Department of Materials Science & Engineering; U. of Washington.
  - Agreement in place with Dr. Krishan’s lab for the use of Physical Properties Measurement System to measure the heat capacity of several rare earth alloys as a function of T & B to obtain the adiabatic temperature change as a function of T & B (4 K to 330 K; 0 T to 7 T).
  - This work is pending the choice of the rare earth alloy refrigerants to augment Gd spheres in layered regenerators to extend the temperature span of AMRR.

Future Work

- **FY11 (April 2011 through December 2011)**
  - Debug the magnetic regenerators, the drive, and the heat transfer/process subsystems of the first AMRR prototype.
  - Test the integrated AMRR prototype with Gd refrigerants to measure detailed performance including: efficiency, heat and work flows, etc as a function of parameters.
  - Validate Dr. Rowe's results and extend temperature span from ~85 K to ~170 K.
  - Measure the effect of bypass flow of heat transfer fluid for optimum temperature span using Gd regenerators.
  - Define the design methodology for fabricating layers of magnetic materials in regenerators to optimize heat transfer fluid bypass flow.
  - Test a series of increasingly complex layered regenerators as a function of heat transfer fluid bypass flow.
  - Analyze the results and compare to predictions of performance simulations to further validate our numerical model.
- **FY11/12 (September 2011 through December 2011)**
  - Use lessons learned from 1st AMRL prototype tests to design and fabricate a rotary AMRL prototype spanning ~290 K to ~20 K to make ~25 kg/day of LH_2.
- **FY12 (January 2012 through May 2012)**
  - Complete tests and characterization of the ~290 K to ~20 K AMRL prototype for $LH_{2.}$
  - Document engineering database for larger AMRL designs for LNG and LH_2.
  - Write commercialization plans for pilot-scale, beta-site, and commercial use.

Summary

- The DOE-EERE FCTP plan clearly establishes importance of simultaneously reducing capital costs and increasing energy efficiency for hydrogen liquefaction.
- Active magnetic regenerative liquefaction (AMRL) has the potential to achieve DOE's target for H_2 liquefaction Figure of Merit (FOM).
- This project is focused on sequential analysis, design, fabrication and testing of two AMRL prototypes to assess technical feasibility to economically increase FOMs from ~0.3 to ~0.5 or higher.
- GO Decision for phase 2 of project approved in September 2010
- All eight subsystems of the integrated AMRR prototype to eventually span from ~290 K to ~120 K are being tested as of 5/10/11.
- The major test results from this AMRR prototype will answer key questions of the impact of heat transfer fluid bypass flow on optimal layered magnetic regenerators for large temperature spans.
- Will validate detailed performance simulation code for AMRL design
- Several 'lessons learned' from first design are being incorporated into advanced design of a rotary AMRL prototype that spans from ~290 K to ~20 K for LH_2 .
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- pd019_barclay_2011_p