

# Active Magnetic Regenerative Liquefier

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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%  $\eta_{DOE}$

## 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<sub>2</sub> Liquefier

- LH<sub>2</sub> is a potential pathway for large-scale H<sub>2</sub> 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<sub>2</sub> to become economically viable for large-scale utilization.

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

$$\dot{W}_{Real} = \dot{W}_{ideal} + T_H \dot{S}_{IrrevTotal}$$

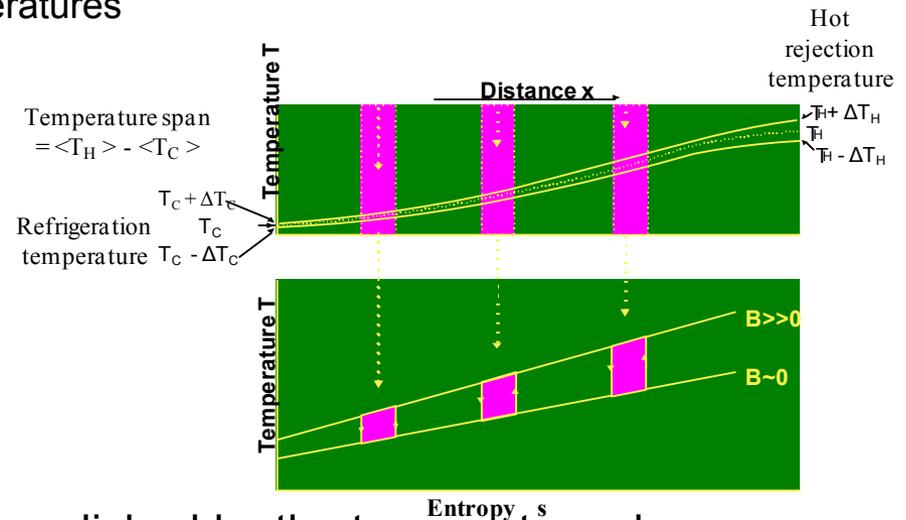
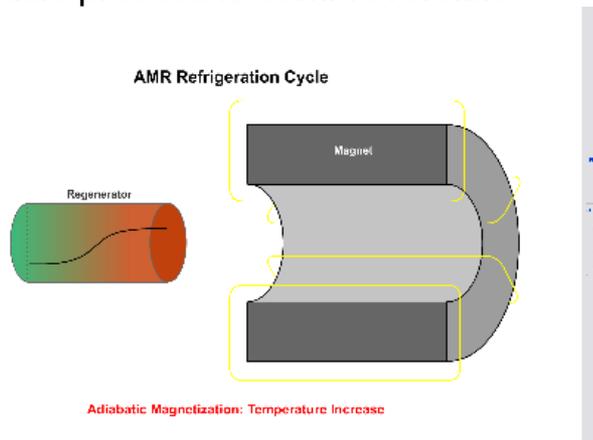
$$\dot{S}_{IrrevTotal} (magnetic) \ll \dot{S}_{IrrevTotal} (gas)$$

$$FOM = \frac{\dot{W}_{Ideal}}{\dot{W}_{Real}} \text{ so } FOM (magnetic) \gg FOM (gas)$$

- 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<sub>2</sub> delivery.
- DOE's efficiency target is 75 % @ 30 te/day [ $\sim 113,229$  gpd] with \$40 MM for a 'turn key facility' [ $\sim \$353$ /gpd].
  - FOM (magnetic cycle)  $\sim 0.6$  ; FOM (best gas cycle)  $\sim 0.35$

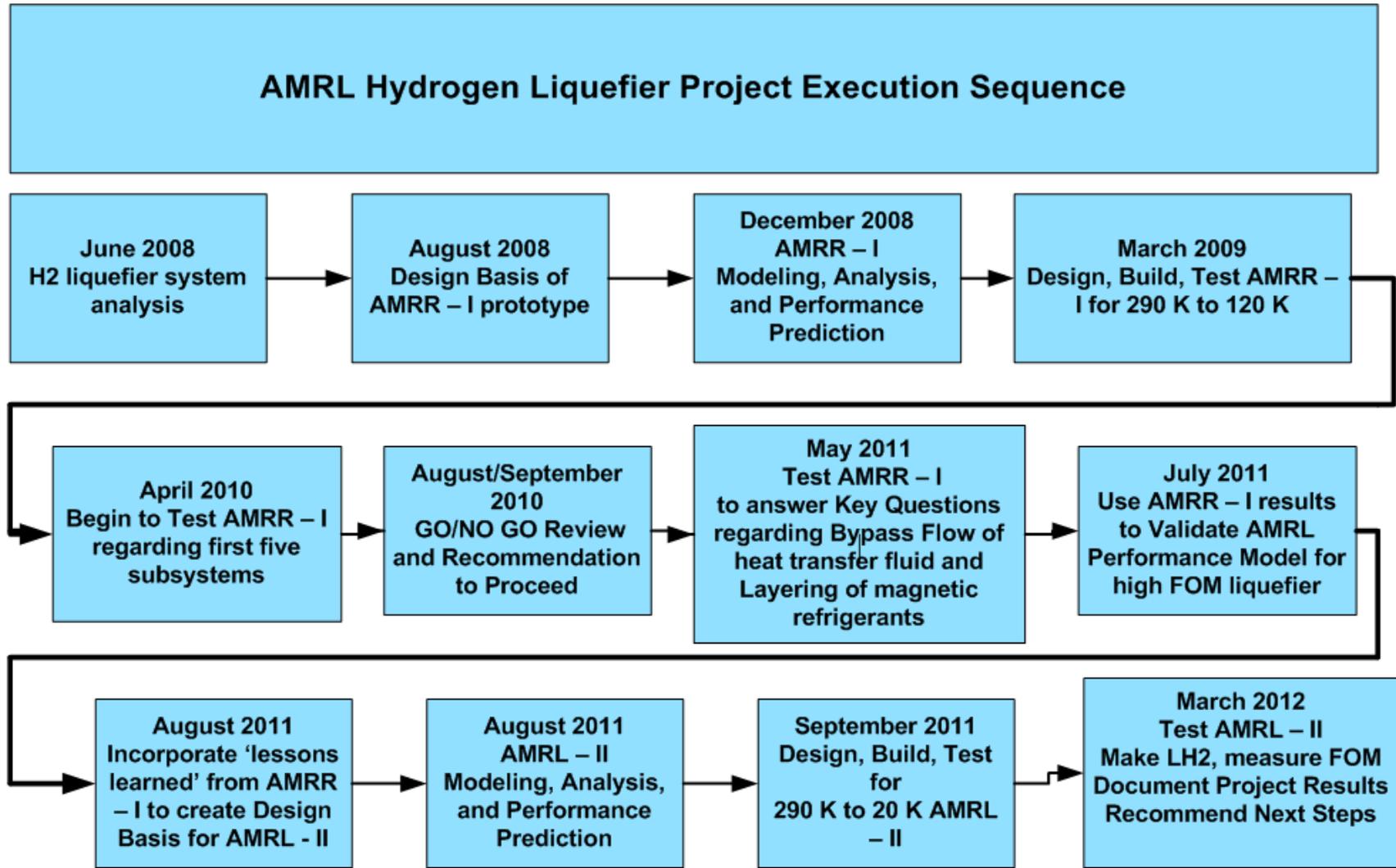
# What is an Active Magnetic Regenerative Liquefier (AMRL)?

- 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

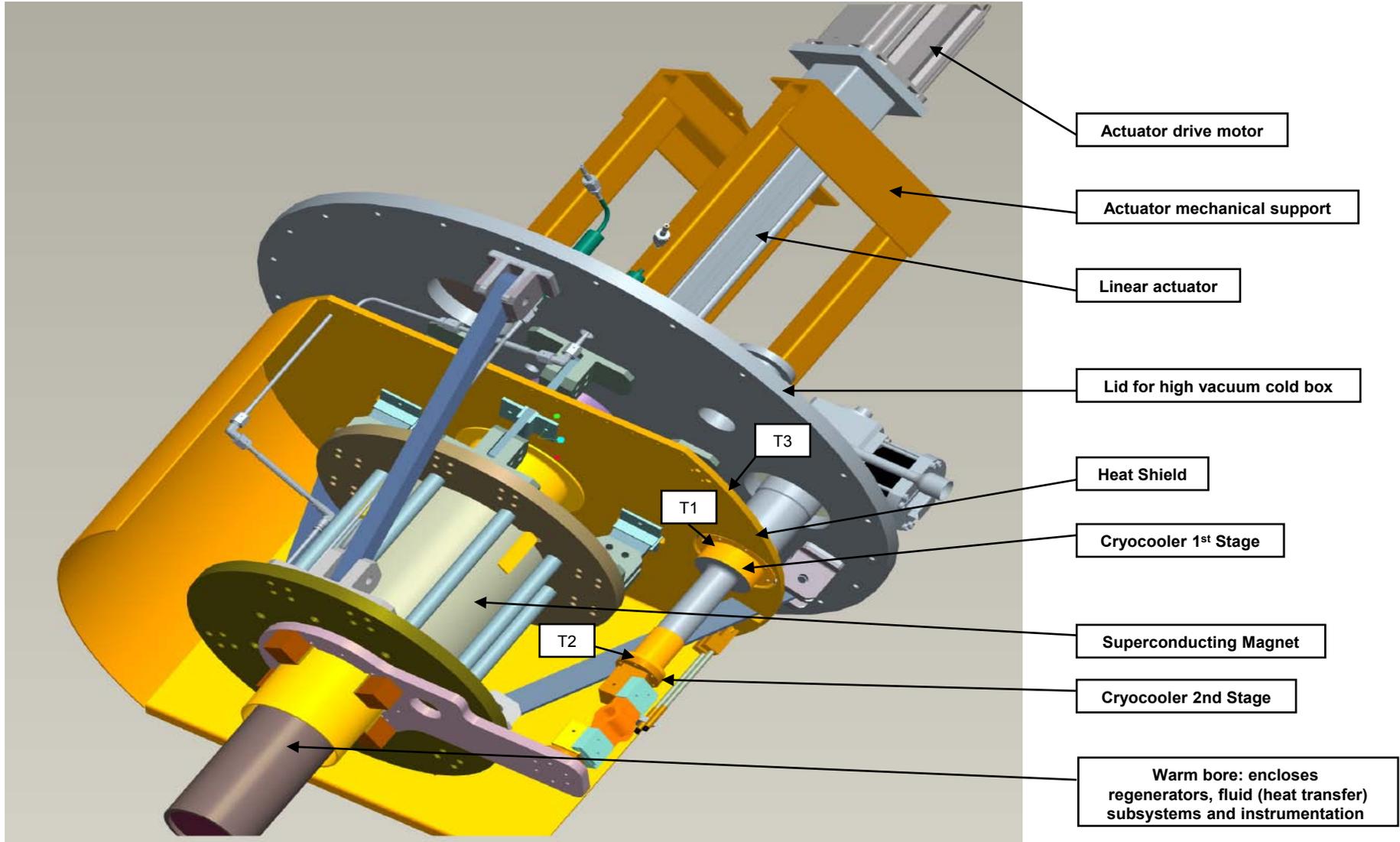


# Project Effort/Milestones Over the Past Year

- 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<sub>2</sub> 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 1 <sup>st</sup> 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



# Technical Accomplishment – Gd Magneto-caloric Effect Verified

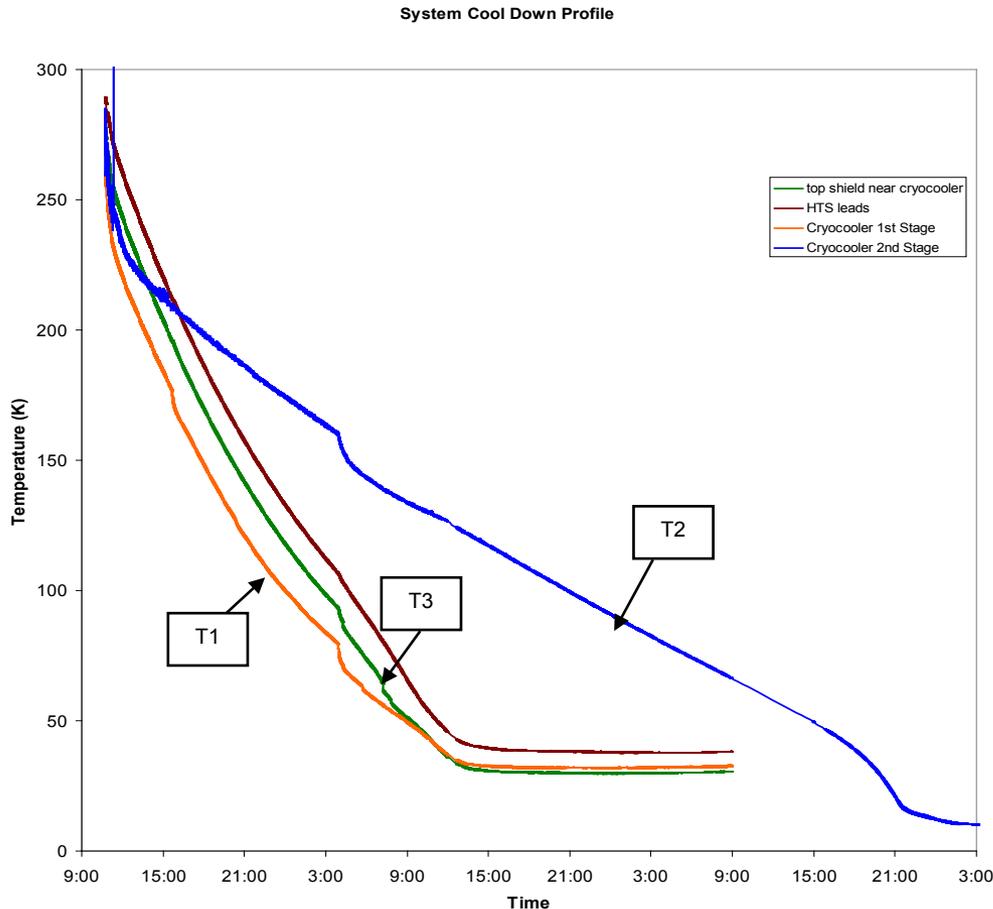
- Validated the magnetocaloric behavior of Gd refrigerant material with respect to the published literature ( $\Delta T$  vs. B)

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 from radiation and convection to very low values.
- Central bore of AMRR where dual reciprocating magnetic regenerators remain between  $\sim 290$  K and  $\sim 120$  K while superconducting magnet is  $\sim 4$  K.
- Measured heat leaks to magnet are  $\sim 0.3$  W compared to 1.5 W 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

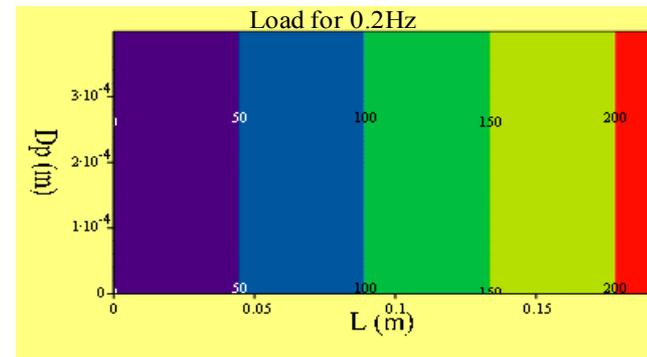
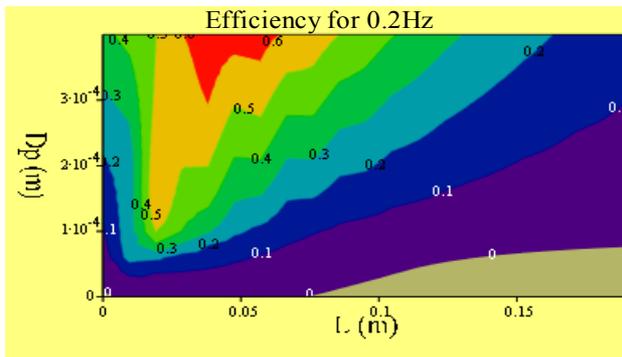
- A irreversible entropy minimization MathCad model was written to calculate comparative thermodynamic performance of different regenerators. Efficiency and cooling power were simultaneously optimized simultaneously with respect to:
  - $T_{\text{cold}}$  ; regenerator length; Gd particle diameter; drive 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 ( $\Delta T_{\text{cold}}$ ) 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.

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

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

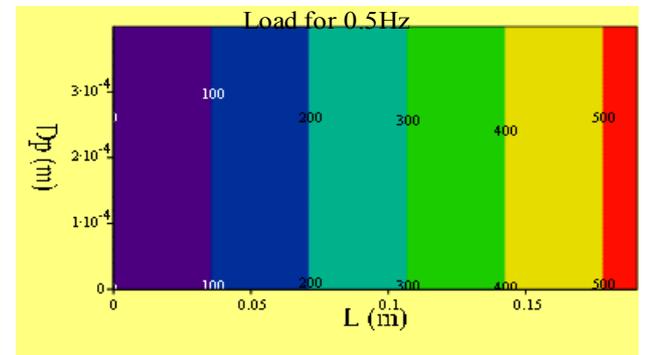
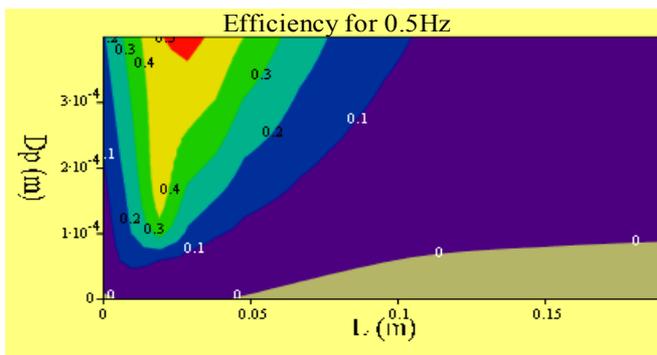
# Technical Accomplishment - Results of optimized regenerator design parameters

- 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.



$$\left[ (\text{Selfun}(X_{\text{cut}}, T_g, 0.2))^{(2)}, (\text{Selfun}(X_{\text{cut}}, T_g, 0.2))^{(4)}, (\text{Selfun}(X_{\text{cut}}, T_g, 0.2))^{(15)} \right]$$

$$\left[ (\text{Selfun}(X_{\text{cut}}, T_g, 0.2))^{(2)}, (\text{Selfun}(X_{\text{cut}}, T_g, 0.2))^{(4)}, (\text{Selfun}(X_{\text{cut}}, T_g, 0.2))^{(9)} \right]$$



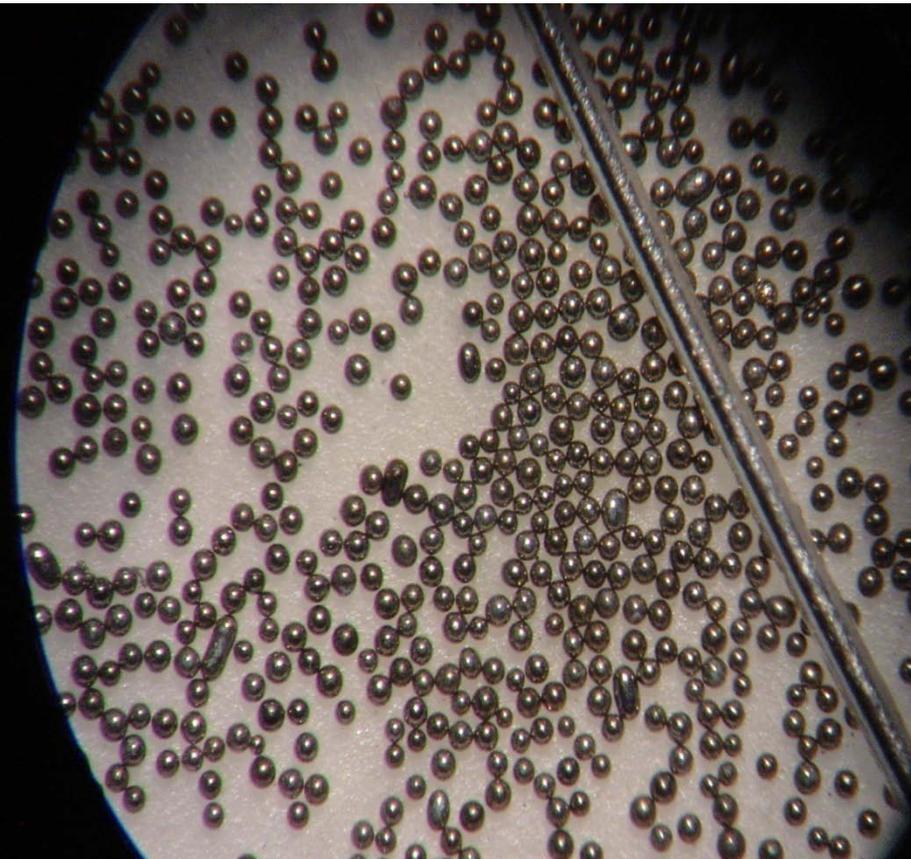
$$\left[ (\text{Selfun}(X_{\text{cut}}, T_g, 0.5))^{(2)}, (\text{Selfun}(X_{\text{cut}}, T_g, 0.5))^{(4)}, (\text{Selfun}(X_{\text{cut}}, T_g, 0.5))^{(15)} \right]$$

$$\left[ (\text{Selfun}(X_{\text{cut}}, T_g, 0.5))^{(2)}, (\text{Selfun}(X_{\text{cut}}, T_g, 0.5))^{(4)}, (\text{Selfun}(X_{\text{cut}}, T_g, 0.5))^{(9)} \right]$$

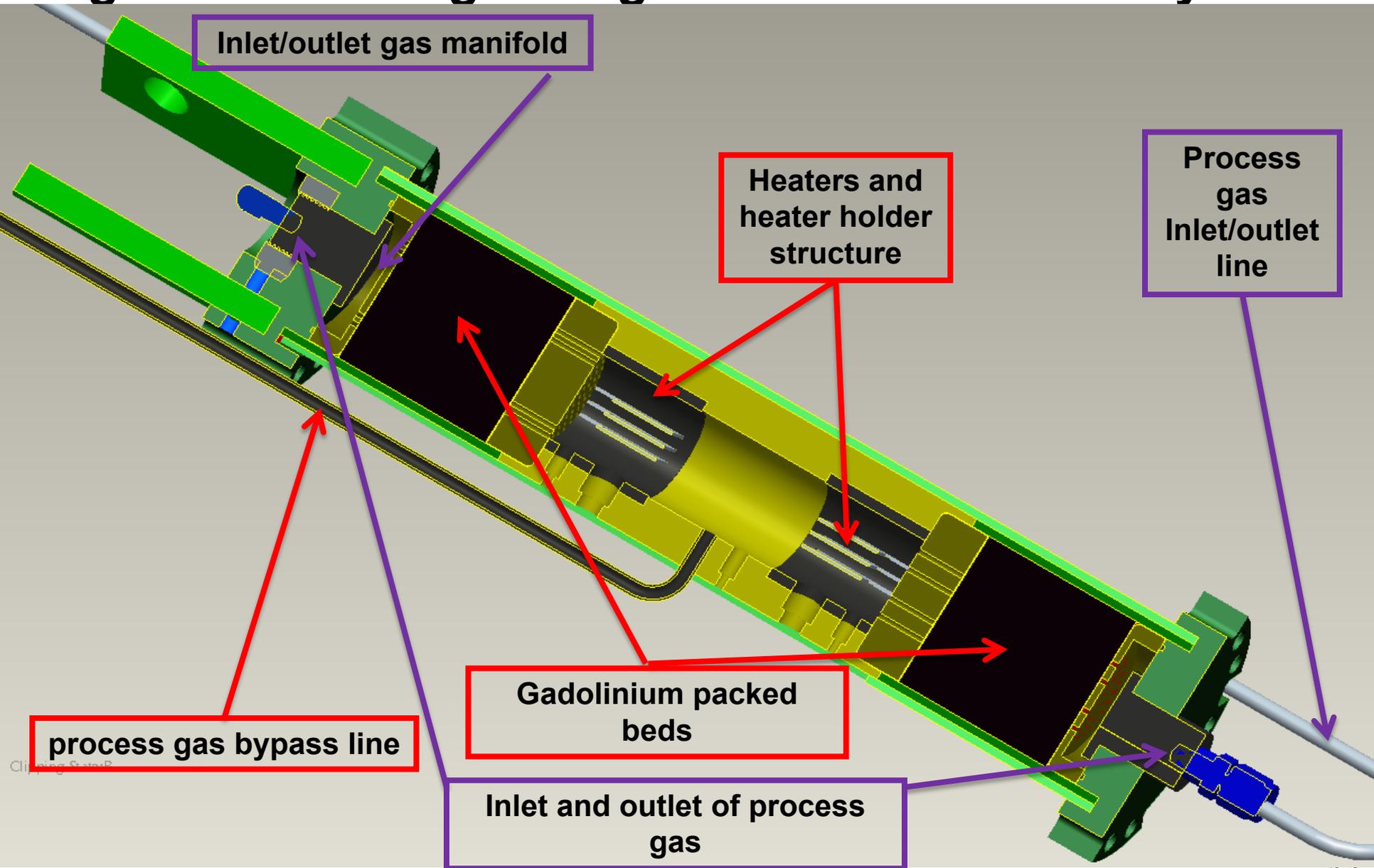
# Technical Accomplishment – Spherical magnetic refrigerants substantially reduce fabrication costs and improve heat transfer fluid flow mechanics for regenerators

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



# 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



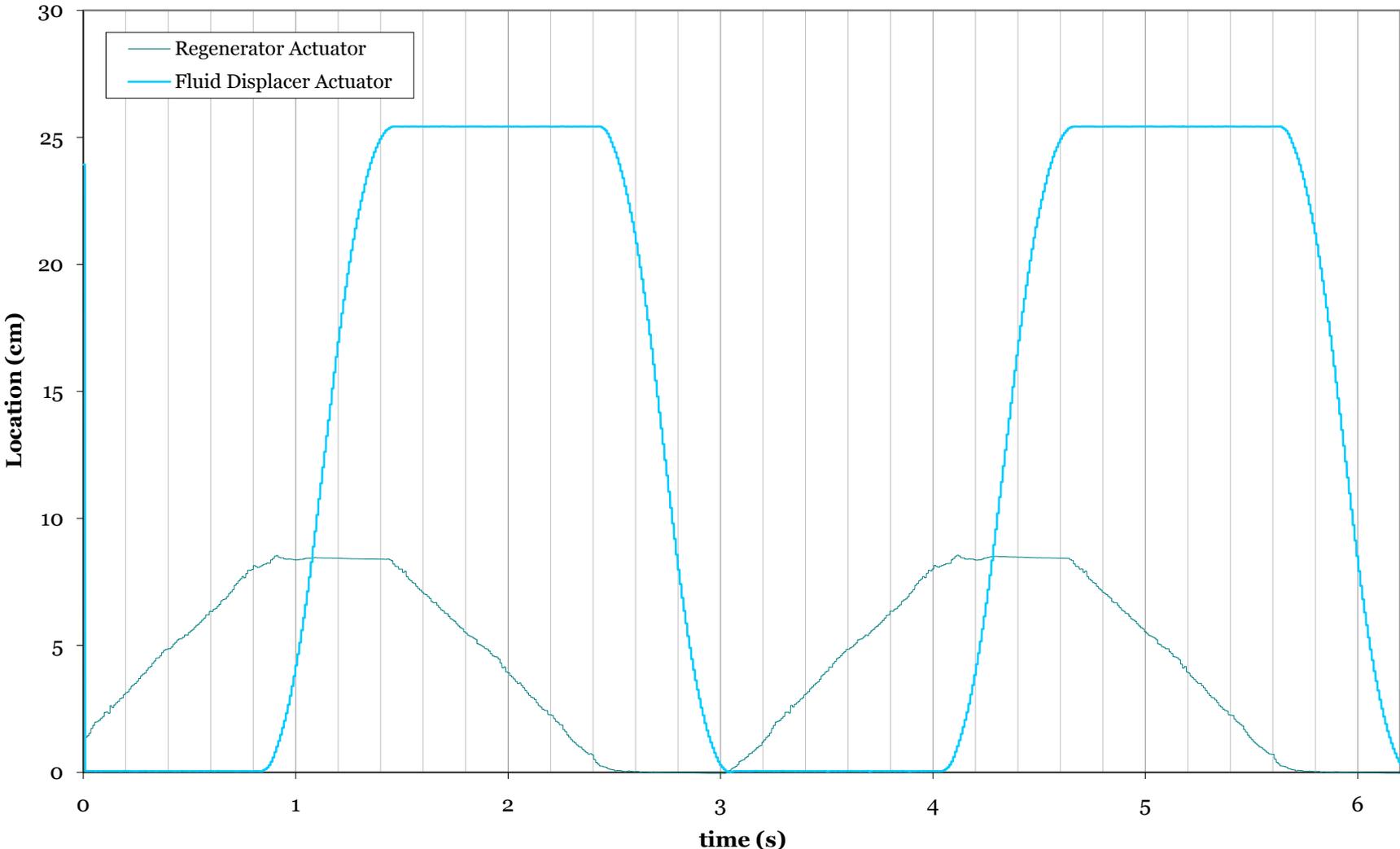


# Technical accomplishment – AMRR drive actuator was purchased, assembled, & interfaced to LabVIEW

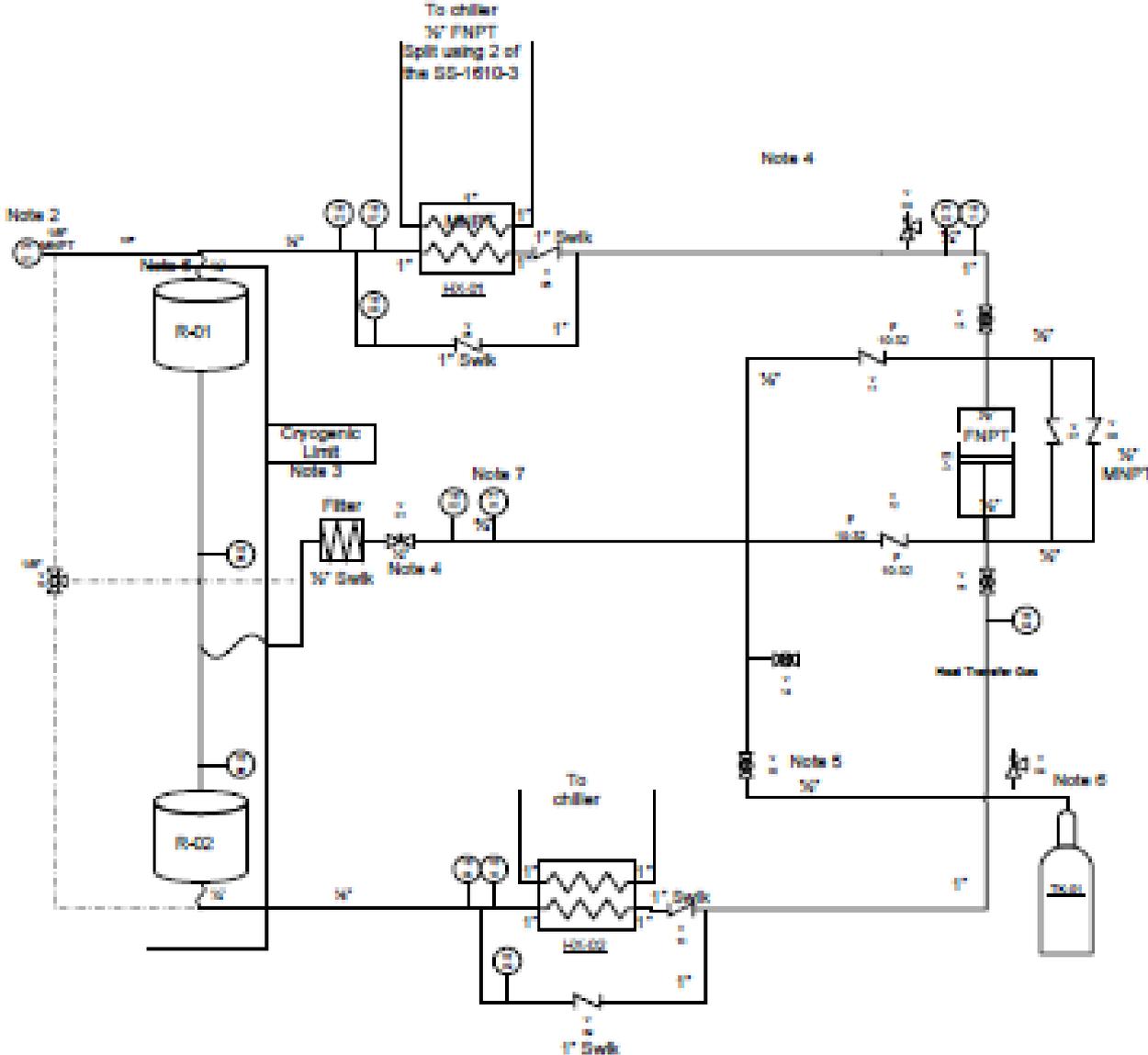


# Technical accomplishment – The heat transfer fluid flow and regenerator drive motions for AMRR cycle

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

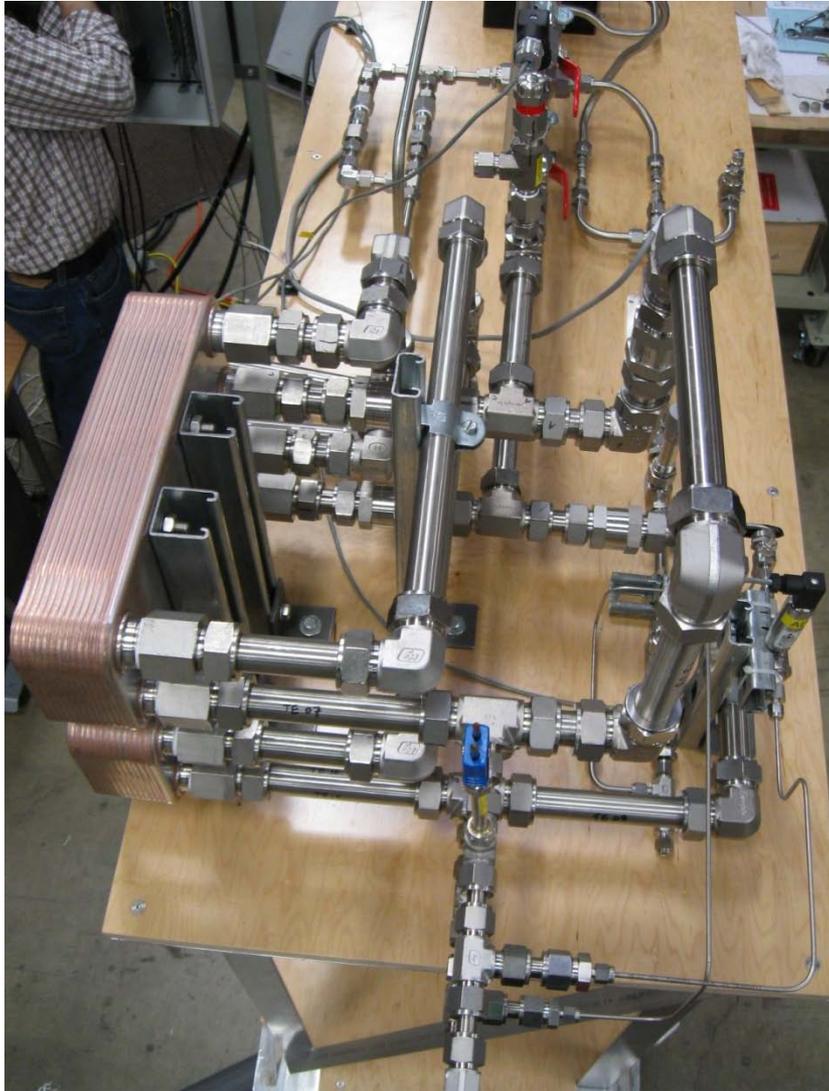


The He HTF flows in a reciprocating motion from hot to cold and cold to hot through the dual magnetic regenerators as they are moved in/out of the magnetic field.

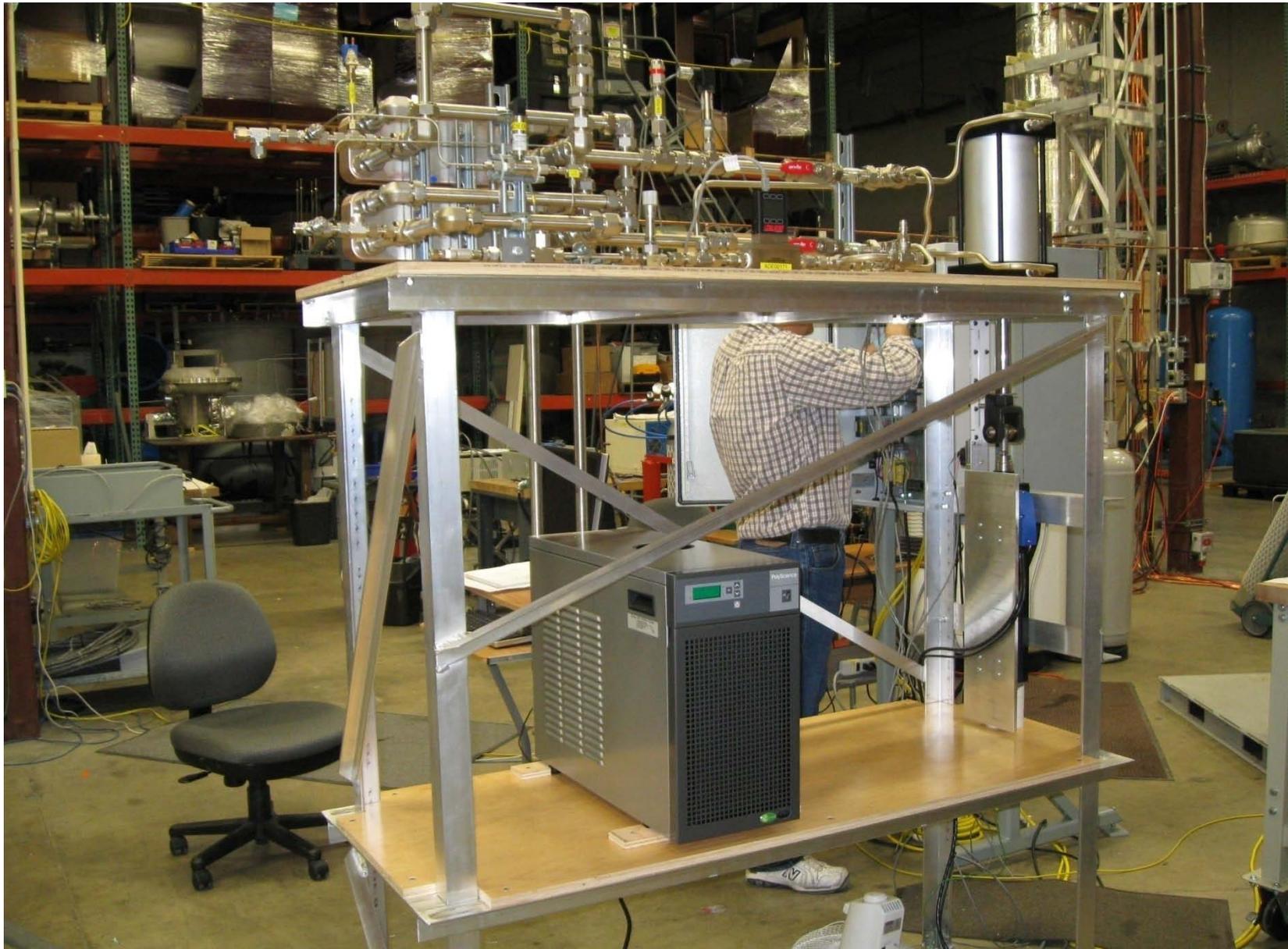
Note 1  
The chiller insures that  $T_H$  is constant during the hot to cold blow period.

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

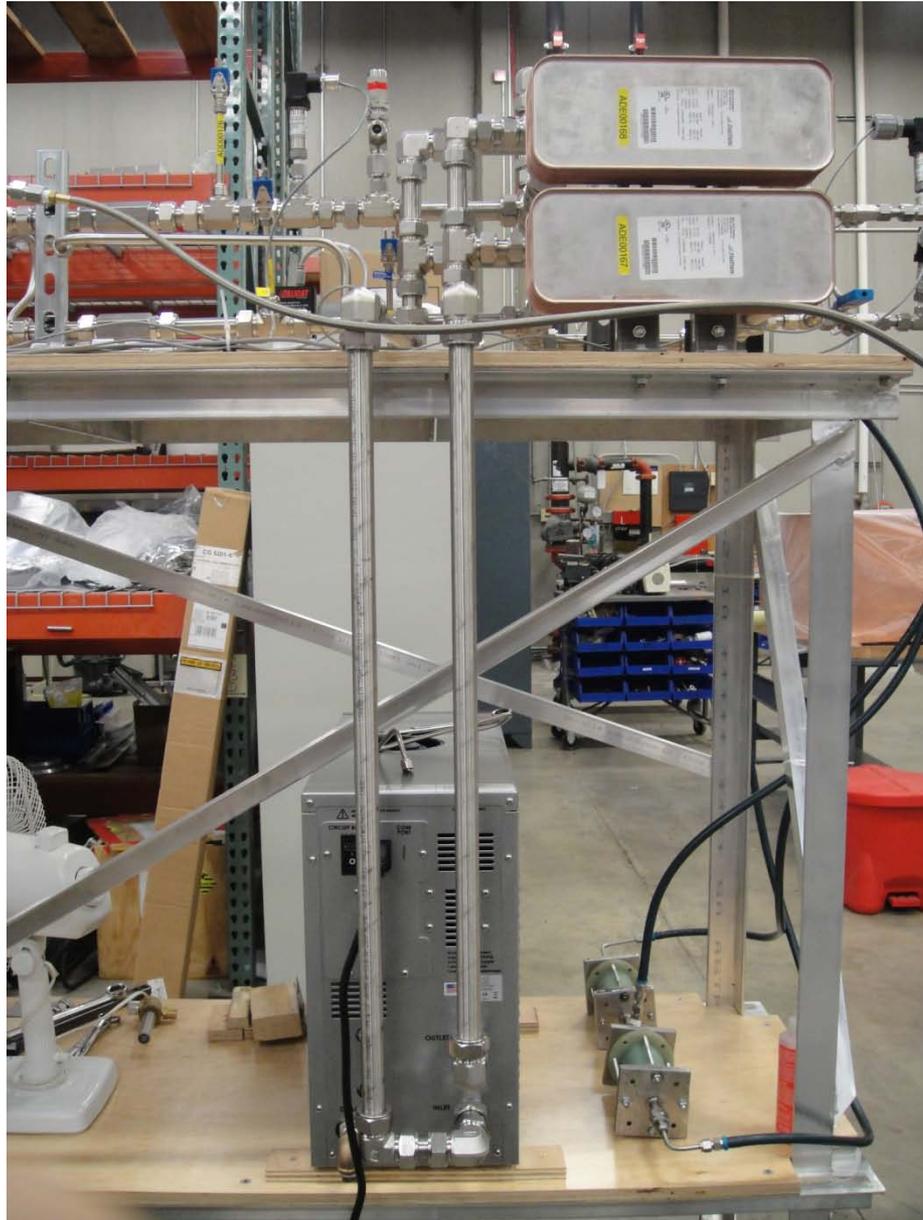
# Technical accomplishment – AMRR fluid actuator with coupling to HTF positive displacement pump



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

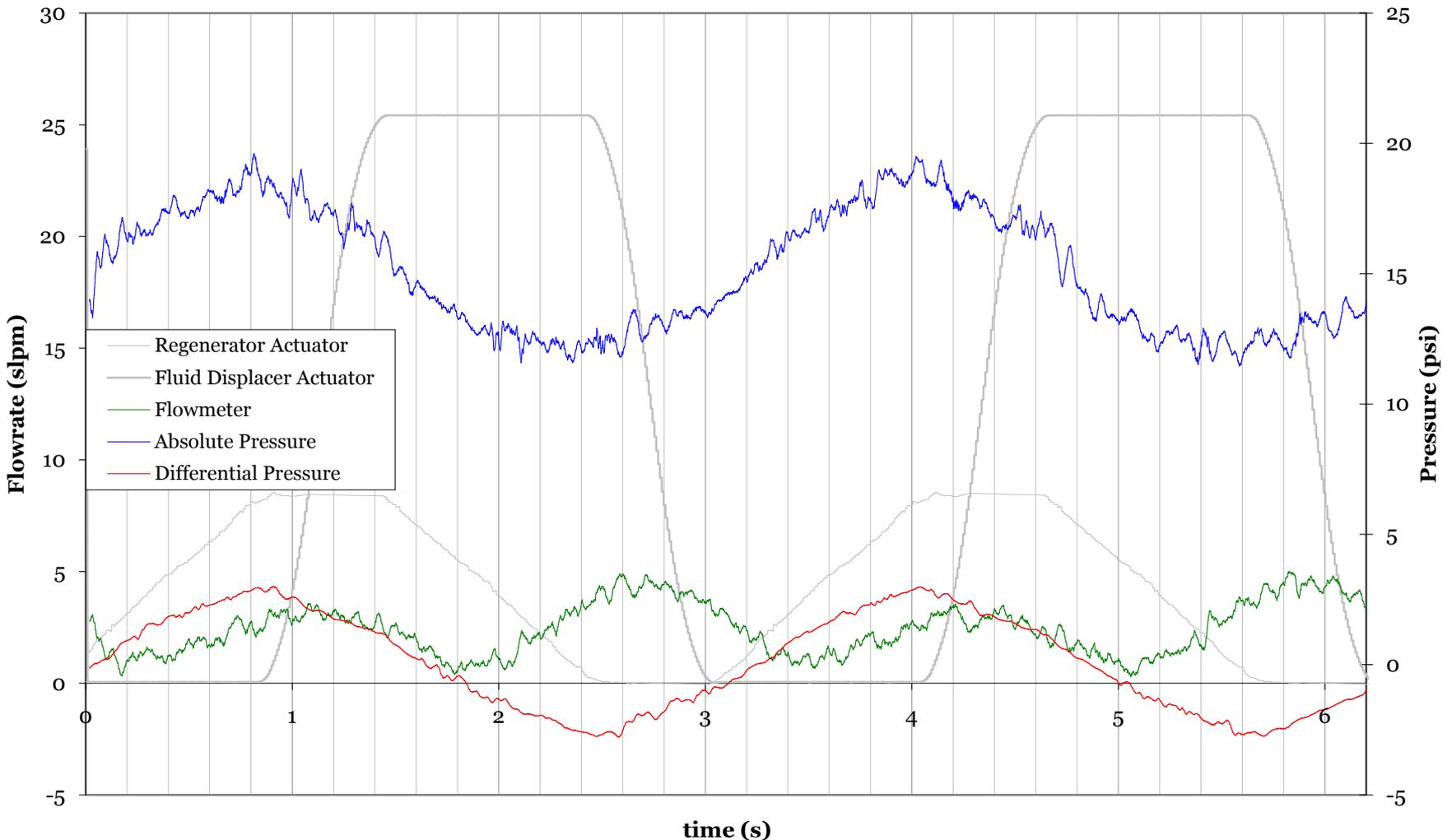


# Technical accomplishment – the chiller coupling to HTF circuit allows controllable $T_H$ fluid temperature

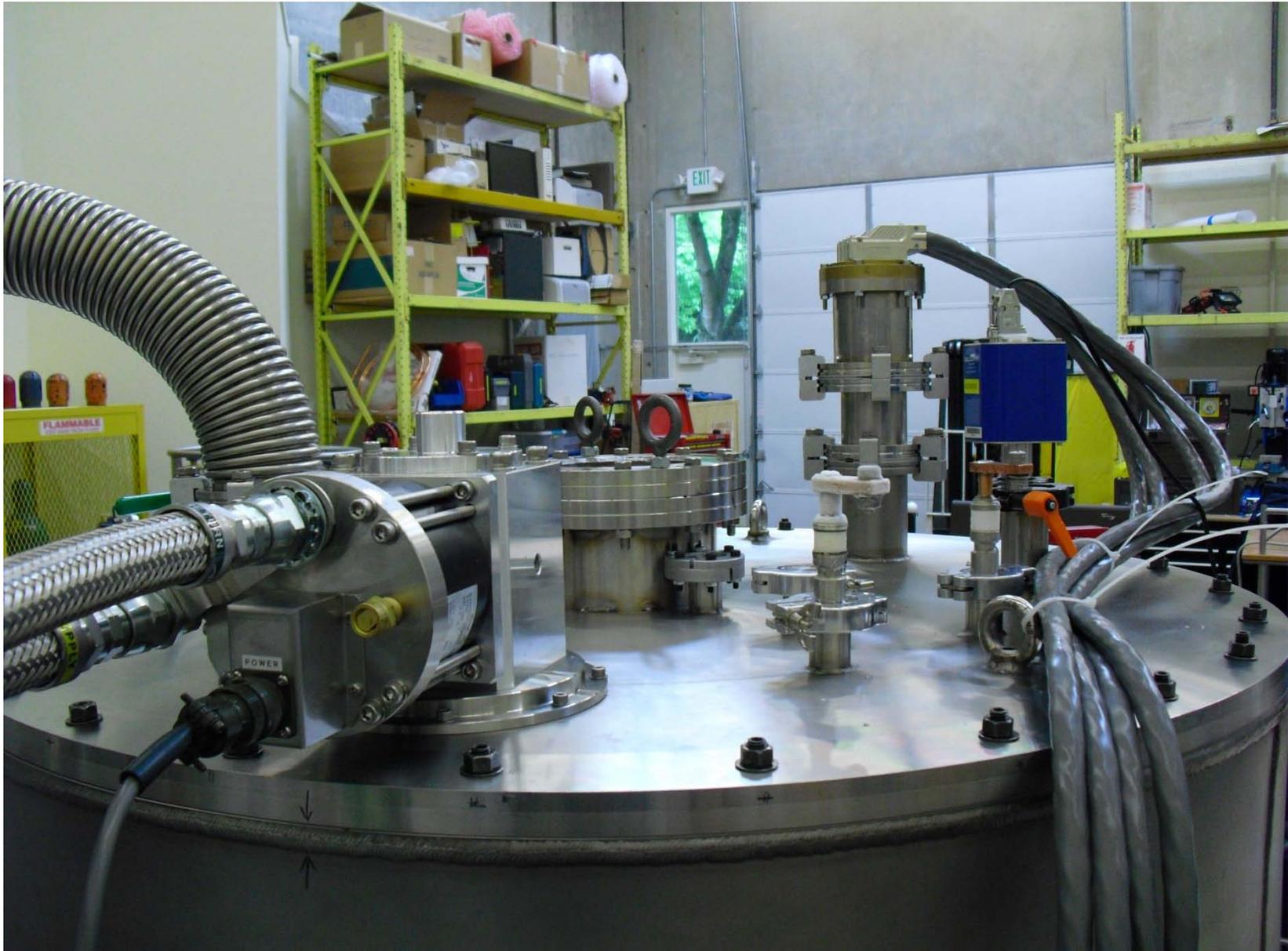


# Technical accomplishment – The heat transfer fluid flow and regenerator drive motions for AMRR cycle

Results of HTF Flow-Regenerator Motion Synchronization using LabVIEW DAQ  
He flow measurements through regenerators (with displacements in the background)



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

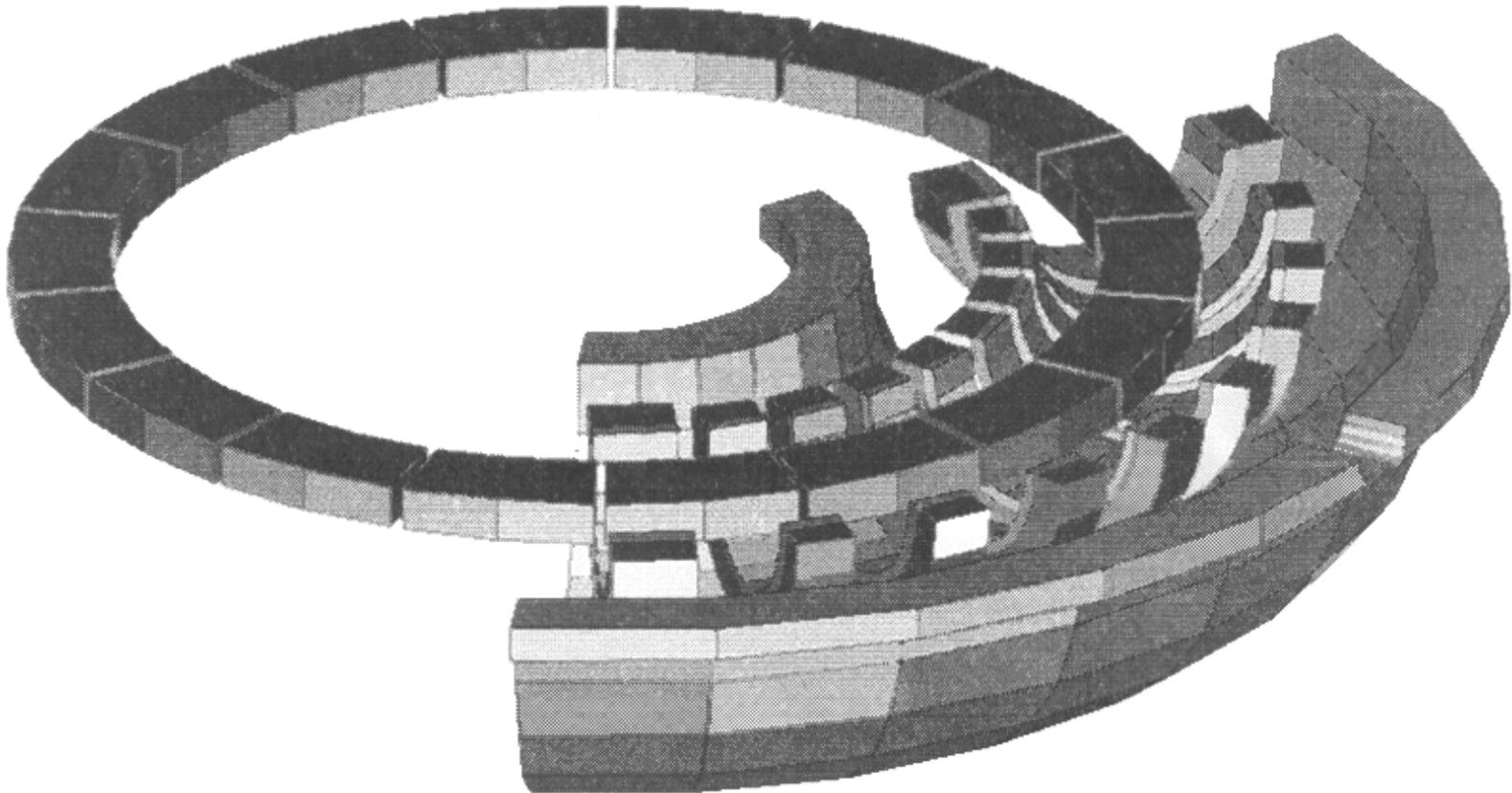


# Technical Accomplishment - 1<sup>st</sup> AMRR Prototype Provides Excellent Insight for 25 kg/day LH<sub>2</sub> Design

- 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 1<sup>st</sup> AMRL prototype tests to design and fabricate a rotary AMRL prototype spanning ~290 K to ~20 K to make ~25 kg/day of LH<sub>2</sub>.
- **FY12 (January 2012 through May 2012)**
  - Complete tests and characterization of the ~290 K to ~20 K AMRL prototype for LH<sub>2</sub>.
  - Document engineering database for larger AMRL designs for LNG and LH<sub>2</sub>.
  - 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<sub>2</sub> 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<sub>2</sub> .
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