

Active Magnetic Regenerative Liquefier

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Overview

Timeline

- July 2008
- December 2010
- ~8-10 % as of 3/2009

Budget

- \$2.5 MM
 - DOE: \$2.0 MM
 - Prometheus: \$0.5 MM
- Funding FY08: ~\$0.15 MM
- Funding FY09: ~\$0.85 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

Partners

- Prometheus Energy is project lead
 - Specialized vendors are being used for different components



Objectives-Relevance

- To collect/create a validated engineering basis for an advanced H₂ liquefier technology that meets or exceeds DOE's targets for both capital and energy efficiency.
 - Identify areas where more applied research is needed.
 - Examples – fabrication techniques for high performance regenerators; different s/c magnets; and others.
- To apply our technical knowledge of and experience with active magnetic regenerative liquefaction to sequentially analyze, design, fabricate, and test three experimental liquefier prototypes to validate performance simulation model used to design AMRLs.
 - Especially applicable to LH₂, but also to other cryogenes
- From July 2008 through March 2009, our aim has been:
 - to collect AMRL design literature and create the design basis for the first lab-scale AMRL prototype; and
 - to analyze, design, fabricate, and test an AMRL prototype operating from 290 K to 120 K with a FOM >0.5



Technical Project Plan I-Approach

- Our overall project plan includes tasks to analyze, design, build, test and validate three prototypes; a single-stage AMRL spanning from ~290 K to ~120 K; a multi-stage, lab-scale AMRL from ~290 K to ~20 K making LH₂; and an engineering-scale AMRL making LH₂
- Task 1 – System design and analysis of an AMRL for LH₂.
 - Establish design basis for mechanical design of the first prototype.
- Task 2 – Design, build and test a lab-scale AMRL prototype for 290 K to 120 K
 - Use our detailed AMRL performance simulation code to calculate performance of various configurations to design layered magnetic regenerators for 290 K to 120 K operation
 - Design and procure all other sub-systems, e.g., the s/c magnet and its components.
 - Integrate subsystems with DAQ system to test the prototype and validate performance
- Task 3 – Design, build, & test lab-scale prototype of AMRL to make LH₂
 - Use results of task 2 to extend design of additional stages for an AMRL
 - Fabricate and test the complete AMRL prototype to make LH₂
 - Use results to make an informed Go/No Go decision for next stage of project.
- Task 4 – Design, build & test engineering-scale prototype of AMRL for LH₂
- Task 5 – Perform reliability and durability tests on engineering prototype
- Task 6 – Project management, documentation, and reporting.



Technical Project Plan II-Approach

- Each major task in our plan is divided into subtasks to enhance parallel execution of the design and fabrication of the interrelated sub-systems of AMRL prototypes.
- For example: Task 2 – Design, build and test a lab-scale AMRL prototype for 290 K to 120 K
 - Subtask 2.1 - Design and fabricate the magnetic regenerators for 290 K to 120 K operation
 - Subtask 2.2 - Design and procure the superconducting magnet subsystem
 - Subtask 2.3 - Design and procure the drive subsystem
 - Subtask 2.4 - Design and build the conduction cooled s/c magnet and regenerator access subsystem
 - Subtask 2.5 - Design and build heat transfer fluid circulation subsystem
 - Subtask 2.6 - Design and build the process stream flow subsystem
 - Subtask 2.7 - Design and assemble electrical, instrumentation, controls, and integrate with the test DAQ
 - Subtask 2.8 - Integrate all subsystems for 290 K to 120 K prototype
 - Subtask 2.9 - Shake down, test, validate and operate first prototype



Original Milestones-Approach

Month/year	Major Project Milestones
July 3, 2008	Contract signed and Project began
March, 31 2009	Initial operation of AMRL lab prototype for ~290 K to ~120 K
June 1,2009	Begin to design and fabricate lab-prototype of AMRL for ~290 K to ~20 K operation
September 30, 2009	Initial operation of AMRL to make LH ₂ and execution of tests to validate design calcs
December 31, 2009	GO/NO GO decision for engineering-scale prototype of an AMRL for LH ₂
December 2010	Test and validate engineering-scale prototype of an AMRL for LH ₂
Dec. 31, 2010	Complete testing of engineering-scale prototype and publish final project report



Progress toward Milestones-Approach

Month/year	Progress toward milestones
July 3, 2008	Contract signed and Project began
August 31, 2008	Completion of draft design basis document for 290 K to 120 K lab-scale prototype
September 2, 2008	Prometheus Energy Company has new owner; Heracles Energy Corporation d.b.a. Prometheus Energy Company
December 31, 2008	Completion of contract amendment to change award from PEC to HEC d.b.a. PEC
January, 2009	Reassembled technical team and refocused on 290 K to 120 K AMRL lab-prototype
March, 31 2009	Long lead items ordered for lab-scale AMRL prototype for ~290 K to ~120 K
July 31,2009	Complete assembly of lab-prototype of AMRL for ~290 K to ~120 K and begin testing.



Technical Accomplishments/ Progress/Results-I

- To achieve a liquefier with high FOM, the following principles were used to make design choices
 - Use an inherently efficient thermodynamic cycle; AMR cycle
 - Use an efficient work input mechanism; magnetic forces
 - Use an efficient work recovery mechanism; regenerators
 - Ensure small temperature approaches for all heat transfer between streams; multiple stages
 - Use high specific area heat exchangers; small dimensions
 - Keep pressure drops for fluid flows low; channel geometry
 - Ensure low longitudinal thermal conduction mechanisms; material and geometry choices
 - Minimize frictional and parasitic heat leak mechanisms; these can be subtle
 - For hydrogen, perform ortho-to-para conversion at the highest possible temperature during cooling in process heat exchangers; important feature



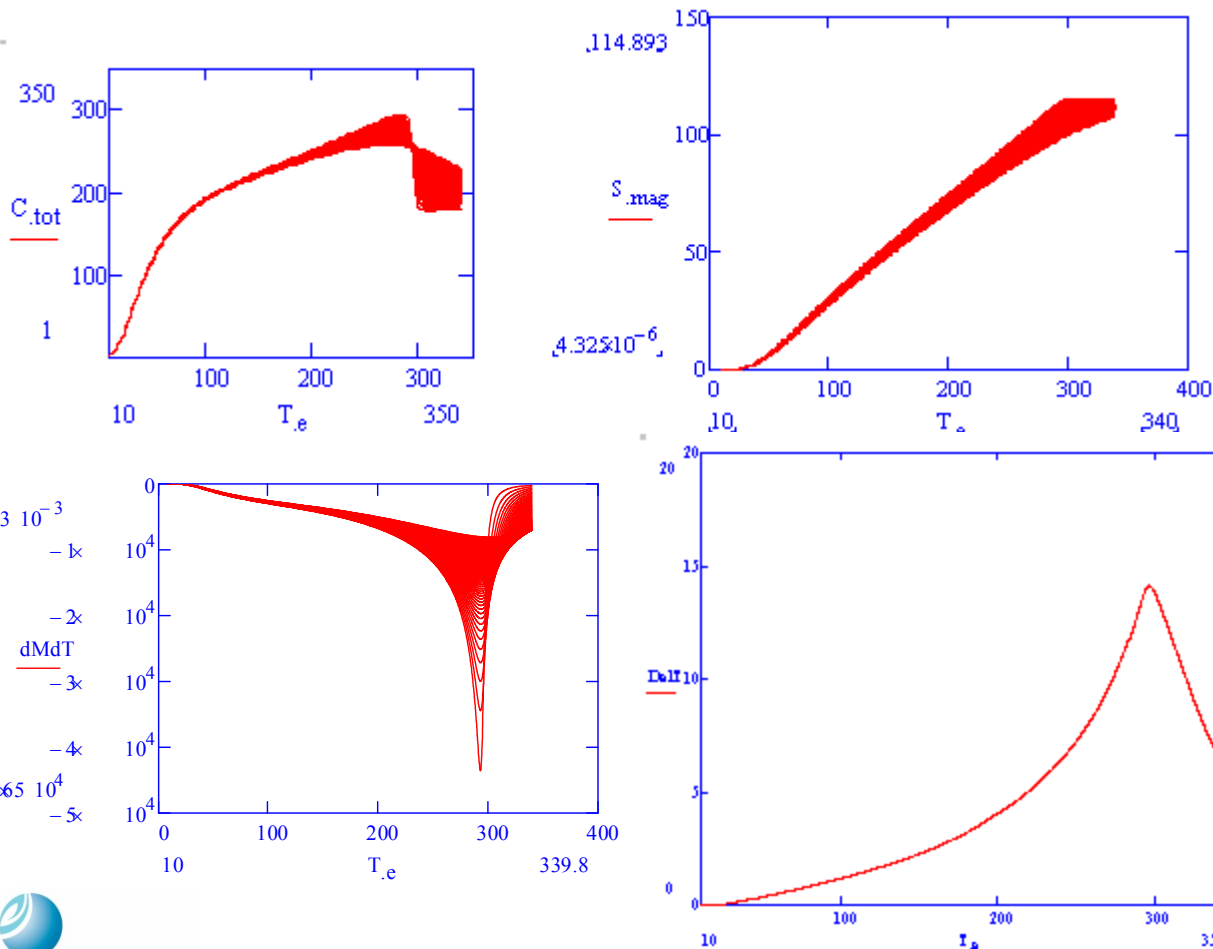
Technical Accomplishments/ Progress/Results-II

- Created a detailed design basis for 290 K to 120 K lab-scale ARML prototype
 - Solenoidal s/c magnet subsystem
 - NbTi multifilament wire; potted; 4 K operation; PMS;
 - Conduction cooling to 4 K via GM cryocooler; diode quench protection
 - Low thermal conduction/high electrical conduction leads
 - Reciprocating drive of dual magnetic regenerators subsystem
 - Magnetic regenerator subsystem
 - Rare earth alloys for refrigerants; layered materials per model;
 - Matched regenerator design; aspect ratio 1-2; 10,000 m²/m³;
 - Low pressure drop; low longitudinal thermal conductivity
 - Regenerator heat transfer fluid subsystem
 - Pressurized He gas; closed loop circulator with reversing switch for reciprocating flow; bypass flow controls
 - Anchored at 290 K at input to hot end of regenerators
 - External process stream
 - Anchored at 290 K at heat sink; controllable flow
 - Cold box and structural subsystem
 - Double walled Dewar; G-10 structural braces; high vacuum experimental space
 - Instrumentation and control subsystem
 - LabVIEW based DAQ and control
 - Full set of temperature, pressure, mass flow, work rate, thermal loads, magnetic field sensor



Technical Accomplishments/ Progress/Results-III

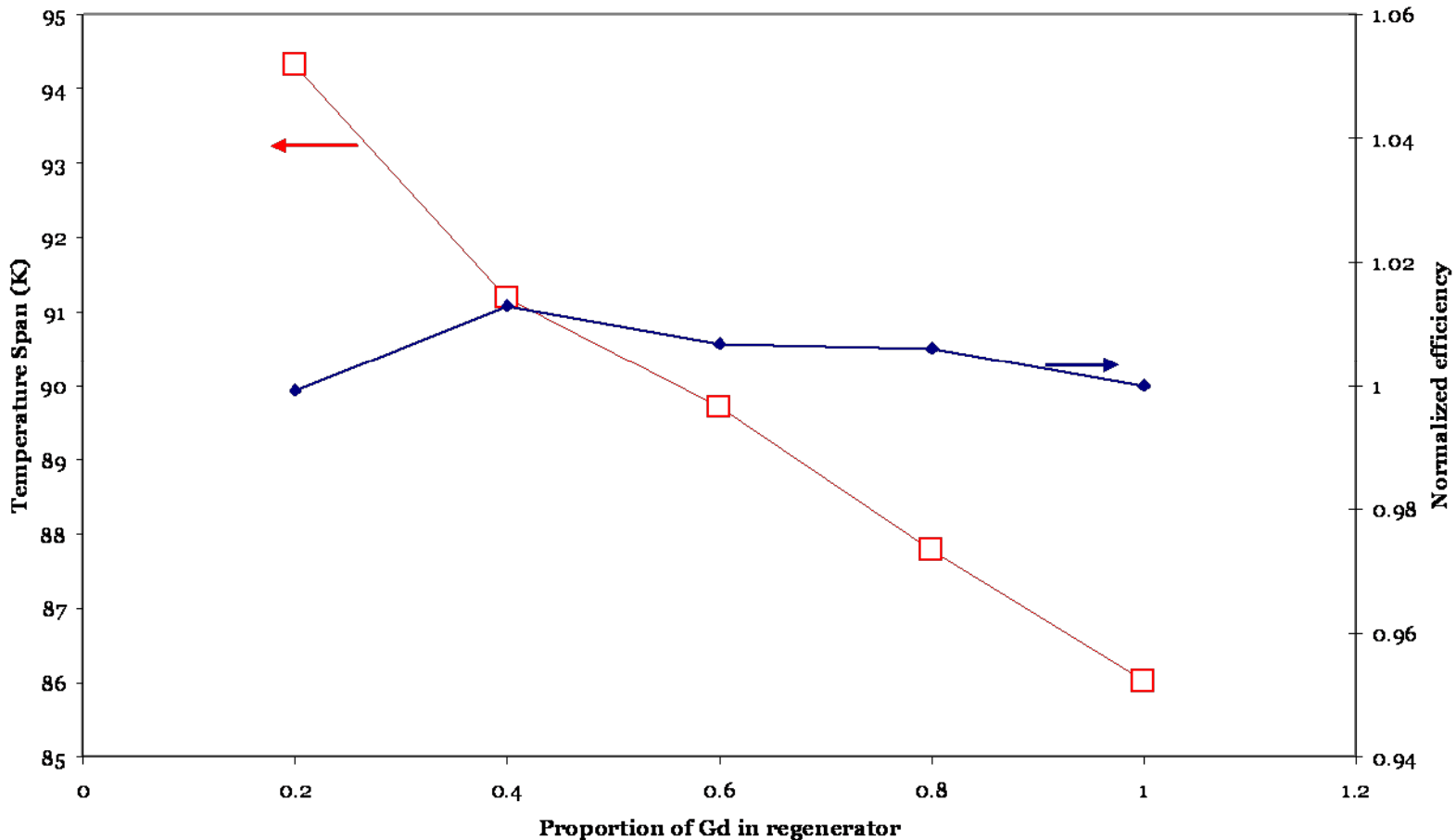
- Example of magnetic materials and their properties, e.g., typical MathCAD results for a single material (Gd or GdDy alloy); 0.1 T to 6.5 T; ingots of arc melted alloys and particles.



Technical Accomplishments/ Progress/Results-IV

E.g., Calculated temperature span of an AMRL using $T_{\text{hot}} = 290$ K with different amounts of various magnetic materials in an active regenerator

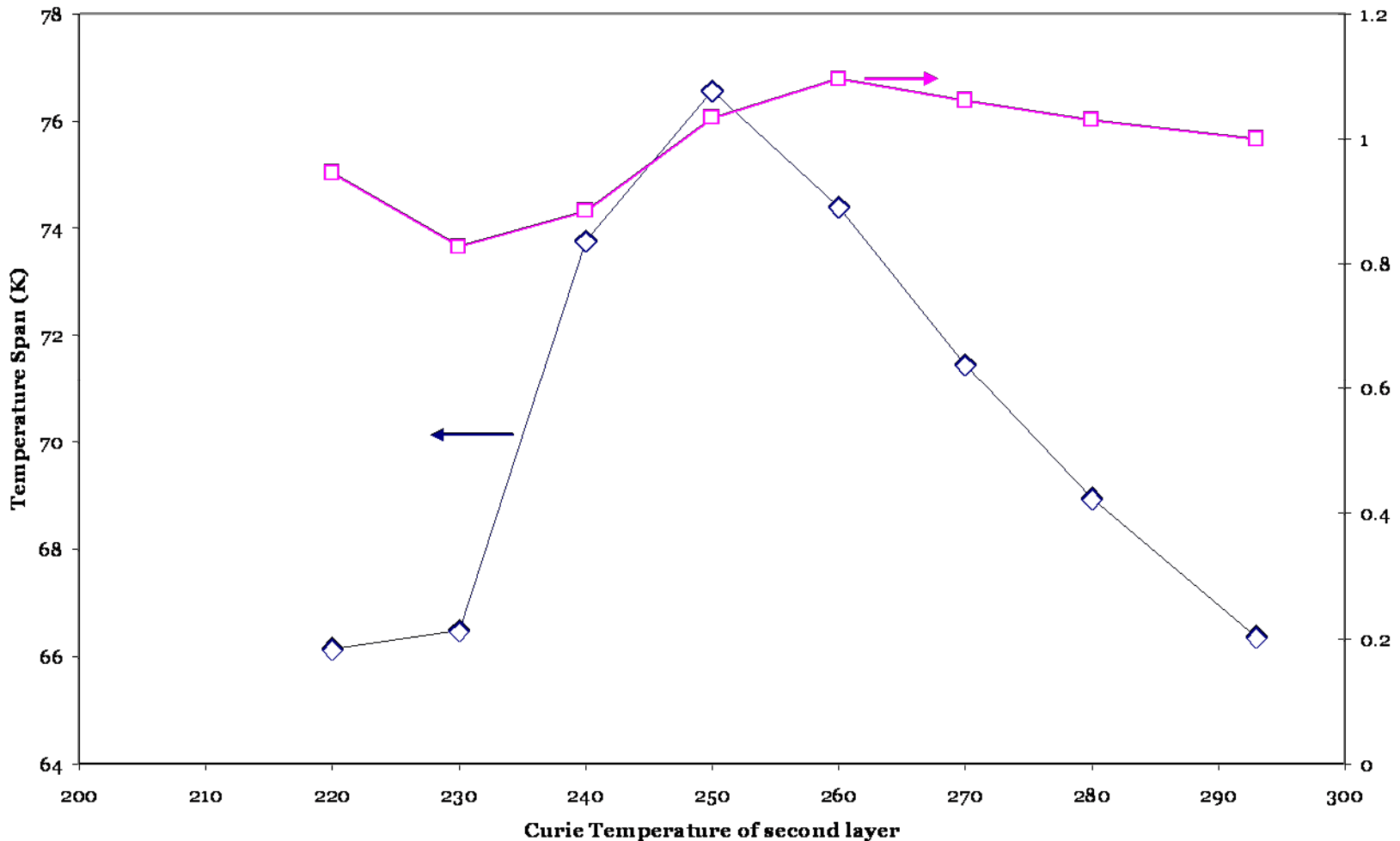
**Temperature Span for a two layer regenerator
Gd first layer, second layer with varying Curie Temperature**



Technical Accomplishments/ Progress/Results-V

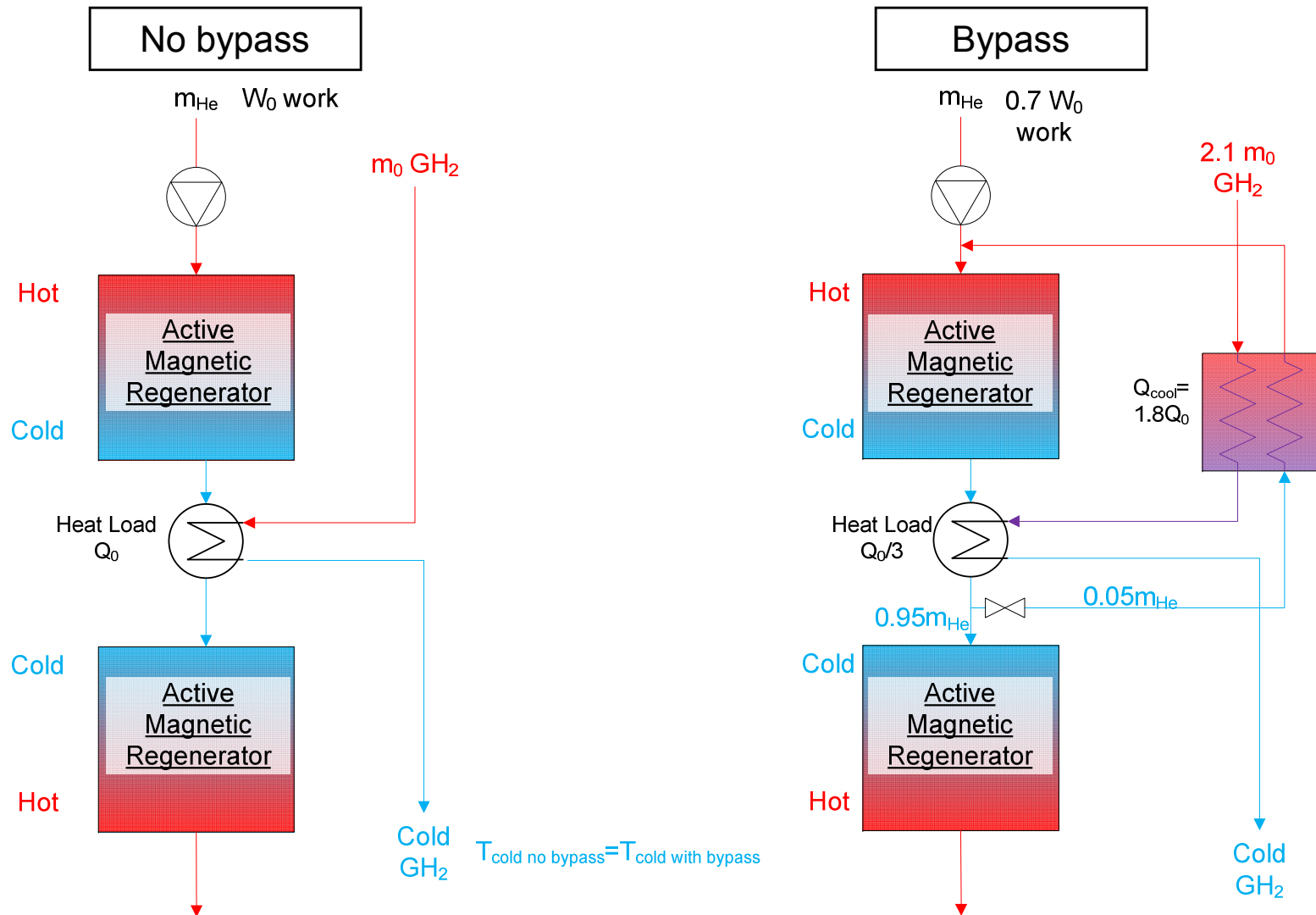
E.g. Calculate the influence of Curie temperature on performance of an AMRL regenerator
with $T_{\text{hot}} = 290 \text{ K}$ and $\Delta B_a = 6.4 \text{ T}$

**Temperature Span for a two layer regenerator
Gd first layer, second layer with varying Curie Temperature**

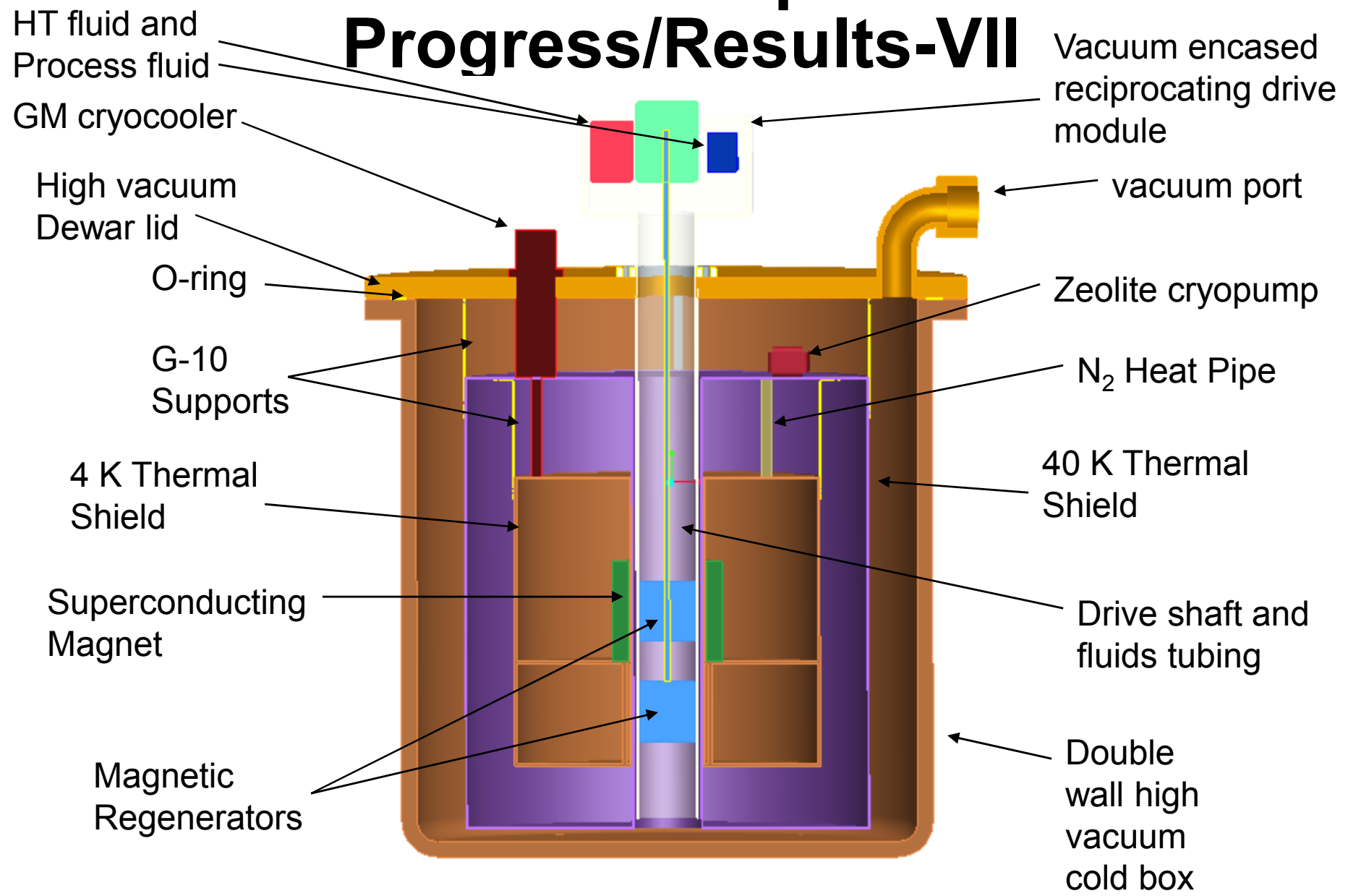


Technical Accomplishments/ Progress/Results-VI

E.g., Calculate the influence of bypass flow on AMRL performance



Technical Accomplishments/ Progress/Results-VII



Technical Accomplishments/ Progress/Results-VIII

- Primary irreversible entropy mechanisms are well defined in high performance passive regenerators; applies to active regenerators
 - Heat transfer
 - Pressure drop
 - Longitudinal thermal conduction
- New results from AMRL performance simulation modeling show the impact of two additional intrinsic irreversible entropy mechanisms
 - Thermal mass differences during AMRL cycle due to the temperature and magnetic field dependence of the magnetic refrigerants
 - Unbalanced heat transfer fluid flow requires bypass
- Two key objectives of 290 K to 120 K prototype tests are:
 - To characterize the performance of an AMRL as a function of thermal mass imbalance and
 - To characterize the amount of bypass of the heat transfer fluid.



Technical Accomplishments/ Progress/Results-IX

- Status of 290 K to 120 K AMRL lab-scale prototype
 - Magnetic regenerators; magnetic materials are selected; raw materials ordered; detailed design and fabrication underway
 - S/C magnet subsystem; magnet, HTSC leads, pms, diode protection, power supply & sensors ordered
 - Conduction cooling subsystem; cold box and GM cryocooler already in our laboratory facilities
 - High vacuum pump and related equipment in place for AMRL operational space
 - Structural support members integrated with shield cooling analysis and design is substantially completed
 - Heat transfer fluid and process fluid flow subsystems; both in design
 - Drive subsystem; in design
 - Instrumentation and controls; P&ID being created as choices are made
 - LabVIEW DAQ; the system is already in our lab facilities



Technical Accomplishments/ Progress/Results-X

The AMRL cold box on the left is a double walled dewar. The AMRL cryocooler on the right is a proven two-stage GM model



Proposed Future Work

- FY09 (April 2009 through September 2009)
 - Complete assembly and test of an AMRL that has ≥ 50 W of cooling power at ~ 120 K and rejects heat at ~ 290 K. **This will be the first of this kind of liquefier in the world!**
 - **Experimentally answer key questions regarding the best design for layers of magnetic materials in regenerators with varying amounts of bypass flow of the heat transfer fluid.**
 - **Measure temperature span and thermodynamic efficiency (FOM) as a function of operating parameters such as frequency, heat transfer fluid flow rate, applied magnetic field change, hot temperature, percentage of bypass flow, layering technique, and other performance measures.**
 - Analyze the results and compare to performance simulations to further validate numerical performance model.
- FY10 (October 2009 through December 2009)
 - Use results of 1st AMRL prototype tests and validated model to design the lab-scale prototype of a multi-stage AMRL to make ~ 10 -15 kg/day of LH₂.
 - Procure and/or fabricate the various components of the 2nd AMRL and assemble the prototype into a complete system.
 - **Test the complete AMRL and make liquid hydrogen for the first time with this device.**
 - Compare measured performance with expected performance of AMRL.
 - **Review 2nd lab-prototype results and present recommendations for an informed GO/NO GO decision for an engineering-scale prototype of an AMRL at the end of December 2009.**
- FY10 & FY11 (January 2010 through December 2010)
 - Design and fabricate or procure the components of an engineering-scale AMRL for LH₂.
 - **Complete assembly, measure detailed performance, and do reliability/durability testing of engineering prototype of AMRL while producing LH₂.**
 - Document engineering database for larger AMRL designs.
 - **Write commercialization plan for pilot-scale, beta-site, and initial commercial installation.**



Summary

- DOE's Hydrogen, Fuel Cell and Infrastructure Technologies 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 H₂ liquefaction Figure of Merit (FOM).
- This innovative project is focused on the sequential design, fabrication and testing of three AMRL prototypes to clearly assess the potential to increase FOMs from ~0.3 to ~0.5 or higher.
- Steady progress toward the first AMRL prototype operating between 290 K and 120 K has been made during the past year in spite of the disruption of a change in Company ownership and the normal time to make the associated contract amendments.
- Members of Prometheus Energy's team have the extensive knowledge and experience of advanced liquefier technology to determine whether an AMRL design can achieve DOE's goals.
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