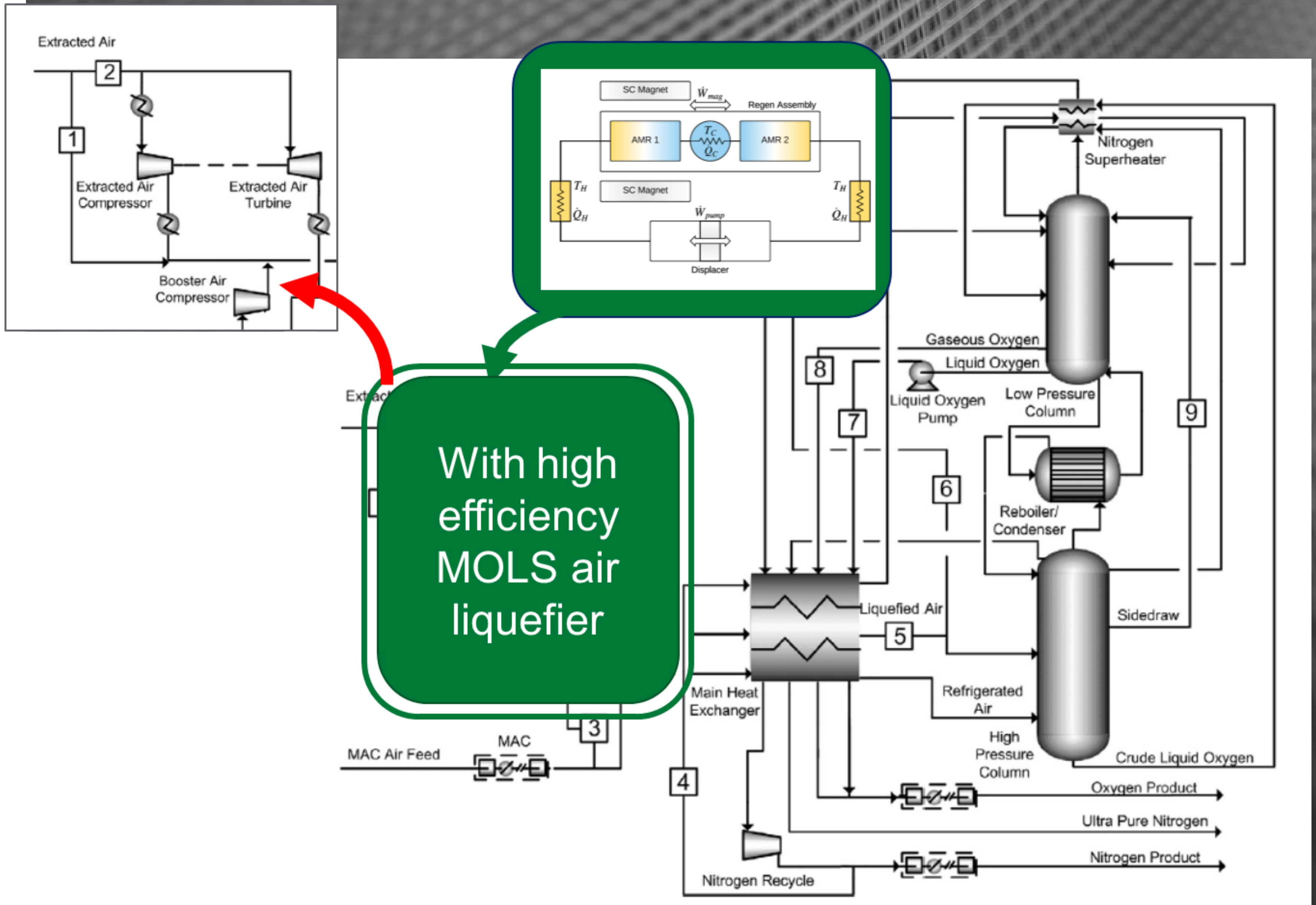
Pacific Northwest
NATIONAL LABORATORY

Magnetocaloric Oxygen Liquefaction System (MOLS) for High Efficiency Air Separation



With high efficiency MOLS air liquefier

April 10, 2019

Jamie Holladay

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

FWP-73143

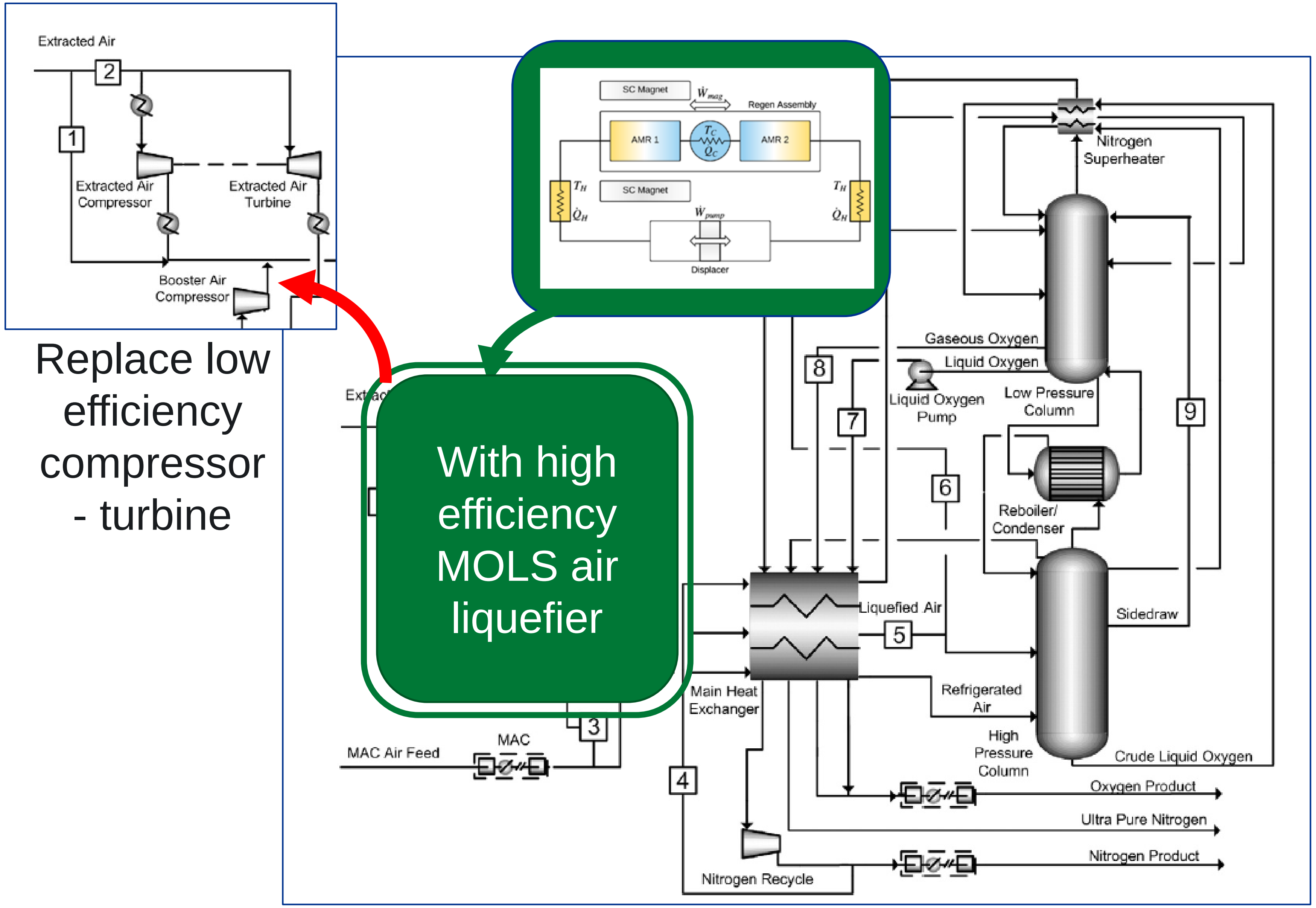
MOLS project summary

- Overall Program Objectives:
  - Air separation unit (ASU) program's overall objective is to develop an efficient oxygen generator for 1-5 MWe small-scale modular power plant to increase power plant efficiency
- PNNL's Objective: 1yr project
  - Feasibility study to determine if modular, innovative magnetocaloric liquefaction (MCL) technology is suitable by liquefying ~1 kg/day of air
  - Projected increase in the air liquefaction portion of ASU's Figure of Merit (FOM) by 60+%
  - Techno-economic analysis (TEA) to show economically viable at small scale (10 tonne/day)
- Time: December 1, 2018 to November 30, 2019
  - Option years from December 2019 to November 2022
- Budget: $1,000,000
- End of first year deliverable: liquefaction of ~1 kg air/day and TEA

Project Objectives:

MOLS enables efficient, small-scale (10 tonne/day) air liquefaction

- Current cryogenic gas liquefaction uses turbo-Brayton cycles
  - Use gas refrigerants which must be compressed, cooled, and expanded
  - Air liquefaction is the biggest energy consumption of the ASU
  - Difficult to scale down to 10 tonne/day
- Magnetocaloric refrigeration
  - Modular and scalable to <10 tonne/day
  - Solid state refrigerants
  - Minimal gas compression and no expansion



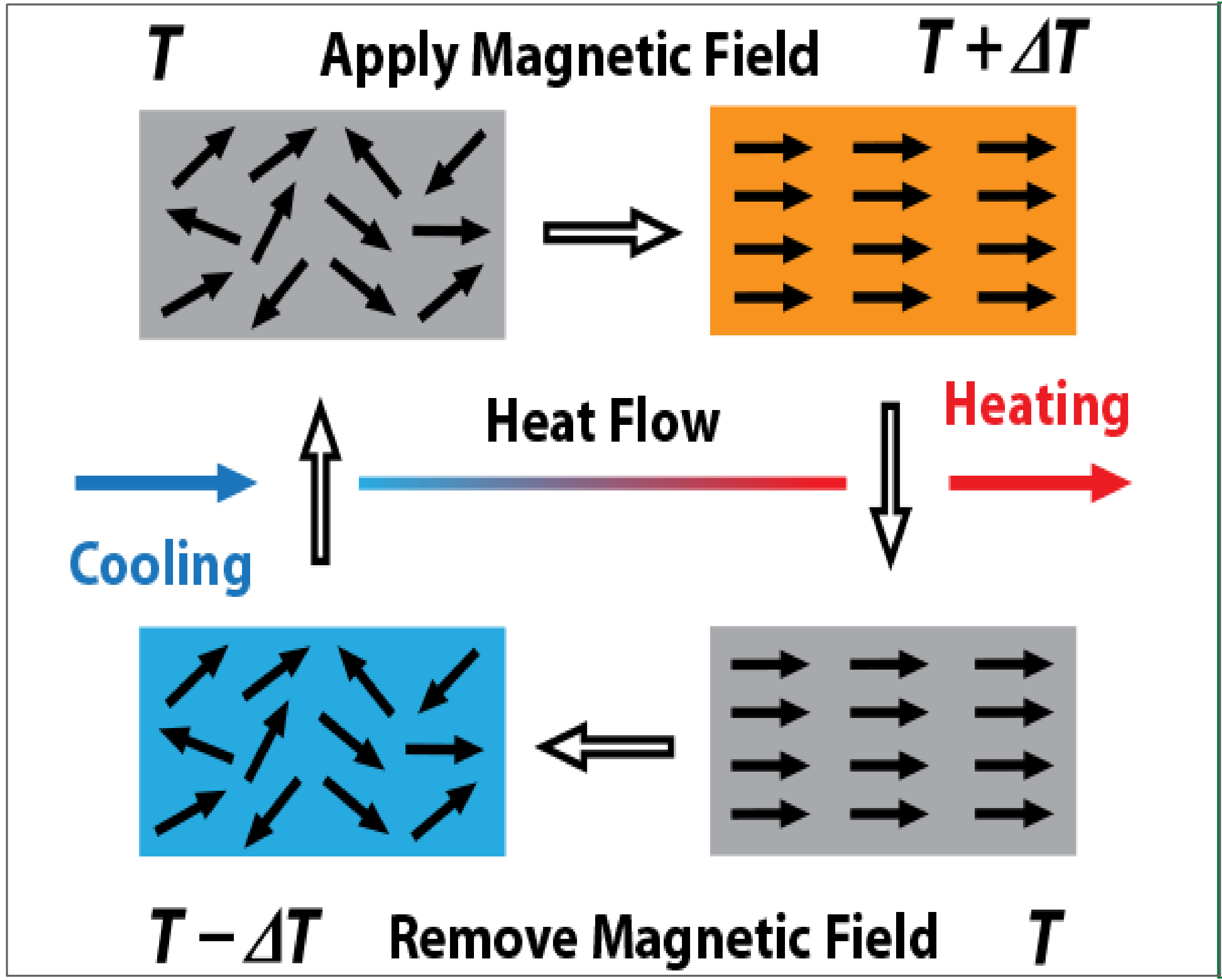
Replace low efficiency compressor - turbine

With high efficiency MOLS air liquefier

Figure from Jones et al, Fuel Processing Tech 92 (2011) 1685

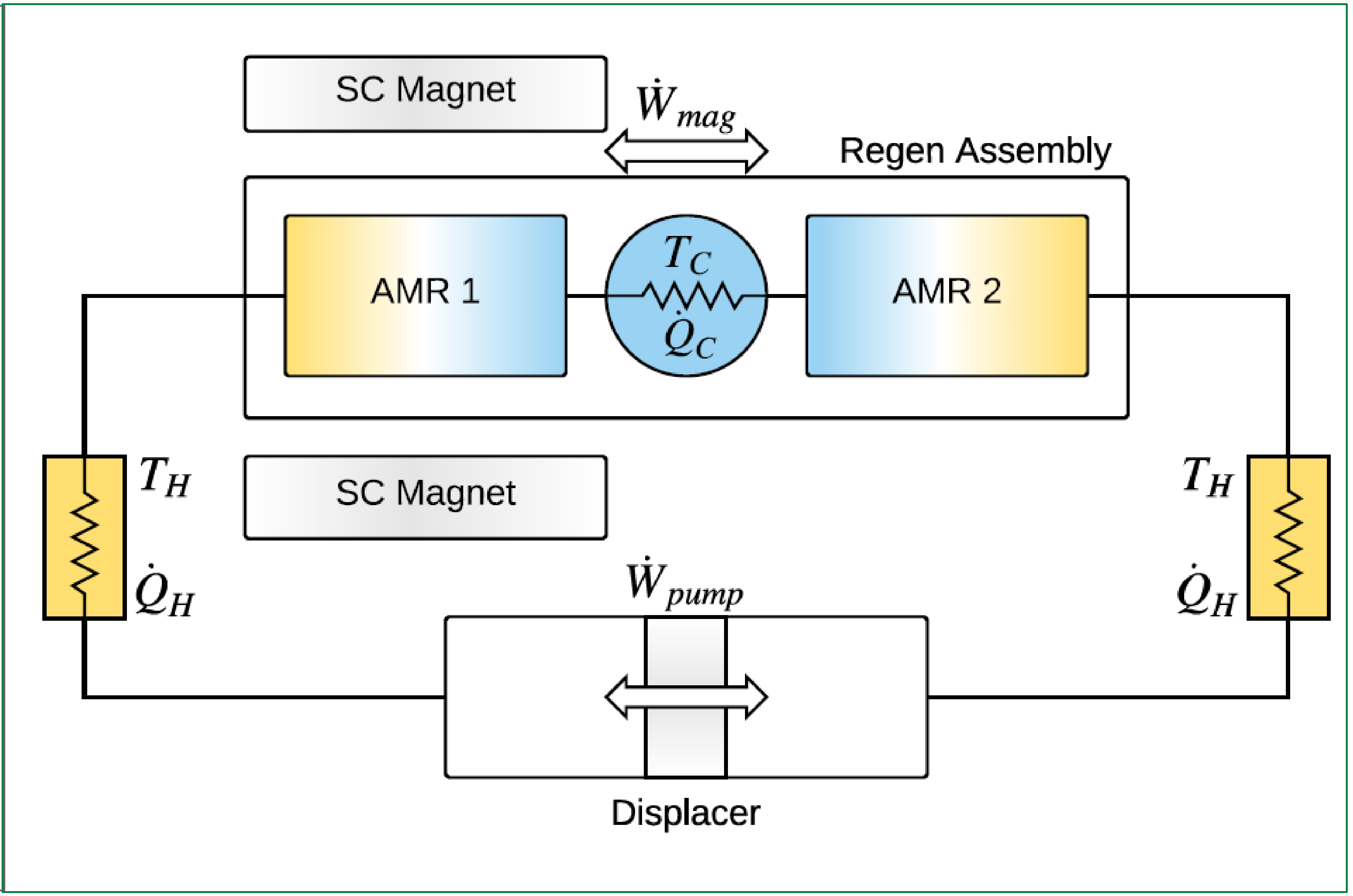
Background:

Active Magnetic Regenerative Refrigeration uses the magnetocaloric effect for efficient cooling



https://www.caloricool.org/area/magnetocaloric-effect.

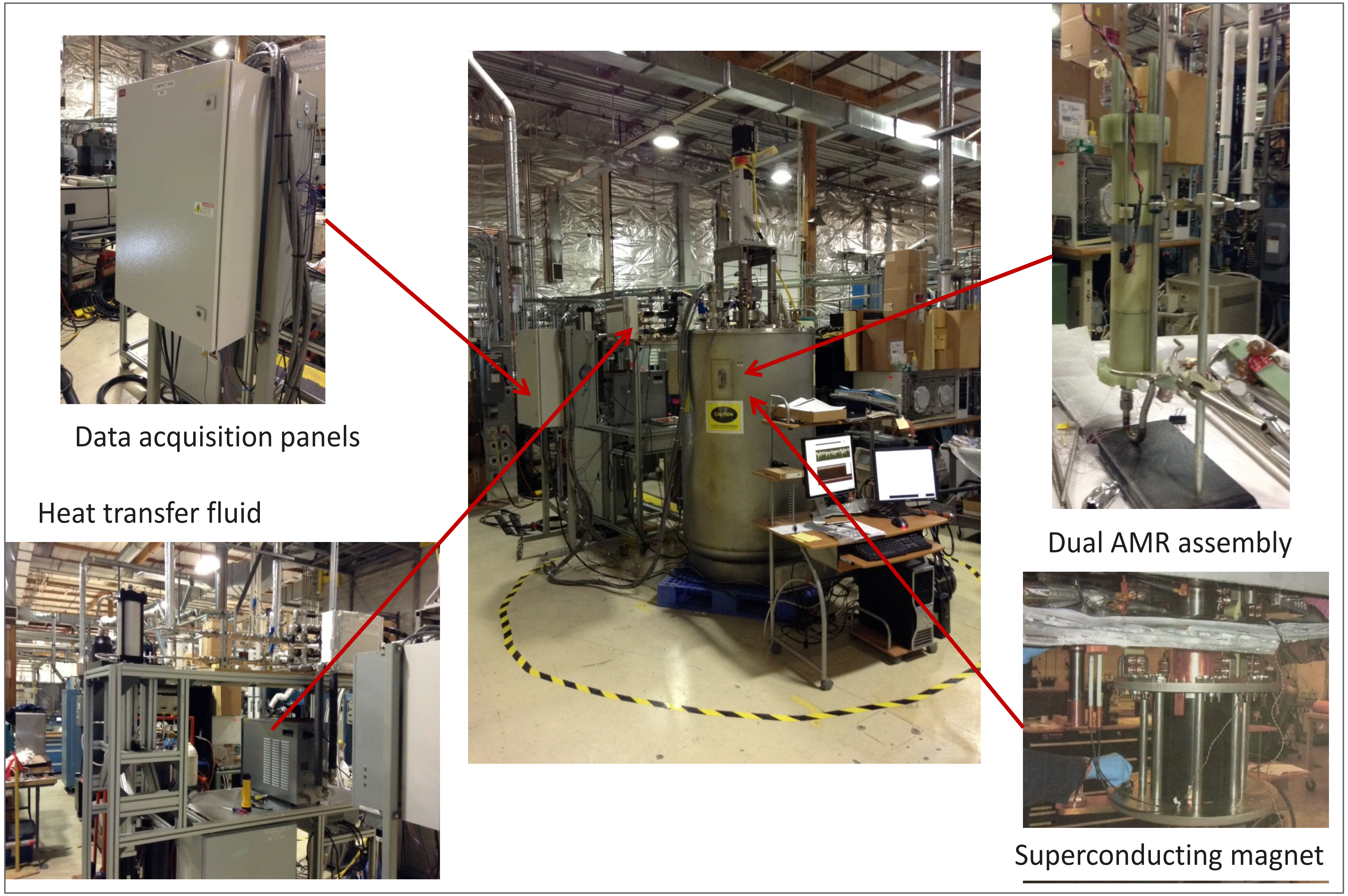
Dual Active Magnetocaloric Regenerator System



Schematic of active magnetic regenerator;
See R. Teyber,; J.D. Holladay, et. al. 2019 *Applied Energy* to be published in Feb.

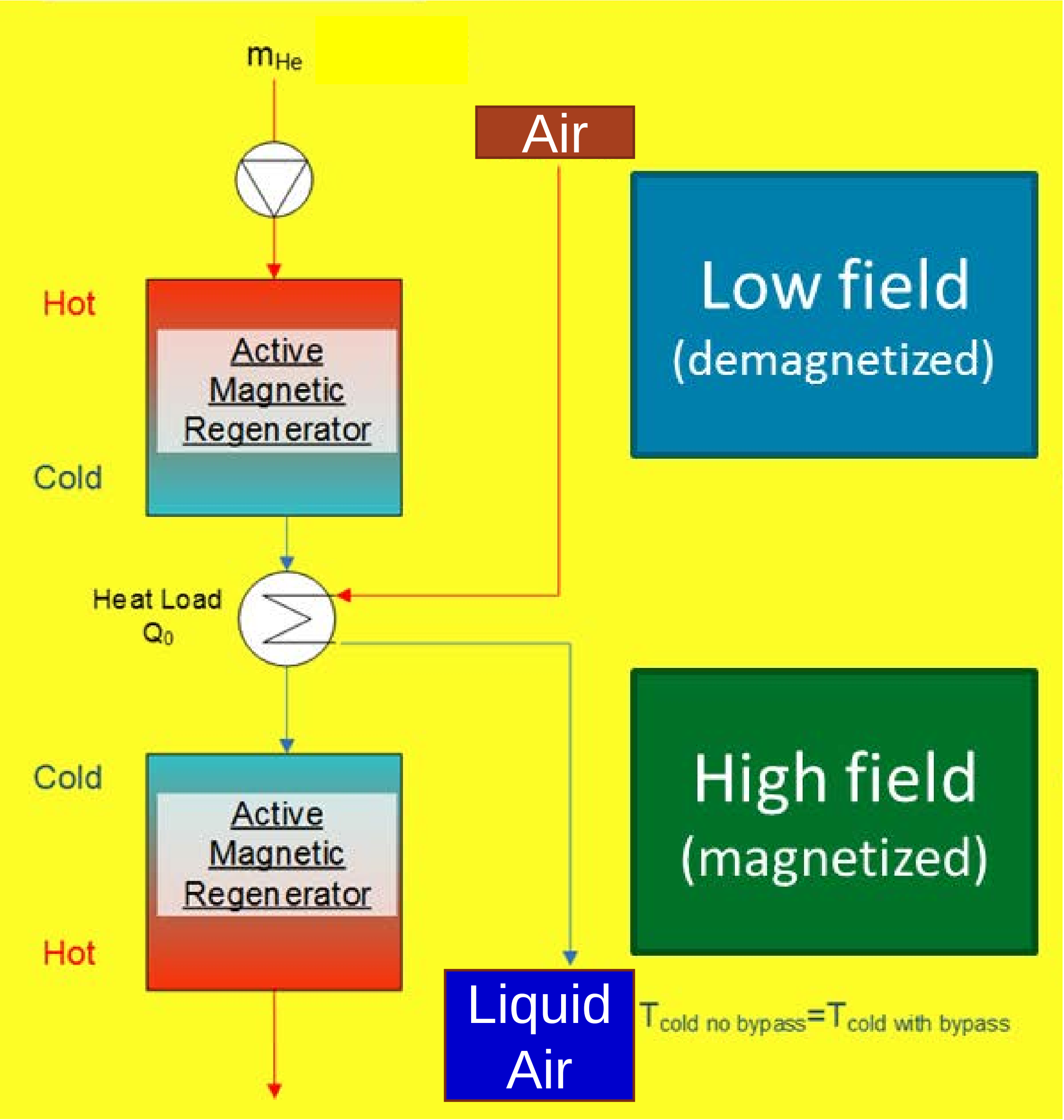
Background:

PNNL's has been working on magnetocaloric cryogenic cooling since 2015



Technical Approach:

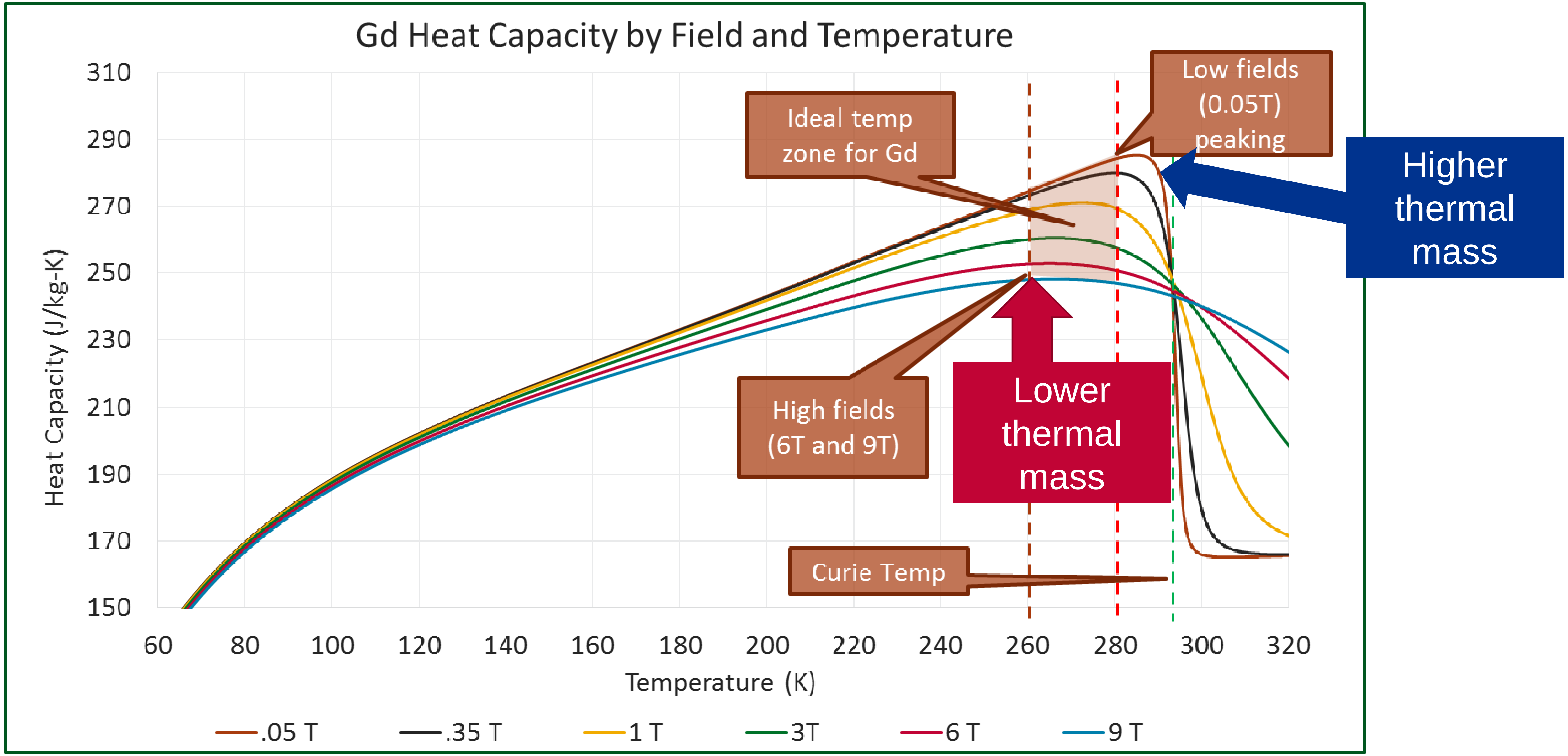
PNNL uses patent pending engineering designs for modular and (potentially) highly efficient operation



Active Magnetic Regenerator = AMR

Technical Approach:

We take advantage of the unique characteristic of 2nd order ferromagnetic materials for high performance

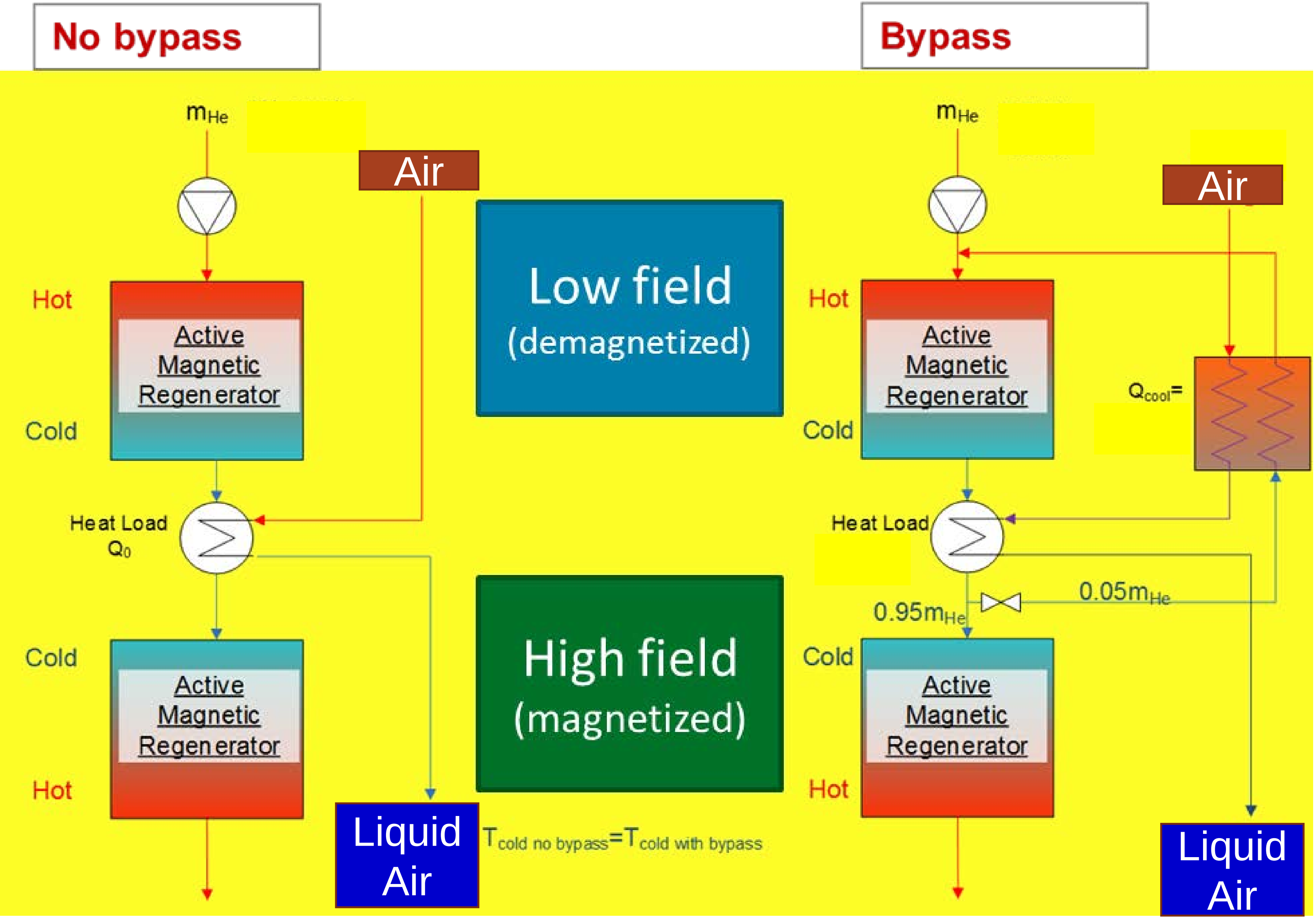


Data measured by AMES in FY17

Technical Approach:

Our liquefier exploits heat transfer fluid bypass to take advantage of the difference in thermal mass

- Bypass enables continuous cooling which decreases the temperature approach in the process heat exchanger thus increasing the efficiency

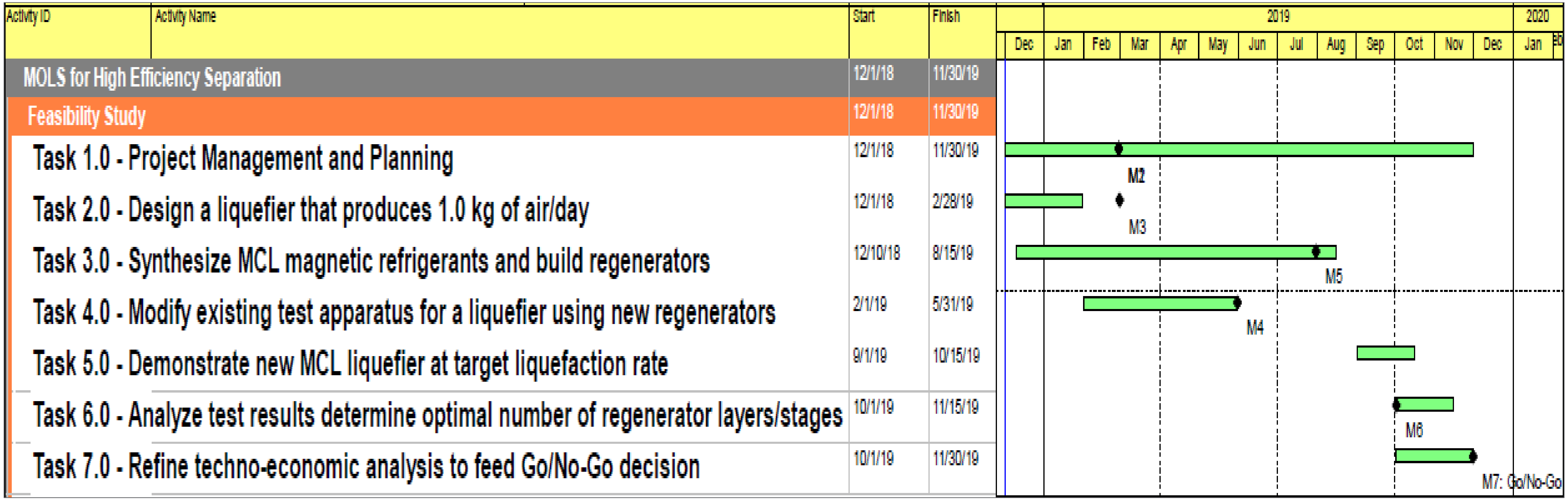


Active Magnetic Regenerator = AMR

Project Structure:

A phased approach will be used for the air liquefier development to minimize risk

- <u>Phase 1: Feasibility Study:</u> Use PNNL's MCL technology for air liquefaction and perform techno-economic analysis to determine the economic and technical viability

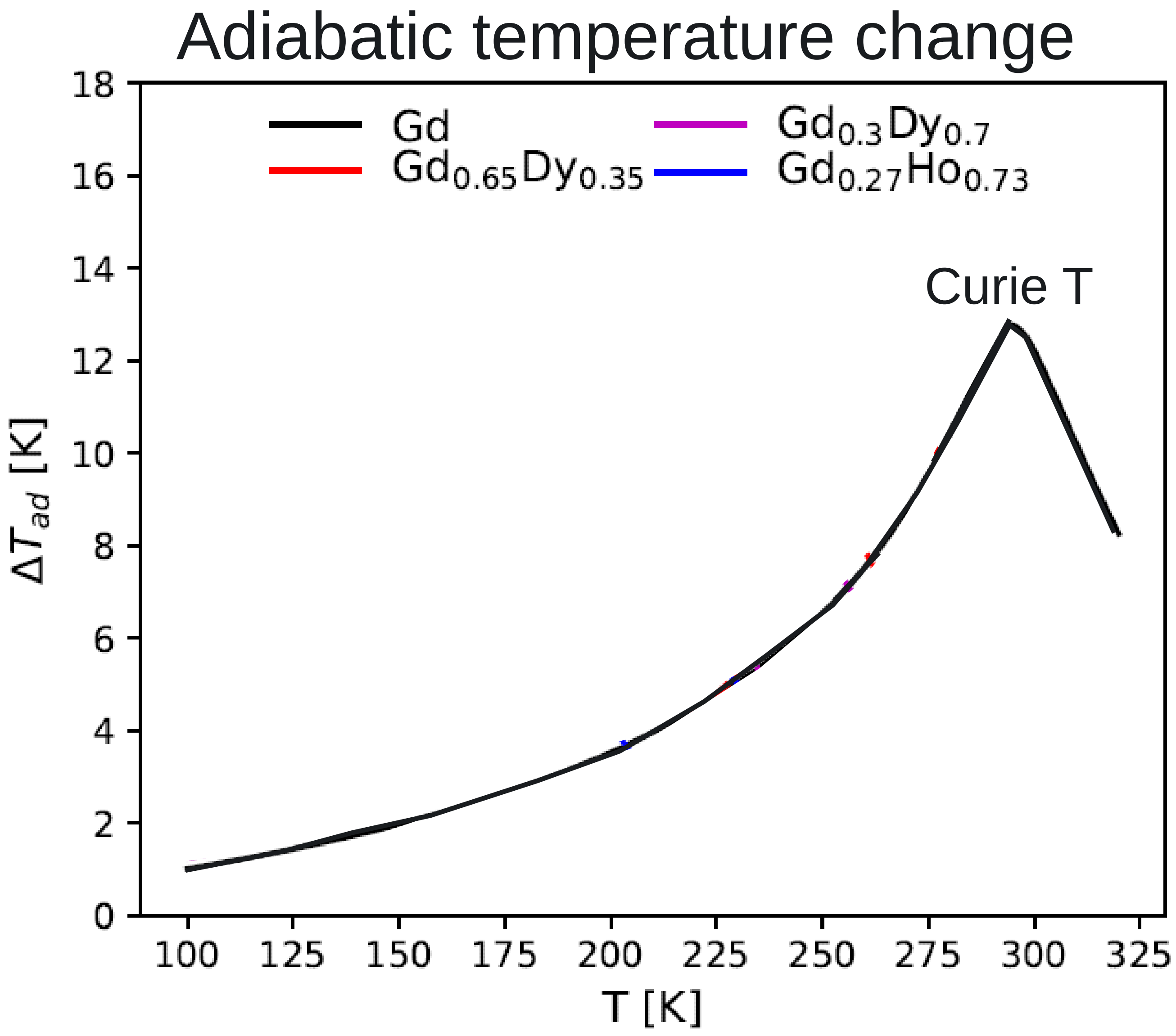


Activity ID	Activity Name	Start	Finish
	MOLS for High Efficiency Separation	12/1/18	11/30/19
	Feasibility Study	12/1/18	11/30/19
	Task 1.0 - Project Management and Planning	12/1/18	11/30/19
	Task 2.0 - Design a liquefier that produces 1.0 kg of air/day	12/1/18	2/28/19
	Task 3.0 - Synthesize MCL magnetic refrigerants and build regenerators	12/10/18	8/15/19
	Task 4.0 - Modify existing test apparatus for a liquefier using new regenerators	2/1/19	5/31/19
	Task 5.0 - Demonstrate new MCL liquefier at target liquefaction rate	9/1/19	10/15/19
	Task 6.0 - Analyze test results determine optimal number of regenerator layers/stages	10/1/19	11/15/19
	Task 7.0 - Refine techno-economic analysis to feed Go/No-Go decision	10/1/19	11/30/19

Progress:

Multiple refrigerants are required to efficiently achieve a large temperature span and bypass

- Cooling power is proportional to adiabatic temperature change
- As move away from Curie Temperature
  - The adiabatic temperature change decreases
  - Difference in thermal mass decreases so bypass is reduced
- To maximize cooling power over a wide temperature span multiple materials are required



- Solid lines show field change from 6 to 0.2T
- Dashed lines internal field change from 3.1 to 0.2 T

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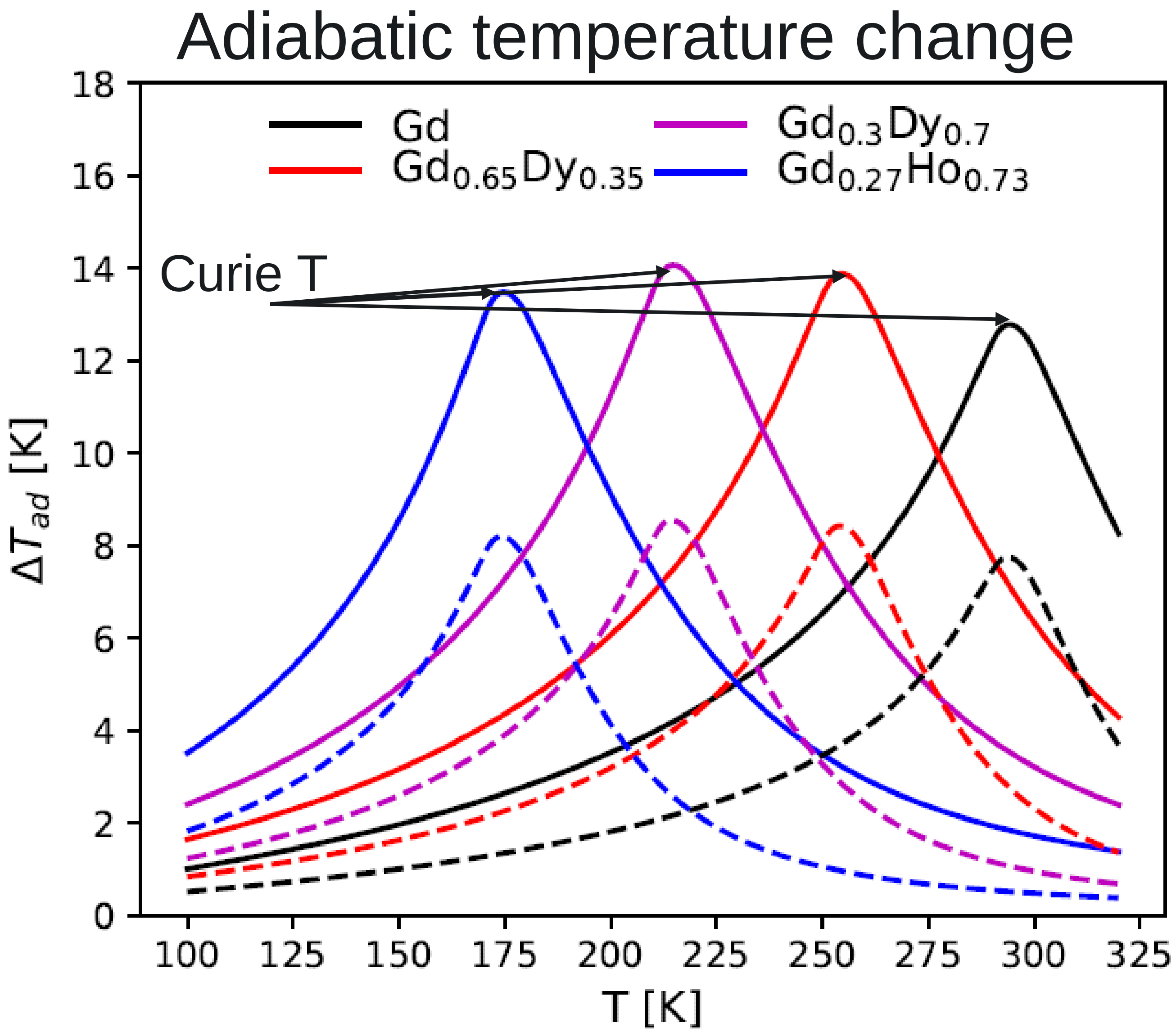


- Solid lines show field change from 6 to 0.2T
- Dashed lines internal field change from 3.1 to 0.2 T

Progress:

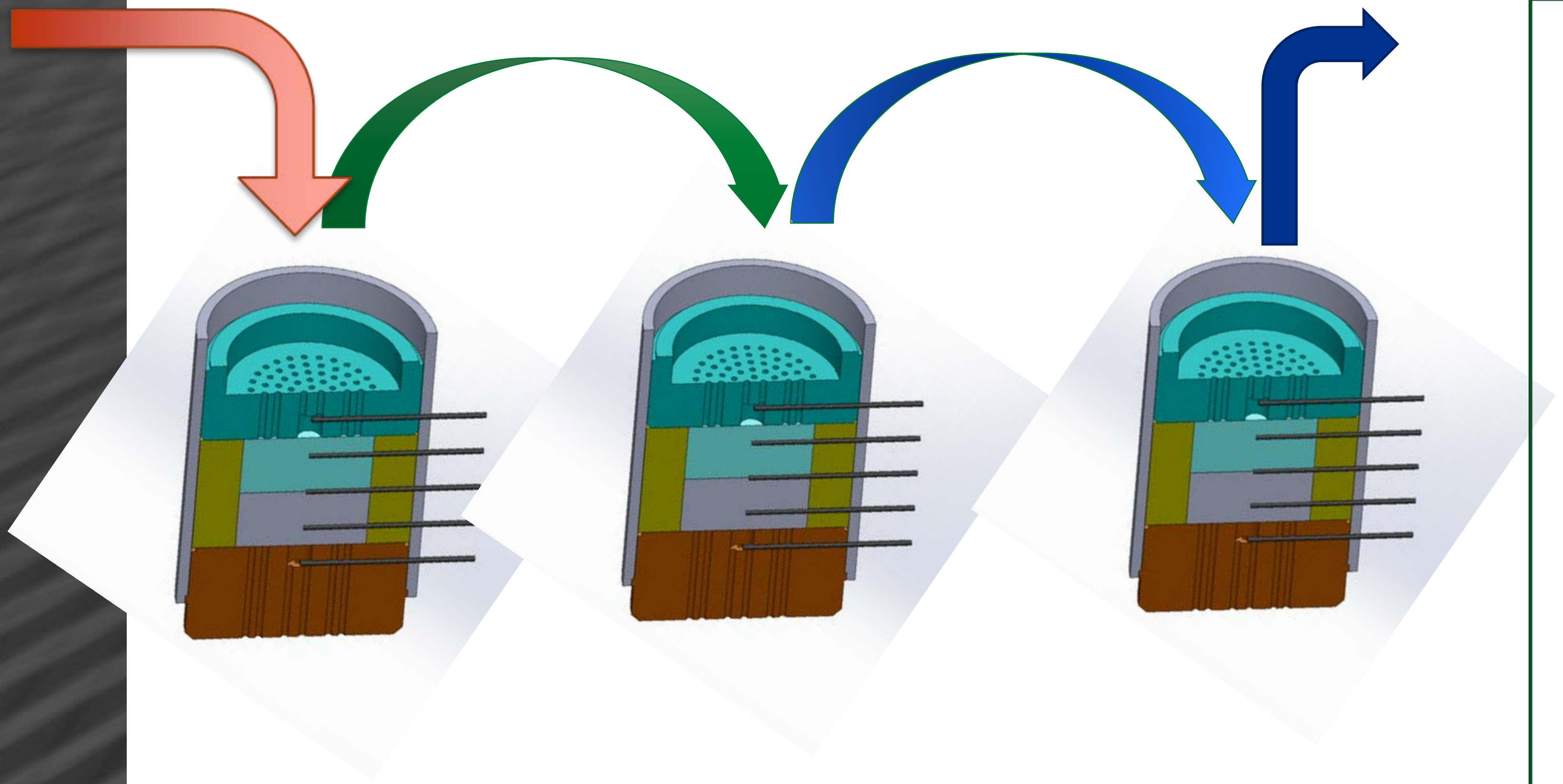
Magnetic materials with large ΔT vs. T for 6-layer dual regenerators selected for MOLS prototype

Layer Number	Magnetic Material Molar Composition	Curie Temperature (K)	Ave Thot Temperature (K)	Ave Tcold Temperature (K)
1	Gd	293	280	250
2	$Gd_{0.75}Dy_{0.25}$	263	250	220
3	$Gd_{0.49}Dy_{0.51}$	233	220	190
4	$Gd_{0.24}Dy_{0.76}$	203	190	160
5	$Gd_{0.27}Ho_{0.73}$	173	160	130
6	$Gd_{0.74}Er_{0.26}Al_2$	143	130	100

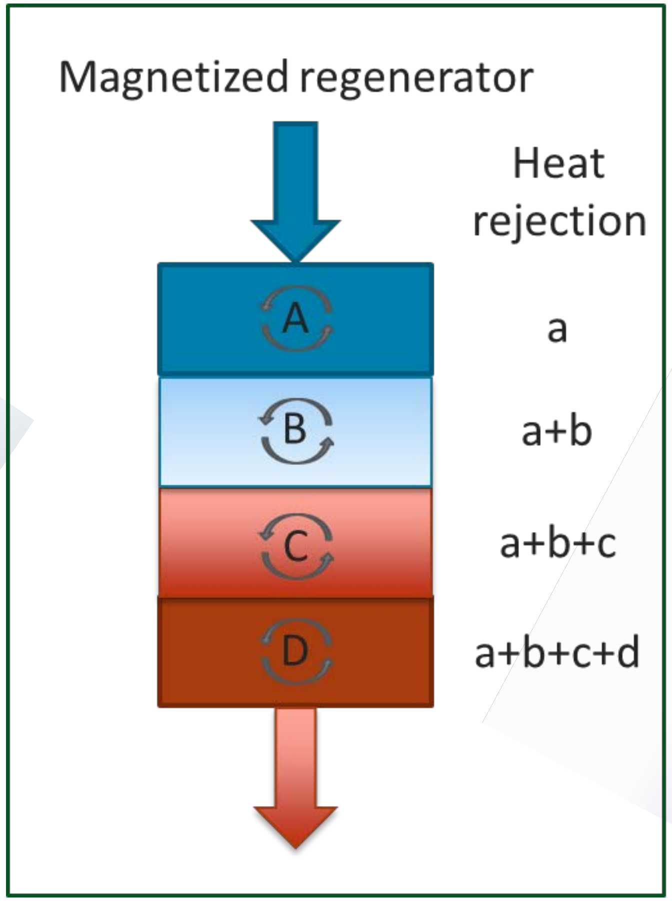
Progress:

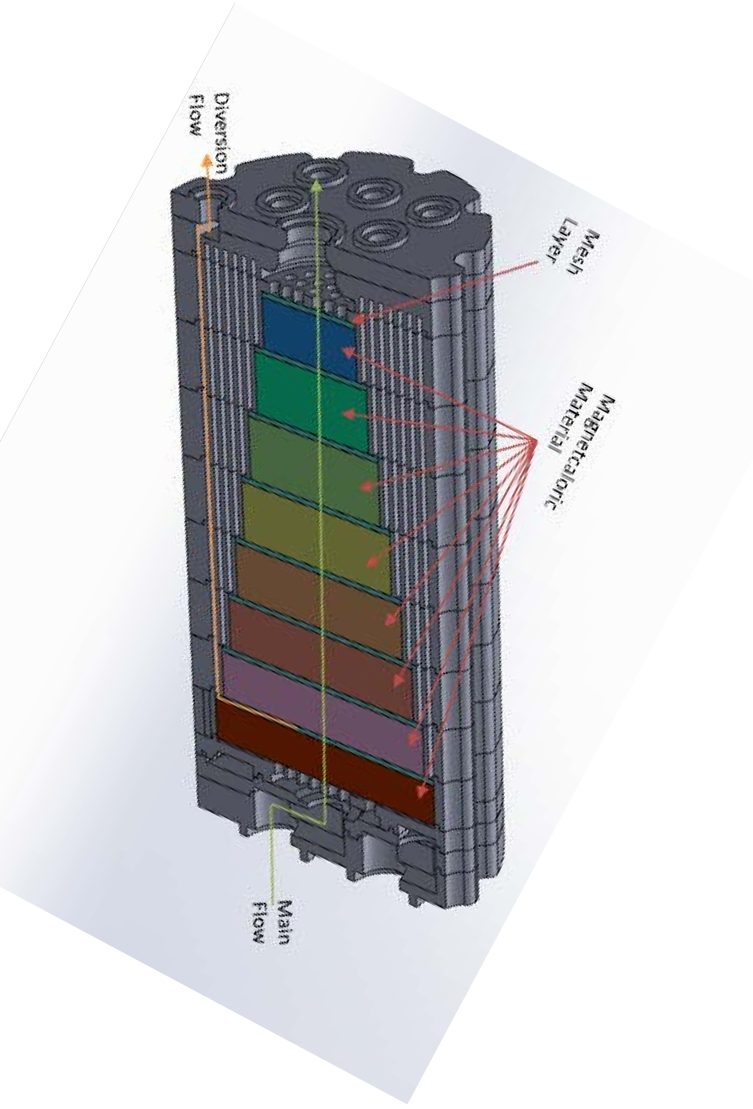
Design options: multi-stage regenerators or multi-layer regenerator

Multi-stage regenerators



Multi-layered regenerator



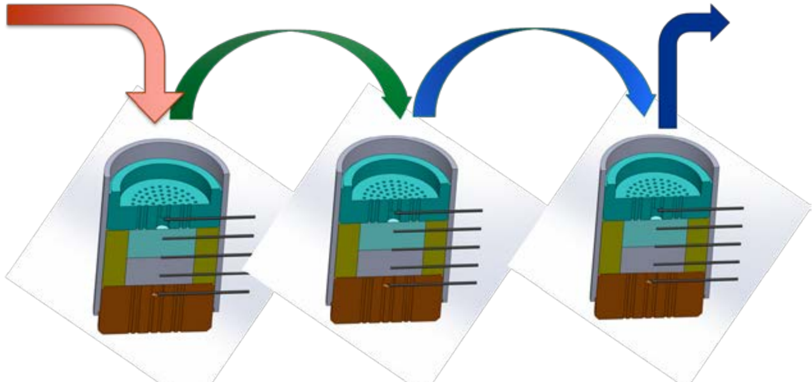


Progress:

Design options: multi-stage regenerators or multi-layer regenerator

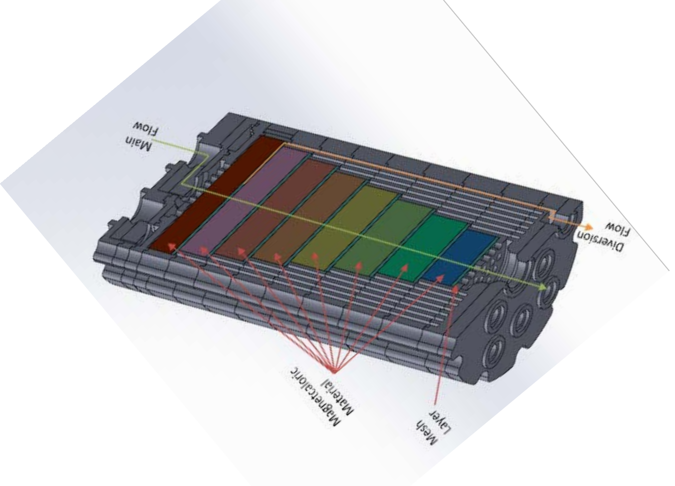
Multi-stage regenerators

- 1-2 materials per regenerator
- Advantages
  - Easy startup
  - Easy control
  - Simple design
- Disadvantages
  - Increased capital cost
  - Inter-stage heat exchangers are required

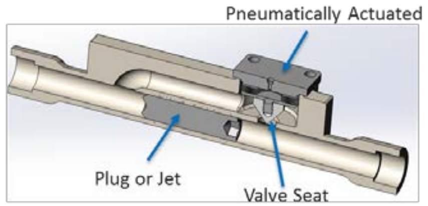


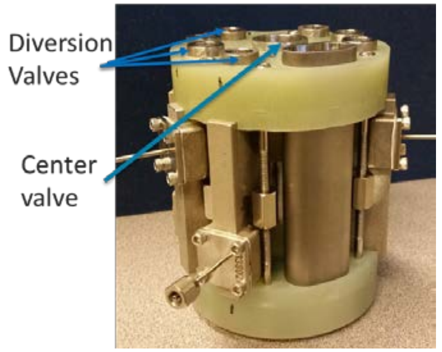
Multi-layer regenerator

- Materials in layers
- Advantages
  - Reduced capital cost
  - Eliminates interstage heat exchangers
- Disadvantages
  - Requires diversion flow
  - Difficult to design and control



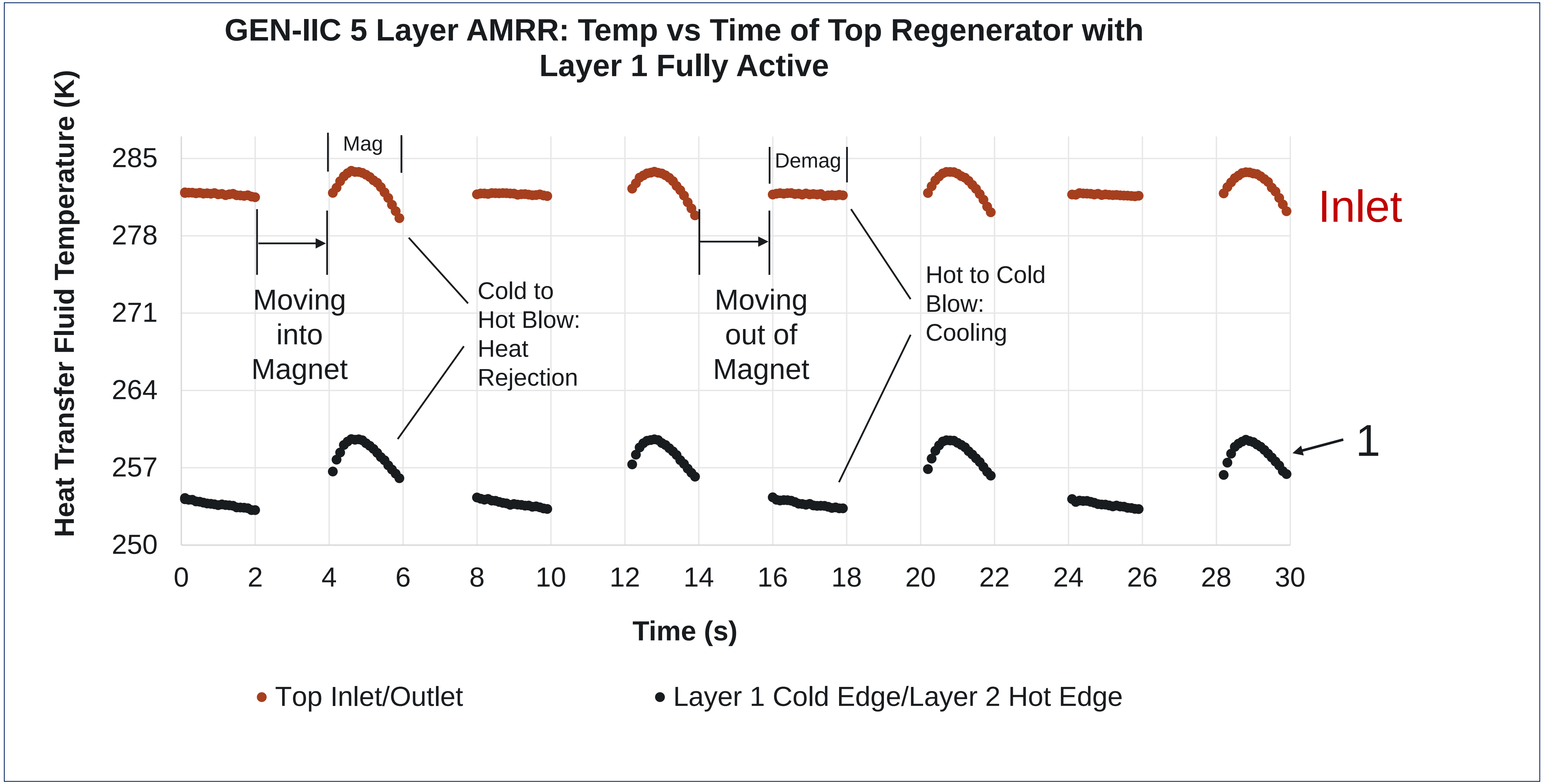
Control valve design





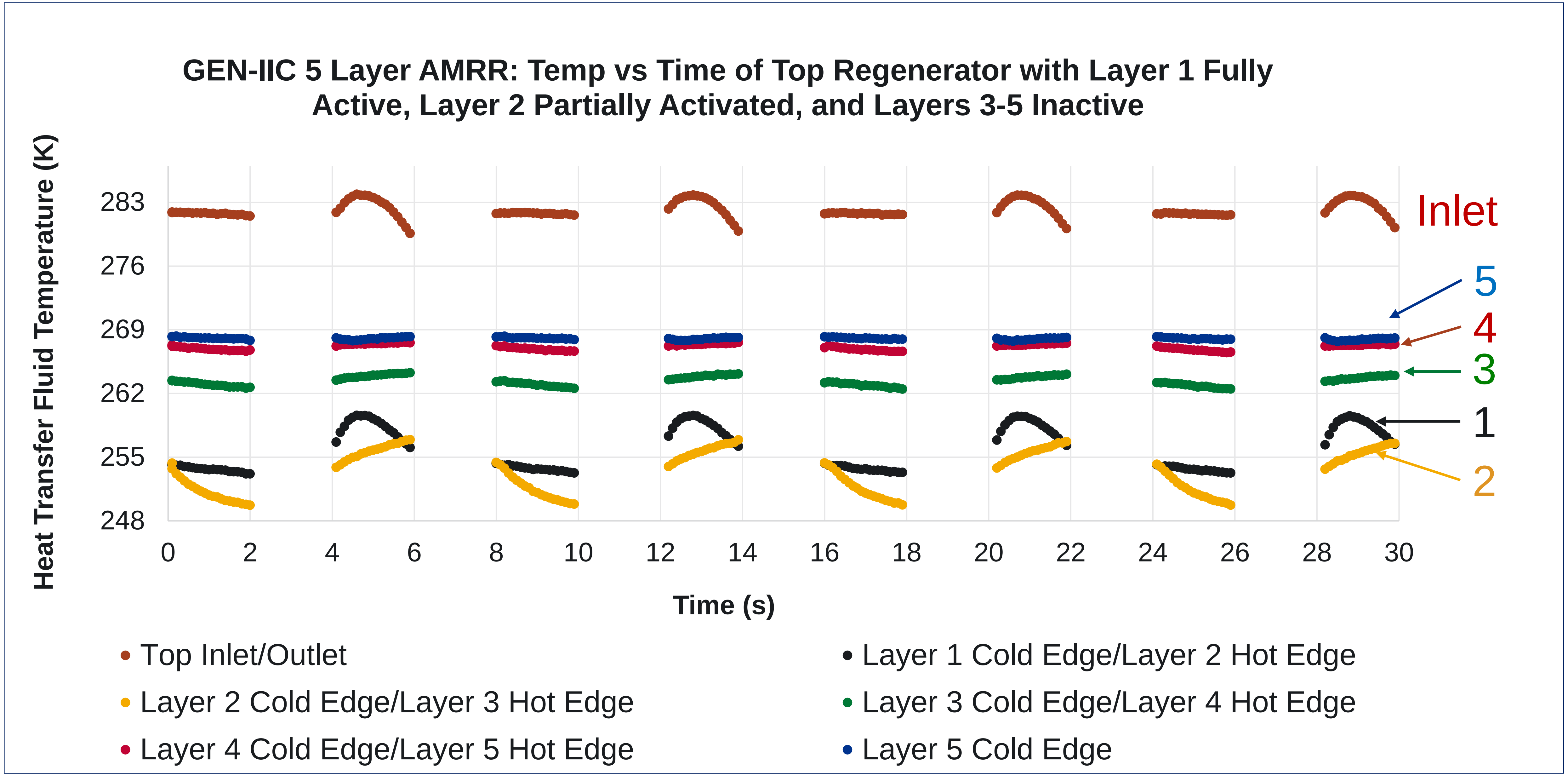
Progress:

New sensors-elimination of systematic errors in data analysis gave proven execution of the AMR cycle



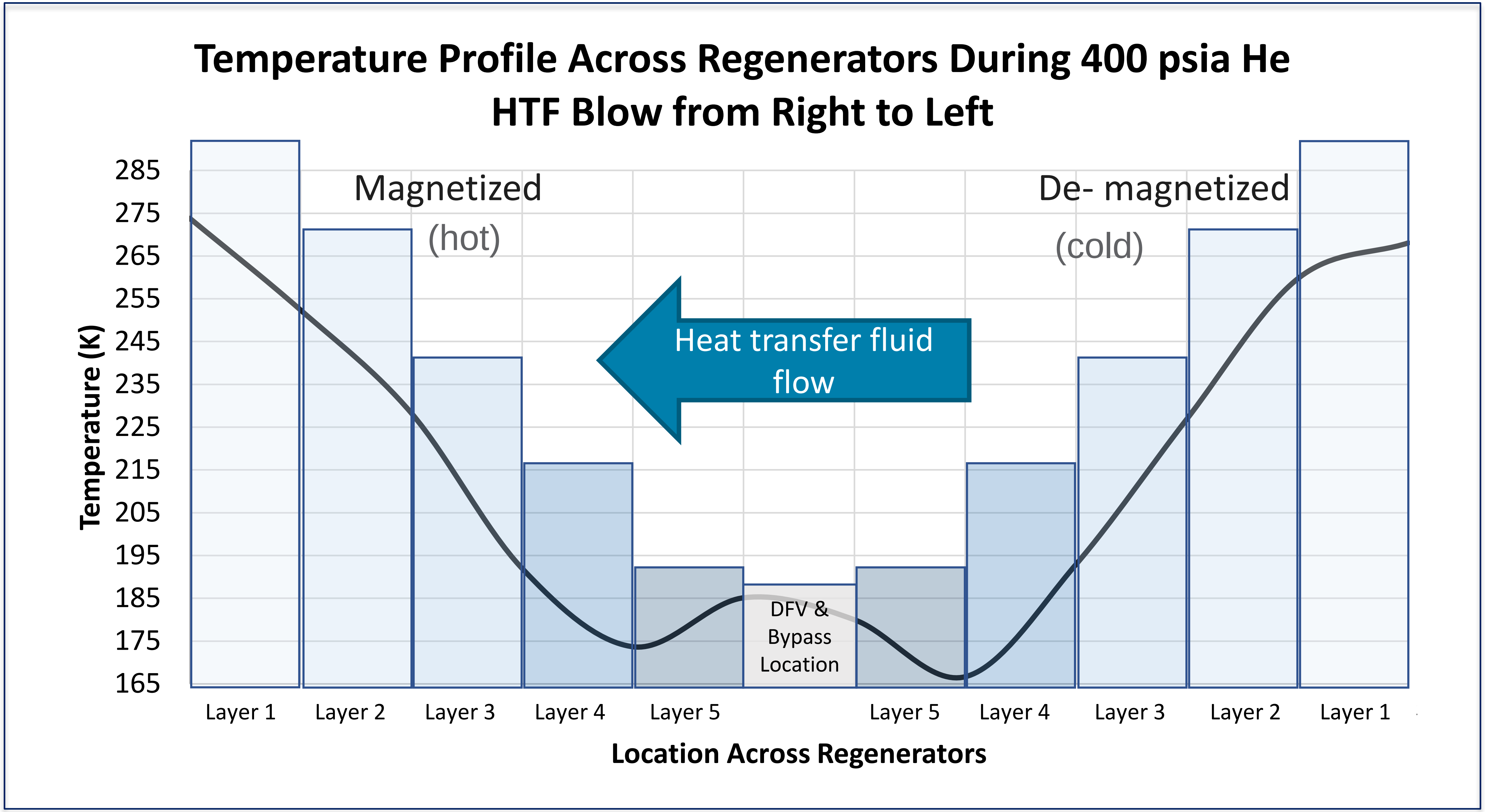
Progress:

Operation with controlled diversion flow; first layer (Gd) has heat transfer fluid flow; other layers do not



Progress:

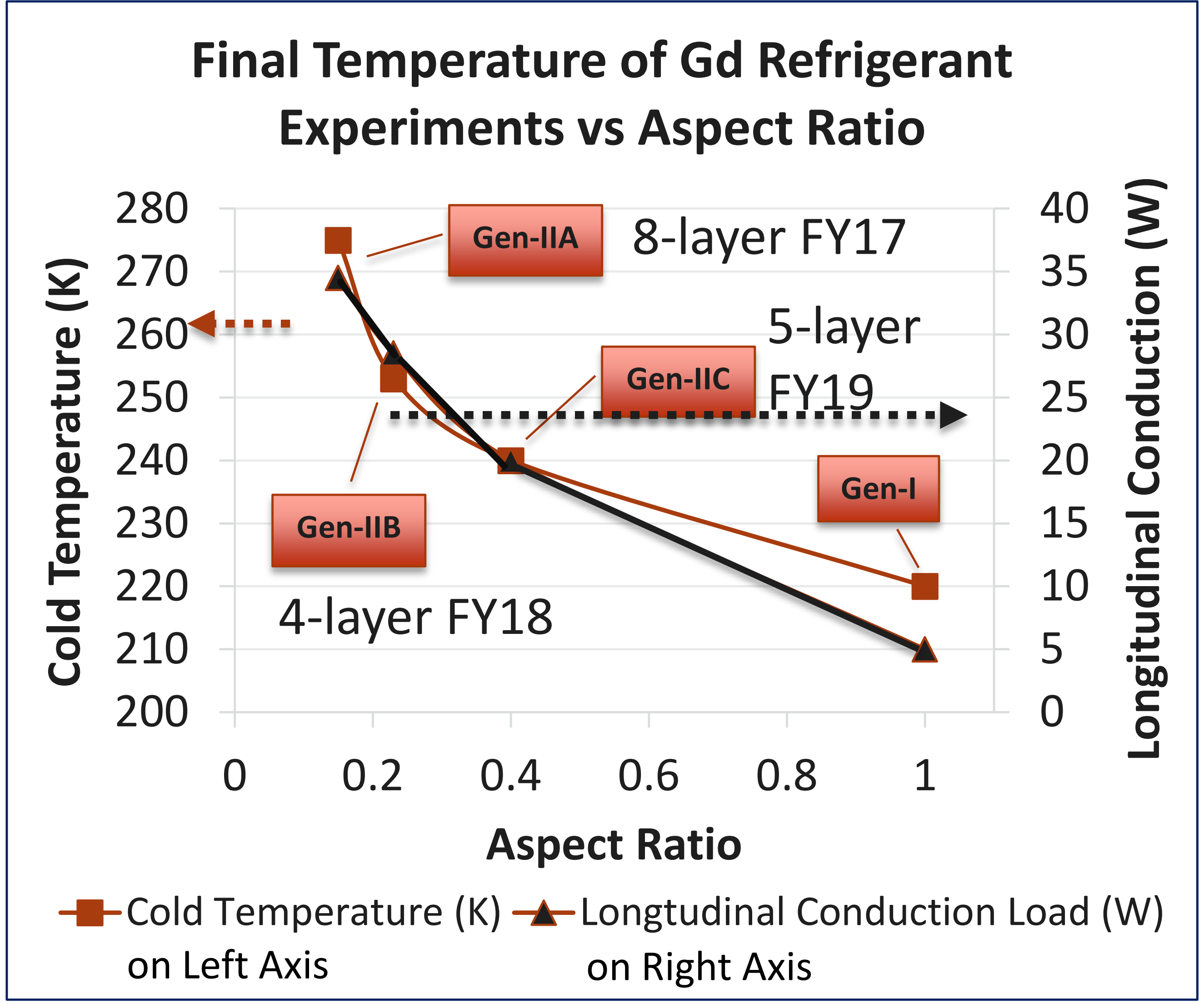
GEN-IIC achieved ~165 K even with large parasitic heat leaks



Progress:

Length/diameter aspect ratio impacts available cooling power

- Small aspect ratios increase longitudinal conduction loads
- Reduces available cooling power/layer of refrigerants
- GEN-I (single-layer) prototypes had 1:1 aspect ratios within original s/c magnet dimensions
- GEN-II (multi-layer) required smaller aspect ratios to fit multiple layers into s/c magnet
- All GEN-II results are fully explainable once longitudinal conduction is subtracted from refrigerants gross cooling power
- Developed new equations to take aspect ratio (background section) into account and updated models
- **Future designs: Aspect ratios > 0.6-0.7 + *longer magnets*!**

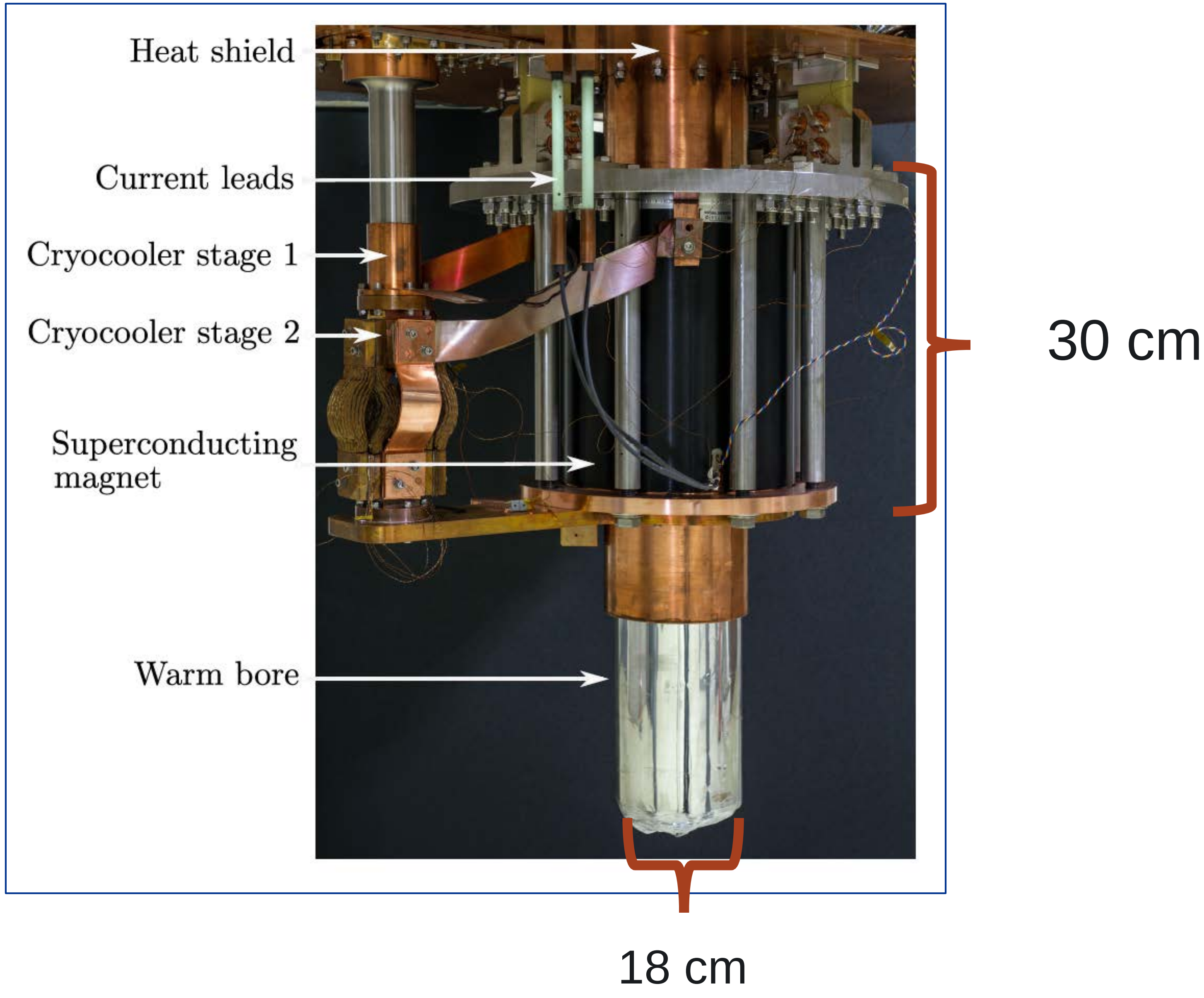


First time identified the aspect ratio affects on available cooling power enabling allowing balance between eddy diffusional and ΔP

Progress:

Current super-conducting magnet is not long enough and has poor magnetic field design

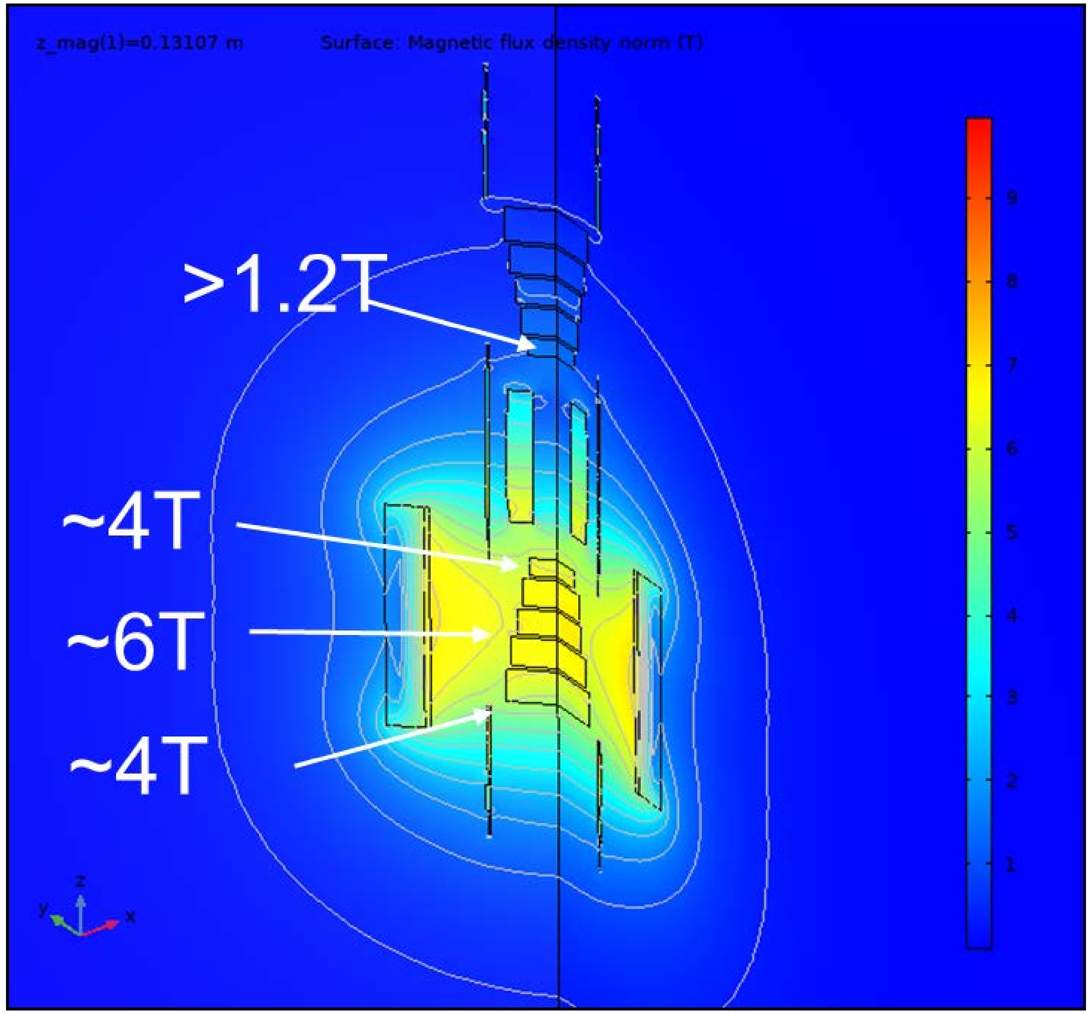
- New s/c magnet designed for uniform 6.5 T axial field so each layer has same high field
- Includes counter windings to taper field down to uniform 0.1 T low field at correct position
- Magnet windings and length designed in tandem with regenerator geometries for 0.7 aspect ratios for all layers
- These criteria and known refrigerant masses result in a ~65 cm long s/c magnet with ~20cm open bore



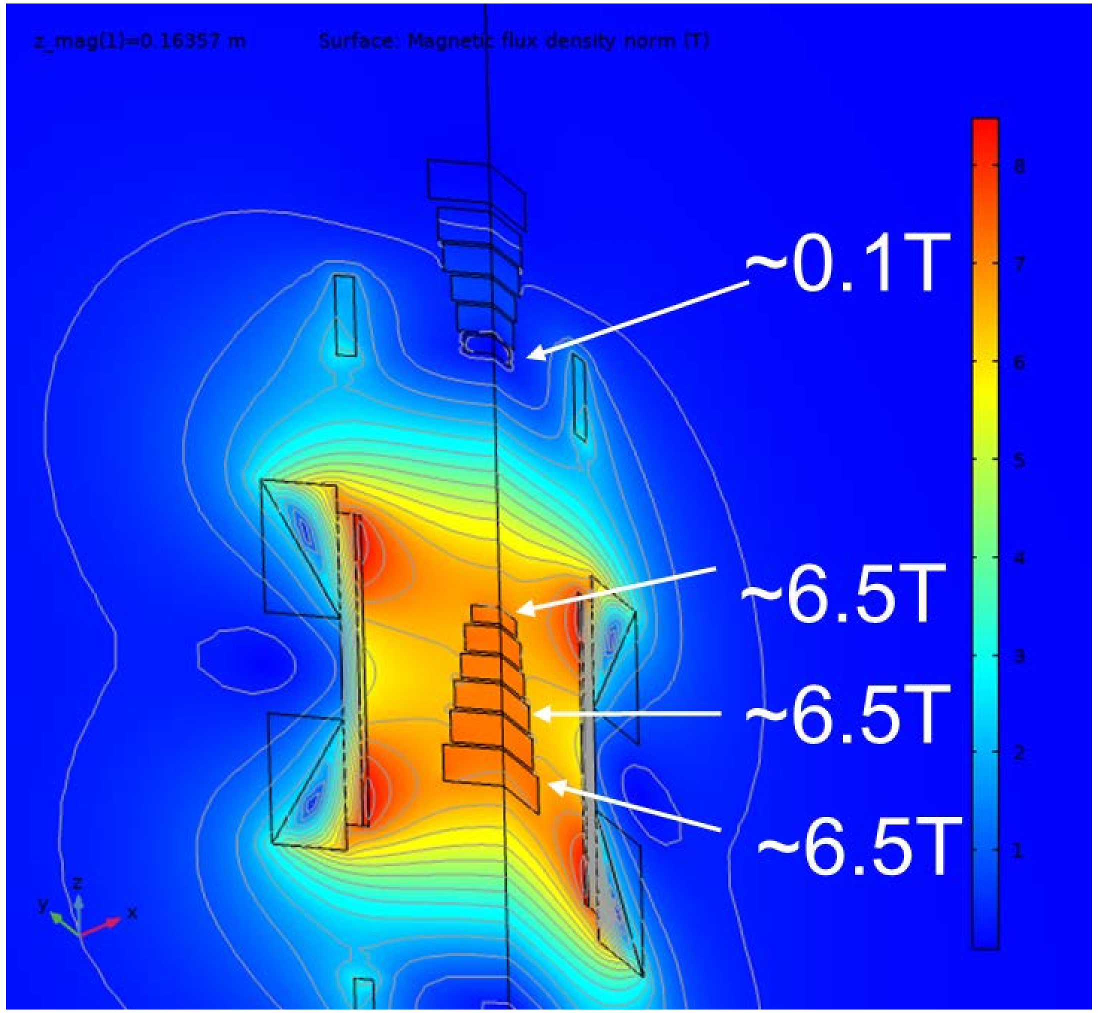
Progress:

New s/c magnet will improve magnetic field profile and magnetic field gradients

- Current s/c magnet and drive stroke limit regenerators field changes + range of field gradients



- New design with “ears and counter coils” has constant magnetic high/low fields and same field gradients



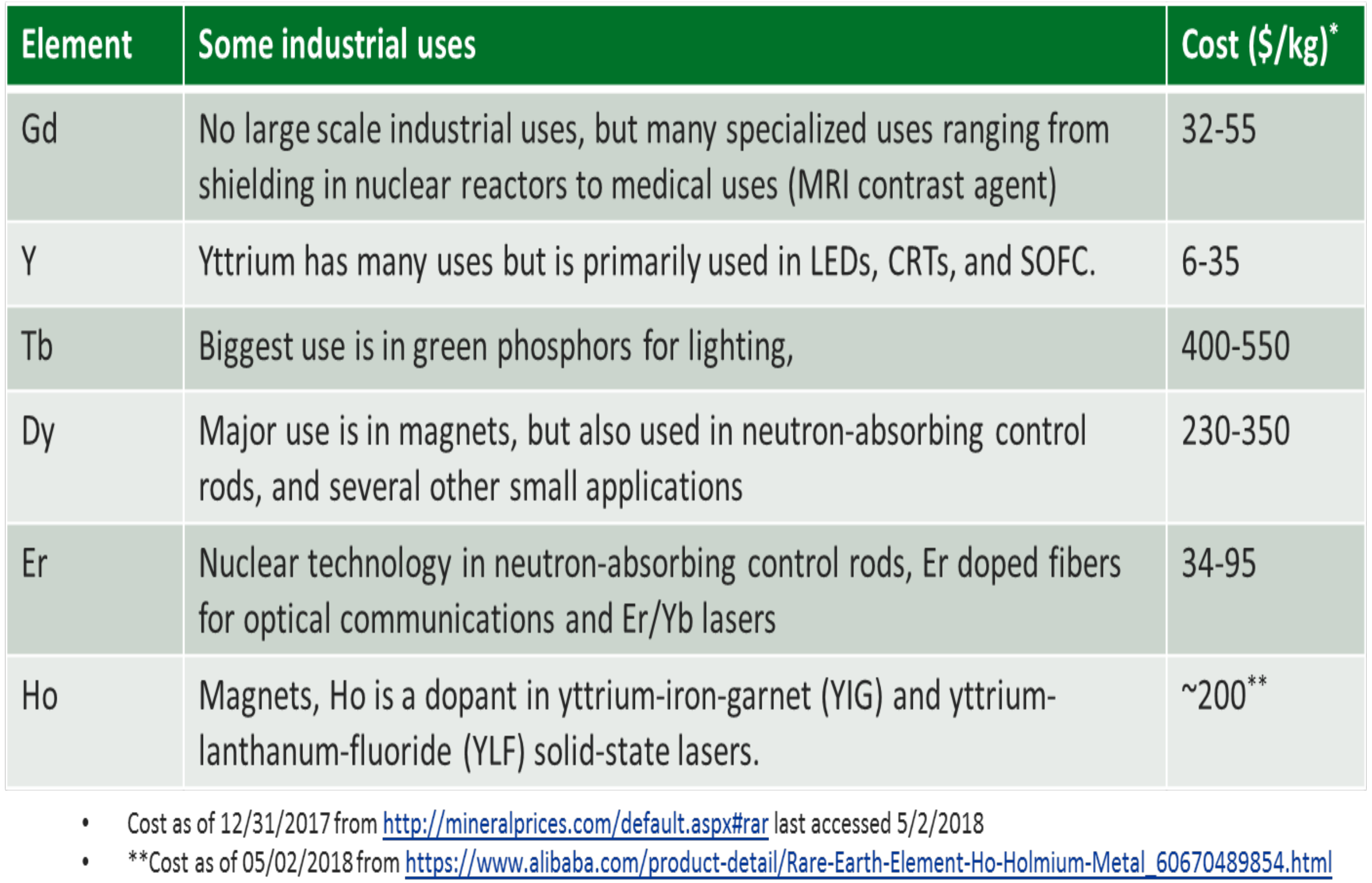
Progress:

Design basis for MOLS prototype

- Process gas:
  - Inlet is clean, dry air at 100 psia and 295 K; outlet is liquid air at ~100 psia and ~100 K.
  - Flow synchronized with AMR cooling steps of dual regenerators
- Active Magnetic Regenerative Liquefier subsystem specifications for MOLS
  - Temperature span is ~280 K to ~100 K with cooling of ~30 K/layer
  - Six layers integrated into each ~20cm dual regenerator; one proven refrigerant per layer
  - Ferromagnetic refrigerants have Curie temperatures that are ~30 K apart
  - Validated T, B_a dependent heat capacities and adiabatic temperature changes
  - Layers aspect ratio (L/D) ~0.7; porosity of ~0.37; spheres of ~150-250 μm; monolithic
  - Superconducting magnet; 6.5 T uniform field over 25cm; 0.1 T over 25cm; 13cm change regions
  - Frequency is ≥ 0.25 Hz
  - Heat transfer fluid is liquid that freezes at ~90 K so total pressure drops low from blows
  - Diversion flow valves to adjust flows/layers; bypass flow valve between coldest layers into counterflow process heat exchanger

Market benefit & assessment

- Benefits:
  - Modular system, scale-up by numbering up
  - Increase efficiency by up to 50% even at “small scale”
- Techno-economic analysis, Task 7, not officially started yet
  - Have surveyed cost of materials
  - Gd
  - $Gd_{0.75}Dy_{0.25}$
  - $Gd_{0.49}Dy_{0.51}$
  - $Gd_{0.24}Dy_{0.76}$
  - $Gd_{0.27}Ho_{0.73}$
  - $Gd_{0.74}Er_{0.26}Al_2$

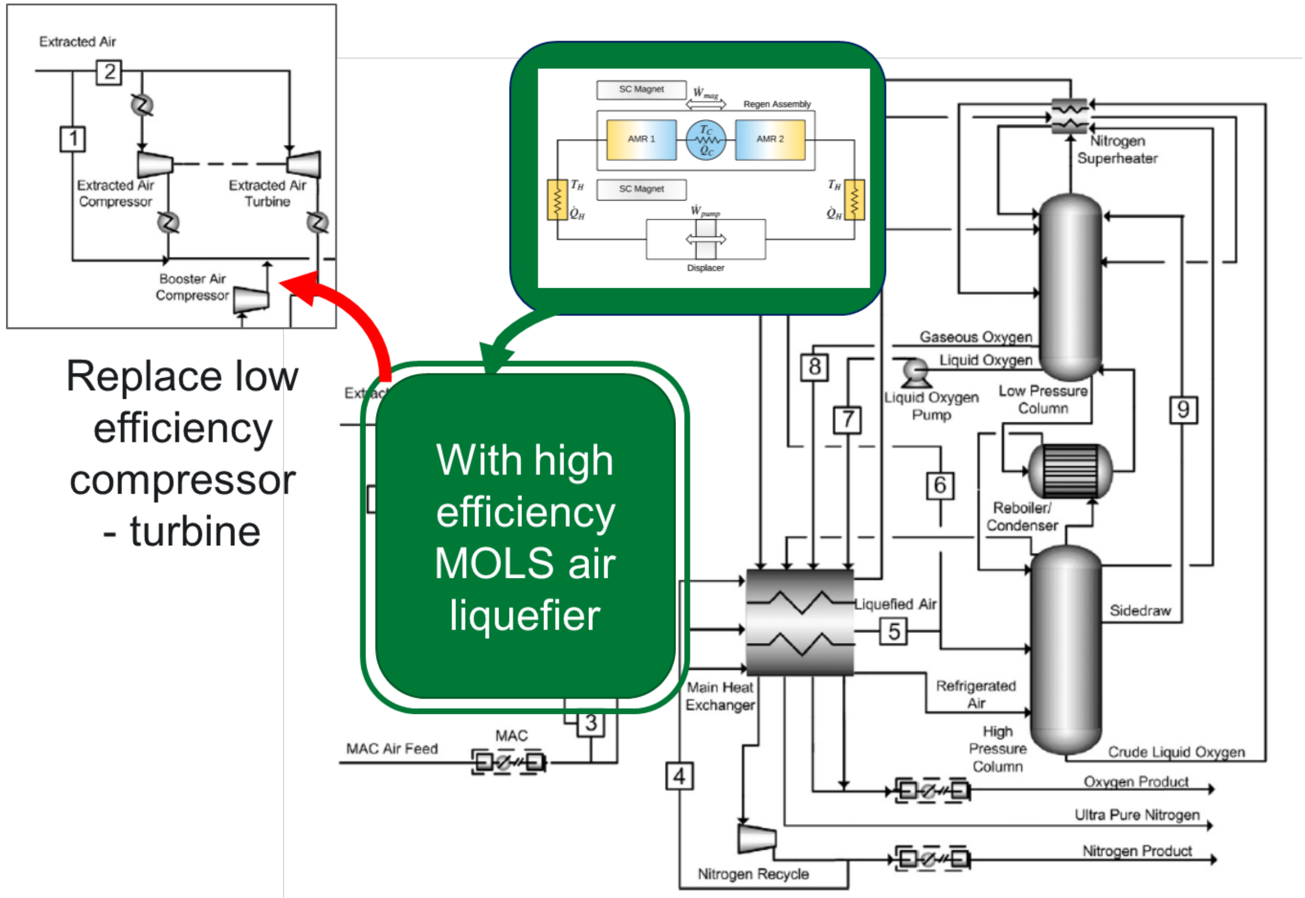


Element	Some industrial uses	Cost ($/kg)*
Gd	No large scale industrial uses, but many specialized uses ranging from shielding in nuclear reactors to medical uses (MRI contrast agent)	32-55
Y	Yttrium has many uses but is primarily used in LEDs, CRTs, and SOFC.	6-35
Tb	Biggest use is in green phosphors for lighting,	400-550
Dy	Major use is in magnets, but also used in neutron-absorbing control rods, and several other small applications	230-350
Er	Nuclear technology in neutron-absorbing control rods, Er doped fibers for optical communications and Er/Yb lasers	34-95
Ho	Magnets, Ho is a dopant in yttrium-iron-garnet (YIG) and yttrium-lanthanum-fluoride (YLF) solid-state lasers.	~200**

- Cost as of 12/31/2017 from http://mineralprices.com/default.aspx#rar last accessed 5/2/2018
- **Cost as of 05/02/2018 from https://www.alibaba.com/product-detail/Rare-Earth-Element-Ho-Holmium-Metal_60670489854.html

Technology-to-Market

- Modular air liquefaction units
  - 1-4 tonne O_2/day modules in cargo containers
  - Scale-up by numbering up
- Potential industry collaborators: in discussions with gas providers



Replace low efficiency compressor - turbine

With high efficiency MOLS air liquefier

Remaining challenges- MCL

- Validate the aspect ratio results
  - Build intermediate system to test while new s/c magnet is being built
- Seals
  - New energized seals and epoxy
- Startup – diversion flow
- Increase frequency
- Scale-up of the lab-scale unit to pilot plant
- Operation mode: reciprocating (current design) vs rotary
- Oxygen separation and purification: we propose microchannel technology, but this is not in our current scope

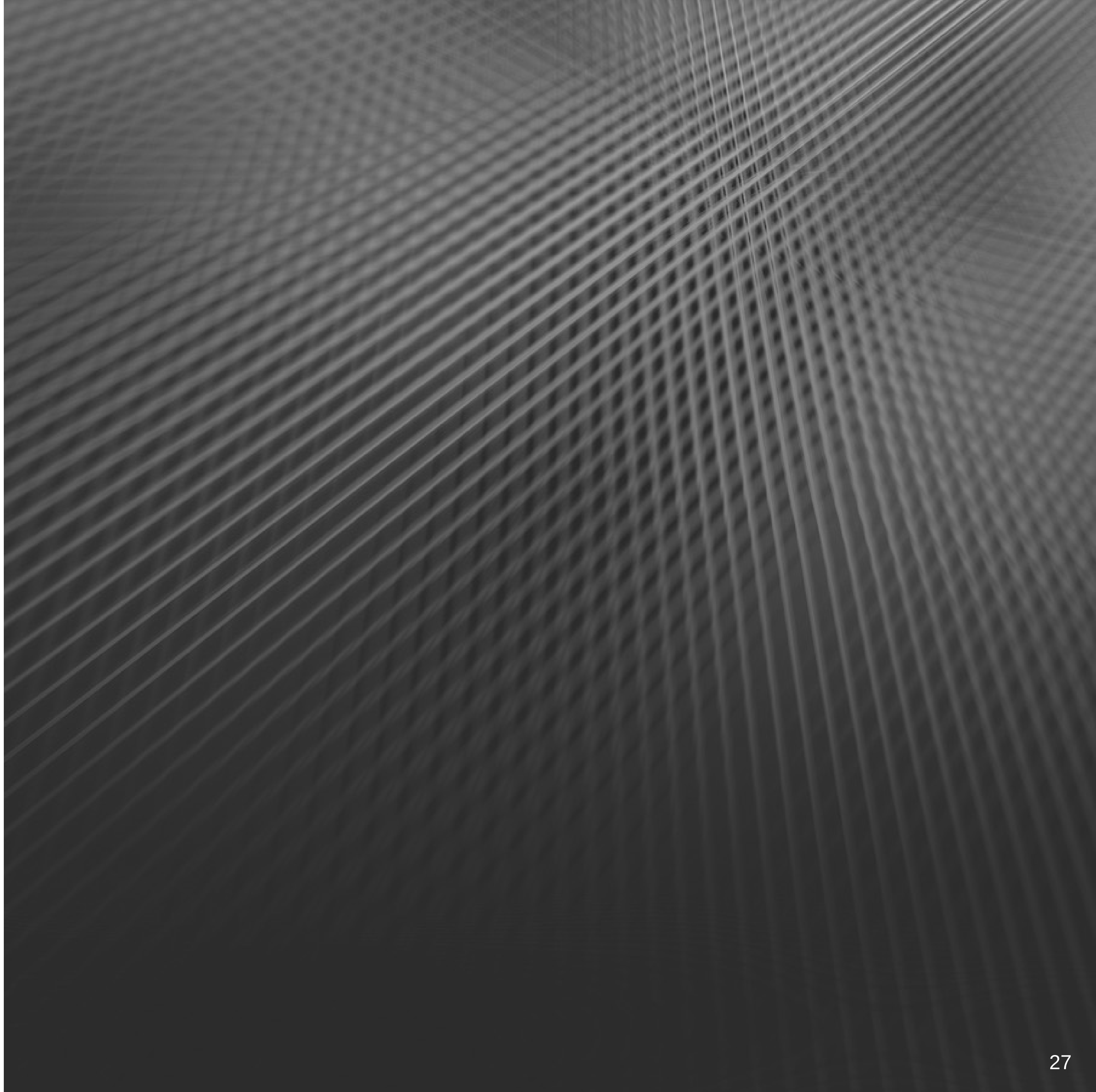
Concluding remarks

- Objective and Deliverable:
  - Feasibility of magnetocaloric demonstrated by liquefying air at a rate of 1kg/day
  - Techno-economic analysis:
    - ✓ Aspire to increase the FOM by 50%
    - ✓ Modular 1-4 tonne/day air liquefier,
    - ✓ Use optimal design to calculate expected liquefier FOM, perform techno-economic analysis for larger liquefier
    - ✓ Propose next steps
- Next steps
  - Finalize the design
  - Build and test
- Current technical challenges
  - Seals
  - Increase the frequency

Acknowledgements

- DOE- Fossil Energy
  - David Lyons
  - Venkat Venkataraman
- DOE- Fuel Cell Technology Office
  - Neha Rustagi
- The Team
  - Kerry Meinhardt
  - Ed Thomsen
  - Evgueni Polikarpov
  - John Barclay
  - Corey Archipley

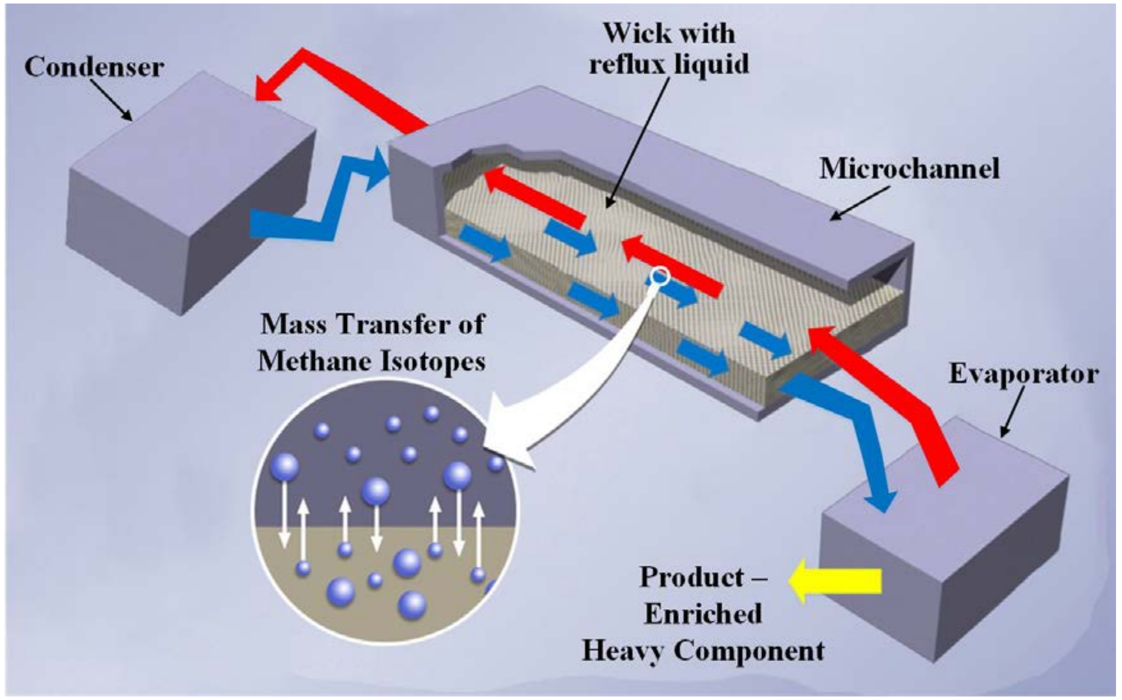
Thank you



Back-up

Remaining challenges: O_2 separation & purification: microchannel technology

- What about scaling the air separations?
  - Microchannel based distillation to separate the O_2
  - **This is not in current project scope**
- Distillation
  - Mass transfer is dominated by liquid phase diffusivity (*D*)
  - Liquid phase mass transfer is enhanced by increasing liquid phase surface area
  - HETP – Height equivalent to a theoretical plate
    - ✓ Origins in distillation theory relating mass transfer efficiency of packed columns to tray or ‘plate’ columns
    - ✓ Each ‘plate’ represents one theoretical stage of separation and HETP is the height of column needed for each stage
    - ✓ Air dual column distillation can have up to 75 stages* (combined)
- Process Intensification
  - The hypothesis is that microchannel architecture can be used to reduce the size of the separations equipment by reducing required residence time via enhanced mass transfer



Comparison to other distillation techniques

Cryogenic Distillation Technique	HETP (cm)
Commercial packing	30-60
Sulzer’s best laboratory packing – Best Available Technology (BAT)- theoretical	2-8[a]
Cryogenic microchannel distillation – Velocys Inc.	4.3[b]
PNNL’s work in 4” Device	
Propane/propylene	1.0
Methane isotopes	0.5
CFD modeling (Propane/Propylene)	0.1

- Commercial Packing
  - Minimum HETP is ~30 cm
  - **100 separations stages in 30 meters**
- Best Available Technology- theoretical
  - Minimum HETP is ~2 cm
  - **100 separations stages in 2 meters**
- Our Technology
  - HETP of 0.5 cm
  - **100 separation stages in 0.5 m w/ room for improvement**

[a] Sulzer Structured Packings for Distillation, Absorption and Reactive Distillation. https://www.sulzer.com/cs/-/media/Documents/ProductsAndServices/Separation_Technology/Liquid_Liquid_Extraction/Brochures/Structured_Packings.pdf

[b] Hickey, T. Advanced Distillation Final Report. Velocys Inc., https://www.osti.gov/scitech/servlets/purl/1000368

Axial thermal conduction → irreversible entropy in low L/D aspect ratio regenerators

$$FOM = \frac{\dot{W}_{ideal}}{\dot{W}_{real}}$$

$$\dot{W}_{ideal_{Layer}} = \dot{Q}_{C_{Layer}}\left(\frac{T_H}{T_C} - 1\right)$$

$$\dot{W}_{real_{Layer}} = \left(\dot{Q}_{CHEX} + \dot{Q}_{LC} + \dot{Q}_{Para}\right)\left(\frac{T_H}{T_C} - 1\right) + \frac{T_H \int_{T_C}^{T_H} \Delta\dot{S}_{IRR} dT}{\int_{T_C}^{T_H} dT}$$

$$\Delta\dot{S}_{IRR} = \Delta\dot{S}_{IRR_{HT}} + \Delta\dot{S}_{IRR_{DP}} + \Delta\dot{S}_{IRR_{LC}} + \Delta\dot{S}_{IRR_{EC}}$$

$$\Delta\dot{S}_{IRR_{HT}} = 2 * \left(\frac{\dot{Q}_{Reg}}{NTU + 1}\left(\frac{1}{T_C} - \frac{1}{T_H}\right)\right)$$

$$\Delta\dot{S}_{IRR_{DP}} = \frac{\dot{m}_{He}}{\rho_{He}} * \frac{\Delta p_{Reg}}{T_H}$$

$$\Delta\dot{S}_{IRR_{LC}} = 2 * \left(\frac{\pi * k_{Reg_{eff}} * D_{Reg}}{4 * a_{ratio}} * \frac{(T_H - T_C)^2}{T_H T_C}\right)$$

$$\Delta\dot{S}_{IRR_{EC}} = 2 * \left\{\left(\frac{16}{5 * \pi}\right)\left(\frac{\pi {d_p}^2}{4}\right) * \frac{V_{MM} * \nu^2 * \Delta B^2}{32 * \rho_{eMM} T_{ave}}\right\}$$

$$k_{Reg_{eff}} = k_{MM_{eff}} + k_{He_{static}} + \rho_{He} c_{p_{He}} D_{L_{Reg}}$$

$$\dot{Q}_{LC} = k_{Reg_{eff}} * \frac{\pi}{4}\frac{D_{Reg}}{a_{ratio}} * (T_H - T_C)$$

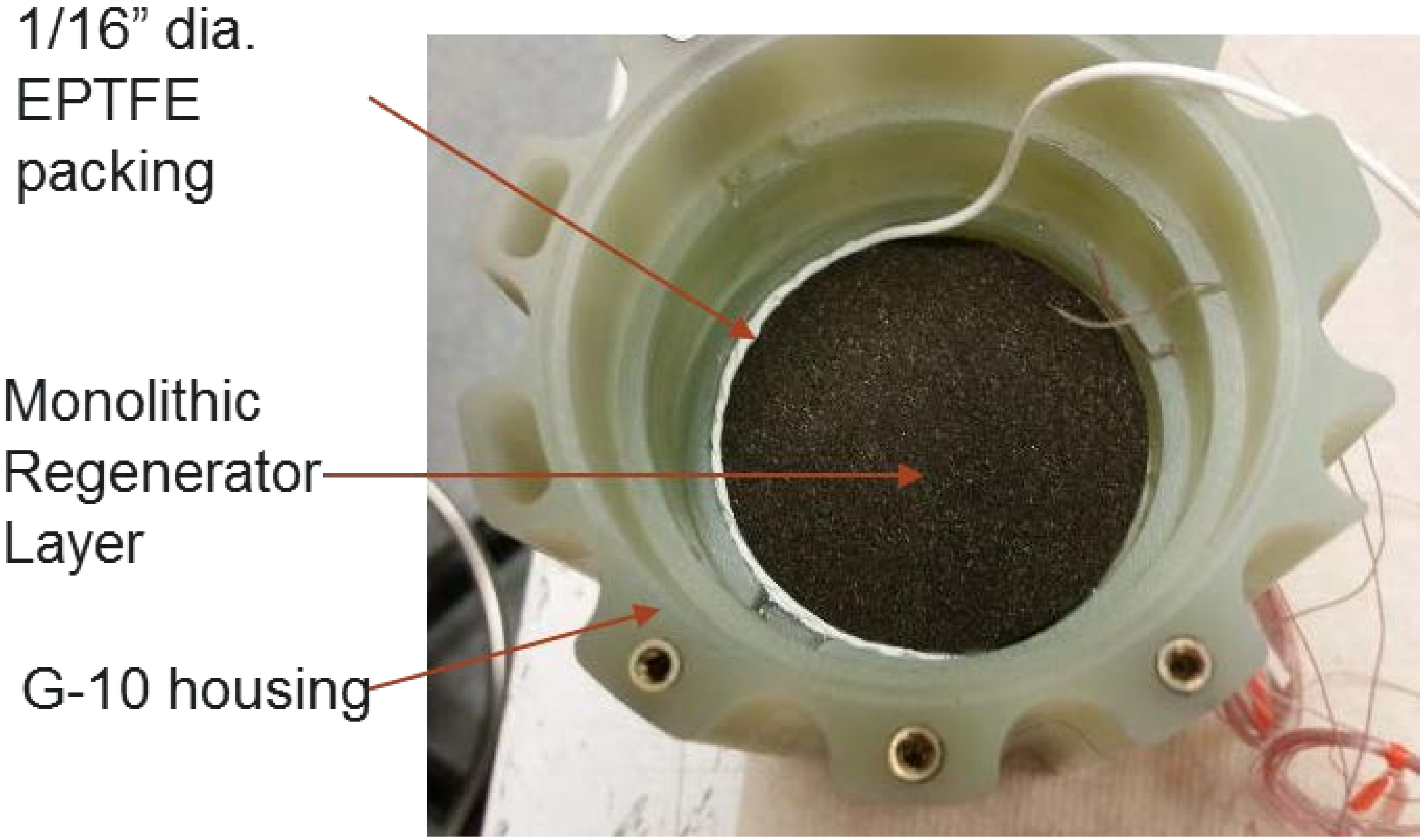
EXAMPLE

- 280 K to 242 K; 0.25 Hz; 493 gram Gd; 200 micron spheres, 0.37 porosity; 6T field change; 400 psia He HTF @ 4 gm/s;
- $Q_{coldMAX}$= 56W @ 242 K
- D_{layer} =7 cm; L/D_{ratio} = 0.37
- **k_{Regeff} = 2.69 W/m K when $k_{Hestatic}$ = 0.145 W/m K!**
- **Q_{dotLC} = 15.1 W**; $Q_{dotPARA}$ = 5 W
- Q_{dotNET} = 56 – 15.1- 5 W = 36 W!
- FOM reduced to 0.47 in this example
- Design needs be changed to increase L/D for FOM = 0.65
- **LONGER Regenerator requires LONGER Magnet**

Project Structure:

Task 3.0 – Synthesize magnet refrigerants and build regenerators

- **Status:**
  - **Materials ordered**

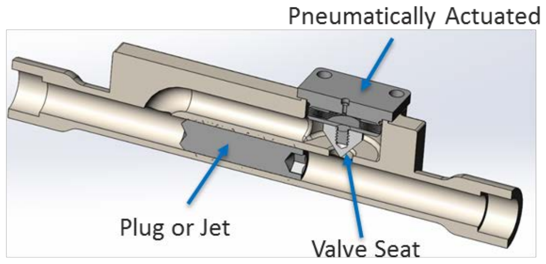


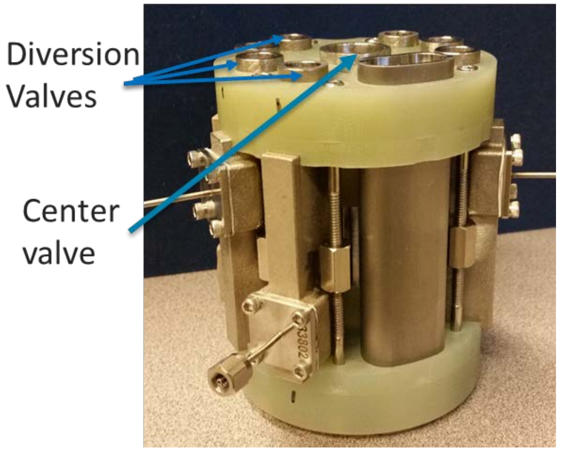
Critical (bold) and progress milestones

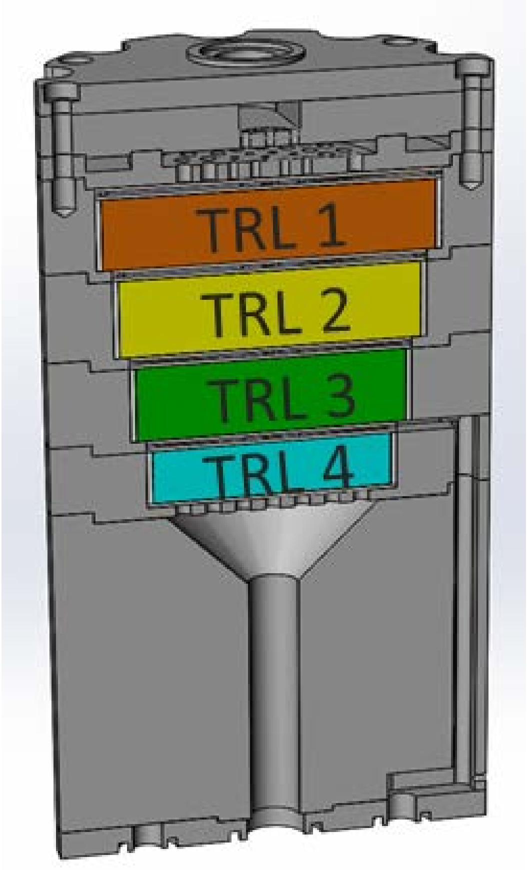
Milestone	Description	Date	Explanation
M1, progress	Regenerator Design	2/28/2019	Design a MCL that can cool 1.0 kg air/day from <100 K. Magnetocaloric material types and amounts for each layer/stage (6-10) will be determined.
M2, progress	Modify the MCL demonstration platform	5/31/2019	PNNL will modify previous MCL refrigerators and build the new liquefier system. This will include upgrading the pumps for improved heat transfer fluid flow and building the new regenerator housing designed.
M3a progress	Materials characterization	7/30/2019	Quality check on the materials identified in task 1 to ensure the Curie Temperature is with 5K of target specs.
M3b: critical	**Complete shake-down testing of the system**	**9/30/2019**	**Activities will include assembly of spherical materials into new regenerators, loading the regenerators into the system and ensuring that all liquefier system components are working within acceptable ranges. Shakedown tests should show cooling from ~280 K to below ~150 K with 100 K as ultimate target cold temperature.**
M4: critical	**Demonstrate air liquefaction**	**11/30/2019**	**Demonstrate the ability to liquefying air at a rate of > 1.0 kg/day. Projected performance of the commercial version of system, based on the testing data, should have a FOM of >0.5.**

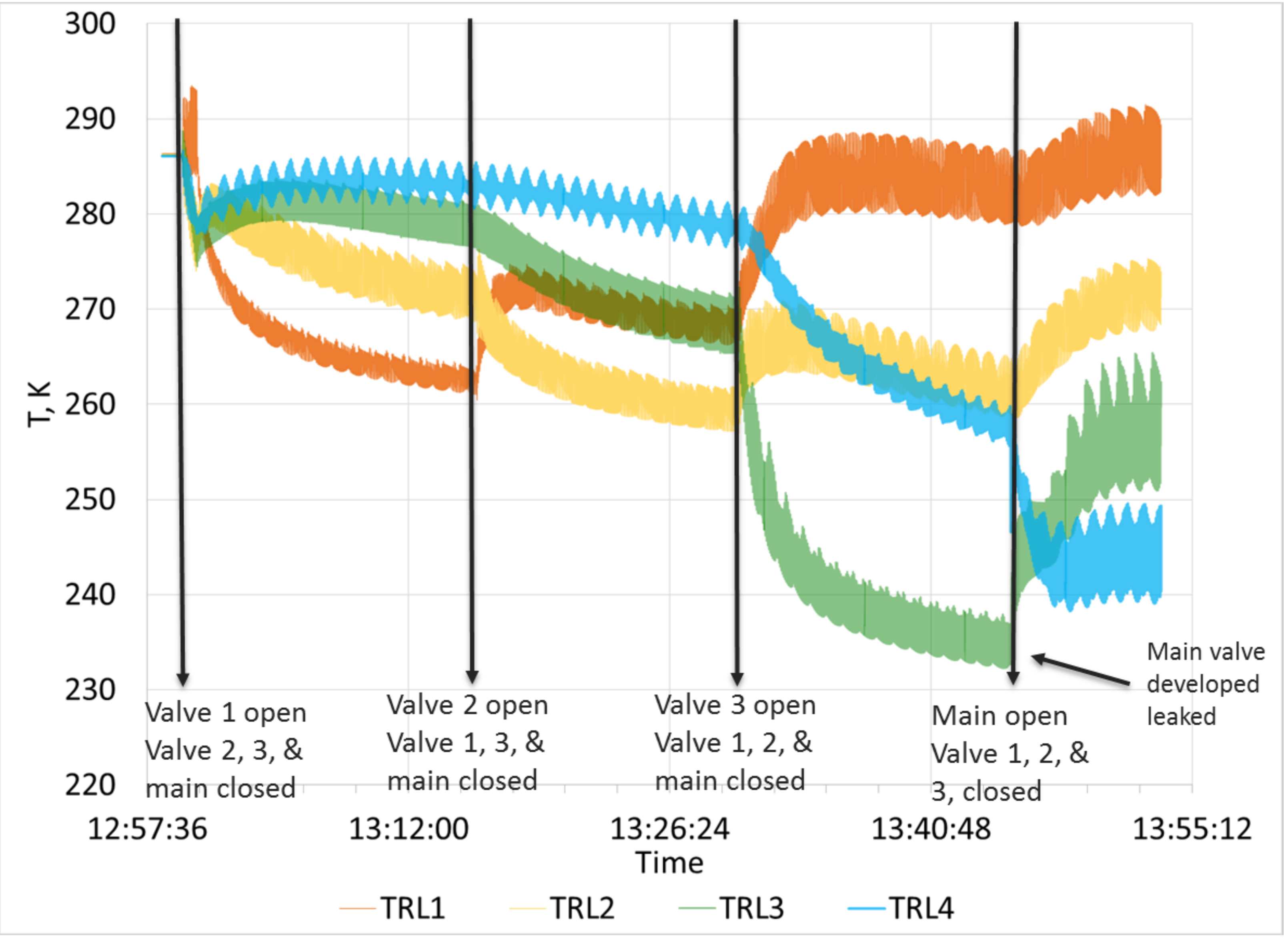
Diversion of heat transfer fluid flow allows control of cooling power of each layer, but increases complexity

Control valve design





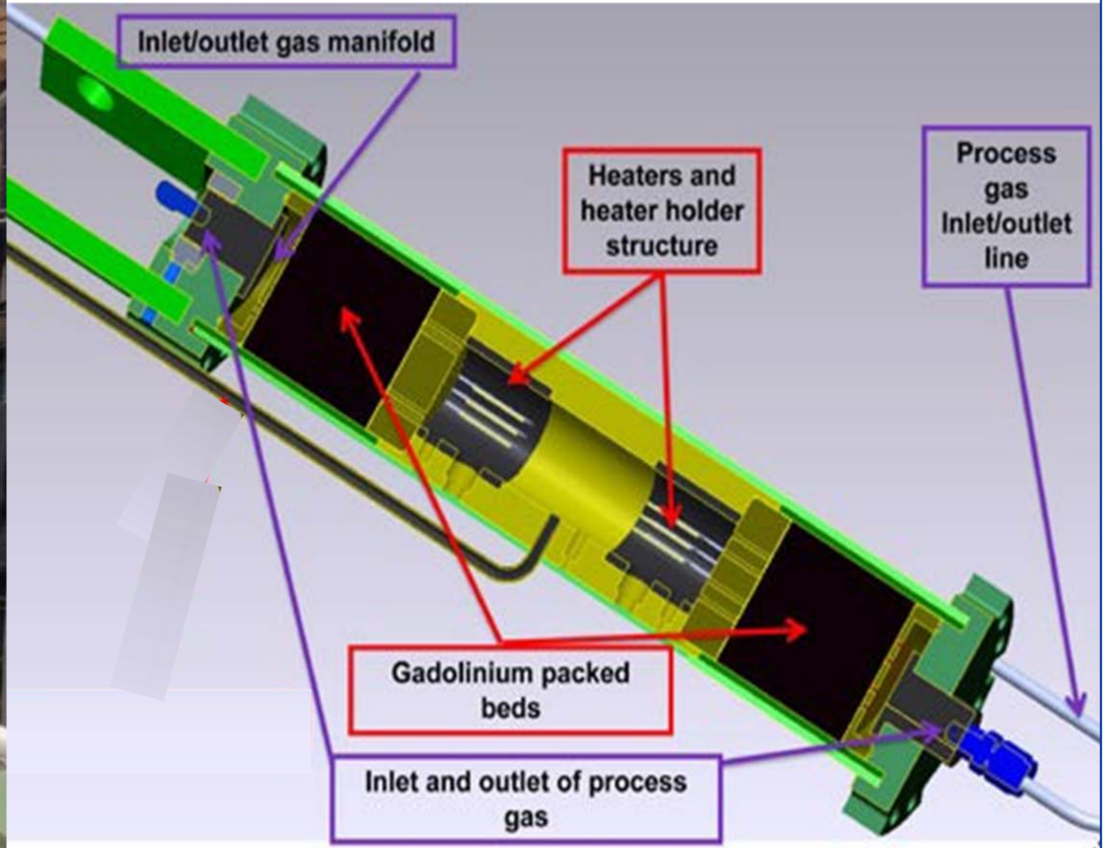




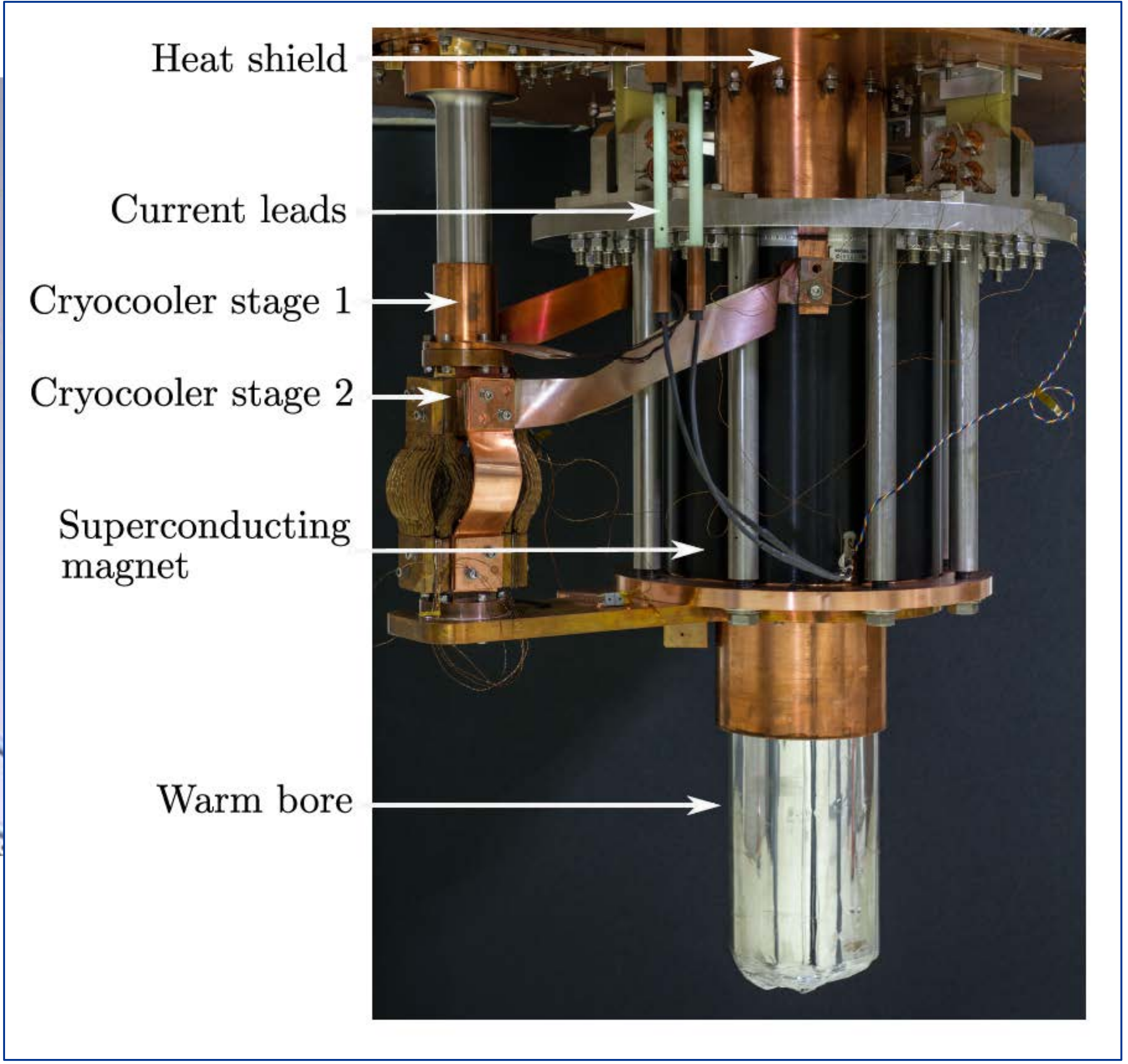
Background:

Dual active magnetic regenerators and super conducting magnet are key subsystems

Active Magnetic Regenerator



Super conducting magnet

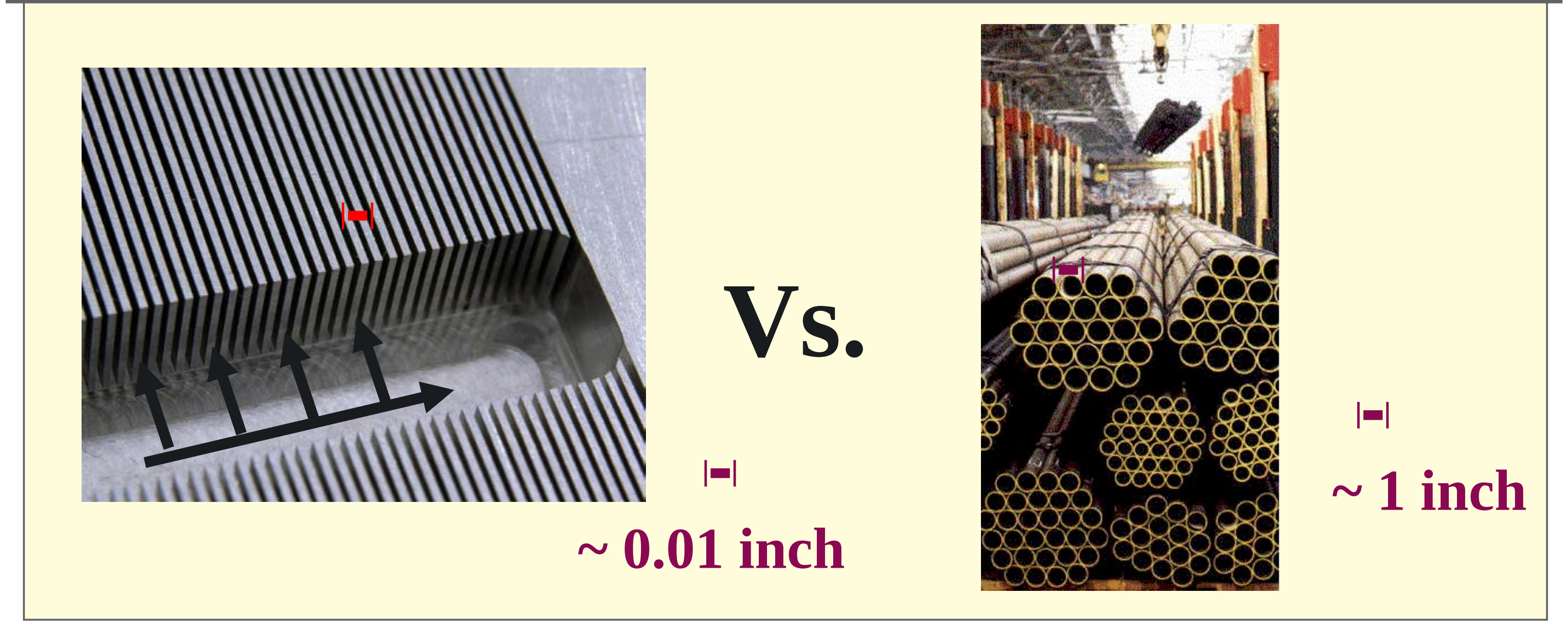


What about oxygen separation?

Note: this is not part of our current scope

- We can potentially use microchannel architecture for scaling down the distillation

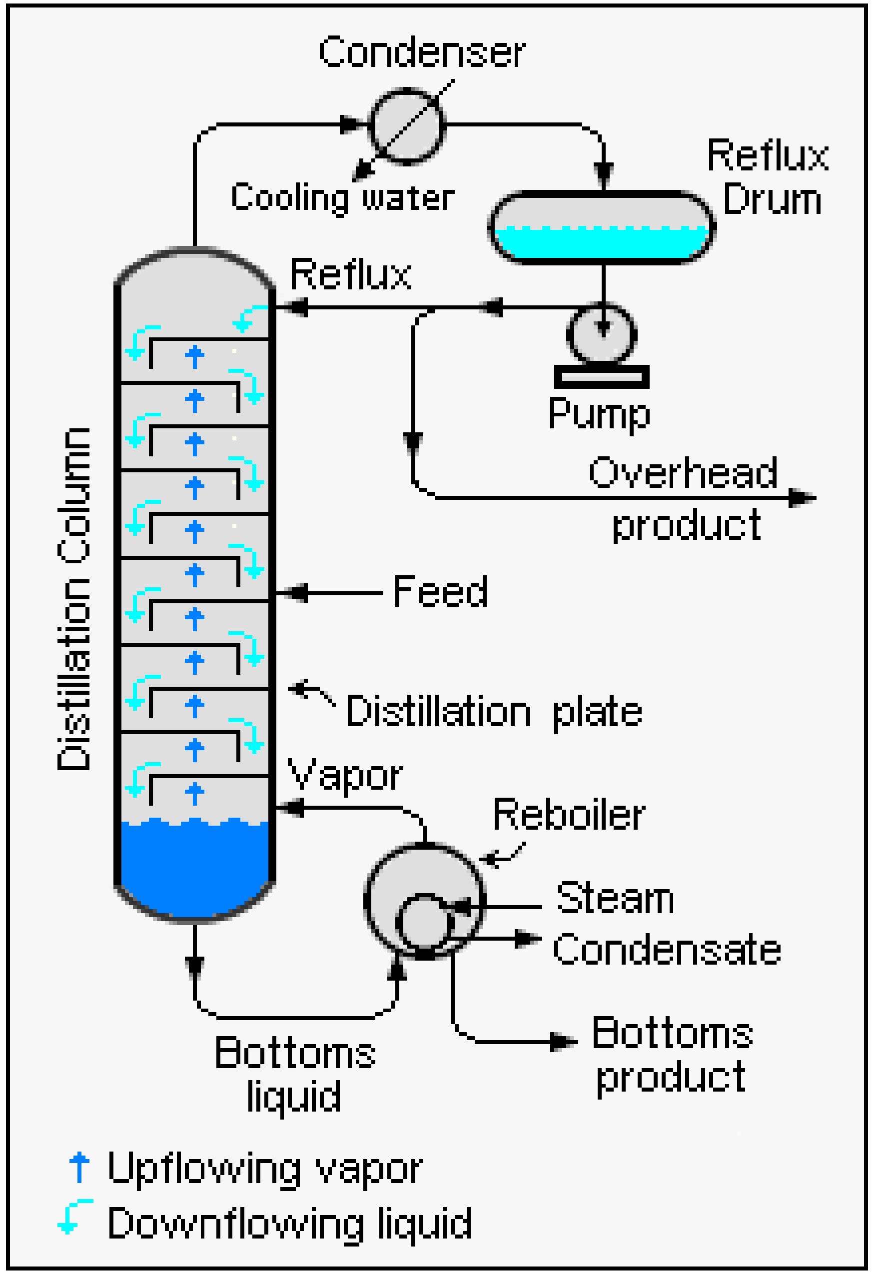
1 – 2 orders of magnitude reduction in hardware size



- High heat transfer coefficients
- High heat transfer surface area per unit volume
- Low pressure drop achievable through short flow distance

Traditional distillation

- Separation of chemical components via boiling point differences
- Relative volatility (α) – ratio of vapor pressures of components in a liquid mixture
  - $\alpha < 2.4^{*}$ for 20% O_2 in N_2
- Challenge – enhance mass transfer



https://en.wikipedia.org/wiki/Distillation

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* Din, F. Trans of the Faraday Society, 1960. https://pubs.rsc.org/-/content/articlepdf/1960/tf/tf9605600668

Distillation and process intensification by microwick technology

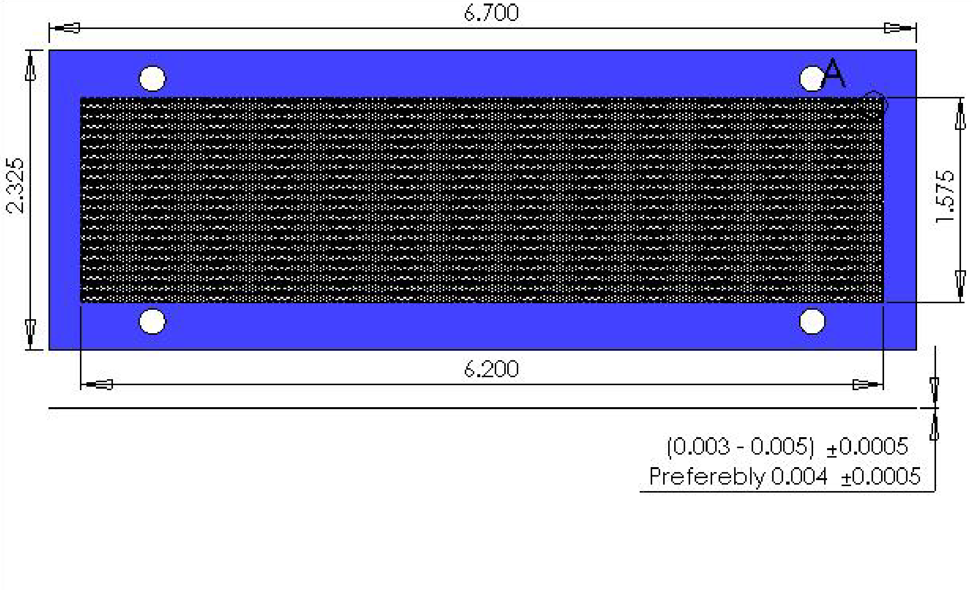
- Distillation
  - Mass transfer is dominated by liquid phase diffusivity (*D*)
  - Liquid phase mass transfer is enhanced by increasing liquid phase surface area
  - HETP – Height equivalent to a theoretical plate
    - Origins in distillation theory relating mass transfer efficiency of packed columns to tray or 'plate' columns
    - Each 'plate' represents one theoretical stage of separation and HETP is the height of column needed for each stage
    - Air dual column distillation can have up to 75 stages* (combined)
- Process Intensification
  - The hypothesis is that microchannel architecture can be used to reduce the size of the separations equipment by reducing required residence time via enhanced mass transfer
- Microchannel Distillation
  - Enhance mass transfer by incorporating microwicks

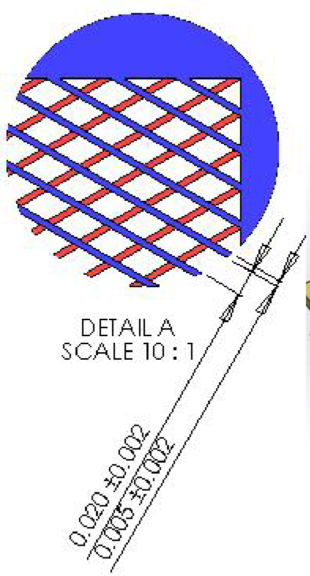
http://www.certech.be/en/activities/intensification/

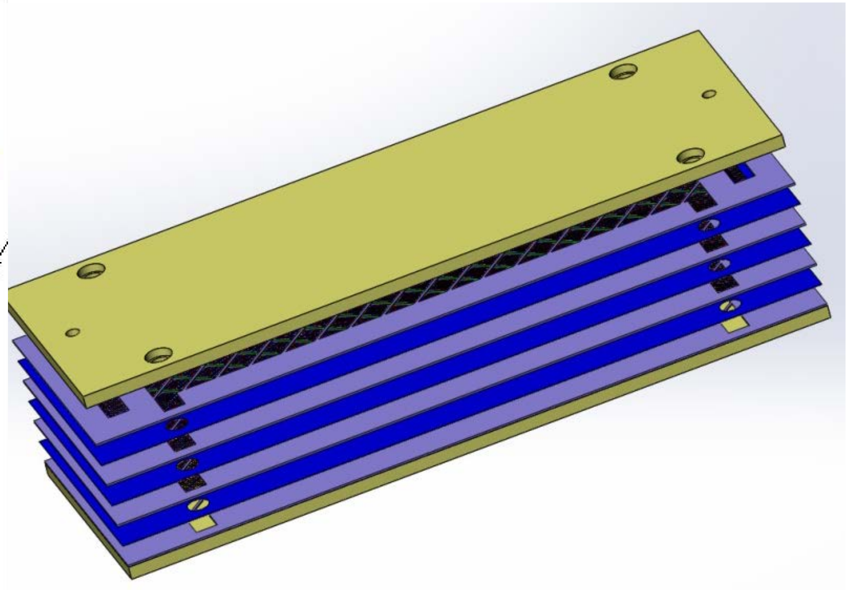
*Jones et al, Fuel Processing Tech 92 (2011) 1685

PNNL’s patented microwick technology

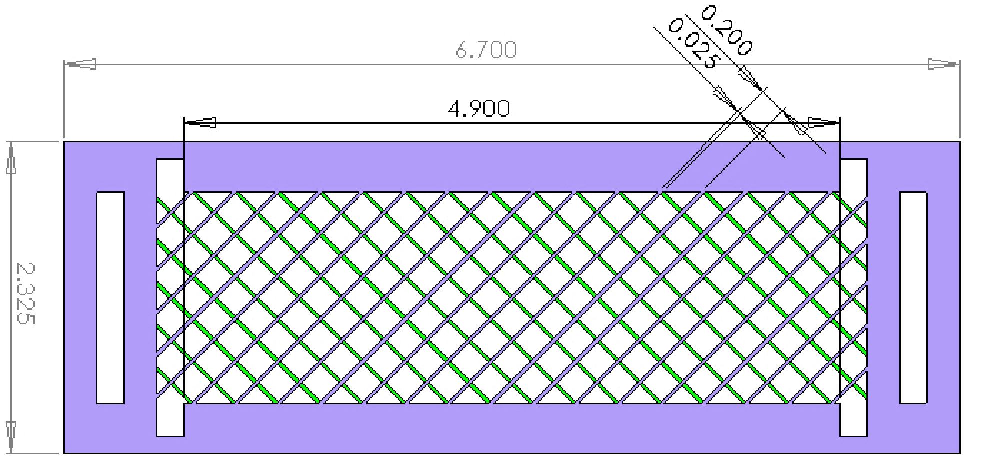
- Thin microchannel wicks for liquid flow – 0.004”

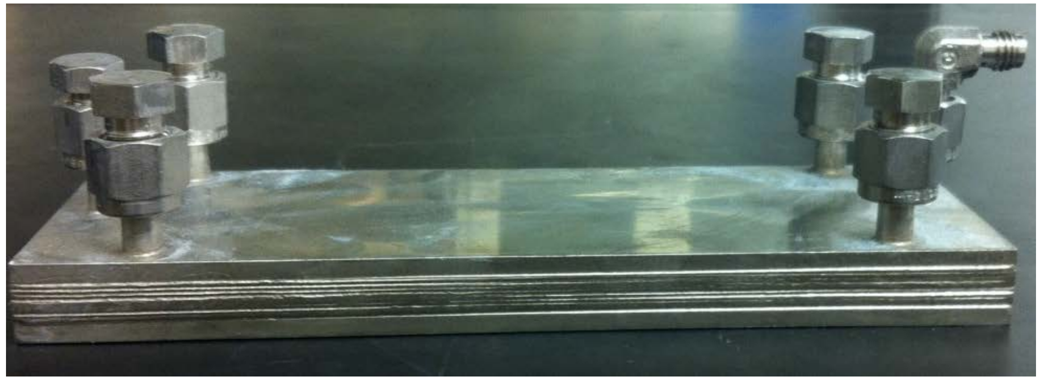






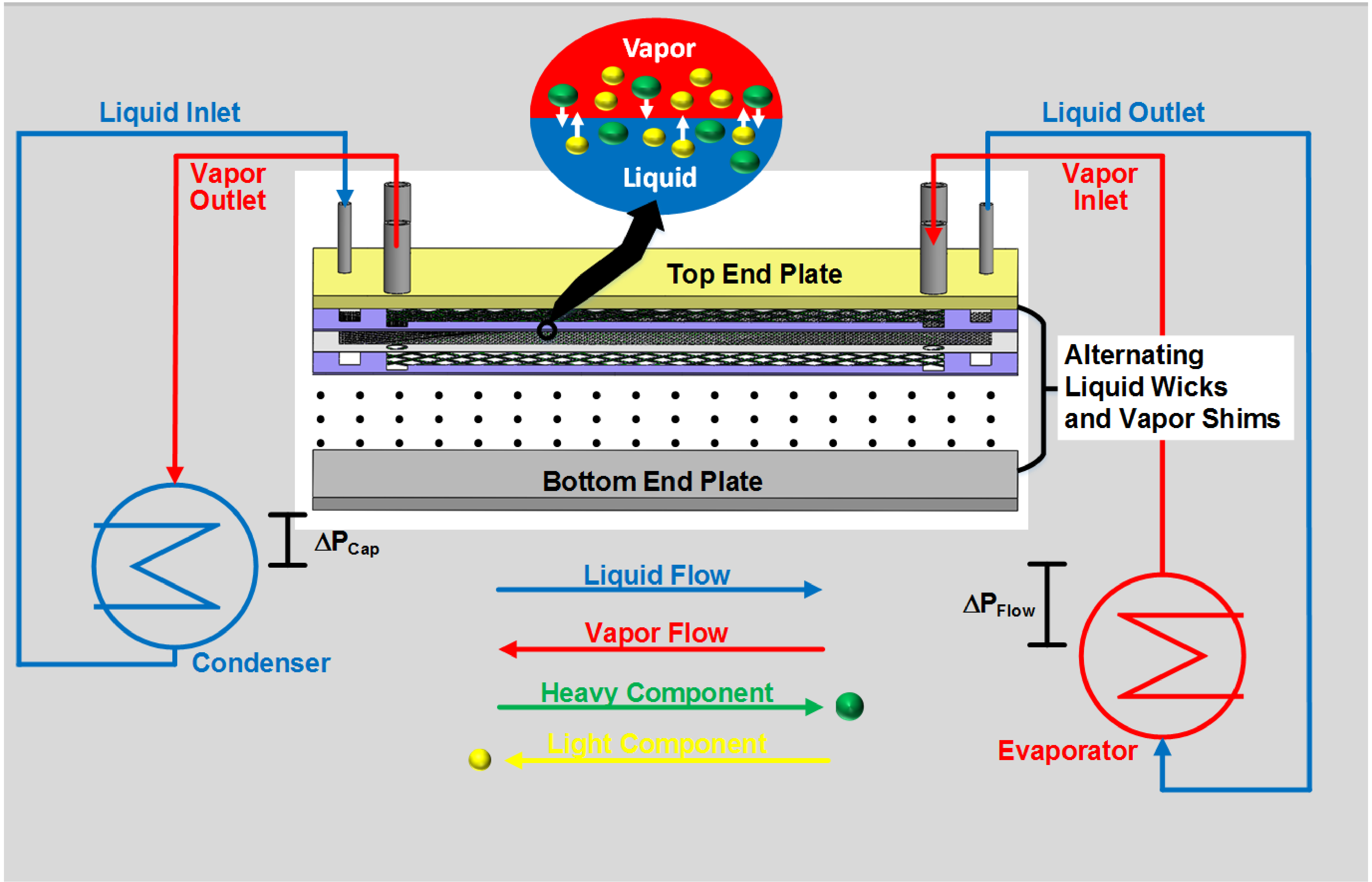
- Thicker microchannel shims for vapor flow – 0.02”





- HETP scales with the square of the wick thickness, *h*: $HETP \propto \frac{h^2}{D}\frac{\dot{m}}{\rho}$

Operating principle

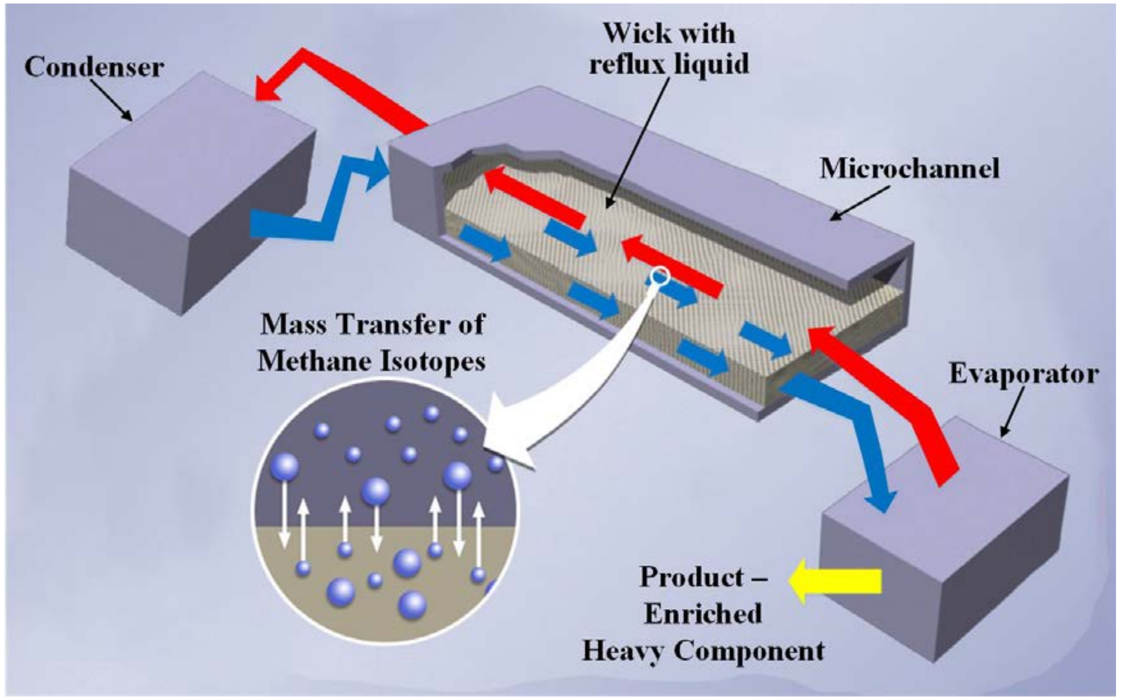


Advantages

- Suitable for scale-up by increasing the amount of layered wicks
- Can be operated over a large temperature range
- Can be operated in the **horizontal** or vertical direction
- Microchannel benefits
  - Small Footprint
  - Portable
  - Rapid mass/heat transfer

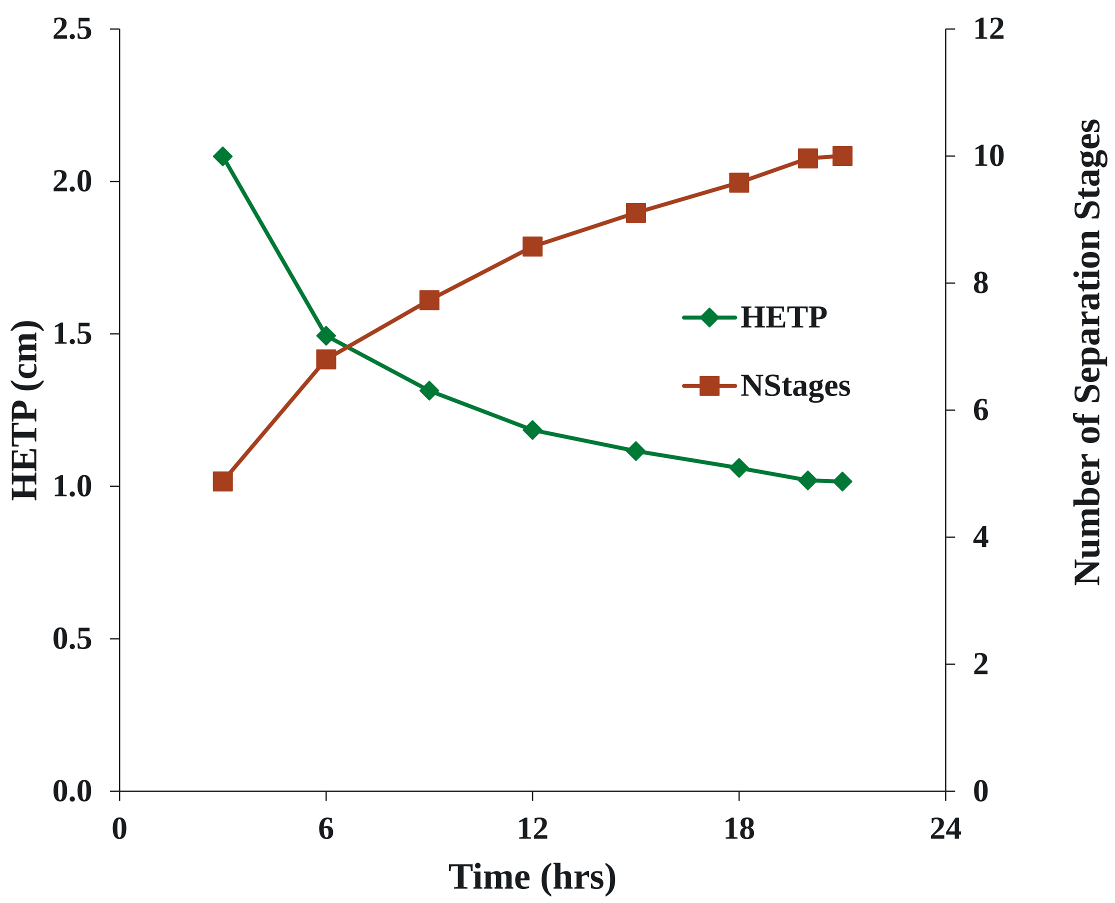
$$HETP \propto \frac{h^2}{D}\frac{\dot{m}}{\rho}$$

- Microchannel "Cryogenic" distillation
  - 1% Propane in Propylene: α=1.28
  - ^{12}C/^{13}C isotopes of methane: α=1.0028

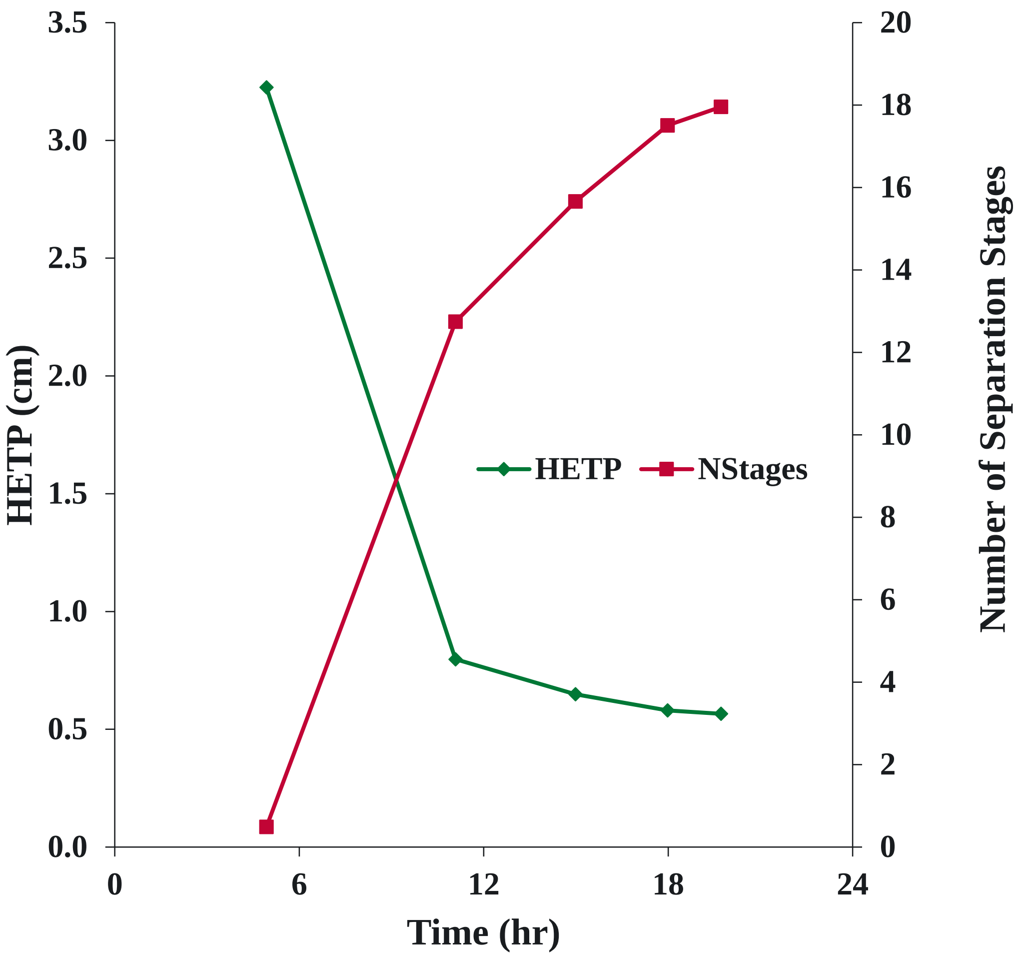


Results in 4” active area microchannel distillation device

- Propane/Propylene



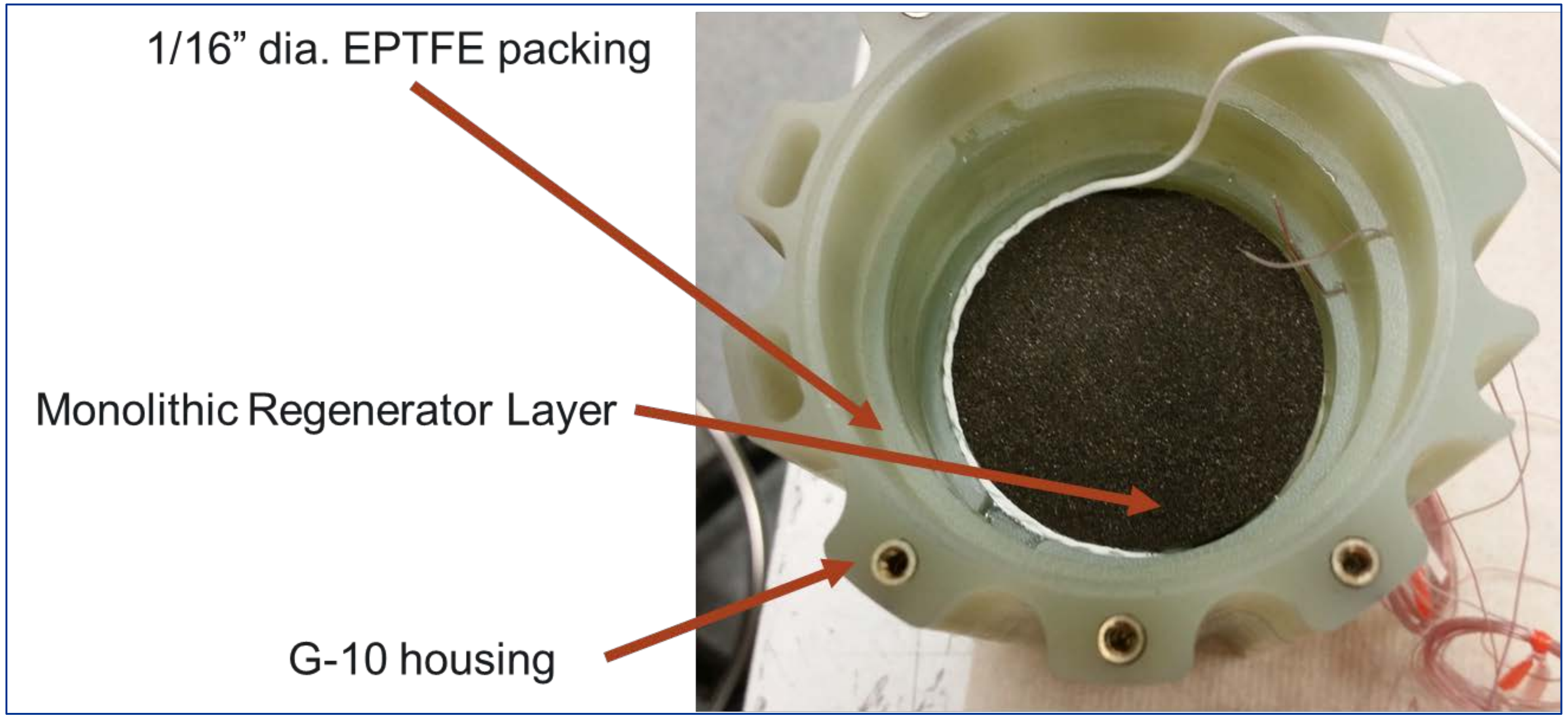
- Methane Isotopes



Project Structure:

Task 3.0 - Synthesize MCL magnetic refrigerants and build regenerators

- Purchase the materials
- Design the regenerators
- Make mechanically stable monolithic regenerators
- Assemble regenerators into hermetic G-10 housings capable of cryogenic cycles with pressurized helium heat transfer gas

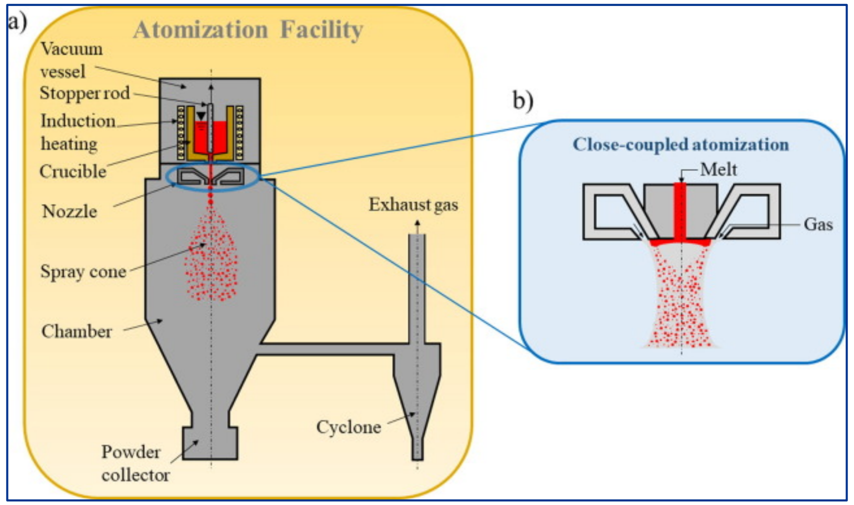


- **Status:**
  - **Discussed with AMES the materials purchase and started work on the purchase agreement**

Progress:

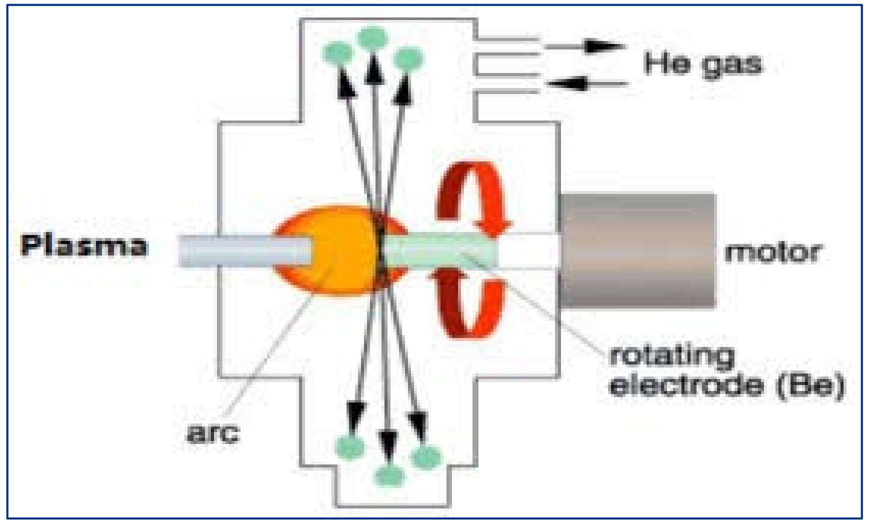
Spherical particle synthesis options

Hot gas atomization



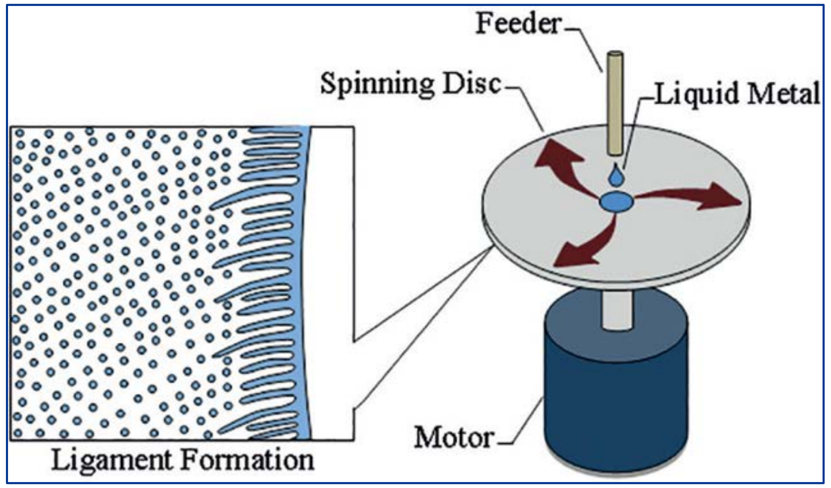
- Industrial used
- Can achieve target diameters
- High interior porosity (bad)
- Wide particle size distribution
- Wide shape distribution

Plasma atomization



- Industrial used
- Low interior porosity
- Fine particles (difficult for our desired range)
- Wide particle size distribution
- Wide shape distribution

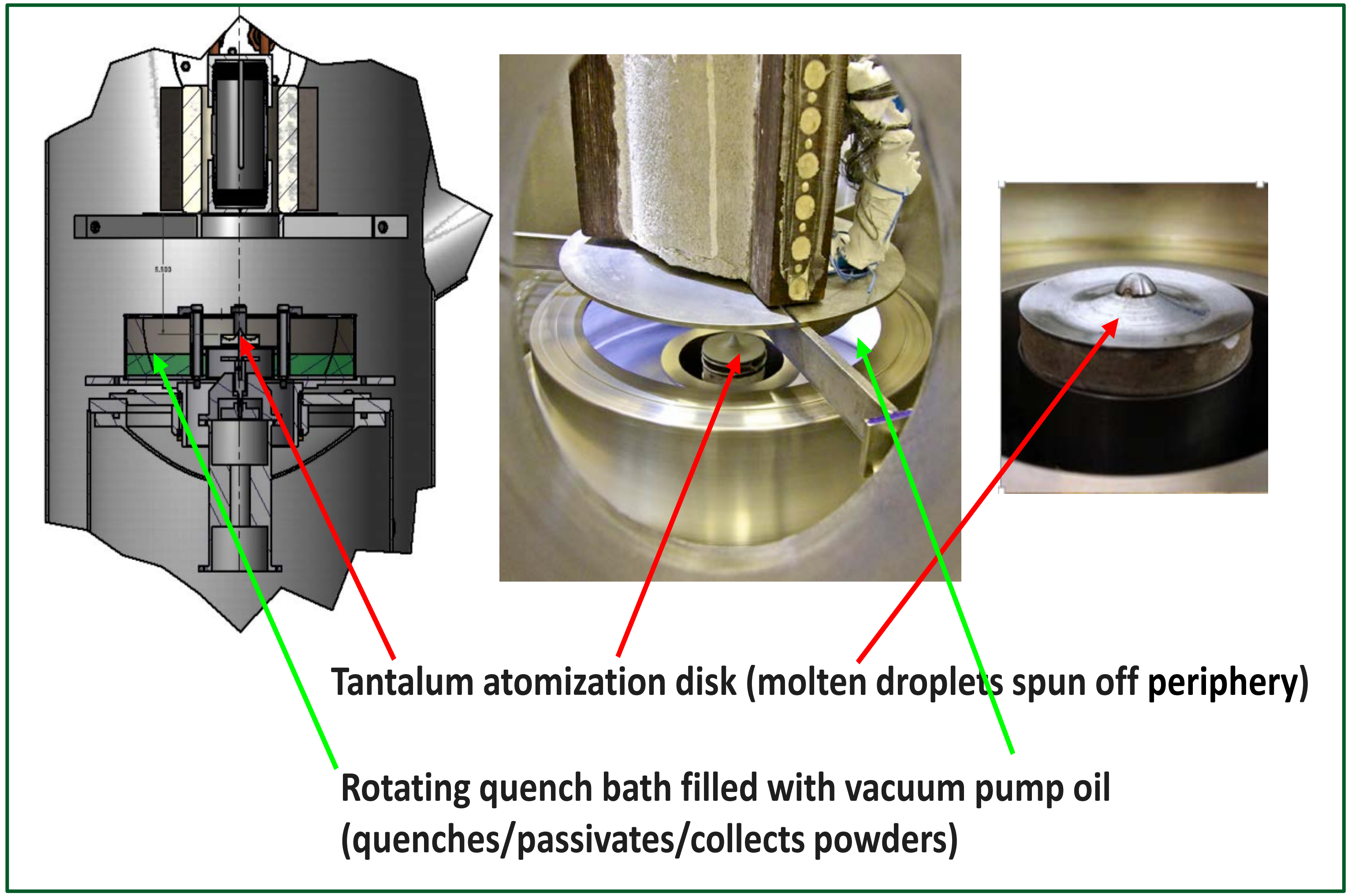
Rotating disk atomization



- Can control size and distribution
- Spherical particles
- **Low interior porosity**
- **Potential to be 30% less expensive**
- Not industrial utilized

Progress:

Rotating Disk Atomization System for RE MC Powders

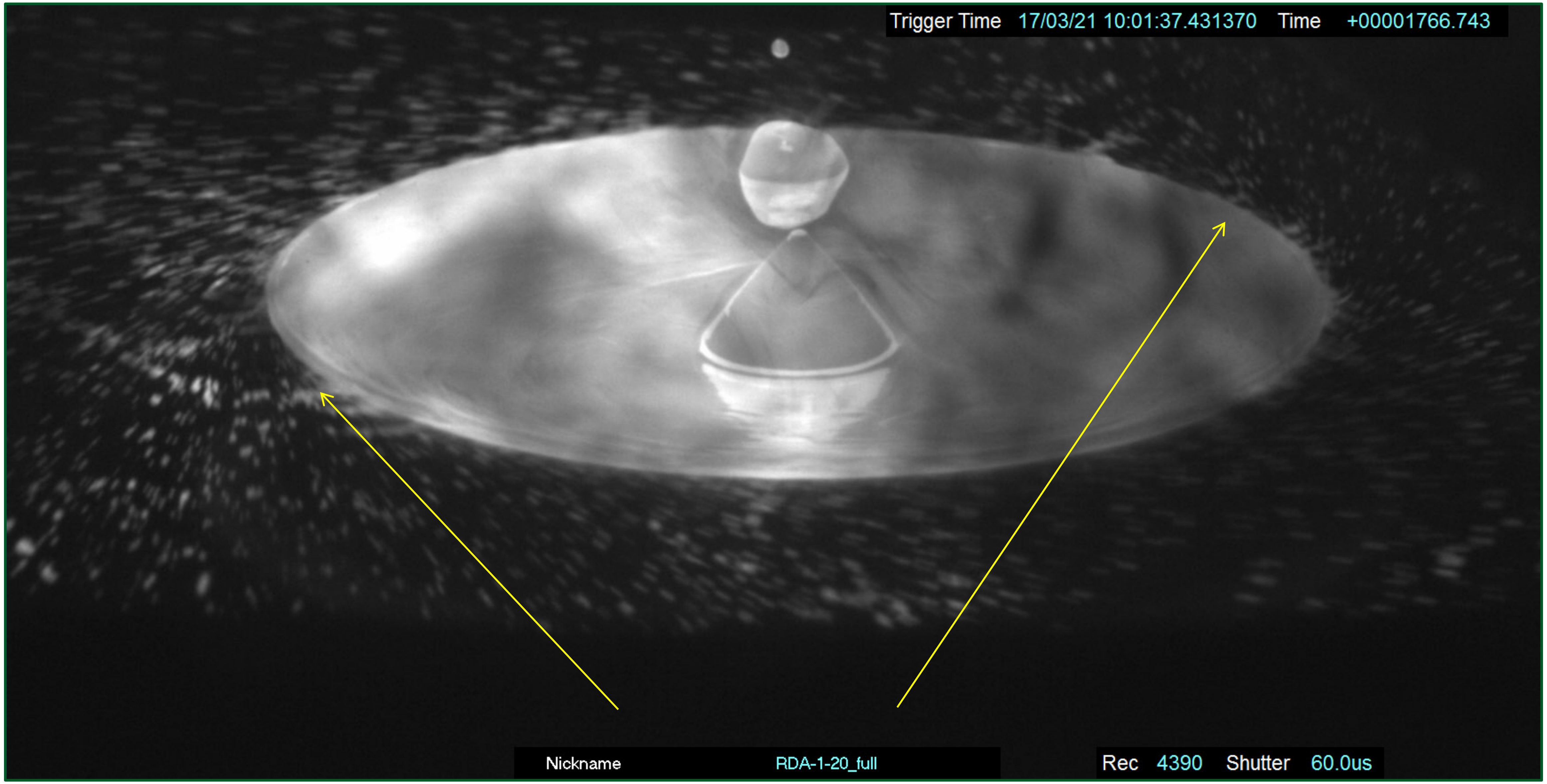


Tantalum atomization disk (molten droplets spun off periphery)

Rotating quench bath filled with vacuum pump oil (quenches/passivates/collects powders)

- Rotating disk atomizer (RDA) makes reactive metal powders.
    - Co-rotating oil quench bath envelopes powders instantly, providing passivated surface film.
- This unique capability was adapted for making pure rare earth (RE) and RE-RE alloys as spherical powders in the right size for magnetic refrigeration.

$Gd_{0.16}Ho_{0.84}$ RDA-1-20: Image of Atomization Process

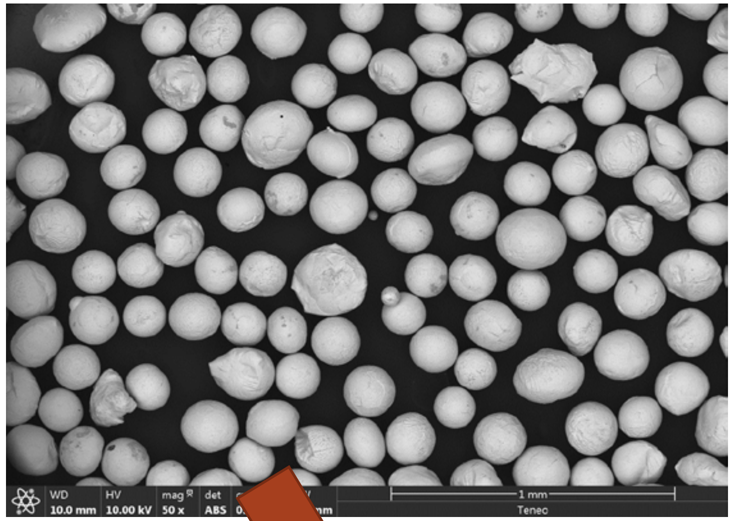


Evidence for ligament/direct drop "mixed mode" disintegration from HS still frame.

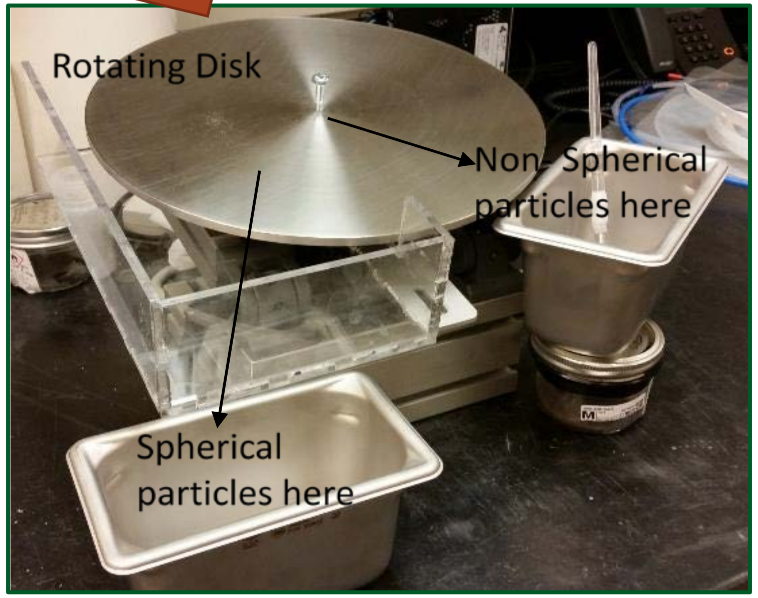
Pacific Northwest
NATIONAL LABORATORY

Progress:

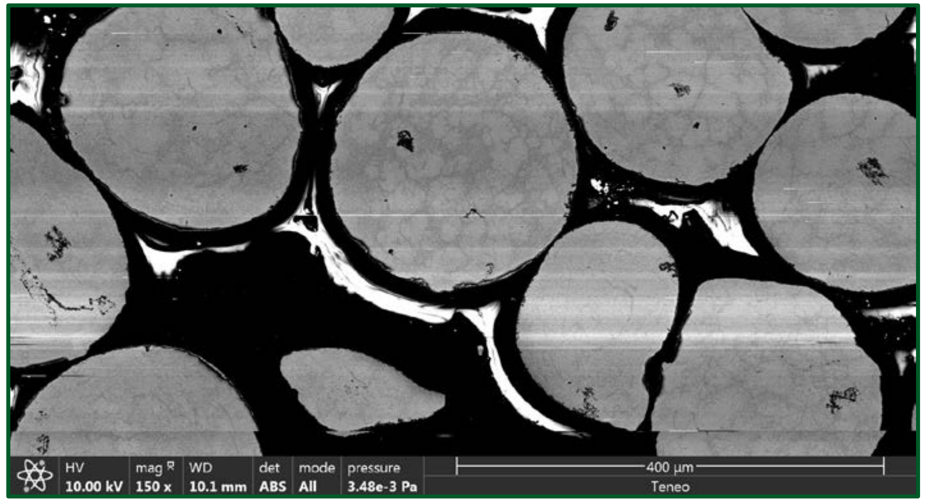
Rotating disk atomization produces high quality spheres at desired diameters

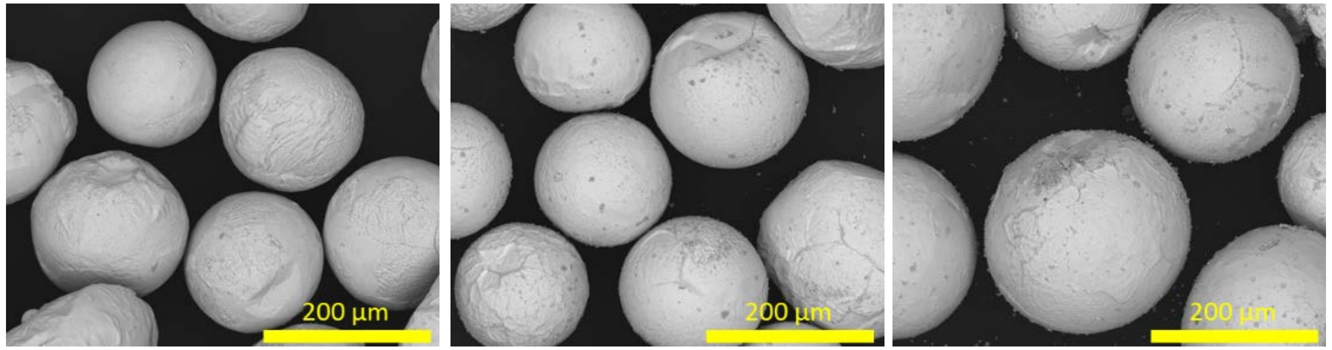


Easy separation of spherical and non-spherical



Cross section shows low porosity



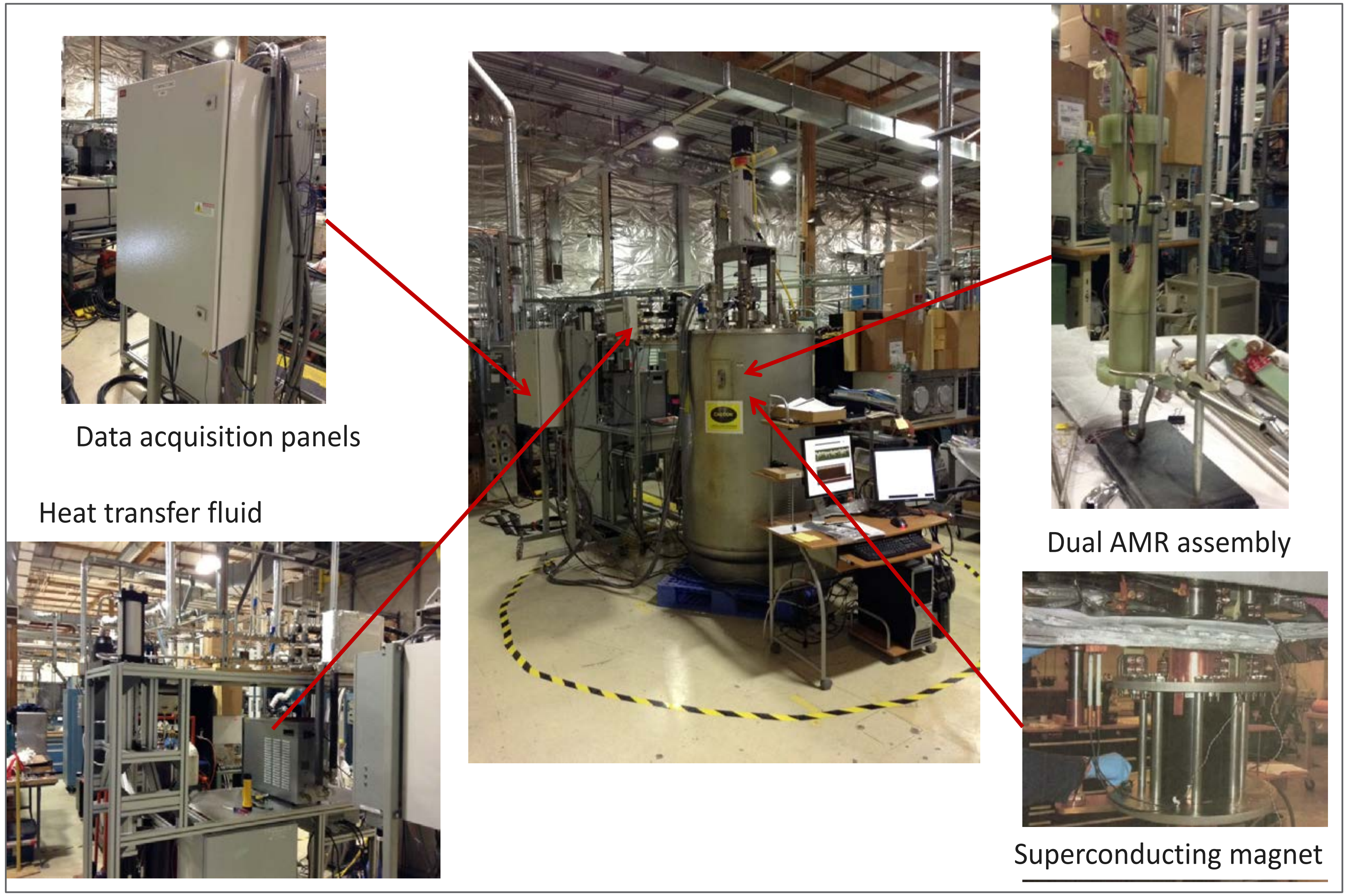


$Gd_{0.83}Dy_{0.17}$ **$Gd_{0.7}Tb_{0.3}$** **$Gd_{0.67}Er_{0.33}$**

Task 4.0 - Modify existing test stand for new regenerators

- Upgrade reciprocating pump for heat transfer gas to increase mean pressure (and mass flow rate)
- Upgrade the s/c magnet system to enable layered or staged designs

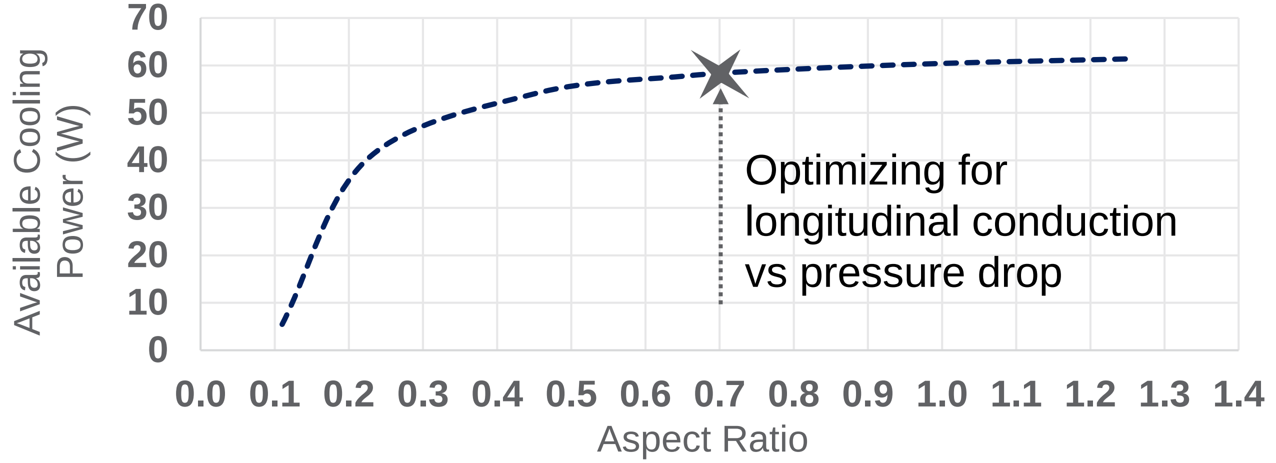
- **Status:**
  - **Begun preliminary magnet design**



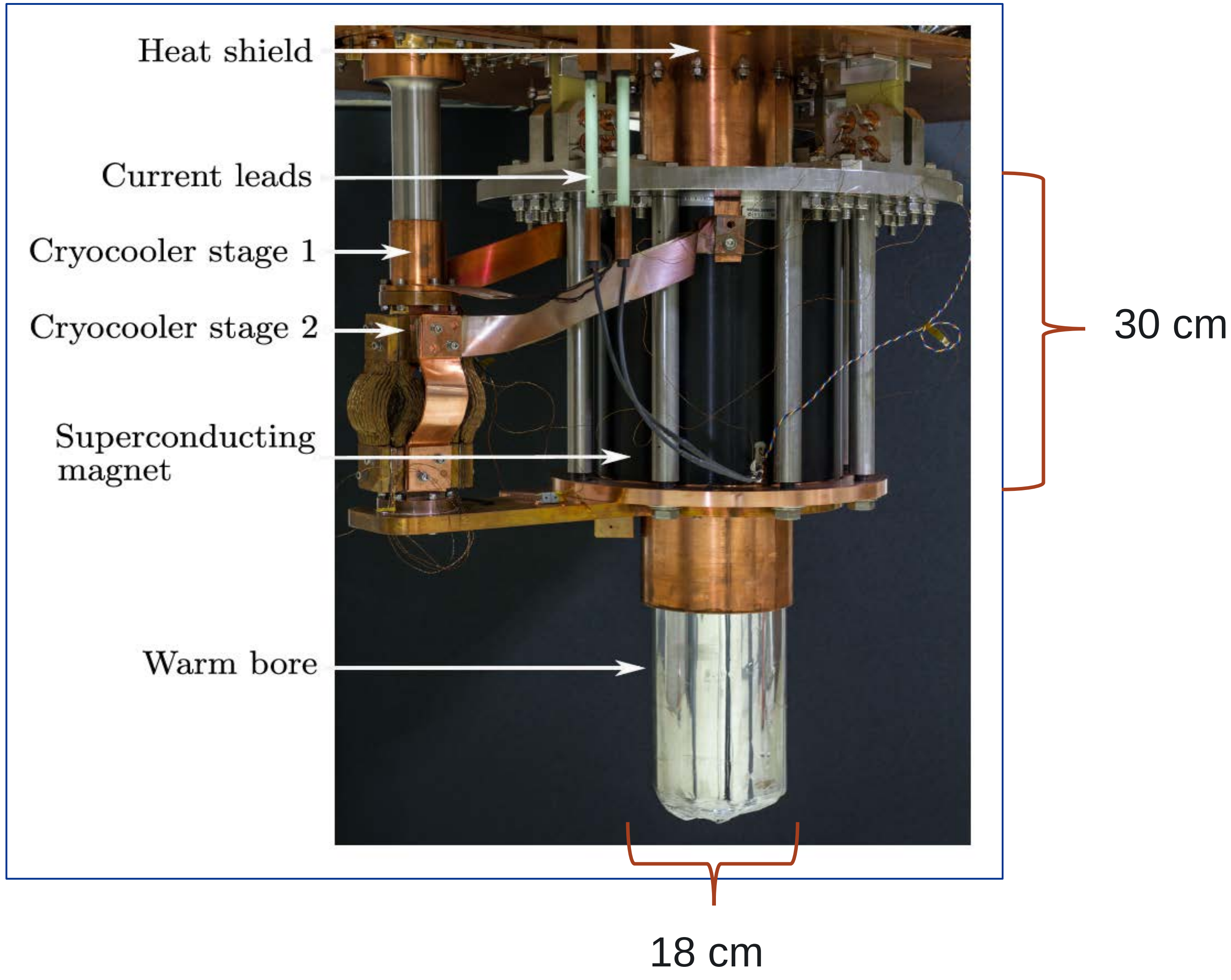
Current super-conducting magnet is not long enough and has poor magnetic field profile

- **New Magnet designed for uniform 6.5 T axial field so each layer has same high field**
- **Includes counter windings to taper field down to uniform 0.1 T low field at correct position**
- **Magnet windings and length designed in tandem with regenerator geometries for 0.7 aspect ratios for all layers**
- **These criteria and known refrigerant masses result in a ~65 cm long s/c magnet with ~20cm open bore**

NET Cooling Power vs. Aspect Ratio for 0.3 kg Gd w/ 20 K Span

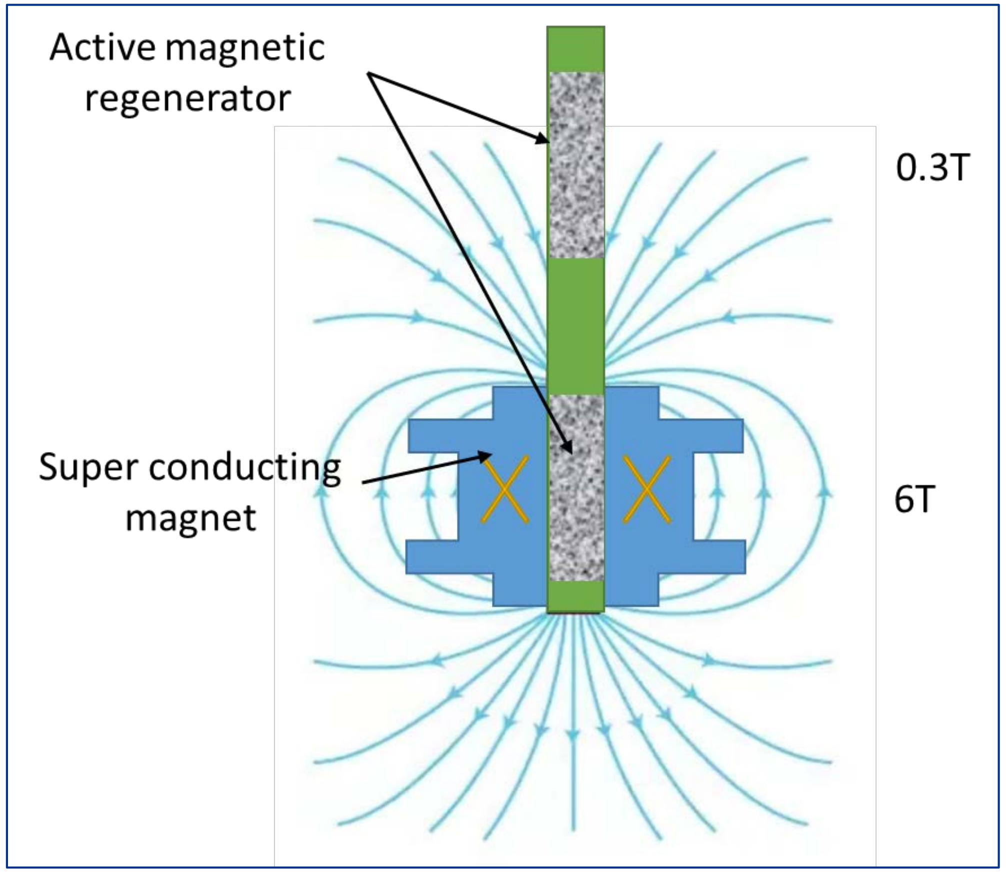


Current Super-Conducting Magnet

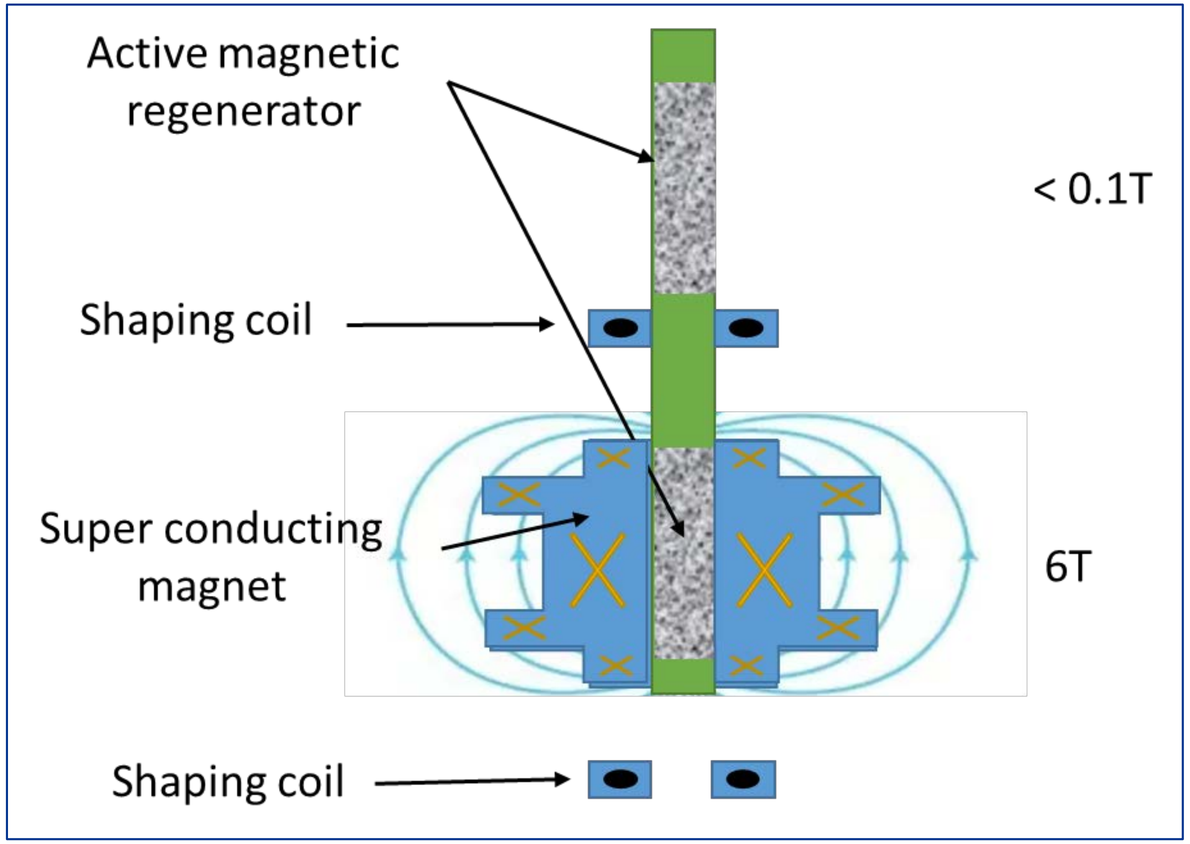


Current super-conducting magnet is not long enough and has poor magnetic field profile

- The current s/c and regenerator design doesn’t allow the regenerator to completely leave the magnetic field
  - Range of magnetic field across the regenerator



- New design with shaping coils
  - Improves magnetic field profile
  - 6T across regenerator

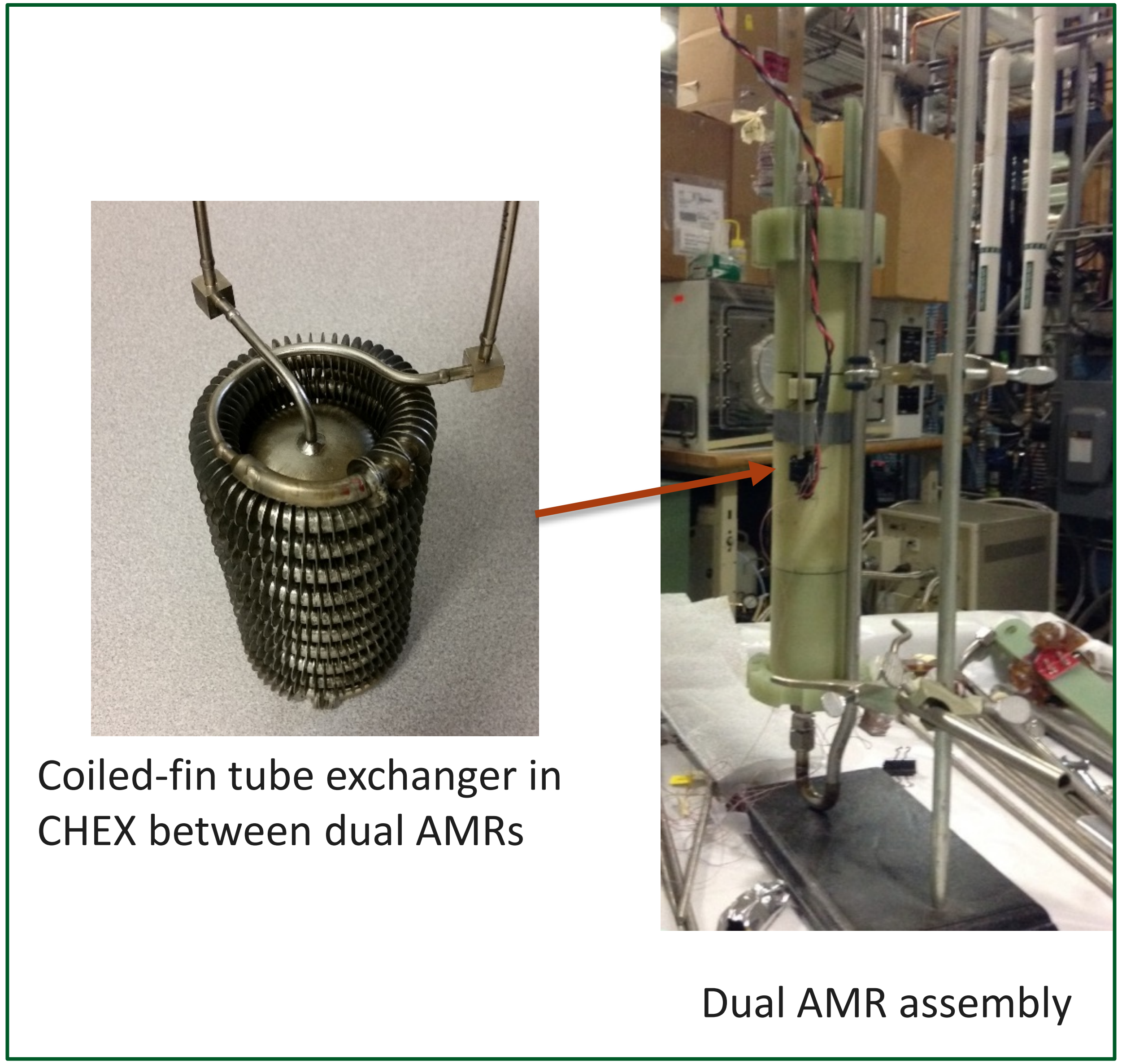


Task 5.0 - Demonstrate new MCL Liquefier at target air liquefaction rate

- Design compact, highly effective ~100 psia air condensing heat exchanger cooled by cold helium bypass flow CHEX
- Operate system to liquefy air

- **Status: Not started**

Heat exchanger design used in propane liquefaction



Coiled-fin tube exchanger in CHEX between dual AMRs

Dual AMR assembly

Project Structure:

Task 6.0 – Analyze test results to determine optimum number of regenerator layers/stages

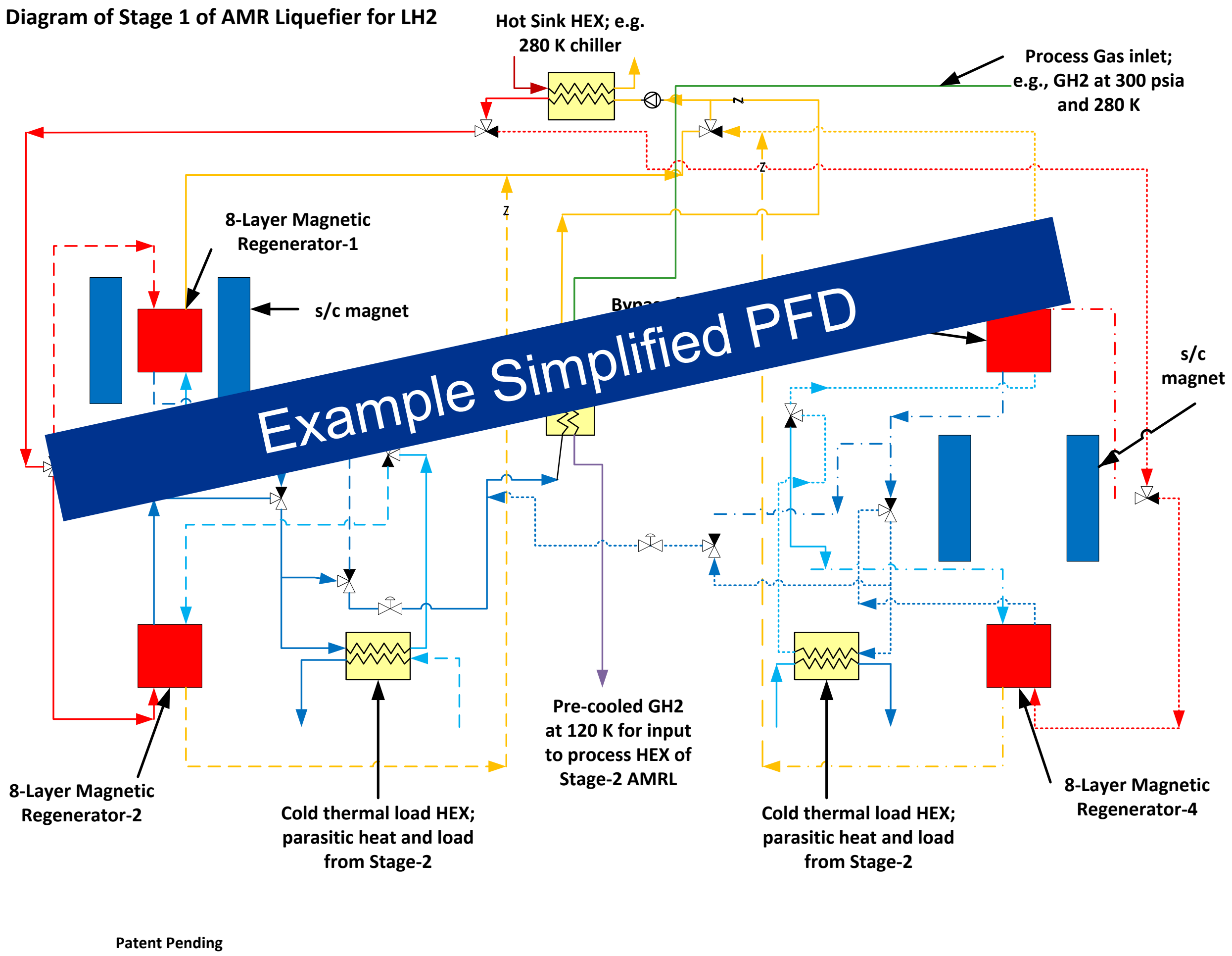
- Since this is a feasibility test and there are multiple design options, we will evaluate our results and consider if/how improvements can be made
- Compare actual performance with modeled predicted performance and, if necessary, update model to ensure within 15% of experimental results

- **Status: Not started**

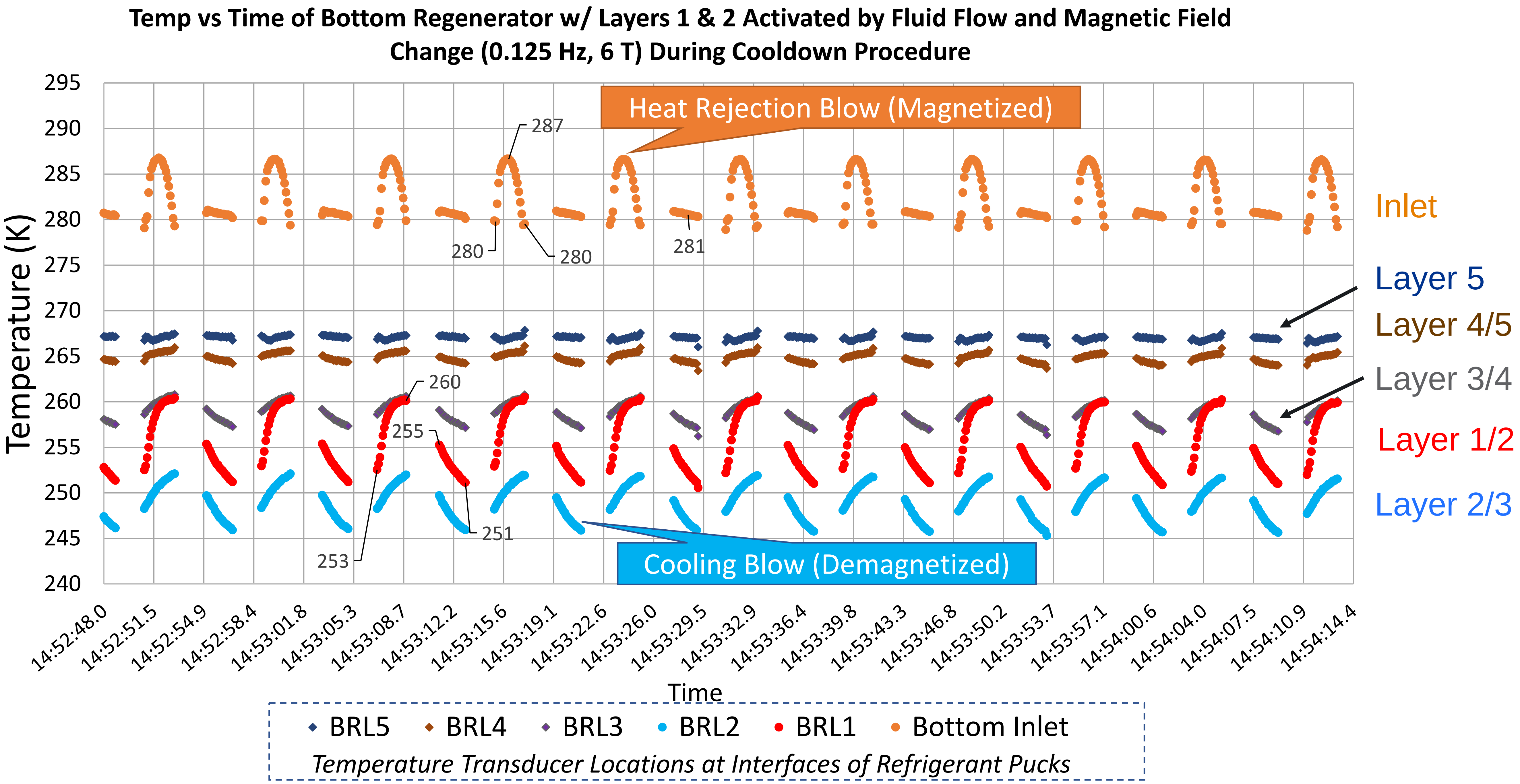
Project Structure:

Task 7.0 - Refine techno-economic analysis to feed Go/No-Go decision

- Some of the design features of scaled-up liquefier are:
    - Reciprocating dual regenerator design
    - Stationary 6-T s/c magnets (2 ea)
    - 1-Hz AMR cycle frequency
    - Heat exchangers
    - Pumps & heat transfer fluid
    - Etc.
- Perform detailed FOM calculation as a function of scale
    - Calculate ideal work rate, real work rates and resultant FOM
    - Include all major sources of inefficiencies
- Techno-economic analysis
- **Status: Not Started yet**



Diversion flow valves are controlling the temperature



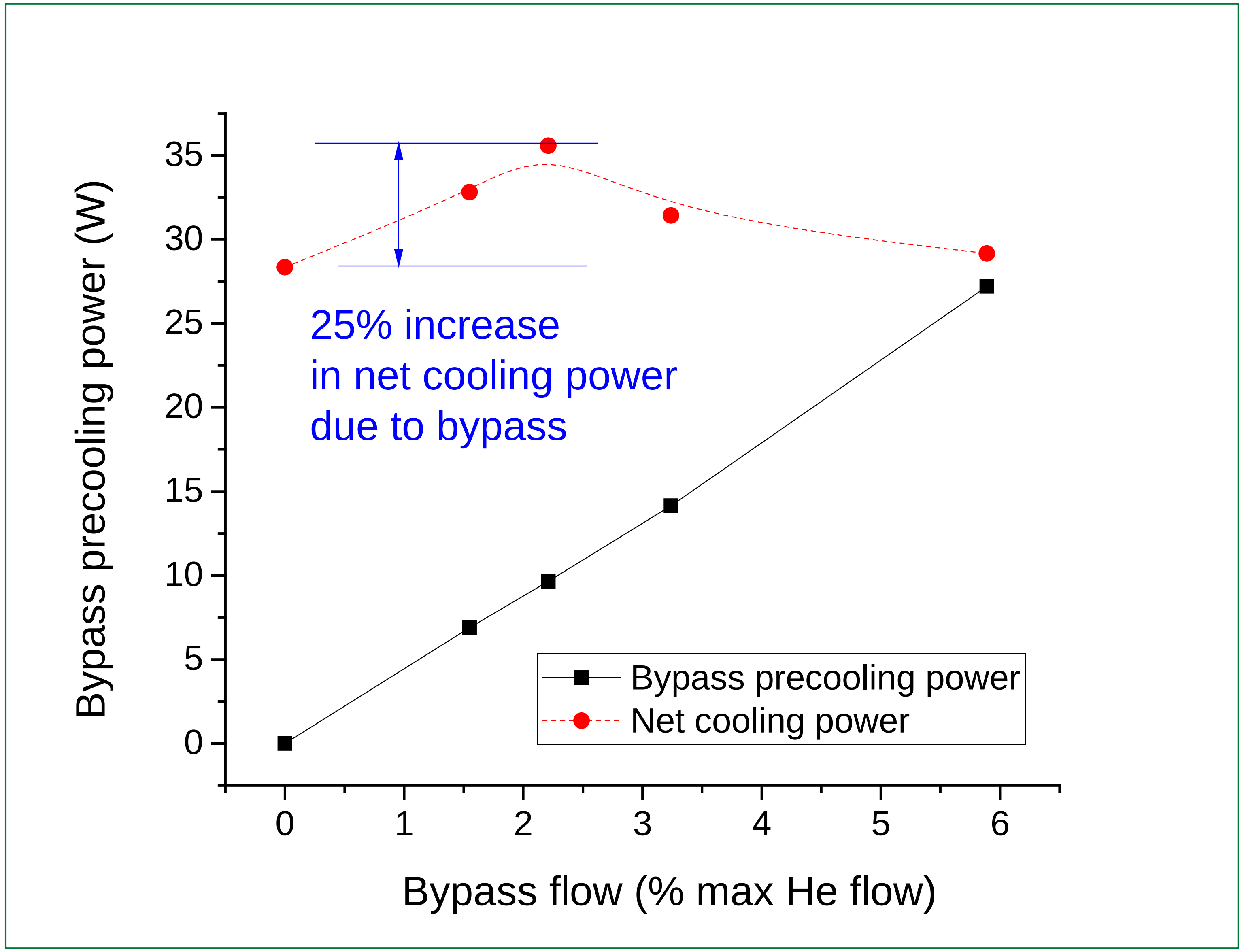
Temperature Transducer Locations at Interfaces of Refrigerant Pucks

Technical Approach:

Demonstrated cooling power increased using bypass

- Bypass flow increases cooling by 25%
- Thermal mass difference increases at 6.5-7 T gives > 6% by-pass flow

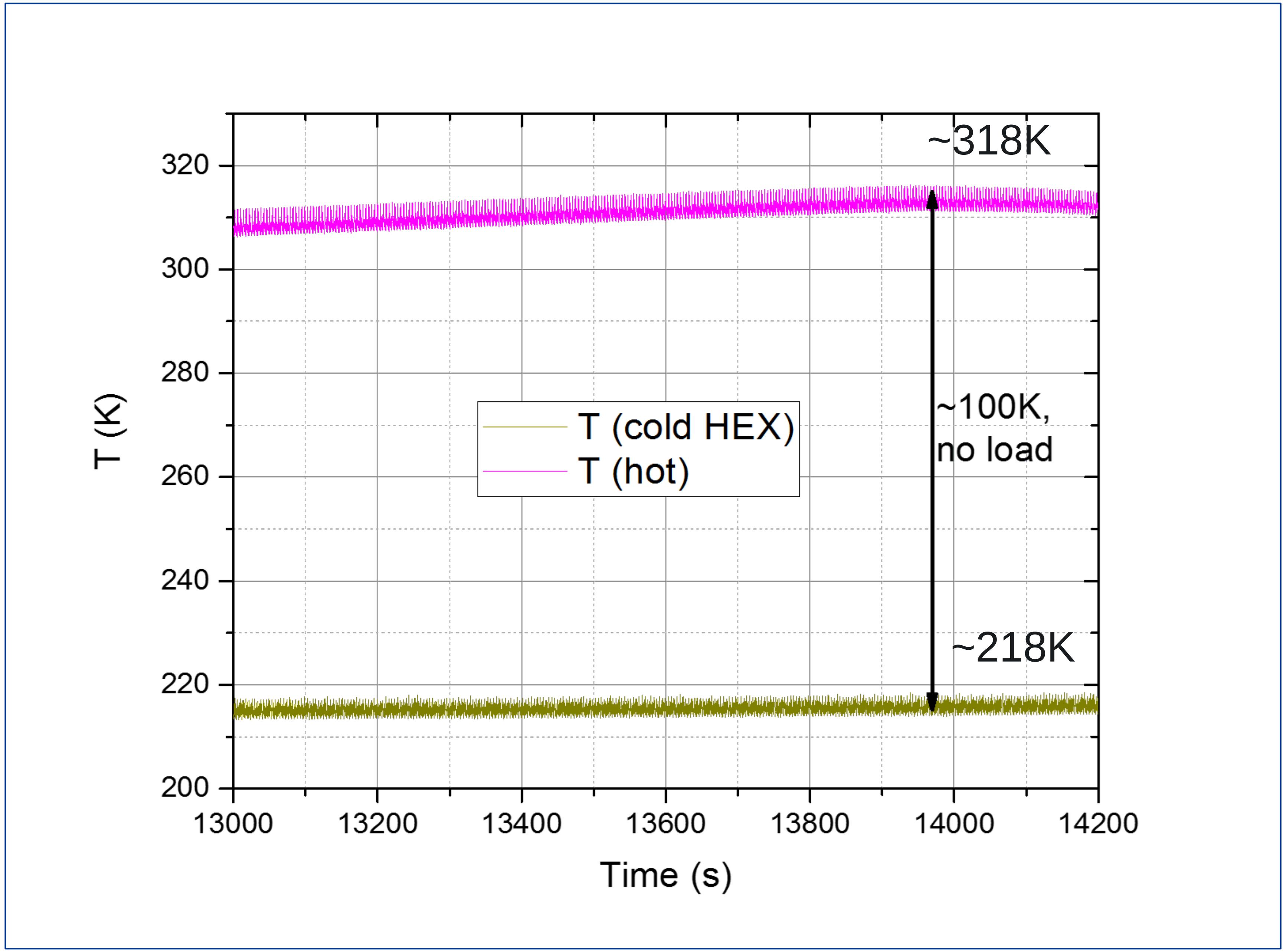
215g Gd Regenerator (upper)
215g Gd/Gd$_{0.74}$Tb$_{0.26}$ Regenerator (lower)
3.3 – 0.6 Tesla field
200 psia He gas HTF
4 sec AMR cycle
HTF flow rate better matched to magnetocaloric cooling power



PNNL’s early hardware achieved 100K temperature span under listed operating conditions

1kg Gd Regenerators
0.6 to 3.3T field
200 psia He gas HTF
4 sec AMR cycle

World Record ΔT span for these conditions to our knowledge



Background:

Efficiency of current air liquefaction units decreases as they are scaled down

	kg/s	kg/s	kW	kWh/t		kWh/t		kg	$$
	Air Mass Flow Rate	O_2 Mass Flow Rate	Total Air Liquefaction Thermal Load	Ideal Work Rate	Conventional Liquefaction FOM*	MOLS Energy Requirements	MOLS Unit FOM**	Magnetic Material Needed	Material Cost***
10 Metric Tonnes/day LO_2	0.5	0.12	96	146	0.25	203	**0.72**	**765**	**$382 k**
90 Metric Tonnes/day LO_2	4.5	1.04	864	146	0.3	184	**0.8**	**6855**	**$3.4 M**

$$FOM = \frac{\dot{W}_{Ideal}}{\dot{W}_{Real}}$$

$$\dot{W}_{Real} = \dot{Q}_C \left(\frac{T_H}{T_C} - 1 \right) + \frac{T_H \int_{T_C}^{T_H} \Delta S_{IRR} \, dT}{\int_{T_C}^{T_H} dT}$$

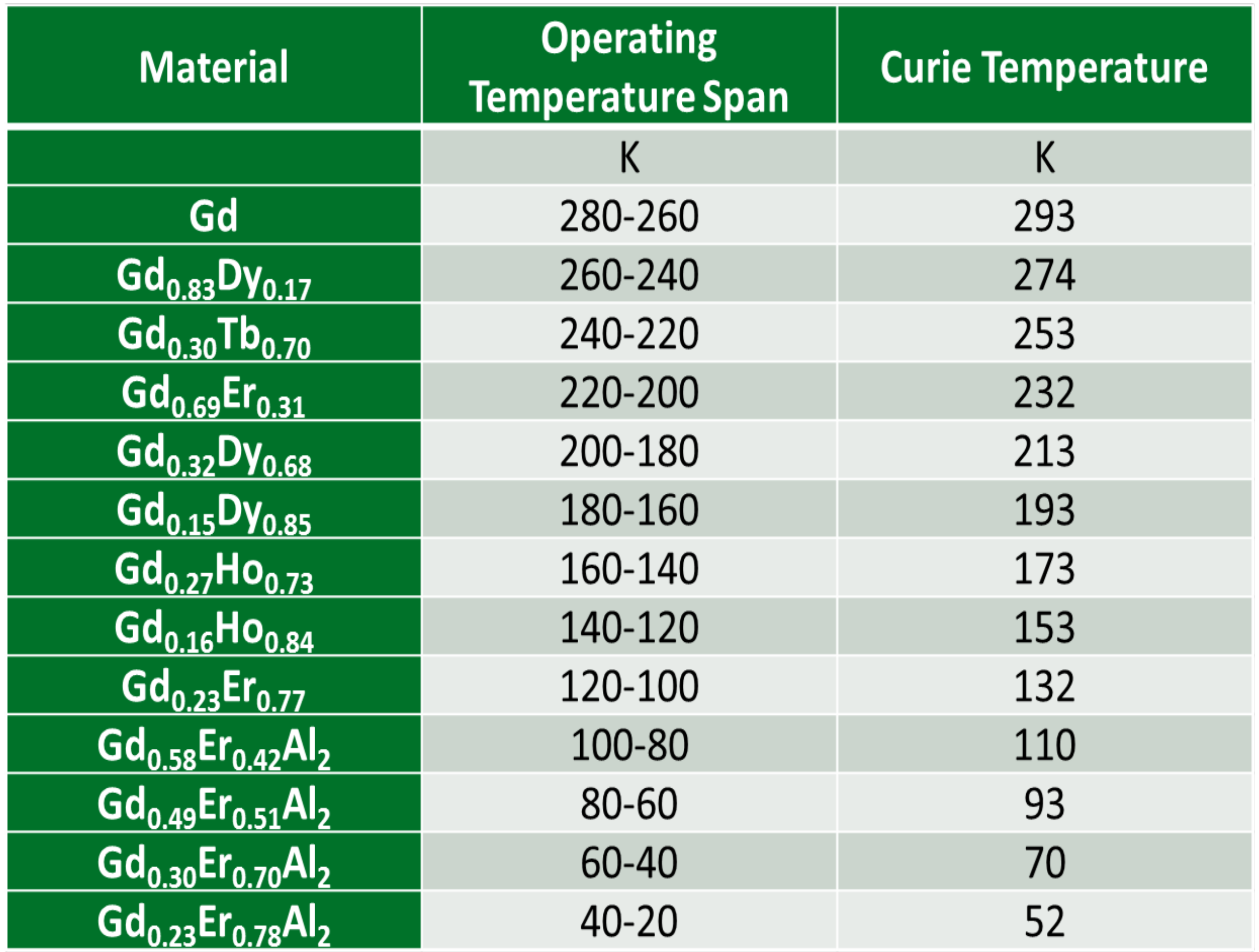
* T. M. Flynn, Cryogenic Engineering 2nd Edition, New York: Marcel Dekker, Inc, 2004.

** FOM includes the work associated with cryocoolers, HTF pumps, drive actuators, etc. Assumes 0.65 kW/kg material at 1hz, 6T field change

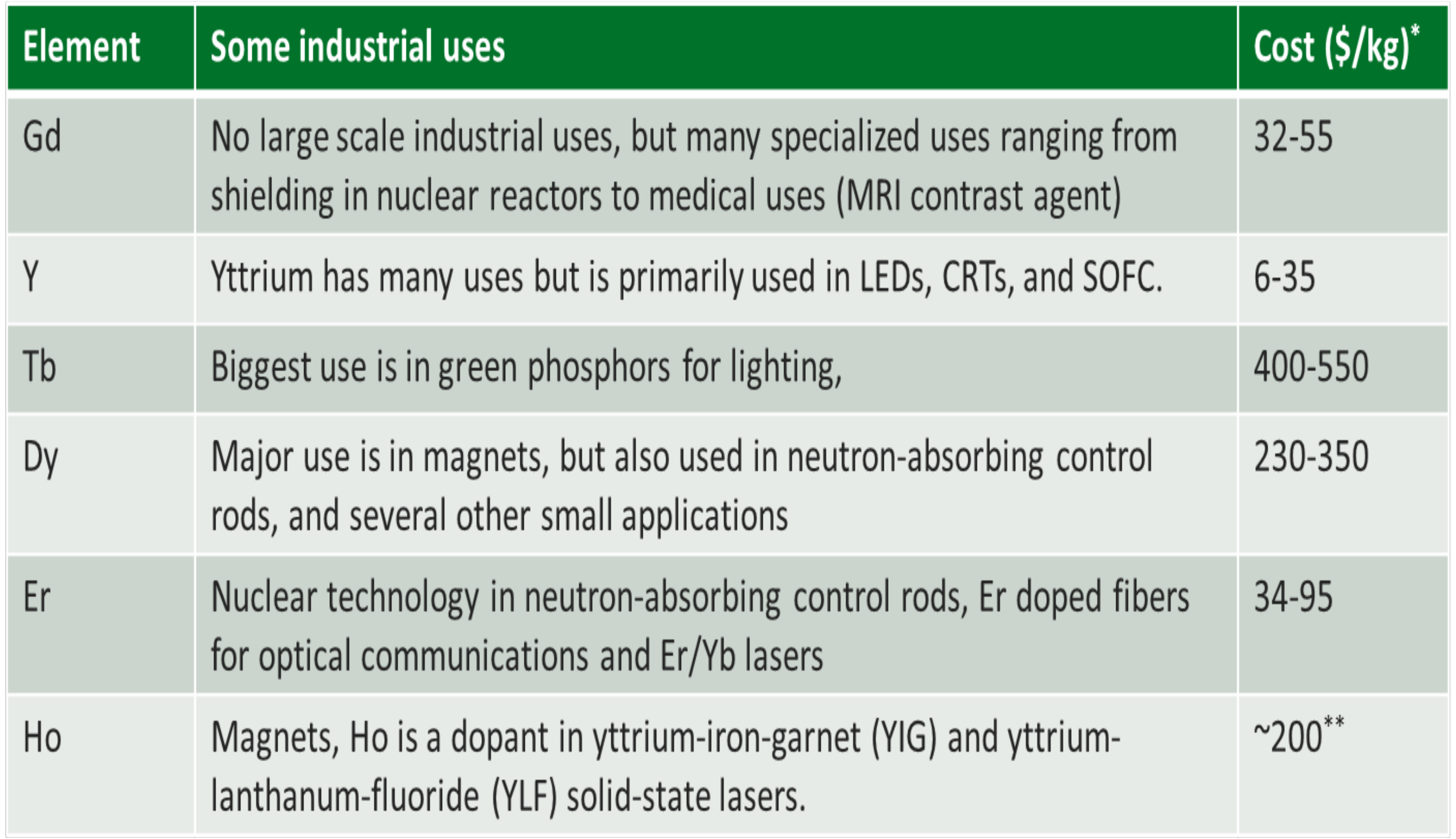
*** Material cost assumes $500/kg for material and processing to spheres.

Technical Approach:

PNNL has identified potential materials to operate over the temperature span

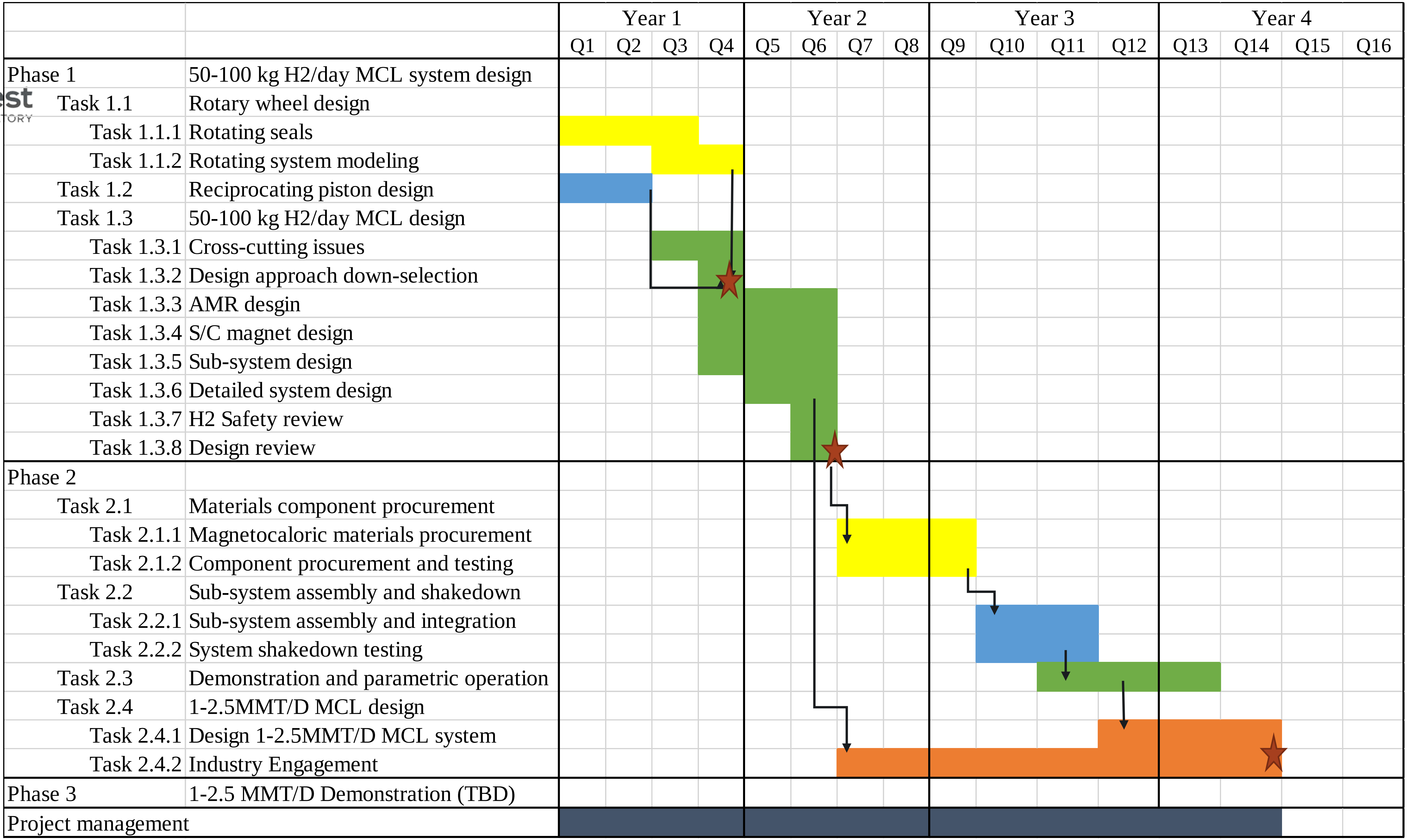


Material	Operating Temperature Span	Curie Temperature
	K	K
Gd	280-260	293
$Gd_{0.83}Dy_{0.17}$	260-240	274
$Gd_{0.30}Tb_{0.70}$	240-220	253
$Gd_{0.69}Er_{0.31}$	220-200	232
$Gd_{0.32}Dy_{0.68}$	200-180	213
$Gd_{0.15}Dy_{0.85}$	180-160	193
$Gd_{0.27}Ho_{0.73}$	160-140	173
$Gd_{0.16}Ho_{0.84}$	140-120	153
$Gd_{0.23}Er_{0.77}$	120-100	132
$Gd_{0.58}Er_{0.42}Al_2$	100-80	110
$Gd_{0.49}Er_{0.51}Al_2$	80-60	93
$Gd_{0.30}Er_{0.70}Al_2$	60-40	70
$Gd_{0.23}Er_{0.78}Al_2$	40-20	52



Element	Some industrial uses	Cost ($/kg)*
Gd	No large scale industrial uses, but many specialized uses ranging from shielding in nuclear reactors to medical uses (MRI contrast agent)	32-55
Y	Yttrium has many uses but is primarily used in LEDs, CRTs, and SOFC.	6-35
Tb	Biggest use is in green phosphors for lighting,	400-550
Dy	Major use is in magnets, but also used in neutron-absorbing control rods, and several other small applications	230-350
Er	Nuclear technology in neutron-absorbing control rods, Er doped fibers for optical communications and Er/Yb lasers	34-95
Ho	Magnets, Ho is a dopant in yttrium-iron-garnet (YIG) and yttrium-lanthanum-fluoride (YLF) solid-state lasers.	~200**

- Cost as of 12/31/2017 from http://mineralprices.com/default.aspx#rar last accessed 5/2/2018
- **Cost as of 05/02/2018 from https://www.alibaba.com/product-detail/Rare-Earth-Element-Ho-Holmium-Metal_60670489854.html



		Year 1				Year 2				Year 3				Year 4			
		Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
Phase 1	50-100 kg H2/day MCL system design																
Task 1.1	Rotary wheel design																
Task 1.1.1	Rotating seals	🟨	🟨	🟨													
Task 1.1.2	Rotating system modeling			🟨	🟨												
Task 1.2	Reciprocating piston design	🟦	🟦														
Task 1.3	50-100 kg H2/day MCL design																
Task 1.3.1	Cross-cutting issues			🟩	🟩												
Task 1.3.2	Design approach down-selection				🟩 ★												
Task 1.3.3	AMR desgin				🟩	🟩	🟩										
Task 1.3.4	S/C magnet design				🟩	🟩	🟩										
Task 1.3.5	Sub-system design				🟩	🟩	🟩										
Task 1.3.6	Detailed system design					🟩	🟩										
Task 1.3.7	H2 Safety review						🟩										
Task 1.3.8	Design review						🟩 ★										
Phase 2																	
Task 2.1	Materials component procurement																
Task 2.1.1	Magnetocaloric materials procurement							🟨	🟨	🟨							
Task 2.1.2	Component procurement and testing							🟨	🟨	🟨							
Task 2.2	Sub-system assembly and shakedown																
Task 2.2.1	Sub-system assembly and integration										🟦	🟦					
Task 2.2.2	System shakedown testing										🟦	🟦					
Task 2.3	Demonstration and parametric operation											🟩	🟩	🟩			
Task 2.4	1-2.5MMT/D MCL design																
Task 2.4.1	Design 1-2.5MMT/D MCL system												🟧	🟧	🟧		
Task 2.4.2	Industry Engagement							🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧 ★		
Phase 3	1-2.5 MMT/D Demonstration (TBD)																
Project management		⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛	⬛		

Hot-cold temperatures of layers during 280K - 166K run with 5-layer GEN-IIC