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Rotary Magnetocaloric Air Liquefier for High Efficiency Air Separation

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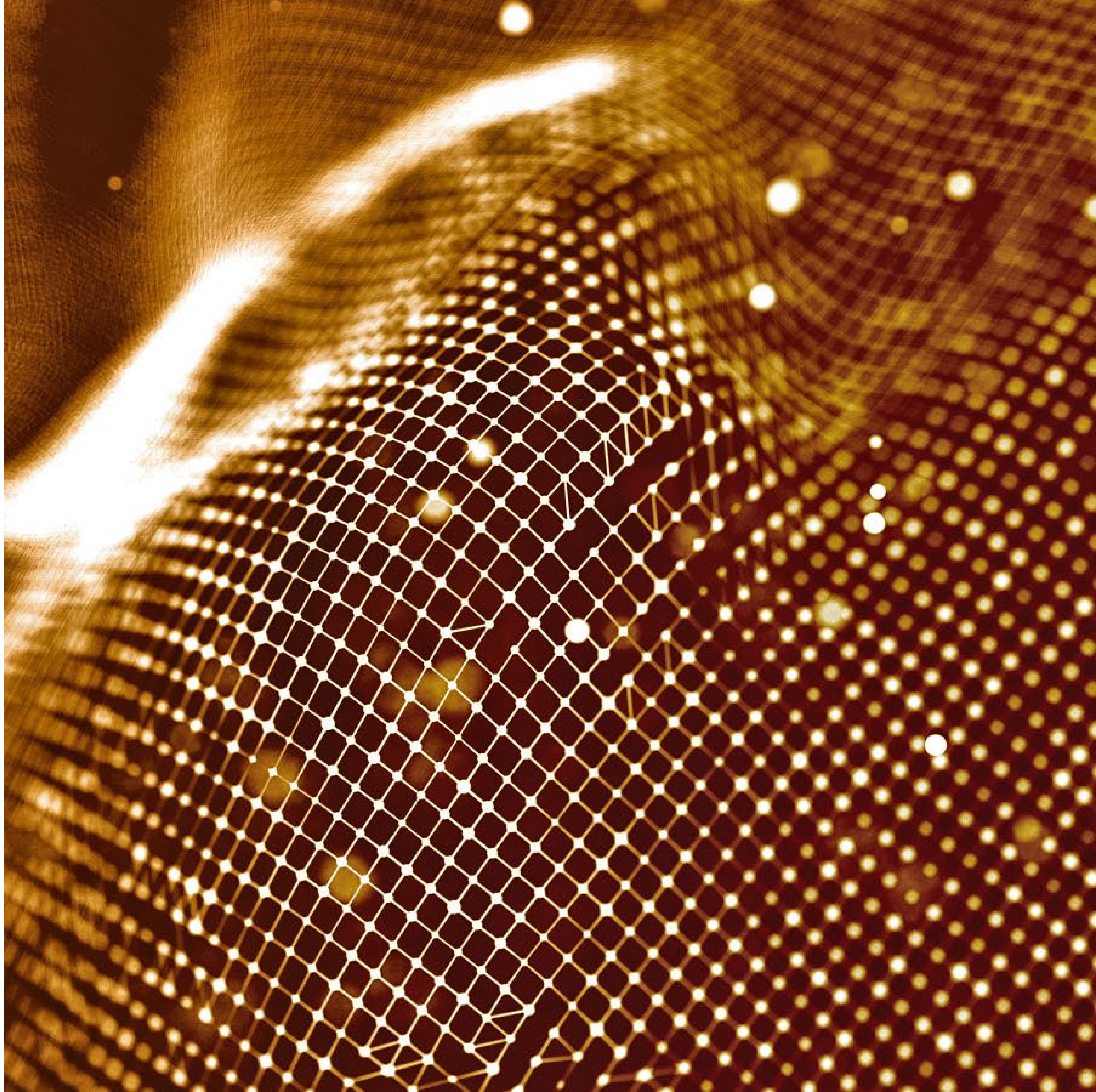
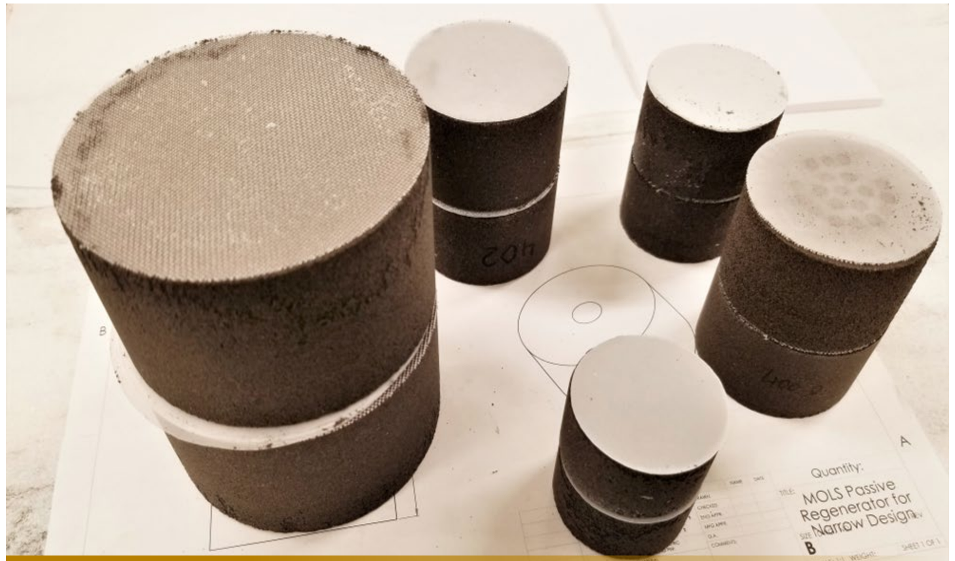
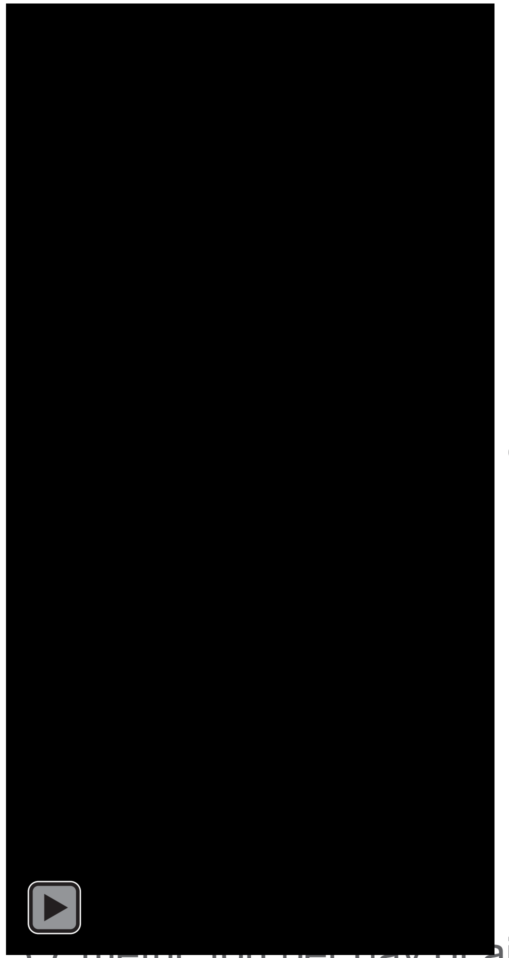


Outline

- Purpose
- Background
- List of milestones
- Technical approach
- Technical progress
- Progress towards milestones

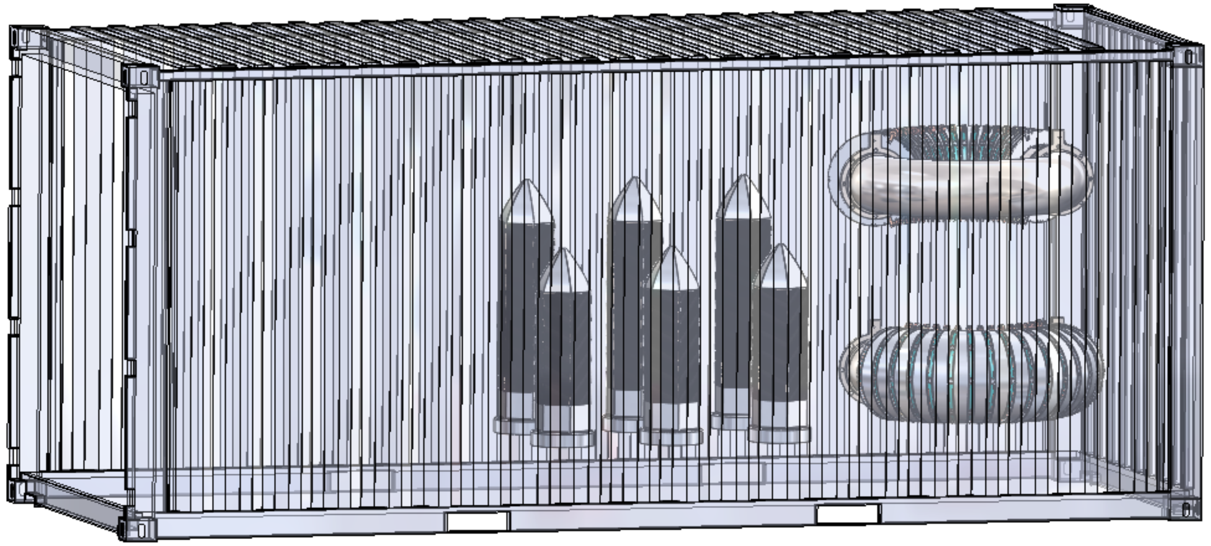


Five refrigerant regenerators for previous MOLS liquefier – refrigerants are solid, rare-earth alloys



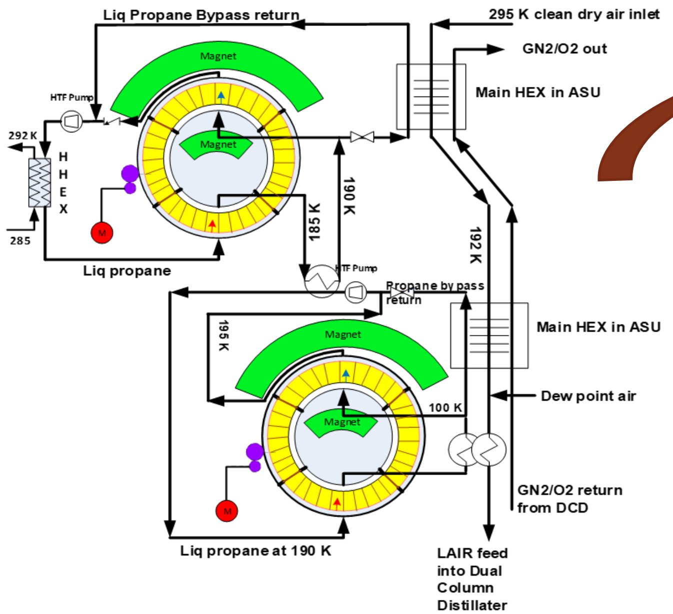
Five layer dual-reciprocating MOLS (magnetocaloric oxygen liquefier system) liquefier executing AMR cycle

[redacted] air MCL (magnetocaloric liquefier) & MCD (microchannel distillation) footprint in 20-foot CONEX

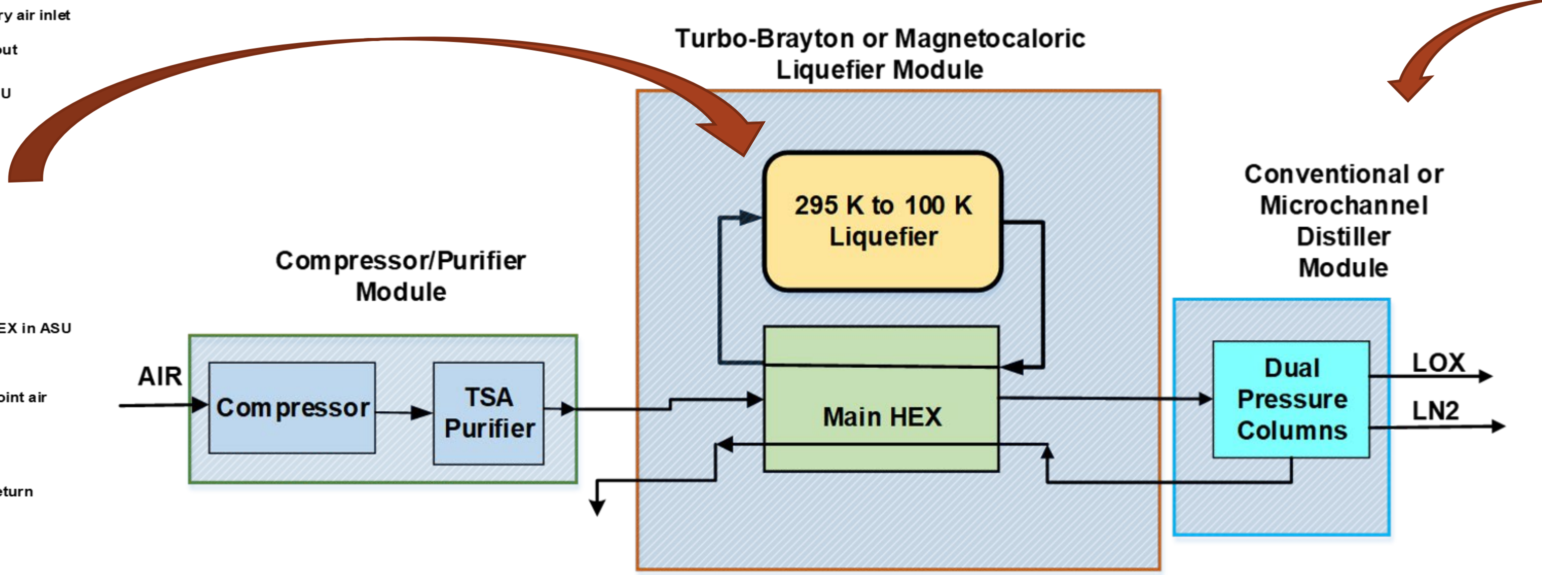


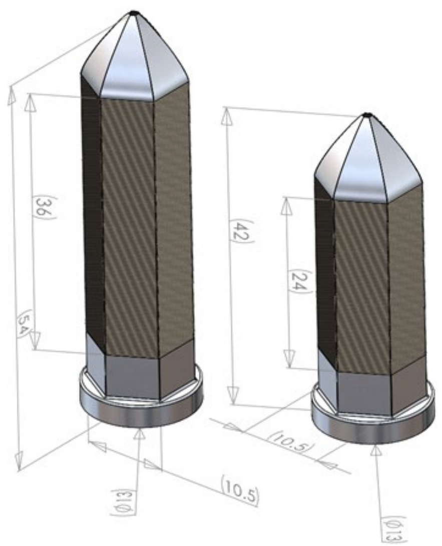
Purpose: Low-cost LO_2 and LN_2 create a path to low cost LH_2 from small gasification projects with CCU

- The objective of this project is to develop an efficient, compact cryogenic air separation unit (ASU) for production of distributed, low-cost LO_2 and LN_2 at engineering scale
- The goal is to replace two of the three modules of an ASU with two innovative technologies:
  - Replace turbo-Brayton cycle air liquefiers with magnetocaloric liquefiers (MCLs).
    - **Increase ASU energy efficiency by ~40% and decrease capex by ~25%.**
  - Replace conventional distillation columns with microchannel distillation columns (MCDs).
    - **Reduce distillation footprint by ~10 times.**



Two-stage magnetocaloric liquefier

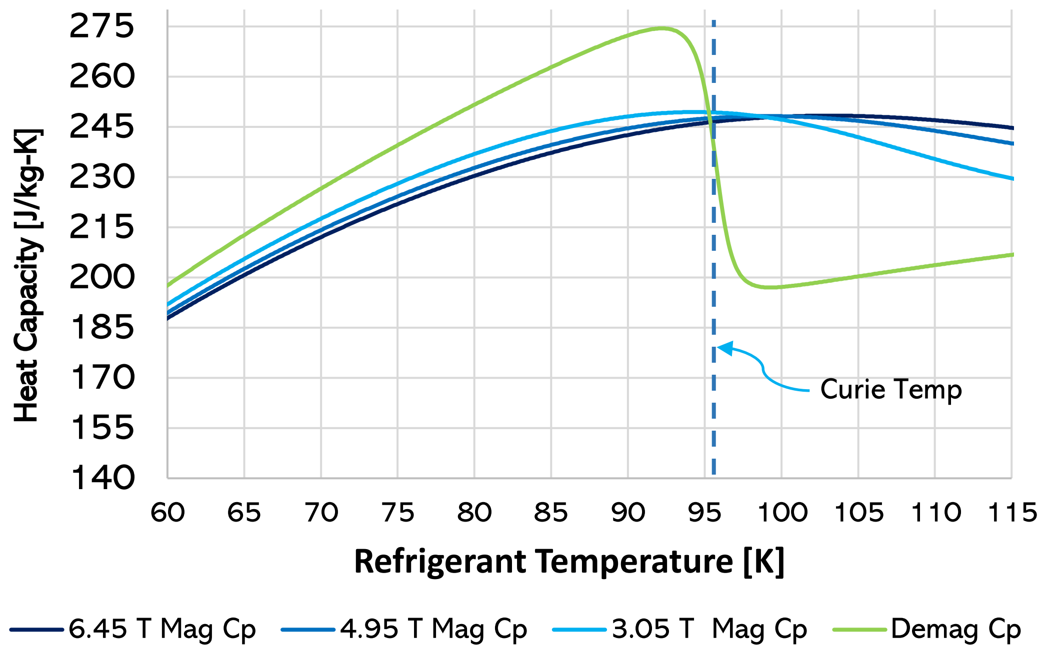




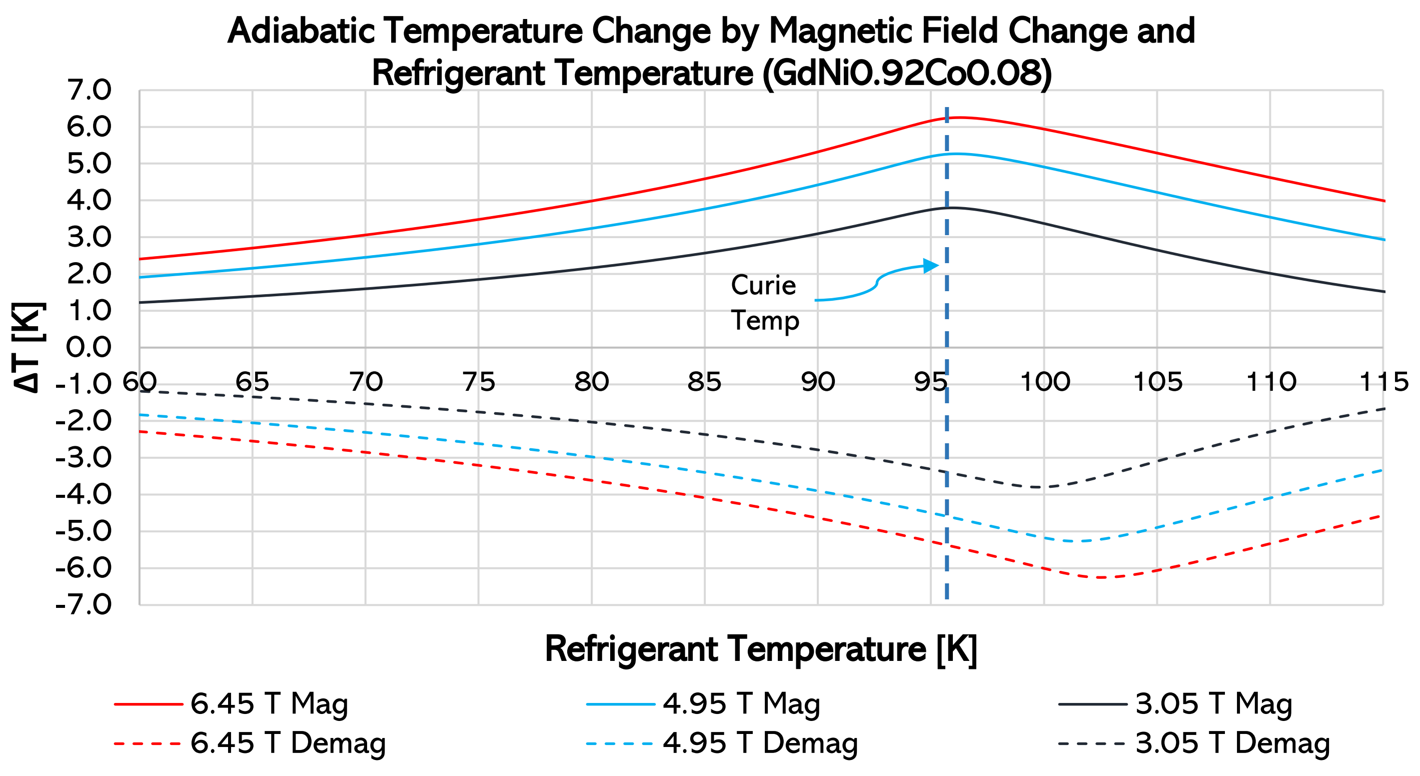
Microchannel distillation developed at PNNL

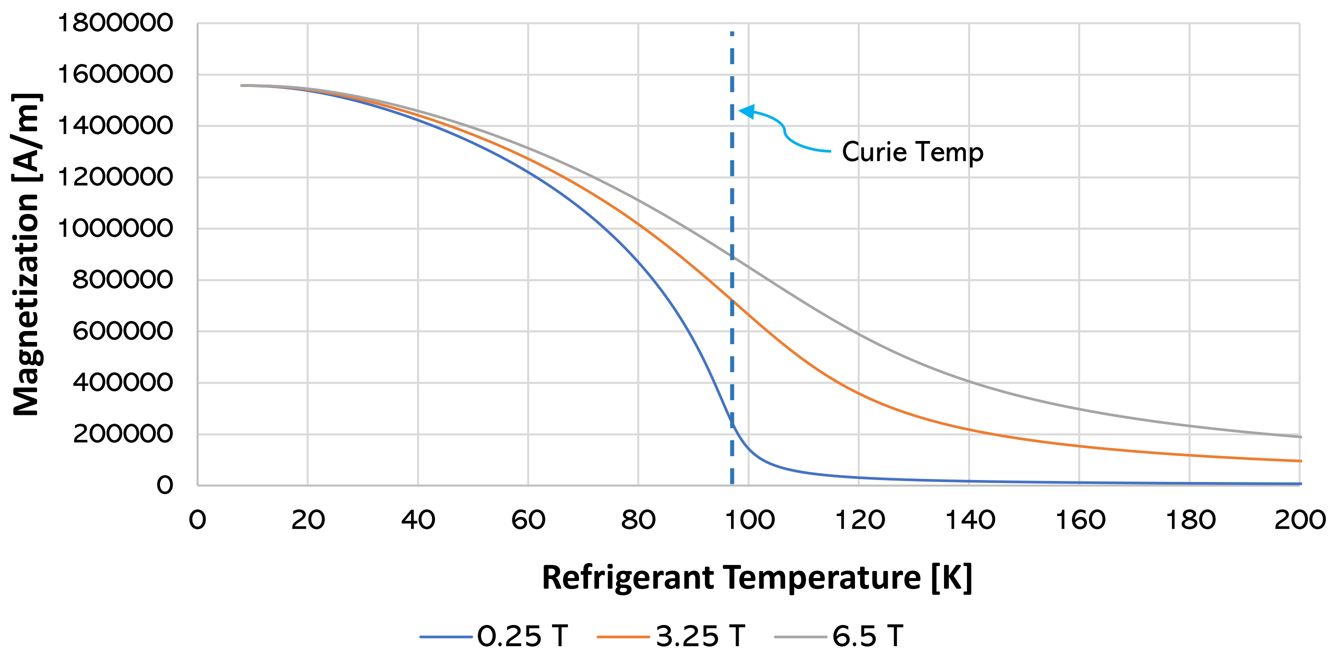
Background: Basic principles of the magnetocaloric effect

$$\Delta T_{adiabatic} = -\int_{H_0}^{H} \underbrace{\left(\frac{T}{C(T,H)}\right)_H}_{\text{Change in entropy}} \underbrace{\left(\frac{\partial M(T,H)}{\partial T}\right)_H}_{\text{Work input}} dH$$



Barclay, et. al., 2019, Propane Liquefaction with an Active Magnetic Regenerative Liquefier, Cryogenics, https://www.sciencedirect.com/science/article/pii/S0011227518302765

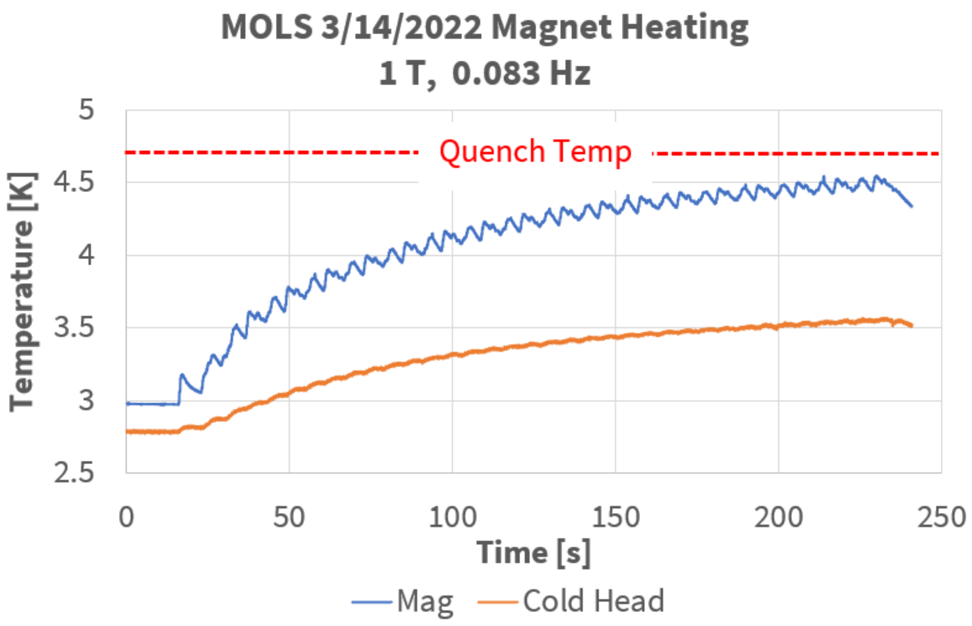


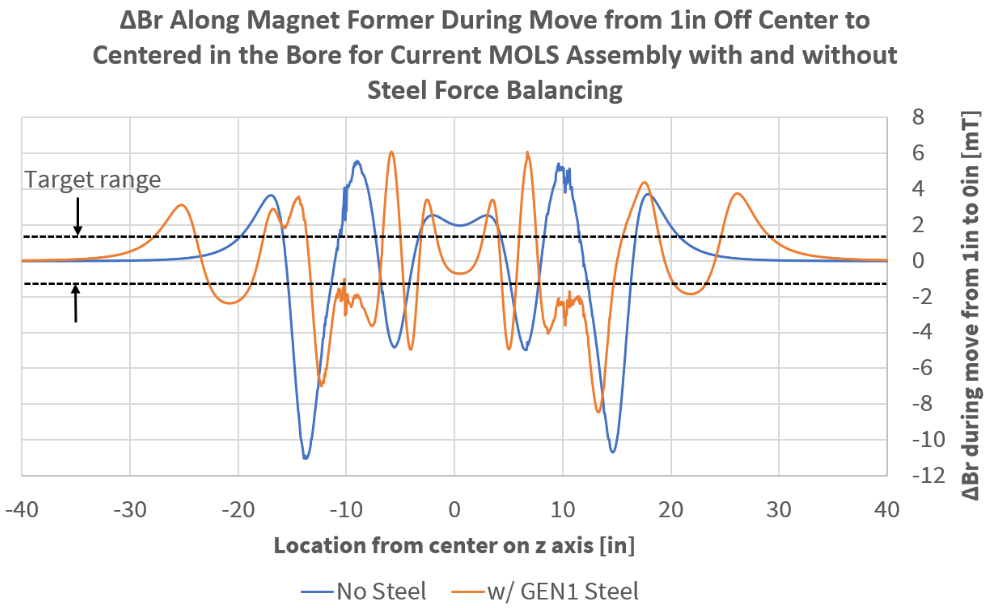


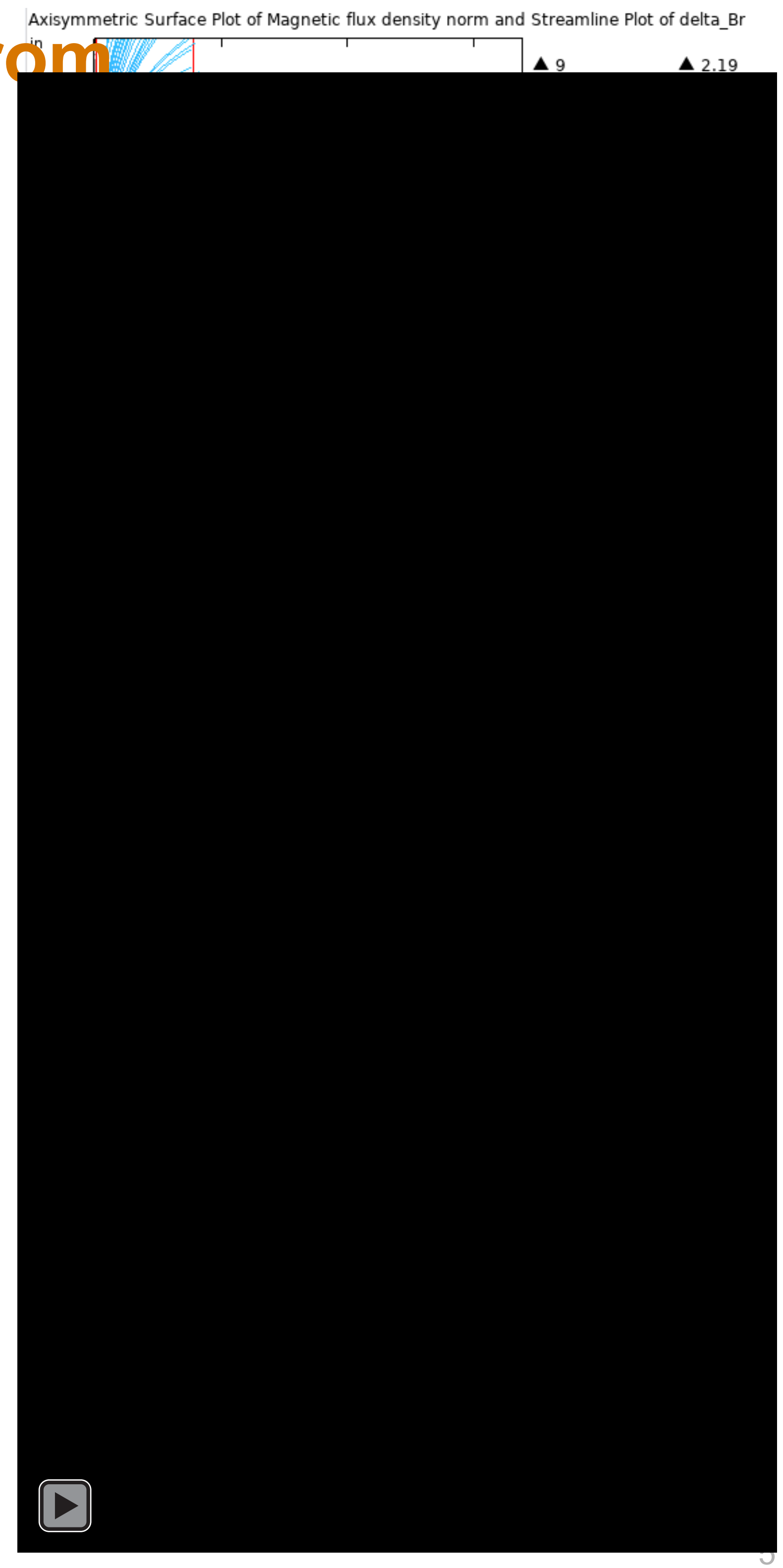
Archipley, et. al., 2023, Methane liquefaction with an active magnetic regenerative refrigerator, Cryogenics https://www.sciencedirect.com/science/article/pii/S0011227522001709

Background: The reciprocating MCL suffers from inherent technical barriers for scale-up

- AC losses are caused by changes in the current in the persistent mode magnet coil to keep the flux density B constant when the magnetization M of objects that move through the bore change where: $B = \mu_0(H + M) = Const.$
- Changes in radial magnetic flux density vector orientations induce eddy currents in magnet structures due to Faraday's Law: $\varepsilon(emf) = -N\frac{d\Phi_B}{dt}$
- Latest tests at 0.25 Hz indicate 5.4 W of magnet heating due to AC losses and eddy currents. At 0.083 Hz, the cryocooler can keep up with eddy current heating. At this lower frequency, MOLS' cooling capacity during start up is too small.
- Force balance and magnetic flux density uniformity issue has been solved which limits both AC and eddy current losses.







Background: TEA performed in 2023 quantifies reductions in capital costs and operational costs → low-cost LOX is achievable

Costs of Plant, LOX, and LN_2 via MCL & MCD are well below market rate for cryogens									Assume LO2 and LN2 share power cost
Integrated Air Separation Unit	Compressor-TSA Purifier Module	Magnetic Liquefier Module	Dual MCD distillation module	CAPEX TOTAL	Input power for ASU (kW)	ASU prdtn rate of LO2 (kg/day)	ASU prdtn rate of LN2 (kg/day)	Cost/day of energy	Cost/kg of cryogen ($/kg)
100 kg/day air	$15,950	$722,199	$114,000	$852,149	1.41	12	36	$3.39	$0.071
443 kg/day air	$31,431	$1,415,263	$231,935	$1,678,630	5.85	53	159	$14.03	$0.066
3700 kg/day air	$90,092	$3,722,998	$670,573	$4,483,663	47.94	444	1,332	$115.06	$0.065*

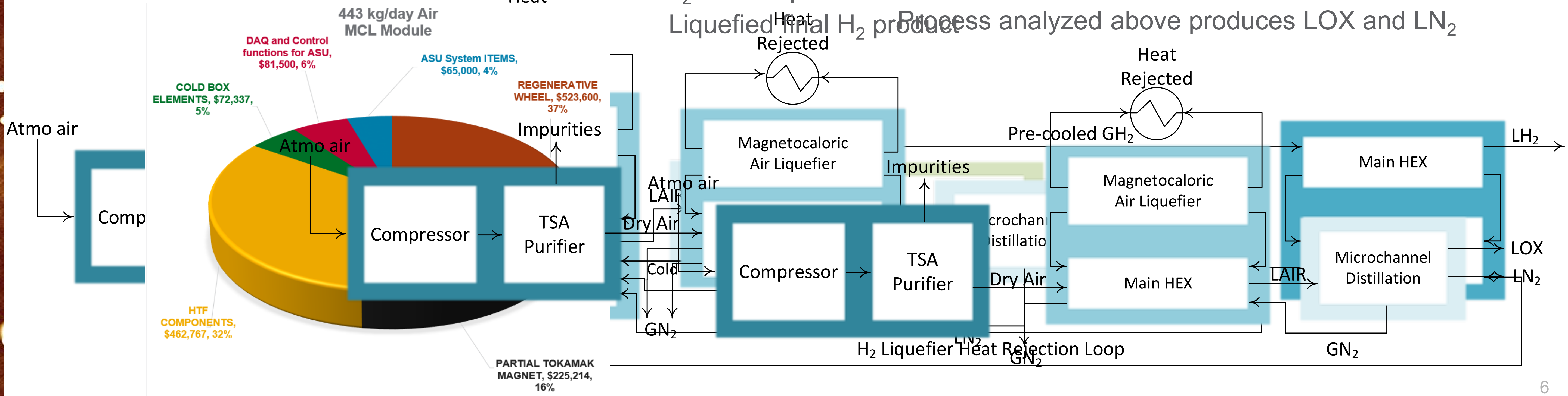
*Market rate for LOX: $0.50-$1.00/kg

System costs by subsystem

LN_2 used to precool air

Liquefied final H_2 product

Process analyzed above produces LOX and LN_2



Milestones identified in Project Management Plan and SOPO

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Phase	Task/ Subtask	Milestone Title & Description	Planned Completion Date	Verification method
1	**1. Complete assembly of rotary MCL system**	**Assemble seals, drive, and instrumentation into pressure vessel for seal testing (no actual refrigerants or magnets)**	**July 30, 2024**	**Report, hardware designs, pictures of assembled hardware**
1	**2. Confirm seal performance (Go/No Go)**	**Test and optimize seal design at cryogenic temperatures (80-120 K) to measure leak rate and friction, with targets less than 2% leak rate and 10 N-m torque due to friction.**	**December 31, 2024**	**Report, test results on leakage and friction measurements**
1	3. Confirm rotary MCL performance via model	Model cycle performance, magnetic field interactions, and structural considerations for the rotary MCL to drive design. Confirm that design will achieve >0.4 FOM at this scale.	December 31, 2024	Report, results from analysis
1	4. Complete internal refrigerant designs for both rotary stages.	Use multi-physics models to develop refrigerant configurations with acceptable coupling and permeability for cooling fluid flow.	December 31, 2024	Report, results from numerical and simulation analysis
2	5. Order and receive refrigerants and magnet for MCL system	MCL refrigerants will be characterized and fabricated by AMES. Partial tokamak magnet with flux-return coils to be fabricated by outside vendor.	March 30, 2025	Report of receipt of components
2	6. Assemble and test Stage 1 rotary MCL unit.	Test Stage 1 to confirm cooling capacity from 295 K to 172 K.	July 30, 2025	Report of test results. Measurements of cooling capacity and efficiency
2	7. Reconfigure MCL unit for Stage 2 testing.	Testing of stage 2 to cool from 172 K to 100 K	October 31, 2025	Report of test results. Measurements of cooling capacity and efficiency
2	8. Total system efficiency	Measure the total system efficiency and compare the measured results with theoretical calculations.	December 31, 2025	Report of calculations
2	9. Final design of 2-stage pilot scale rotary MCL ASU	Apply test results to design scaled up system of a pilot-scale ASU using rotary MCL technology	December 31, 2025	Report on design details, expected performance, balance of plant

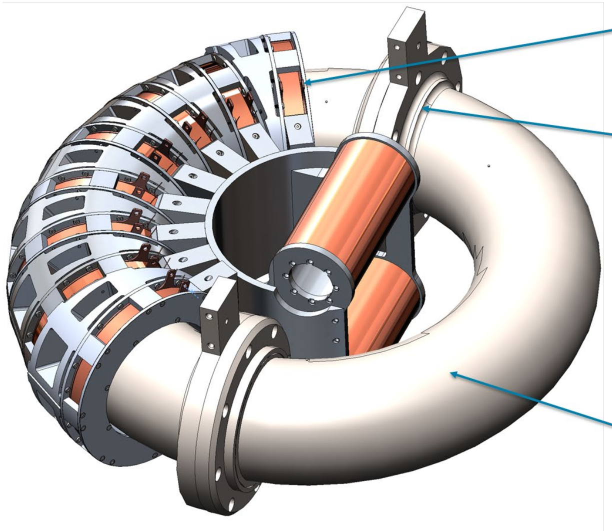
Year 1 (Phase 1 rows)

Success in Phase I focuses on the performance of the flow control seals and their integration into the pressure vessel and drive systems. Leakage rates across the seal of less than 2% of the total flow and friction induced torque of less than 10 N-m during operation at cryogenic temperatures counts as success. This is a 'Go/No-Go' criteria as the success of Phase II relies on effective, low friction flow control.

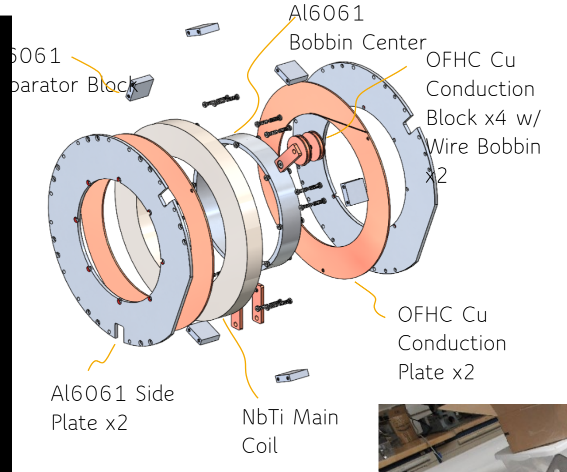
Success in Phase 2 focuses on the ability to execute the magnetocaloric refrigeration in two stages, separately. Obtaining measurements of liquefier performance to compare to predicted outcomes and conventional techniques counts as success. These outcomes inform the decision on whether to proceed in developing a pilot scale demonstration system.

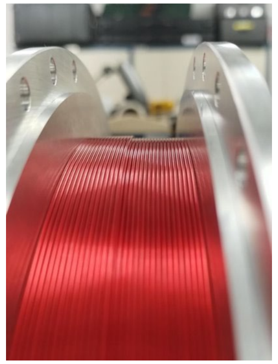
Technical approach: A thermodynamically simpler 2-stage rotary MCL overcomes limitations of reciprocating regenerator prototype

Prototyping magnet and rotary components



- 4 K conduction-cooled NbTi Partial Tokamak Magnet
- Split housing for assembly into the magnet
  - Filled with liquid propane at 200 psia
  - Low density filler around regenerator
  - HTF flow ports for circulating liquid propane
  - Drive feedthrough
  - Instrumentation feedthrough
  - Adjustable bearing supports
  - Controllable diversion flow channels from demagnetized to magnetized regenerator
- Regenerator mounted into frame in sections to assemble rotating wheel



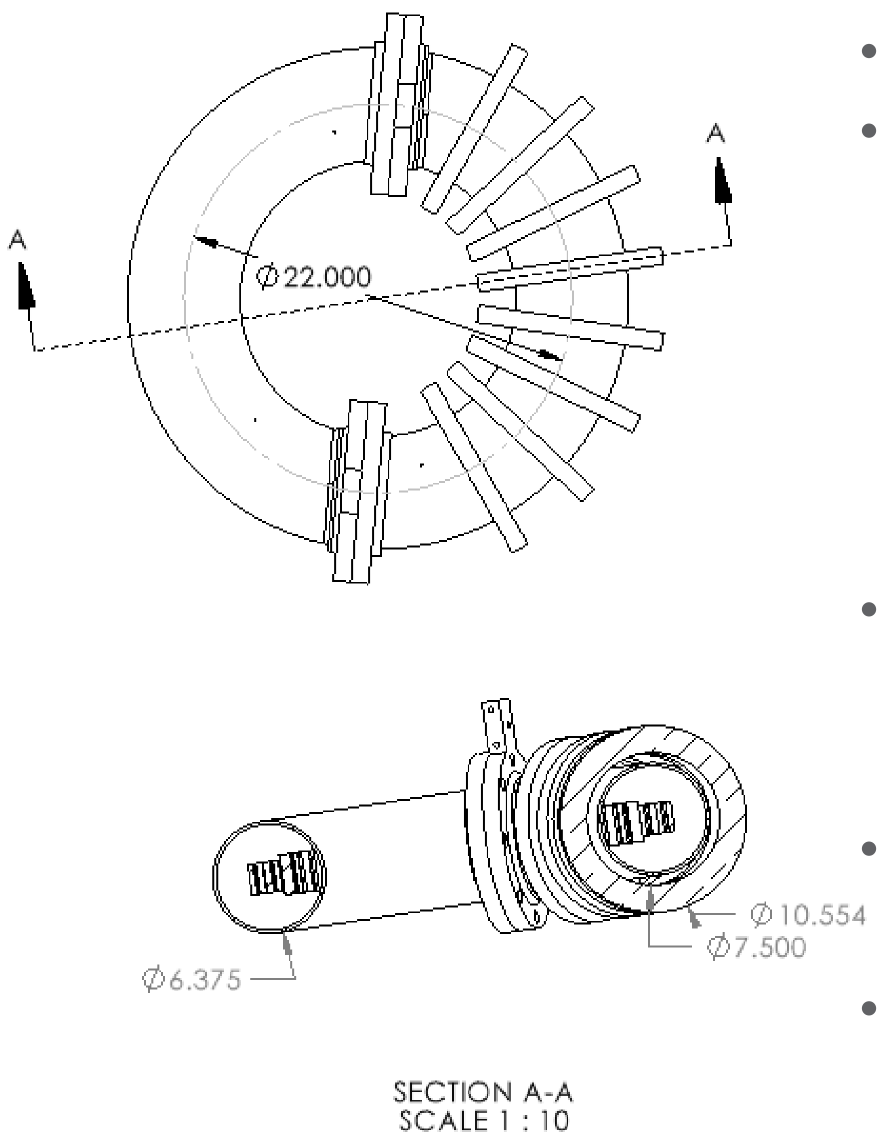


Address high risk challenges first:

Technical Challenges - High Risk Items for Demonstration of Rotary Design	Progress	Current Risk Level	Next Development Steps
Magnet design that provides a homogenous high magnetic field over 120° arc of rotating refrigerant while producing a low field over the opposing 120° arc of rotating refrigerants.	De-risking took place in APRA-e project to identify, design, and mockup partial tokamak magnet with flux return coils	Low	Select vendor, finalize design details such as persistent mode switching and quench protection, fabricate.
Internal seals that provide effective flow control for main and diversion flow paths; transferring flow from demagnetized region, to process load, to magnetized region, and to heat sink.	**Several design types explored, and some tested in modified fixtures.**	**High**	**Further testing of design types, characterization of performance at cryogenic temperatures, developing integration with housing and drive. Prototype, test (room & cryo temps), refine.**
External housing capable of hermitically sealing ~200-400 psia heat transfer fluid bulk pressure that integrates with magnet design.	**Several design types explored and with progress towards fabrication of fully functional (ASTM stamped) prototype.**	Medium	**Identify and explore alternative fabrication methods for cost reduction and potential seal/drive integration challenges. Prototype, test (room & cryo temps), refine.**
Internal and external drive structures that provide the work input for the cycle by rotating the refrigerants through the field; must integrate with housing and seal designs.	**Several design types explored, and some tested via 3D printed parts.**	**Medium/High**	**Material selection, characterization, and fabrication for cryogenic applications. Managing differential CTE. Prototype, test (room & cryo temps), refine.**
Fabrication of refrigerant regenerators designed for minimum irreversible entropy generation over the cycle.	Optimized designs in development Q4 FY23. Some fabrication techniques explored during ARPA-e project.	Medium	Partner with material science and manufacturing specialists to develop scalable techniques. Prototype and test heat transfer capabilities, entropy generation, magnetocaloric behavior.

Design basis for engineering scale liquefier

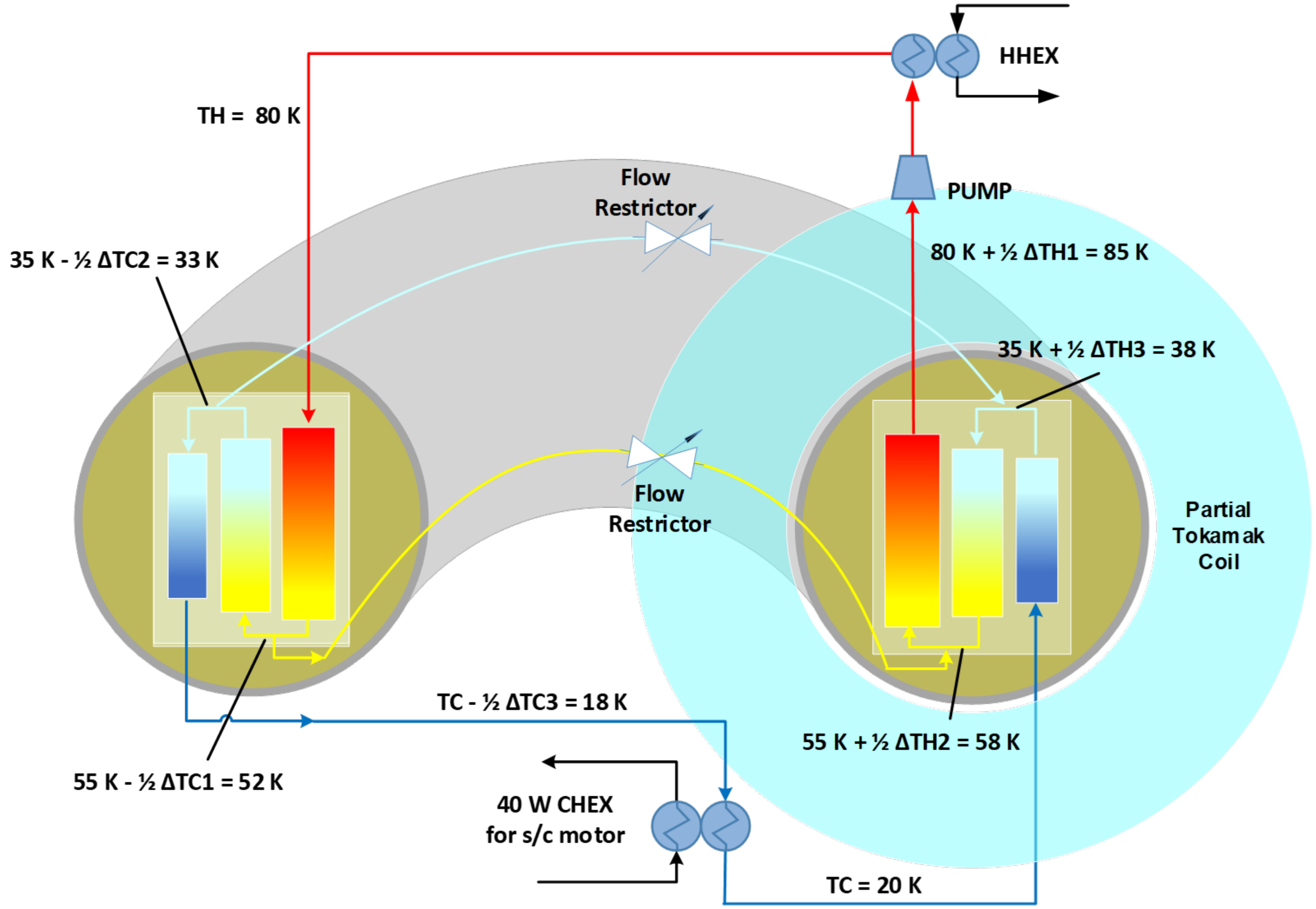
- The rotary design scalability to lab-scale is impractical.
- Engineering scale is the logical path forward with this form-factor.
- Rotary design benefits over reciprocating design:
  - Reduces or eliminates AC losses in magnet.
  - Utilizes less refrigerant.
  - Operates at higher frequencies.
  - Simplifies heat transfer process flows.
  - Scales best.



Simplified rotary concept with dimensions (inches) for scale

- 200 – 400 kg LAIR per day
- Assuming 300 kg/day:
  - 3.5 g/s, 100 psia air flow rate (176 SLPM)
  - Total load: 1.31 kW
  - Load to T_sat: 0.72 kW
  - Load for liquefaction: 0.59 kW
  - 5.32 kW rejected w/ 0.4 FOM
- Same toroidal geometry as AMAC
  - 22-inch toroid major diameter
  - 6.375-inch pressure vessel diameter
- Stage 1, 3 layers
  - 295 – 172 K, 2.82 kW @ 172 K
- Stage 2, 3 layers
  - 172 – 100 K, 0.87 kW @ 100 K
- Propane heat transfer fluid

Task 2.1: Rotary seal (stationary)

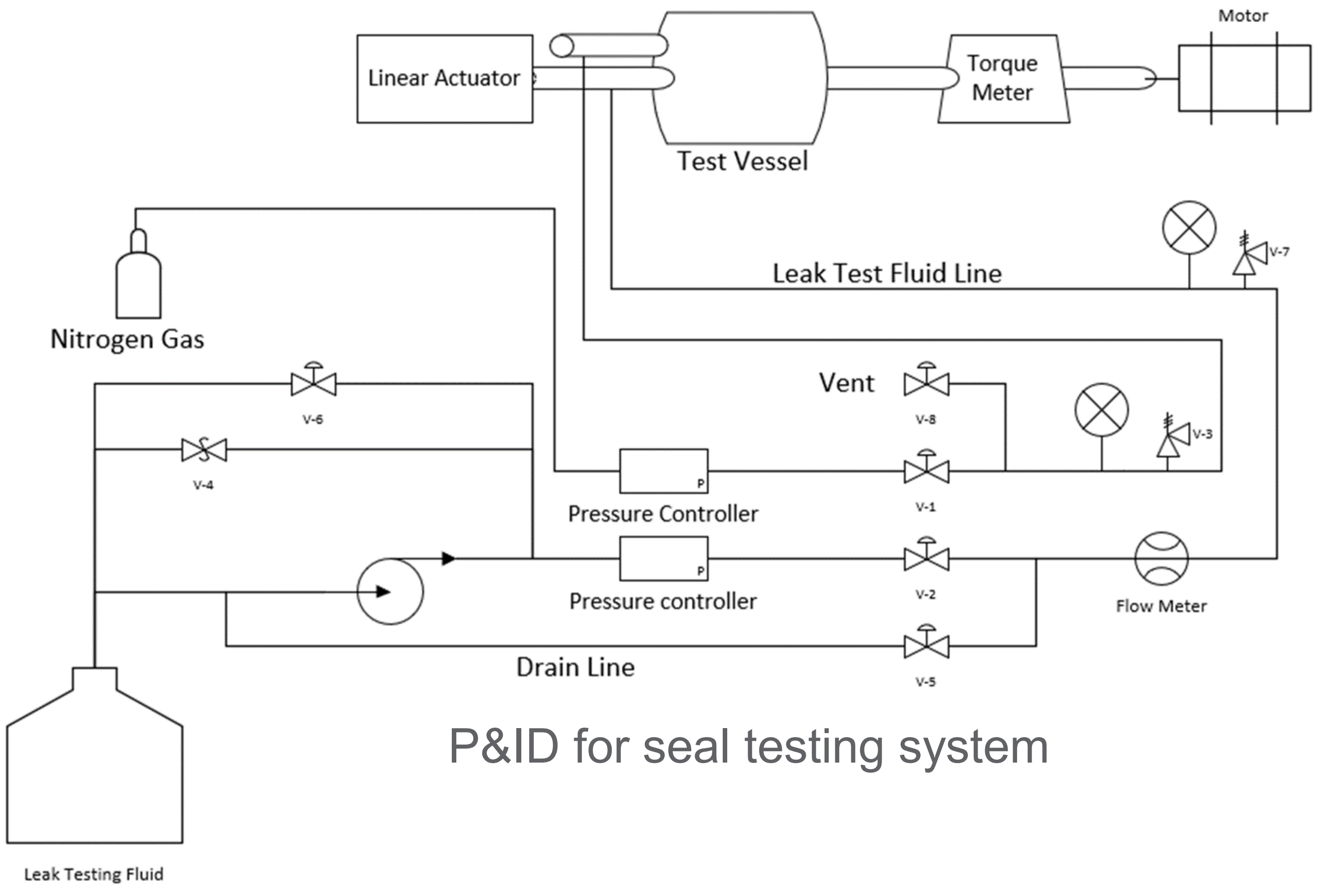


Flow pathways identified in ARPAe hydrogen liquefier project

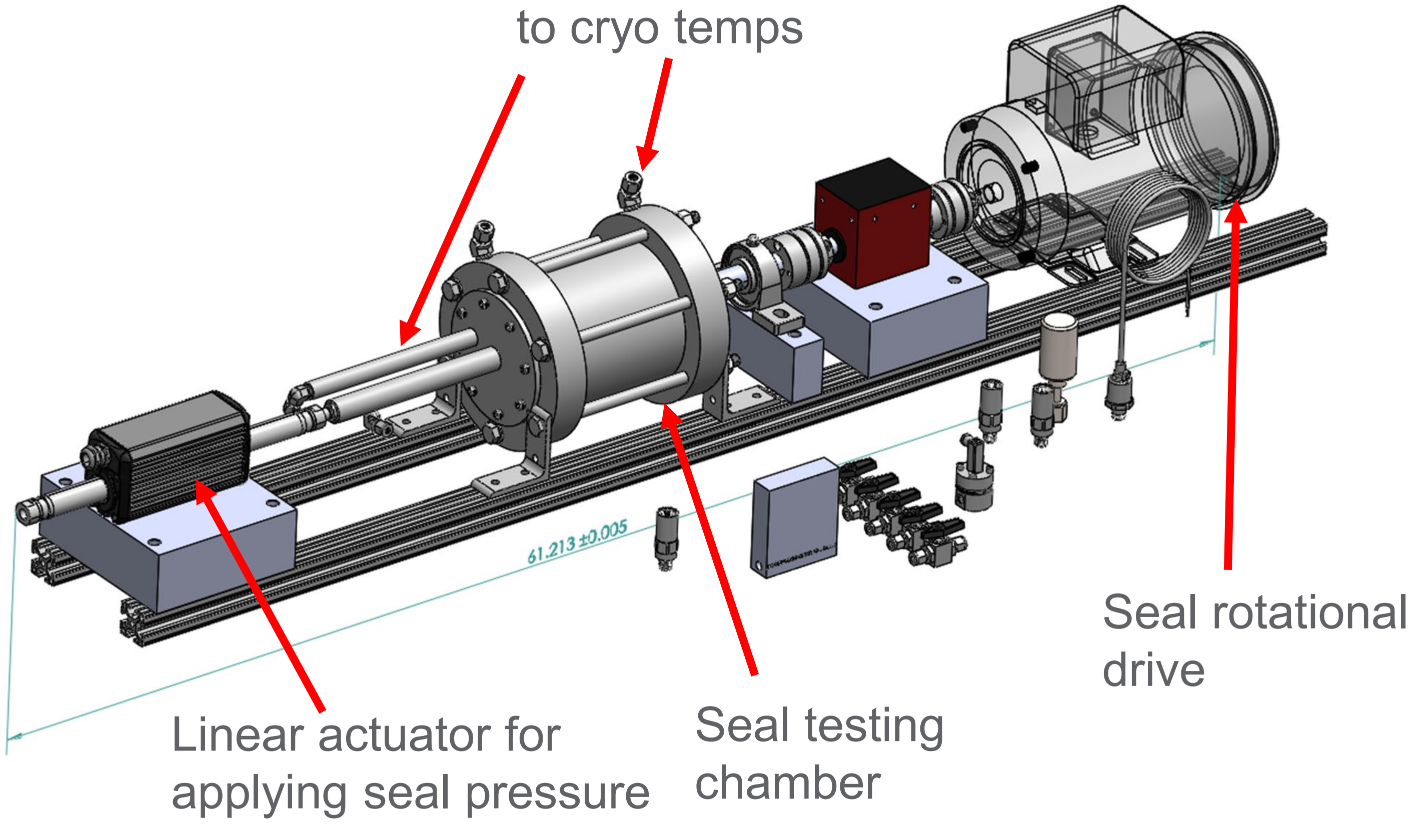
Design criteria:

- 2% leakage rate (20 cc/min).
- 10 N-m toque due to friction (3% of work input torque).
- Handle 1.75 m/s mating surface speed.
- Function at 100 K.
- Manage tolerance variations in surface flatness and varying coefficients of thermal expansion between components.
- Serviceability and longevity considerations.

Task 2.1: Seal testing system



P&ID for seal testing system

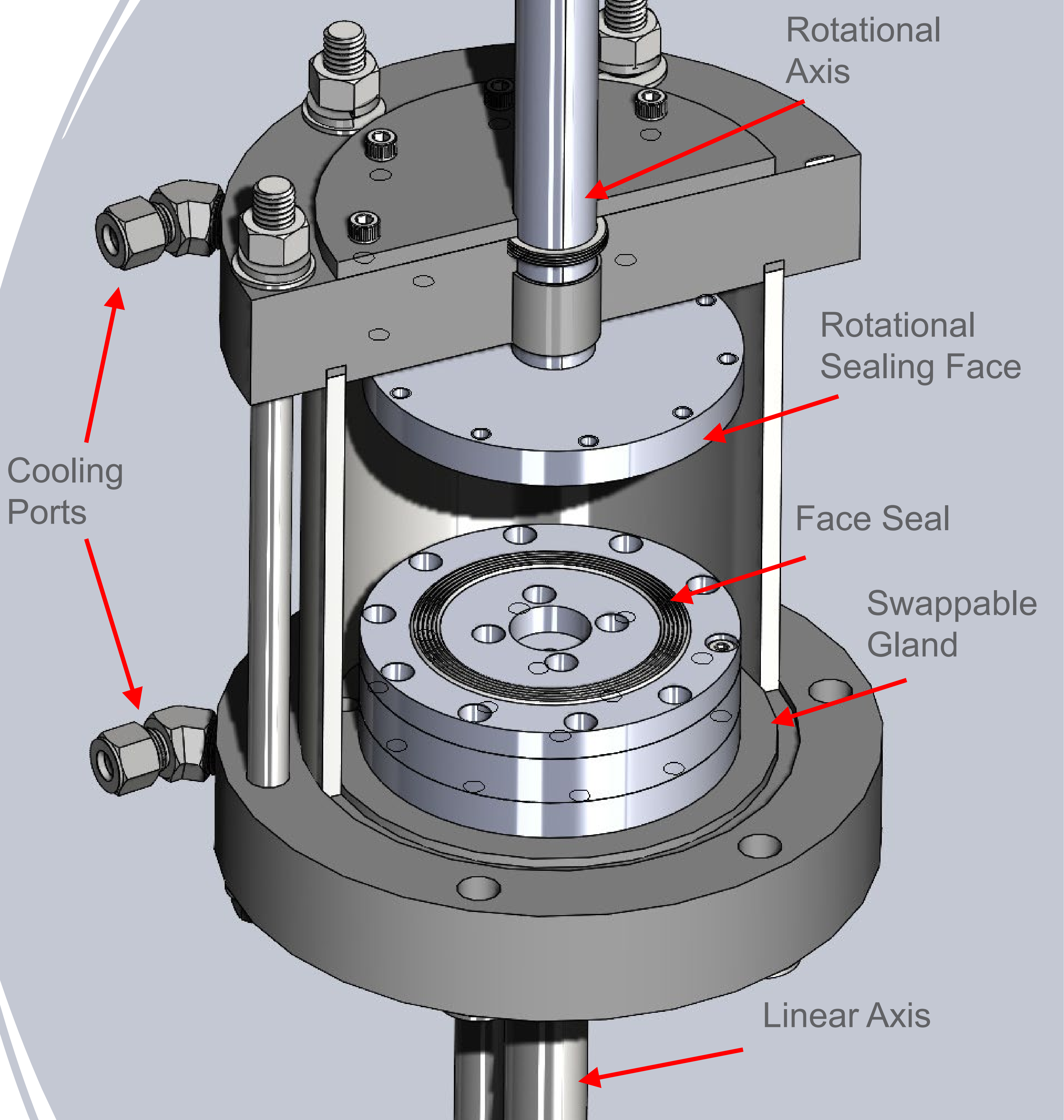


The seal tester is incorporated into a test system which consists of:

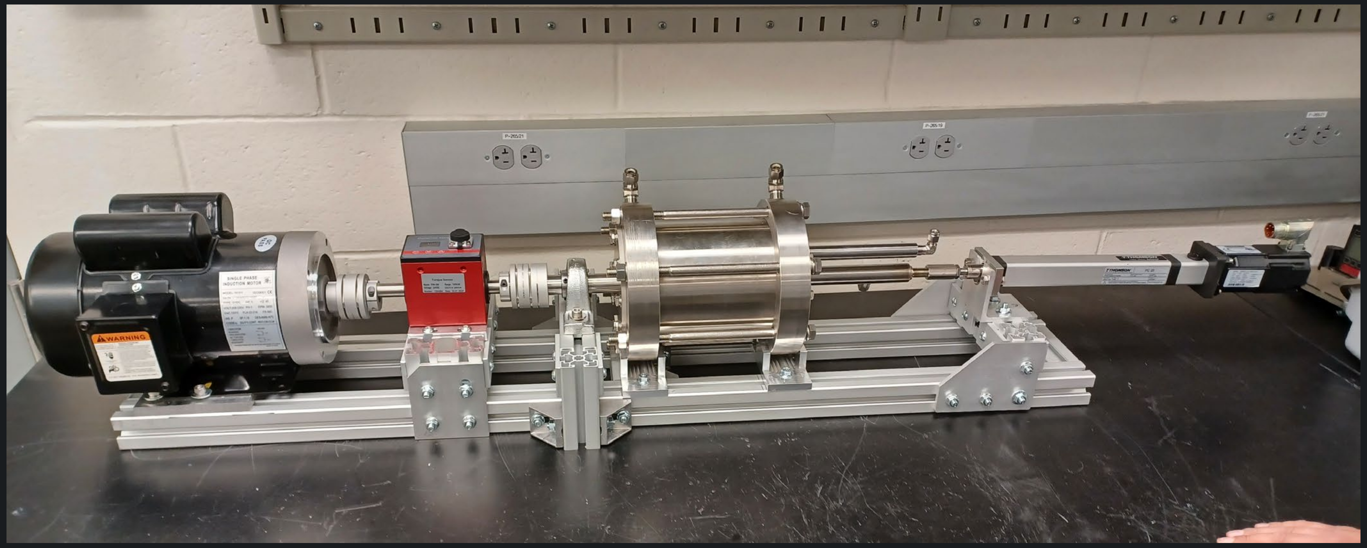
- Motor with speed adjustment.
- Torque and rpm meter.
- Linear actuator with force feedback.
- Leak measurement device.

Task 2.1: Small scale seal testing

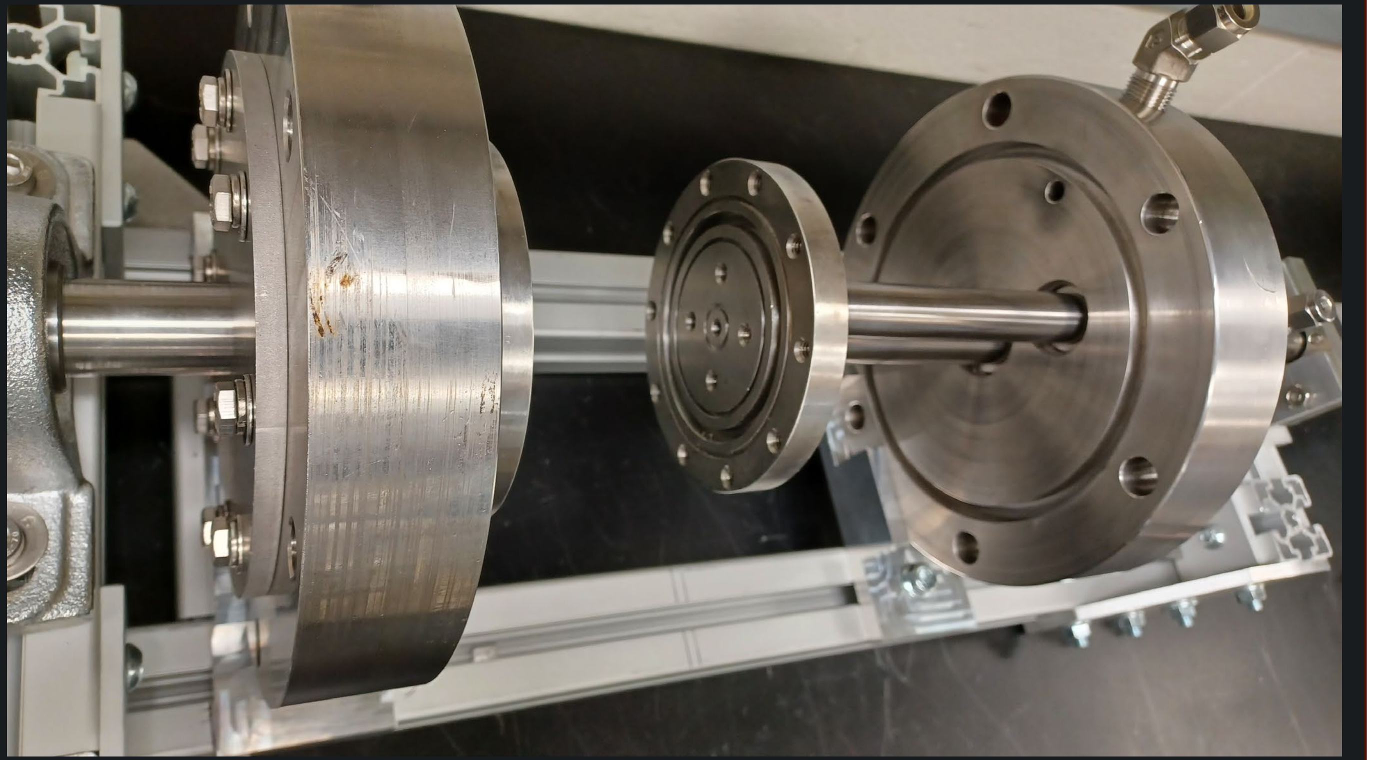
- A seal tester designed to test leak rate of different seal and gland configurations.
- The tester consists of a linear motion axis and a rotational axis. Face seal can be positioned at different clearances from the sealing face.
- Rotational speed controlled to evaluate the effect of different surface speeds on seal performance and longevity.
- Frictional losses estimated from torque measurements on the rotational axis, and applied force is measured on the linear axis.
- System can be cooled down to cryogenic temps to evaluate seal performance over a range of temperatures.
- The effects of the sealing face surface finish can be evaluated.



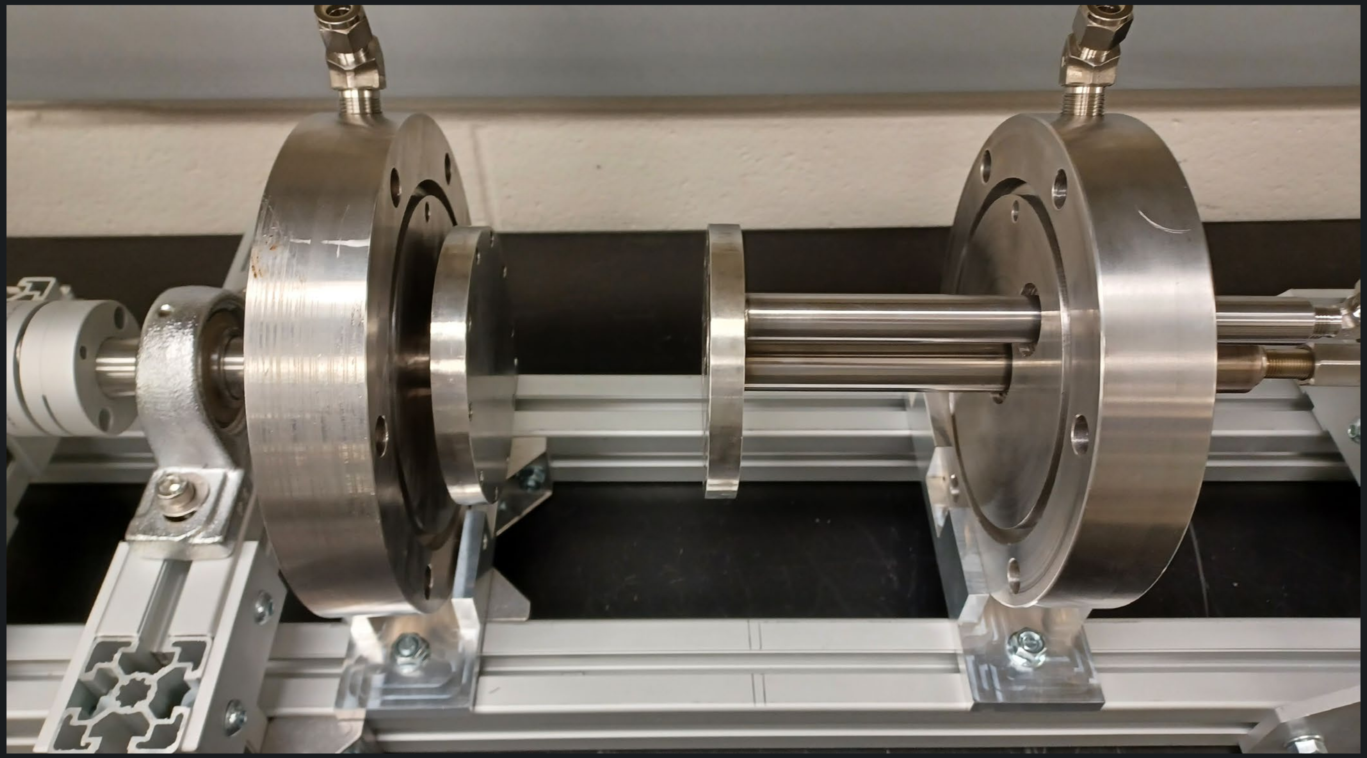
Task 2.1: Small scale seal testing data collection to start early May



←Full test system



Seal gland view

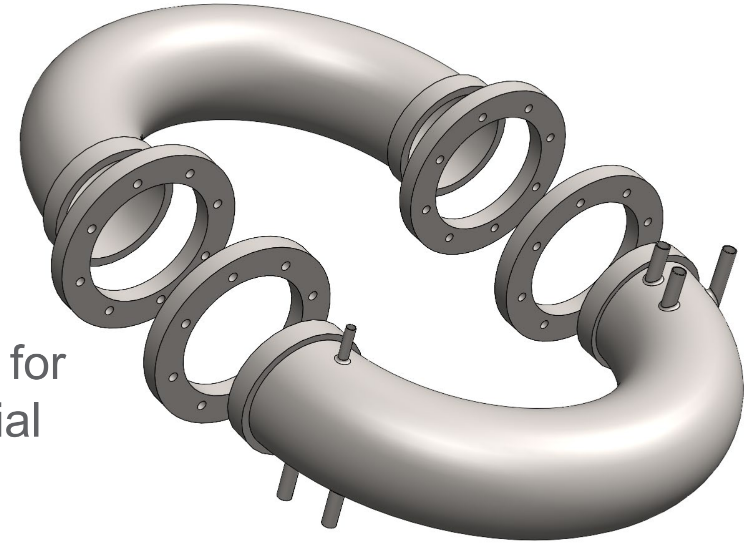


←Rotating surface view

Task 2.2: Pressure vessel

Design criteria:

- 100% hermetic.
- Withstands 210 psia w/ 2x factor of safety.
- Fits into partial tokamak magnet.
- Functional at 100 K.
- Integrates with seal and drive systems.
- Non-magnetic.



Preliminary concept for integration with partial tokamak magnet

Pressure safety engineer feedback:

- ***Machined parts out of solid plate are approved as material properties are well understood.***
- Printed and cast parts are not acceptable at this scale as there is not a standardized method for validating structural properties.
- The vessel can be treated as two bent pipes, as such the minor diameter of *under 6 inches* can be used for sizing, thus no ASME stamp is required.
- If using a welded vessel a material strength knockback must be accounted for.
- Access hole sizing do not affect structural validation in terms of pressure vessel code.

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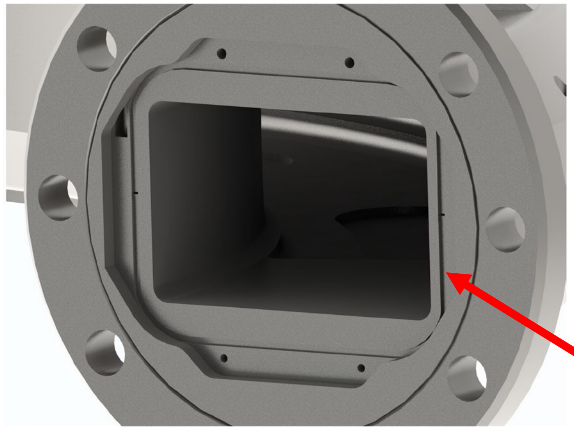
Task 2.2: 316 Stainless toroidal pressure vessel with multiple access points

- Slabs of stainless are CNC machined with internal drive and flow control structures.
- Confined indium seals for hermetic sealing at cryogenic temperatures.
- Novel blind indium seal at each main flange to seal corners of seal mating surfaces.
- Affordable and safety compliant methodology.

Four segment construction (one quarter of a sliced bagel)

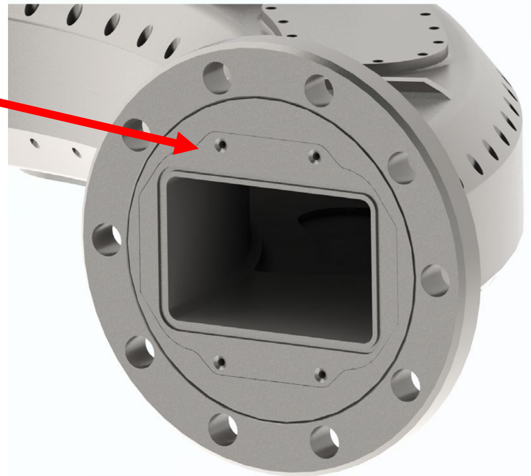
Access plates for seal installation and drive adjustments

Removable flanges for insertion into magnet



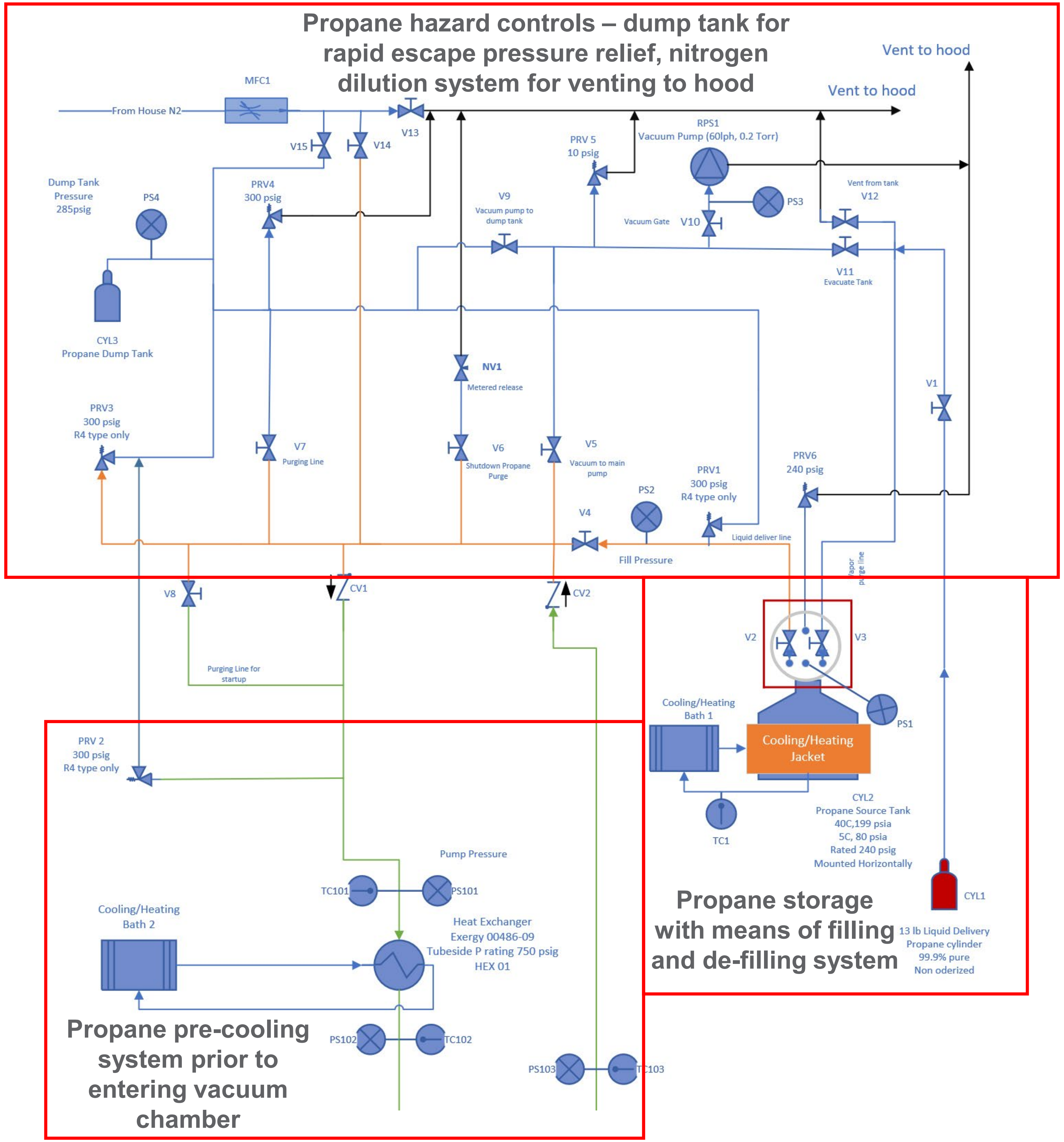
Blind confined indium seal

Blind seal cover with outer circular indium seal groove



Task 2.4: P&ID of system outside vacuum chamber

- Subsystem is focused on propane filling, containment, and dilution-venting to hood.
- Several PRVs, temperature, and pressure sensors.
- Fully automated controls and data collection.



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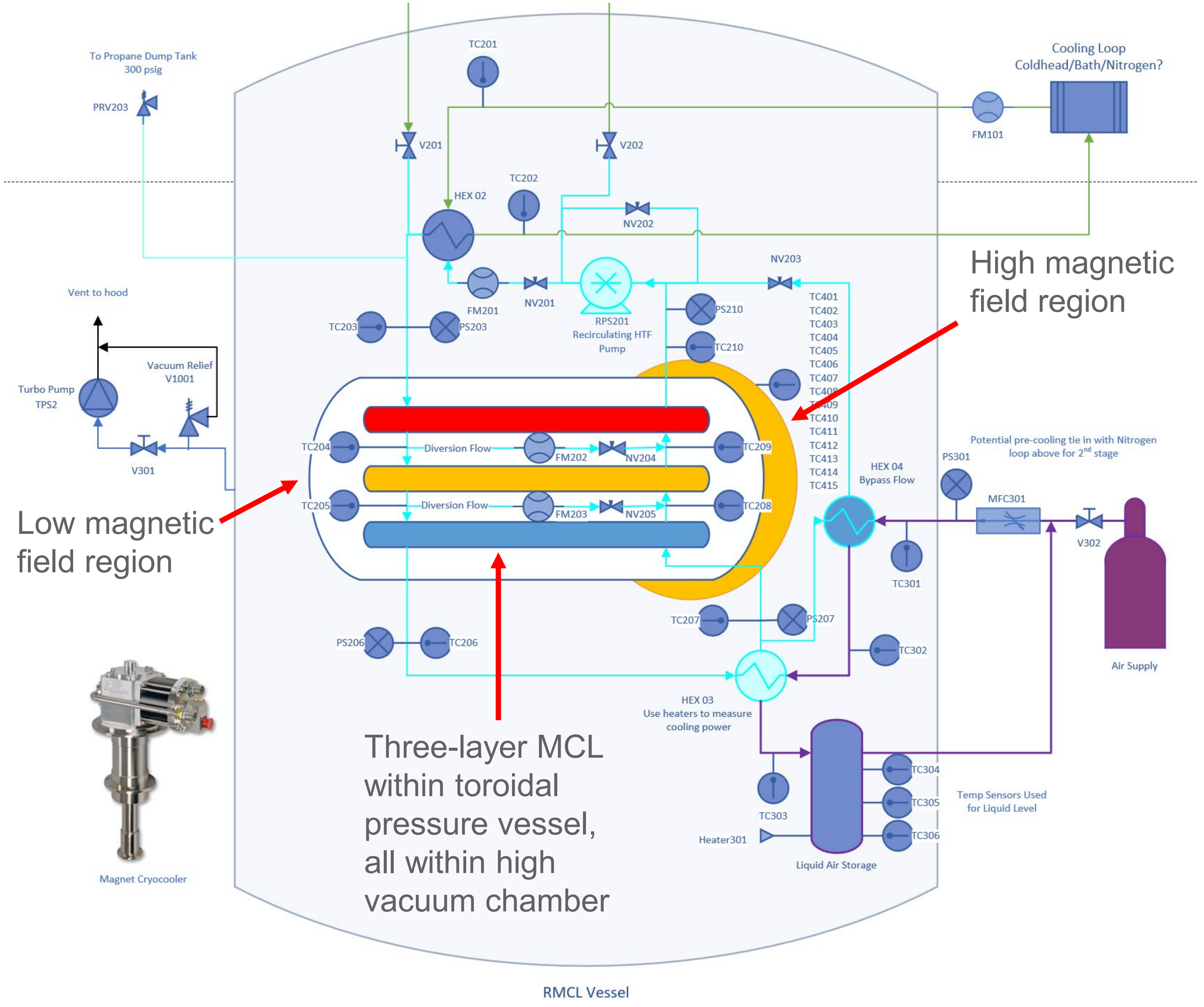
Task 2.4: P&ID of system inside vacuum chamber

- Subsystem is focused on performing and monitoring the liquefaction cycle.
- Several PRVs (vent to external subsystem), temperature and pressure sensors.
- Three primary HEXs:
  - HHEX
  - Main CHEX
  - Bypass CHEX (adds to system efficiency)

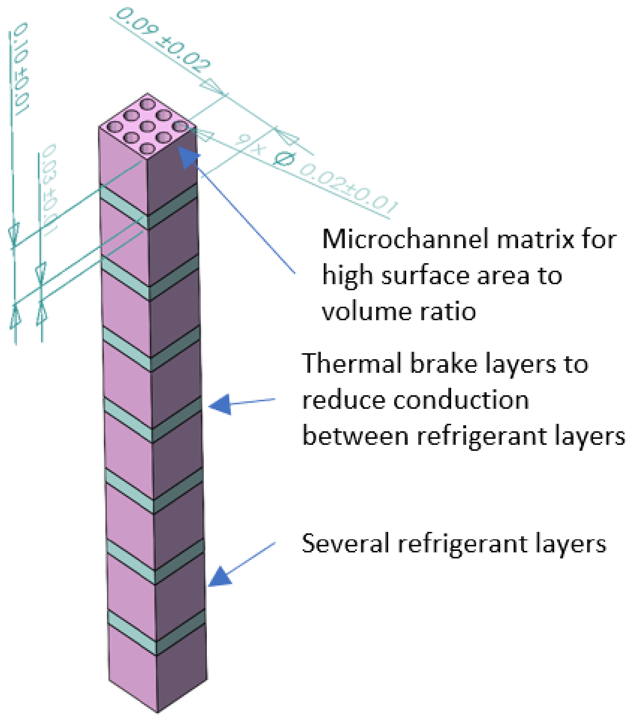


Magnet Cryocooler

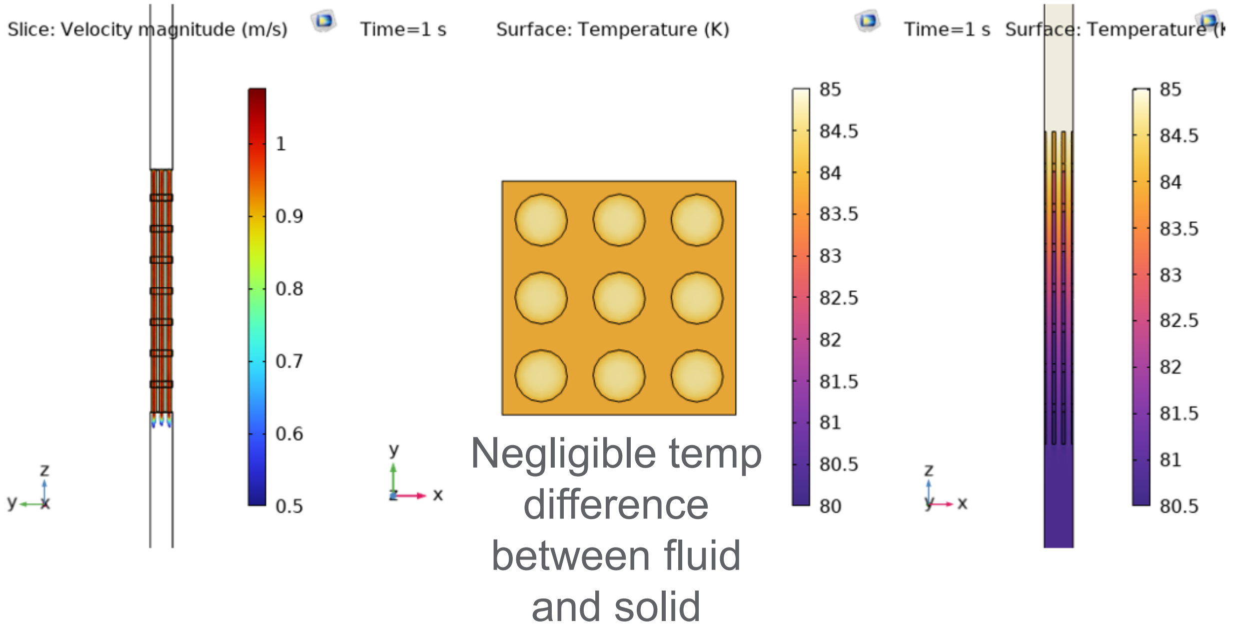
Task 3 & 4: High performance regenerators to achieve high efficiency MCL

	Packed Bed (200 µm, ϵ=0.38) w/ 400 psia Helium					Packed Bed (200 µm, ϵ=0.38) w/ 200 psia Propane					Microchannel (ϵ=0.38) w/ 200 psia Propane				
	Longitudinal Conduction	Eddie Diffusivity	Pressure Drop	Heat Transfer	Heat Leak	Longitudinal Conduction	Eddie Diffusivity	Pressure Drop	Heat Transfer	Heat Leak	Longitudinal Conduction	Eddie Diffusivity	Pressure Drop	Heat Transfer	Heat Leak
Layer 1	15.2%	12.4%	61.7%	6.1%	4.6%	53.6%	15.5%	0.2%	14.9%	15.8%	21.1%	13.3%	0.0%	38.3%	27.2%
Layer 2	4.0%	10.4%	76.7%	4.5%	4.4%	32.8%	19.4%	0.6%	20.4%	26.8%	19.6%	11.6%	0.1%	36.5%	32.2%
Layer 3	3.3%	12.3%	72.3%	6.5%	5.6%	26.7%	19.0%	0.8%	25.3%	28.2%	15.0%	10.7%	0.2%	42.6%	31.6%
Layer 4	14.1%	21.7%	26.8%	11.9%	25.5%	33.0%	22.8%	0.3%	14.1%	29.9%	20.9%	14.4%	0.1%	26.7%	38.0%
Layer 5	7.7%	24.7%	22.4%	19.5%	25.7%	16.8%	33.9%	0.7%	22.5%	26.1%	9.9%	19.9%	0.1%	39.5%	30.6%
Average	**8.9%**	**16.3%**	**52.0%**	**9.7%**	**13.2%**	**32.6%**	**22.1%**	**0.5%**	**19.4%**	**25.4%**	**17.3%**	**14.0%**	**0.1%**	**36.7%**	**31.9%**
Total Parasitics [W]	**253.5**					**80.4**					**62.7**				

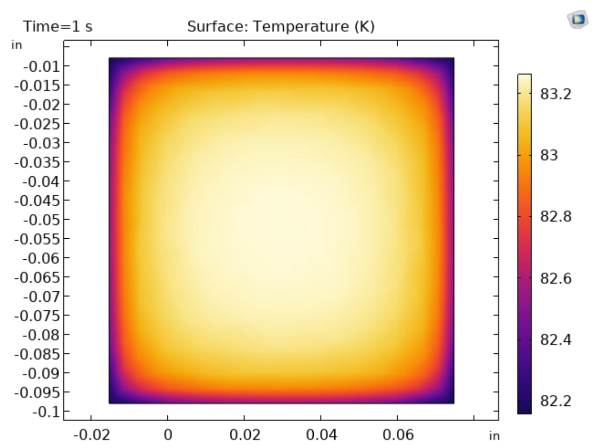
Bed Type	**Surface Area to Volume Ratio [m^2/m^3]**
Packed Bed	18600
Microchannel	4222



3D COMSOL simulations of microchannel and packed beds



Packed Bed

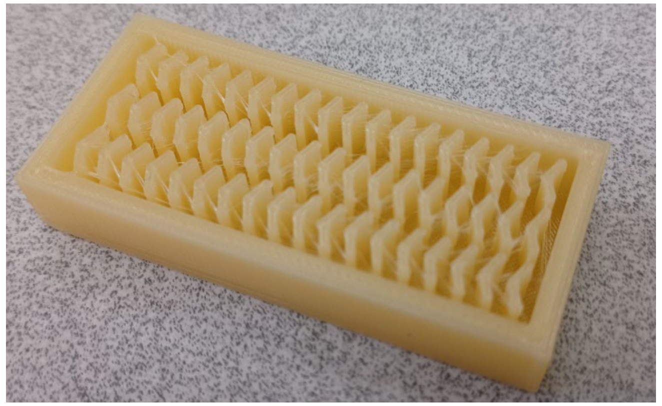


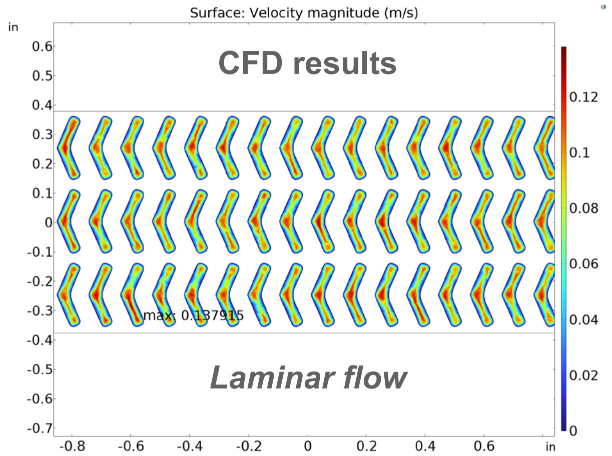
Task 4: Regenerator fabrication

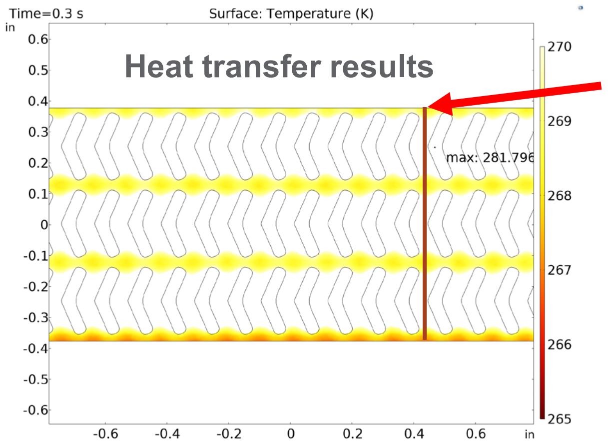
Regenerators will be formed of refrigerant layers with a thermal break between each layer (to reduce longitudinal conduction by 50-70%):

- Each layer will be formed by filling a mold with a mixture of epoxy and the magnetic material. The epoxy is thermal conductive, low viscosity, and has a long setup time. The microchannels for the propane will be formed by the mold.
    - The initial epoxy to be tested will be EP29LPSPAO-1 Black from Masterbond.
- Due to the number and size of channels, removing the part from the mold would most likely prove difficult. Therefore, the mold will be 3D printed from a water-soluble polymer PVA. The mold will simply be dissolved after the epoxy sets.
- The mold design is still in development.
    - Channel size and proximity – optimizing fill, heat transfer, and fabricability

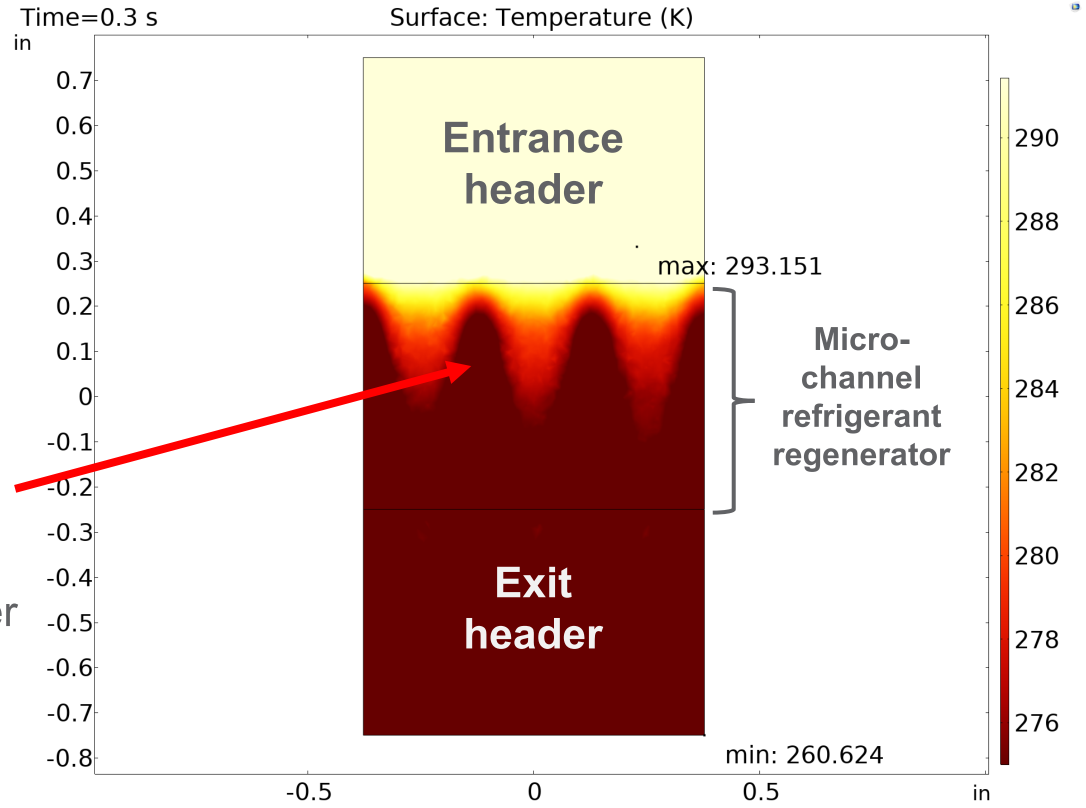
Initial 3D printed test mold







Channel spacing effects on heat transfer



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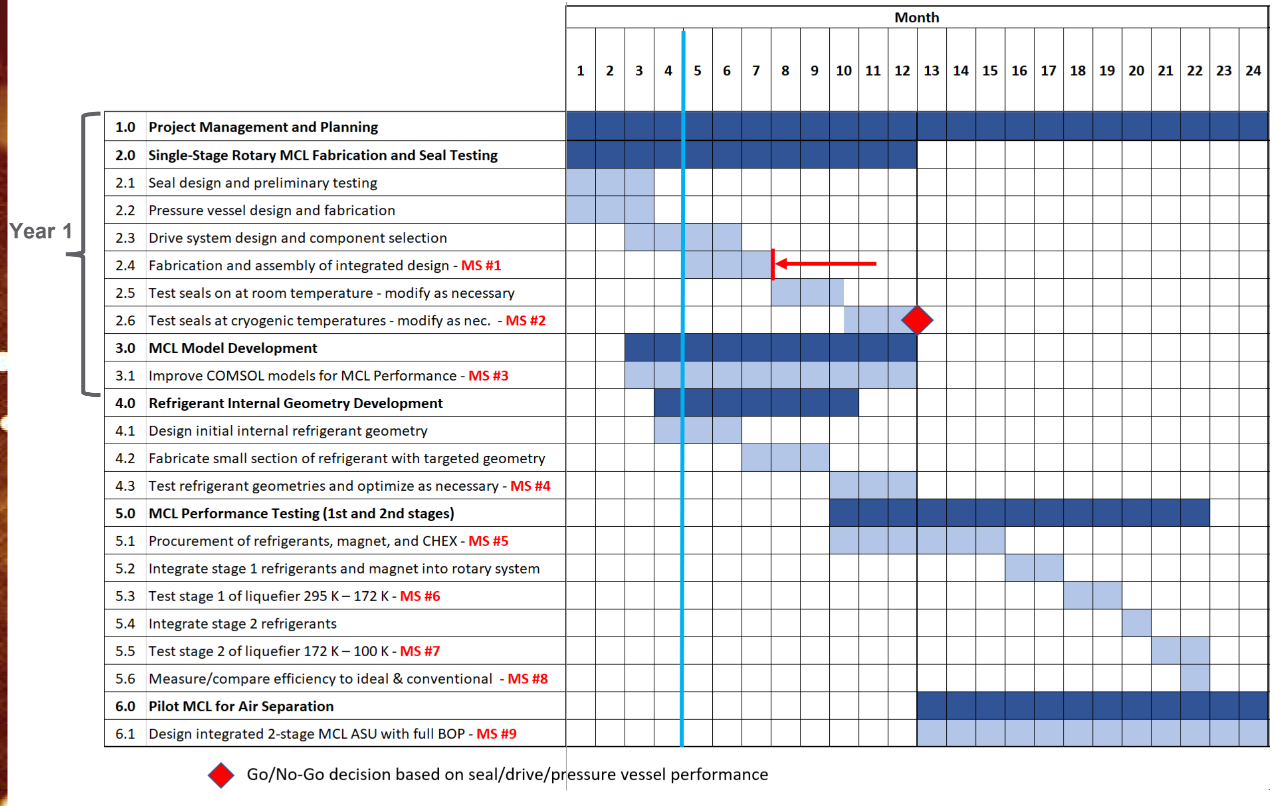
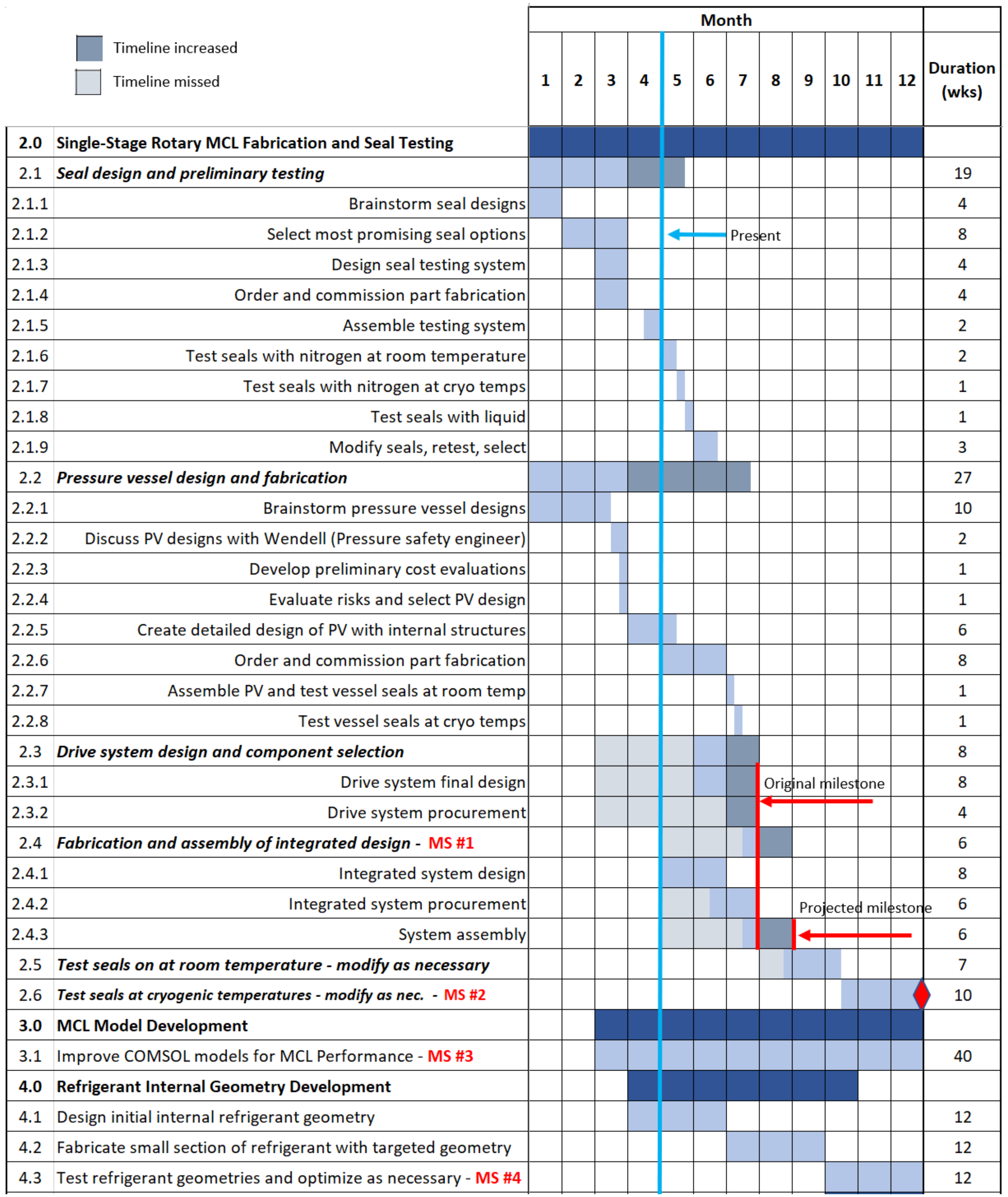
Schedule for de-risking and demonstrating each stage of the two-stage rotary MCL (RMCL) air liquefier

Original scope and schedule from SOW



Modified and discretized scope and schedule



Primary tasks for Milestone 1: 4 weeks behind

Good progress, procurement held

Padded schedule

Well ahead

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Thank you