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Ultra-Cryopump for High-Demand Transportation Fueling

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DOE Hydrogen Program

2024 Annual Merit Review and Peer Evaluation Meeting

AMR Project ID# IN019

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Project Goal

Develop a cost effective, reliable, high flow, high pressure reciprocating liquid hydrogen compressor system to support higher-throughput truck and bus refueling (DE-FOA-0002044, AOI3)

- Extend existing Air Products hydrogen pump technology to increase flow to >400 kg/hr at ≥950 bar discharge pressure
- Increase customer acceptance of hydrogen by matching the fueling experience to existing diesel fueling
  - Minimal/no cooldown prior to fueling, enabling "instant" on/off functionality
  - Fill times roughly equal to comparable diesel fill-up
  - Minimize physical footprint

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Overview

Timeline and Budget

- Project Start: 2/1/2020
- Project End: 9/30/2024
- Total Project Budget: $2,092,630
  - Total DOE Share: $1,675,000
  - Total Cost Share: $420,000
  - Total DOE Funds Spent*: $800,000
  - Total Cost Share Funds Spent*: $200,000

*As of 3/1/2024

Barriers and Targets

- Barrier: Reliability and Costs of Liquid Hydrogen Pumping
- Targets:
  - ≥ 400kg/hr flow rate
  - ≥ 950 bar discharge pressure
  - < $450,000 uninstalled capital cost
  - Minimal/no cooldown period before fueling

Partners

- No external partners

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Potential Impact

- For hydrogen fueling to gain market acceptance as a fuel for heavy duty transportation (trucks and buses), several barriers must be overcome:
  - **Pump capacity:** the pump must be capable of meeting ≥ 400kg/hr at ≥950 bar discharge pressure. No commercial options currently exist.
  - **Vehicle throughput:** flow rates and pressures must enable sufficient vehicle throughputs. The goal is for a fill time approximately equal to diesel refueling.
  - **Cost:** <$450,000 Nth-unit capital cost. Air Products expects to achieve this goal, based on extrapolating costs for our existing pumps.
  - **Reliability:** >90% on-stream time. Air Products has achieved this in our existing hydrogen pumps. This experience has been applied to this design.
  - **Customer experience:** the refueling experience must be familiar to the user and similar to diesel refueling. The hydrogen pump must be instantly ready to refuel – no extended cool-down periods prior to dispensing hydrogen.

Approach

- **Technical approach:**
  - Build on Air Products' 20+ year experience with hydrogen pumps
    - 100+ systems in use up to 8000 psi
    - Development not done in isolation - benefits from numerous other design developments
  - Focus on improvement of piston ring and shaft packing seal technology:
    - Four materials tested recently, others ongoing
    - Two new piston ring designs tested
    - Other developments will continue long after project completion
  - Initial prototype testing on liquid nitrogen (this is standard industry practice)
    - Known scaling factors to convert performance of LIN → LHY
    - Less costly prototype (no hazardous area requirements, more readily available valves and instrumentation, LIN can be directly vented to atmosphere, etc.)
- **Milestones:**
  - **Mar 2024:** BP2 Go/No-Go decision (completed)
  - **June-July 2024:** Prototype assembly
  - **Aug-Sept 2024:** Prototype testing on LIN
  - **Sept 2024:** Completion of DOE-funded scope. Further AP-funded LHY testing to follow.

Approach: Safety Planning & Culture

- Submitted draft Hydrogen Safety Plan to DOE
  - Feedback noted the need for more design details (submitted prior to design finalization)
  - Now that design has been finalized, we will review and resubmit.
  - *Note* – hydrogen testing is not within DOE scope.
- Air Products follows internal safety and design procedures for reciprocating equipment in H2 service
  - Document was first issued in 2002 and updated in 2023; leverages knowledge from 40+ years of LH2 pump experience.
  - Incorporates lessons learned from incidents and near-misses.
- Engineering risks/step-outs captured in formal Technical Risk Statement
- Machinery safety review was conducted per company procedures
- HAZOP will be conducted per company procedures to review safety of entire test system

Air Products' Total Safety Philosophy:
"Nothing is more important than safety…not production, not sales, not profits."

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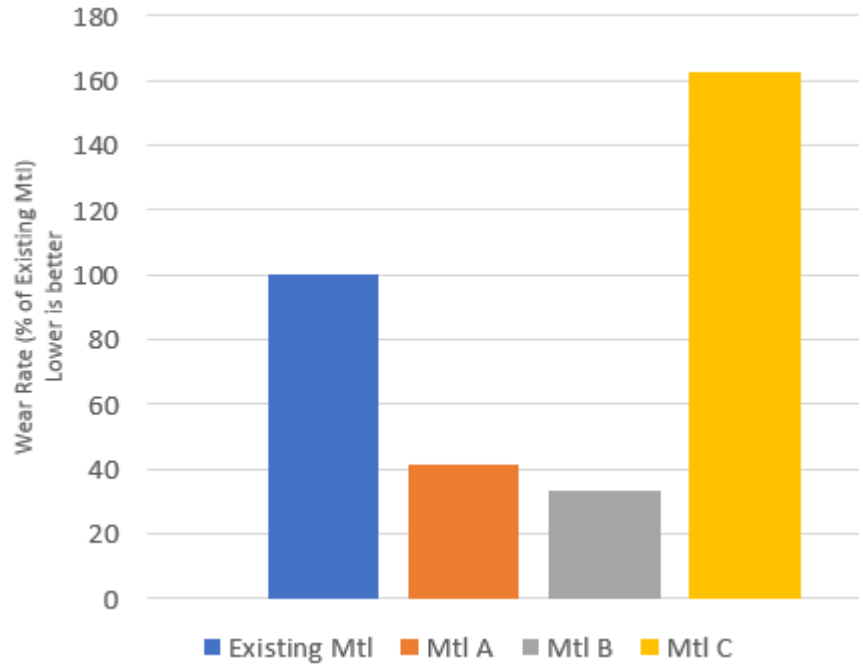
Accomplishments and Progress

- Budget Period 2 (design) deliverables completed:
  - Warm end components received; assembly in progress
  - Cold end design completed; parts fabrication in progress
    - Significant engineering work spent on reducing stress/fatigue in the piston and cylinder, and on maximizing seal performance and longevity
- Budget Period 3 (build & test) deliverables in progress:
  - Test skid weldment design completed; fabrication in progress
  - Test site preparations in progress:
    - Construction of concrete test pad
    - Extension of electrical feeds to test area
    - Preparation of power and control panels (existing equipment)
    - Installation of vaporizer
- Additional engineering resources have been added to accelerate progress and reach the final testing milestone

Accomplishments and Progress

- **Material testing:**
  - 4 materials tested at 7000 psig, LH2
  - Material A and B fared well compared to existing material
  - Material C fared poorly
  - Further testing required
- **1 Piston ring design tested:**
  - Pressure balanced
  - Initial test improved longevity by >200%
  - Second set of testing inconclusive
- **1 Piston ring design undergoing testing:**
  - Planned test examination in April 2024



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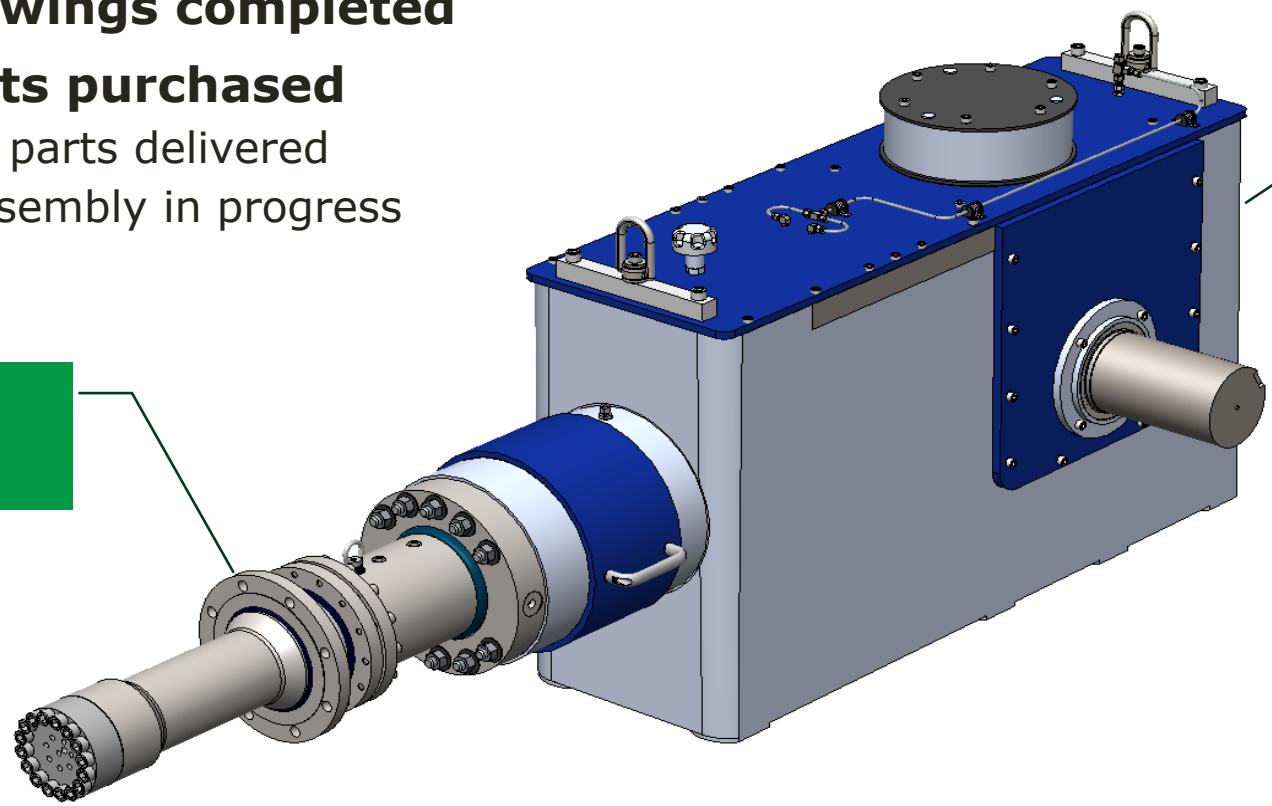
Accomplishments and Progress

- **Cold end drawings completed**
  - Component fabrication in progress
- **Warm end drawings completed**
- **Warm end parts purchased**
  - All warm end parts delivered
  - Warm end assembly in progress



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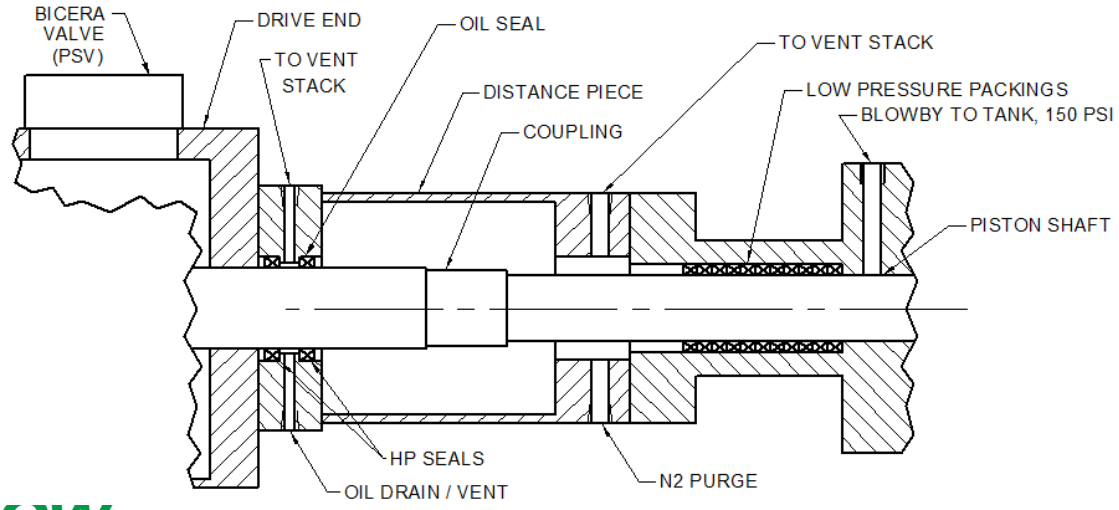
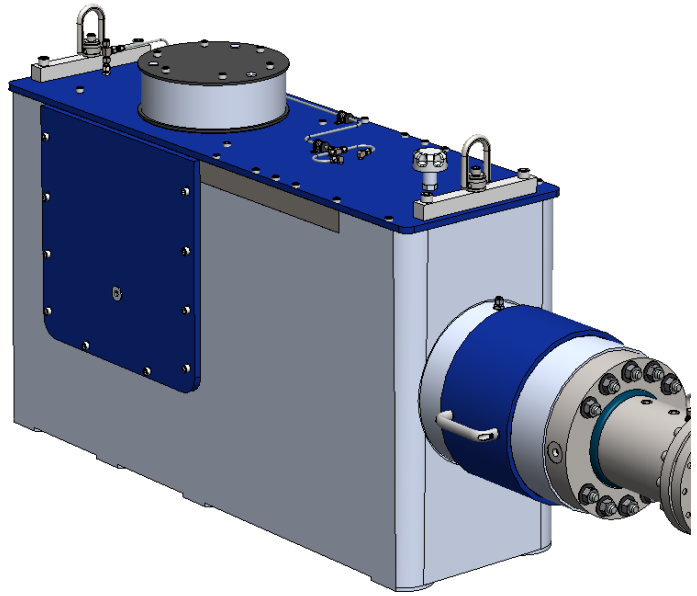
Accomplishments and Progress

AP is demonstrating leadership in safety by complying with new industry requirements

- **Distance piece design exceeds CGA P-96 (2023)**
  - Only low pressure (~120 psi) seals can leak to distance piece
  - N2 purge sweeps gas to vent stack
  - Distance piece rated for pressure due to deflagration of stoichiometric mix *(exceeds req)*
  - Secondary vent prior to crankcase *(exceeds req)*
  - BICERA valve with flame suppression
  - Crankcase with BICERA rated for pressure due to deflagration of stoichiometric mix *(exceeds req)*
  - *Cryogenic compatible materials*





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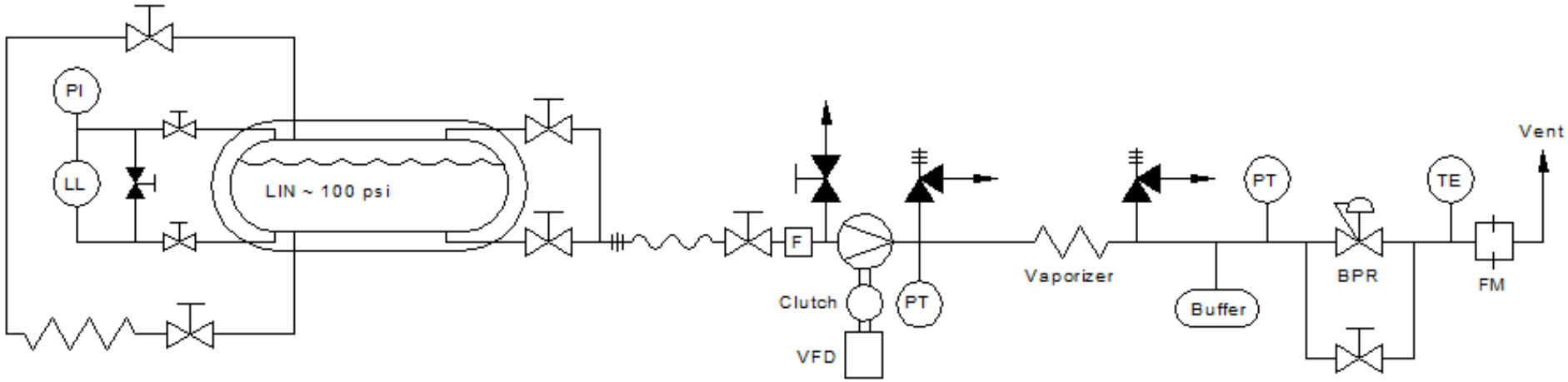
Accomplishments and Progress

- **Test pad**
  - Location finalized
  - LIN tank identified
  - Electric motor (VFD) obtained
  - Control panel & power panel obtained (need modifications)
  - Buffer vessel obtained
  - Vaporizer obtained
  - Some additional long lead items on order



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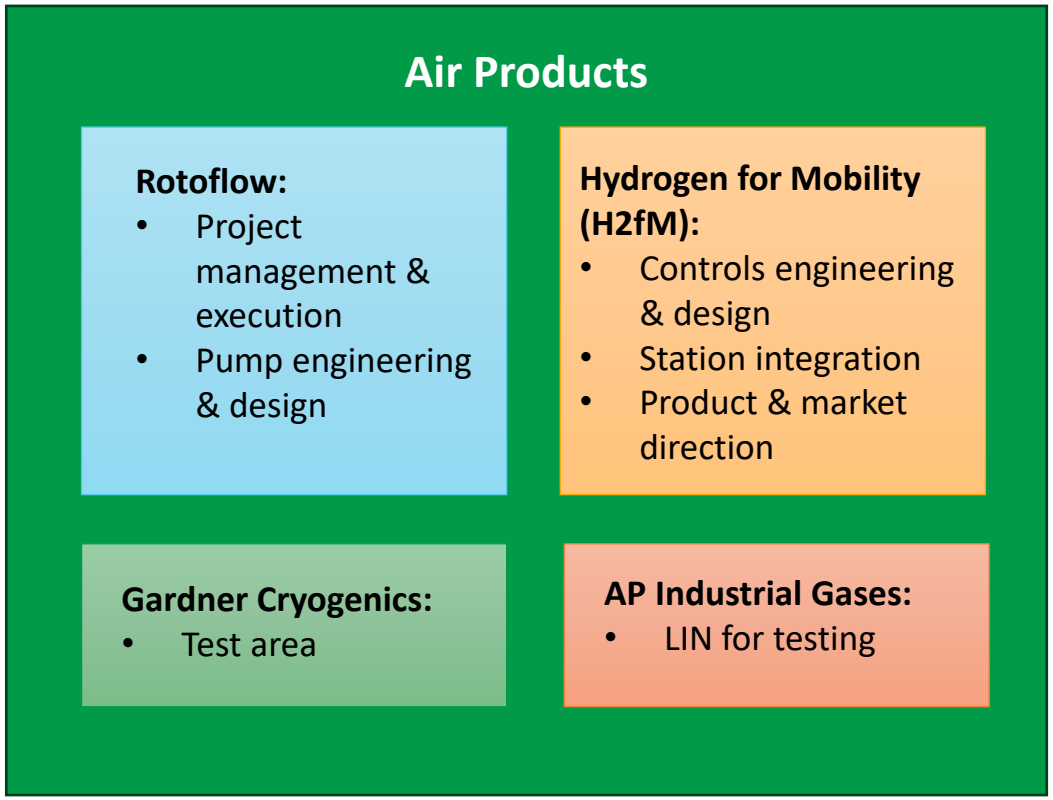
Accomplishments & Progress: Responses to FY23 Reviewers' Comments

FY23 Comment	Response
[The presentation] "does not provide enough detail for us to know that research is being done or that technology is being advanced." "The accomplishments…are not specific enough to be considered measurable achievements."	We agree that sufficient detail is necessary to show significant progress and development. Now that the design and analyses have been finalized, we are able to show further details in this year's AMR.
"The project has no collaboration specified in the proposal […] not collaborating at the minimum level necessary to be an effective participant in the DOE Hydrogen Program." "The project should engage with more partners for the technology development and upcoming testing."	Air Products has adhered to our Statement of Project Objectives (SOPO) as agreed and awarded by the DOE. Air Products has not claimed or proposed any external collaboration. We have extensive experience in the hydrogen space and believe we can further the project and DOE goals sufficiently while leveraging internal expertise. According to the Hydrogen Materials Consortium (H-Mat) website, the areas of research of that group are focused on the effects of hydrogen itself on materials, not wear rates. Therefore, collaboration was not pursued at the time of our seal development.
"The presenter verified that there is no plan for liquid hydrogen testing of this liquid hydrogen pump as part of this project. Hence, there is no way for the project to verify improvement and a return on the taxpayer investment."	Testing on hydrogen has always been outside the DOE-funded scope. Air Products is investing significant capital of our own to conduct hydrogen tests after completion of the DOE scope. While we agree that hydrogen testing is also important, testing on nitrogen is a logical first step which will more quickly and inexpensively verify functionality. It will indeed provide valuable, quantifiable data on the performance of this pump, and will absolutely be a verification of improvement and return on the taxpayer investment.
"The project should include the cost analysis to estimate the CAPEX against the project target."	Since the scope of this project is to develop a prototype for LIN testing, the resulting prototype is not directly comparable to the eventual commercialized product. However, based on our experience, the $450,000 capital cost is achievable.

Collaboration and Coordination

- **Rotoflow** is the primary Air Products business executing this project
  - Technical ownership of pump design
  - Execution and project management
- **Hydrogen for Mobility (H2fM)** supports with business direction and station integration expertise.
- External collaborations were not included in the agreed scope of this project



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Remaining Challenges & Barriers

- **Seal (piston rings & shaft packings) longevity / performance**
  - Update: Materials & designs tested in similar CHC machines
  - Future: Ongoing program to upgrade materials & design
- **Internal pump stresses**
  - Higher pressure requires design and material changes to pump
  - Update: Designs and Safety Reviews complete, fatigue analysis ongoing
- **Gasket leakage**
  - Current sealing technologies may need to be evaluated for higher pressures
  - Update: High pressure gasket testing validated design decisions
- **ON/OFF control**:
  - Direct fill from pump with minimal buffer requires new technology
  - Update: VFD and friction disc clutch on order for testing

Budget Period 2 activities focused on addressing these challenges

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Remaining Challenges and Barriers

- Meeting FOA criteria: 400 kg/hr, 200 kW
  - 200 kW / (400 kg/hr) = 0.5 kWh/kg
  - Air Products goal up to 600 kg/hr @ 0.5 kWh/kg
- Minimum efficiency required shown in chart
- Efficiency affected by
  - Piston ring & shaft friction and leakage
  - Various leakage that affects vapor fraction
  - Various heating that affects vapor fraction
  - Drivetrain inefficiencies
- Rotoflow has proven efficiencies, expects to meet goal

$$\text{Power} = \frac{1}{\mu}(h_o - h_i)\,\dot{m}$$

Vapor Fraction	Effic
0.00	66.8%
0.05	67.8%
0.10	69.3%
0.20	72.2%

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Proposed Future Work

- Finish pump prototype assembly
- Finish test site preparations
- Installation at site, including HAZOP and safety review
- Prototype testing on LIN
- Evaluation of data and learnings
- Completion of DOE scope

Summary

Significant progress has been made since the 2023 AMR, and the team is accelerating toward completion in FY24.

Milestone	Status
Warm End design	**Complete**
Warm End component procurement	**Complete**
Cold End design	**Complete**
Cold End component procurement	In Progress
BP2 Go/No-Go decision	**Complete**
Test area site work	In Progress
Test Prototype Assembly/Installation	Summer 2024
Testing on LIN	Summer 2024
Project completion	September 2024

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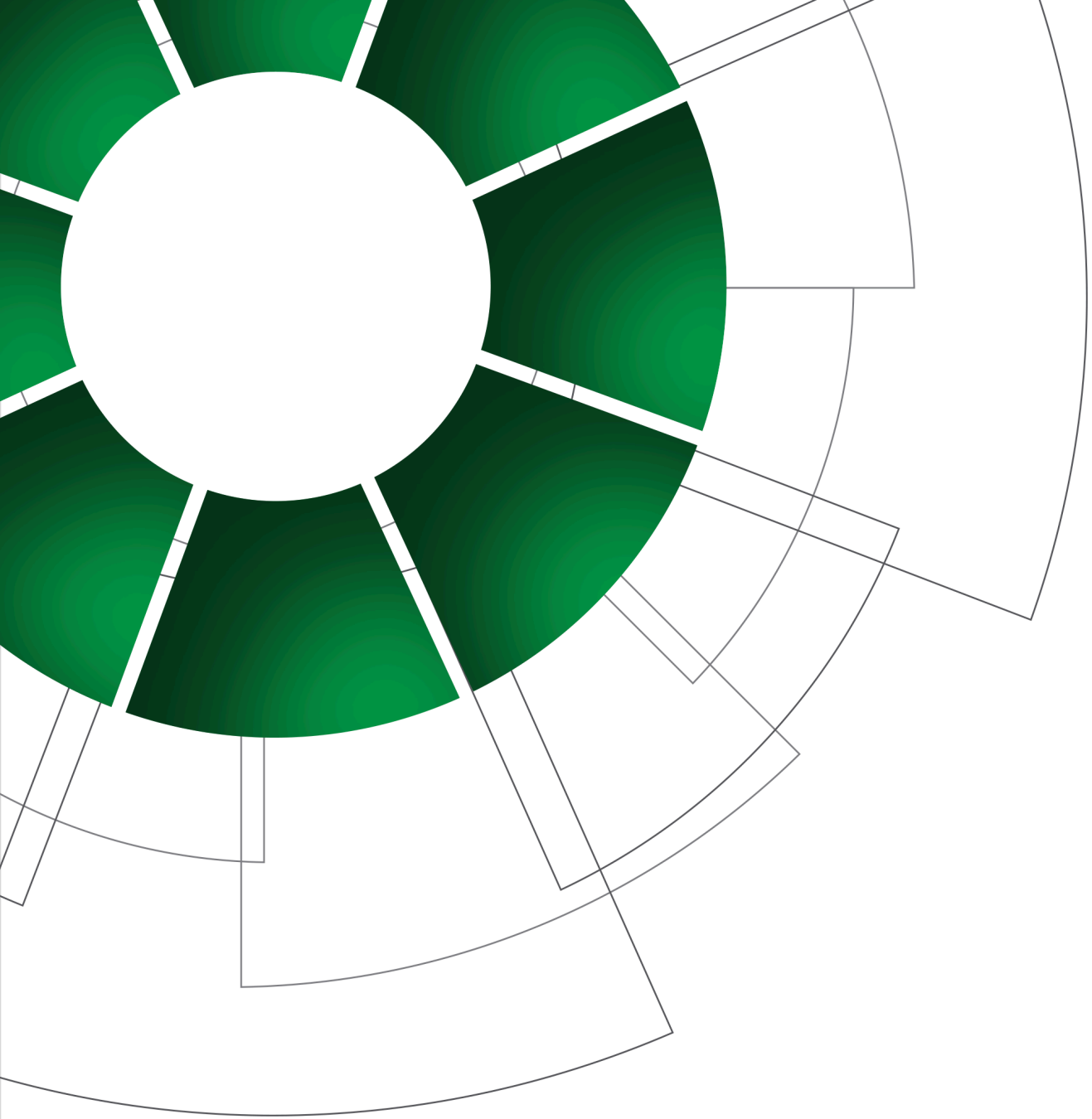

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