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Overview

Timeline
• Project Start Date: 06/01/2018
• Budget Period End Date: 05/31/2020
• Project End Date: 06/01/2021

Budget

<table>
<thead>
<tr>
<th>Year 1 Costs</th>
<th>Year 2 Costs</th>
<th>Year 3 Costs</th>
<th>Total Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE Funded</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>982K</td>
<td>455K</td>
<td>447K</td>
<td>1.88M</td>
</tr>
<tr>
<td>Cost Share</td>
<td></td>
<td></td>
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<tr>
<td>275K</td>
<td>148K</td>
<td>47K</td>
<td>470K</td>
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</table>

Barriers
• Utilization of low temperature waste heat (90°C to 150°C)
• Reduce system footprint
• Matching cooling demand with variable waste heat supply
• Compact low cost heat exchangers
• High efficiency turbomachinery operated over wide range of conditions

Partners
• CSU in Fort Collins, CO, leads project and is site of experimental validation
• Project partners include:
  • Barber Nichols Inc. – Specialty turbomachinery manufacturer in Arvada, CO
  • Modine Manufacturing Co. – Heat exchanger and commercial chiller manufacturer in Racine, WI

AMO MYPP Connection
• Smaller footprint (Target 12.1)
• Cost-effective, low-temperature heat recovery (Target 12.3)
Project Objectives

Challenges in Manufacturing Environments
- AMO Strategic Goal: Improve the productivity and energy efficiency of U.S. through utilization of waste heat
- MYPP Target 12.1: Develop system designs with smaller footprints
- MYPP Target 12.3: Develop innovative, cost-effective systems to recover heat from low-temperature (<230°C) waste heat sources

Validate Turbo-Compression Cooling Concept
- Problem: efficiently convert variable low grade heat (90°C to 150°C) to cooling in manufacturing operations with a small footprint
- Relevance: co-located cooling loads and waste heat are common in many industries (e.g., food, CHP), and significant reduction in manufacturing energy possible
- Challenge: competing absorption units are sensitive to heat load variability and suffer from large footprints and other difficulties
- Solution: develop advanced turbo-compression cooling system that combines high effectiveness compact heat exchangers with highly efficient turbomachinery
- Major risks addressed in this project: (1) high turbine and compressor efficiency (>80%), (2) limited system turndown, (3) high effectiveness HX with low pressure drop, (4) manufacturing system integration
Technical Innovation

Challenges with Current Solutions – Absorption Chillers

- Low refrigerant pressure require large heat exchangers
- Require steady heat input source, and chemical imbalances cause crystallization
- Corrosive fluids reduce lifespan, require expensive materials

Proposed Solution – Turbo-Compression Cooling

- Non-corrosive, moderate pressure refrigerant: smaller, low cost heat exchangers
- System designed to handle transient and variable heat inputs
- High efficiency turbomachinery and power transmission
- Suited for processes with abundant waste heat and co-located cooling loads
- Potentially much smaller footprint than competitive absorption

Integrated System Diagram

Efficient Turbomachinery and Power Transfer

>2.5× Cooling Density Possible without Harmful Refrigerants
Technical Approach

Develop *turbo-compression cooling system at industry standard conditions with high turndown and small footprint*

- Turbomachinery optimized for operating conditions yields high efficiency and turndown (BNI)
- Compact, aluminum brazed heat exchangers reduce system footprint and cost (Modine)
- Advanced cycle design and integration yields viable waste heat to cooling technology with significant market penetration potential (CSU)

**High Efficiency Turbomachinery**

**Compact Heat Exchangers**
## Technical Approach

<table>
<thead>
<tr>
<th>Risk</th>
<th>Challenge</th>
<th>Mitigation</th>
<th>Key Milestones</th>
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</thead>
<tbody>
<tr>
<td>Meeting Cost Target</td>
<td>HX Costs, Misc. Component Cost</td>
<td>Early discussions with Modine, compare with Turbochill product, possible initiation of mfg. estimate of heat exchangers by Modine</td>
<td>M1.1</td>
</tr>
<tr>
<td>Meeting COP Target</td>
<td>High Effectiveness HXs and High Efficiency TC</td>
<td>Early and often Design Reviews, two design concepts</td>
<td>M1.1-M1.4, D1 and D2</td>
</tr>
<tr>
<td>Operation at Various Loads</td>
<td>Compressor Stall at Low Turbine Powers</td>
<td>Early and Often Design Reviews, proprietary mitigation strategy</td>
<td>M1.1-M1.4, D1 and D2</td>
</tr>
<tr>
<td>HX Manufacturing</td>
<td>Large Devices</td>
<td>Only manufacture key components, utilize existing technologies as much as possible</td>
<td>M1.4</td>
</tr>
<tr>
<td>Market Uncertainty</td>
<td>Insufficient Waste Heat and Cooling Load, Recovery and Utilization Mismatch, Test Conditions Do Not Match Market Requirements</td>
<td>Early market analysis will narrow down top industrial prospects, evaluate design changes as needed, test over range of conditions</td>
<td>M7.1, M7.2, M6.2, M6.3</td>
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Results and Accomplishments

- **Go/No-Go Decision Point 2 complete, experimental testing ongoing**
- **Year 1**
  - Market Assessment
  - Finalize Design Points, Cost Assessment (M1.1 & M1.2)
  - Finalize Design Concept 1 (M1.3 & M1.4, D1)
- **Year 2**
  - Heat Exchanger and Turbomachinery Fabrication (M2.1 & M2.2)
  - System Fabrication (M2.3)
  - Experimental Testing to Validate COP (M3.1)
  - Modeling of Design Concept 2 (D2)
  - Secure IP (M7.3)
- **Year 3**
  - Finalize Design Concept 2 (M4.1)
  - Fabrication of HX, TC, and System (M5.1 – M5.3)
  - Experimental Testing to Validate COP (M6.1)
  - Experimental Testing to Validate Turndown Ratio and Varying Ambient (M6.2 & M6.3)
  - Secure IP (M7.4)
  - Final Economic and Commercial Validation (M7.5)
Results and Accomplishments

- Experimental data verified performance of waste heat boiler, power cycle condenser, and operated turbocompressor to design rotational speed

- Validated Design Concept 2 model with initial data to achieve Go/No-Go Decision Point 2 \((D2)\)

- Facility reconstruction ongoing to incorporate waste heat boilers and internally recuperative heat exchangers

- Provisional patent application filed
Transition

Project address key technoeconomic risks and understanding likely adoption pathway for low grade waste heat to cooling systems

- Follow-on funding from DOD to investigate viability of waste heat driven TCCS for shipboard cooling
- Commitment from potential commercial partner on ARPA-e SCALEUP STTR
- Exploring additional commercialization options, including with partner Modine

Proposed Turbo-compression Cooling System

300 kW electrical chiller fabricated by partner Modine
Questions?