Project ID: mat193

# Higher Temperature Heavy-Duty Piston Alloys *

*Task 2A2 under the Powertrain Materials Core Program (PMCP)


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2021 DOE Vehicle Technologies Office Annual Merit Review

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Bridge to the future for medium and heavy-duty vehicle propulsion

# VTO Powertrain Materials Core Program

## 3 National Labs, 30+ researchers, 4 Thrust Areas, 17 Tasks

**THRUST 1.** Lightweight Alloys (200 - 550°C)

**THRUST 2.** Cost-Effective, Higher Temperature Alloys (550 - 1000°C)

**THRUST 3.** Additive Manufacturing for Advanced Powertrains

TRL 1 — Accelerating Development of Powertrain Alloys — TRL 4

**Supported by Adv. Characterization & Computation**

**THRUST 4.**

- Atom Probe
- Synchrotron
- Microscopy
- Neutrons
- ICME
- Thermodynamics
- Modern Data Analytics
- High Performance Computing

$30M/5 years launched in FY19

Oak Ridge National Laboratory

Pacific Northwest National Laboratory

Argonne National Laboratory

# Task 2A2 Overview:

## Timeline/Budget

- Task start: October 2018
- Task end: September 2023
- Percent complete: 50%
- **2A2 Budget**
  - **FY20: $200k**
  - **FY21: $200K**

## Barriers

- Accelerating alloy development time.
- Improving balance of elevated temperature strength, thermal conductivity, oxidation resistance.
- Affordability and manufacturability.

## Thrust 2. Cost-Effective, Higher Temperature Alloys

***2A. Advanced Affordable Wrought Powertrain Alloys***
***2B. Affordable, High Performance Cast Powertrain Alloys***

| Task | Title | TRL | FY20 | FY21 |
|---|---|---|---|---|
| 2A1 | Oxidation Resistant Valve Alloys | Mid | $400k | $400k |
| **2A2** | **Higher Temperature Heavy-Duty Piston Alloys** | **Low** | **$200k** | **$200k** |
| 2A3 | High Temperature Coatings for Valve Alloys | Mid | $175k | $160k |
| 2A4 | High Temperature Oxidation | Low | $175k | $175k |
| 2B1 | Development of Cast, Higher Temperature Austenitic Alloys | Mid | $275k | $305k |
| 2B2 | Selective Material Processing to Improve Local Properties ***PNNL*** | Mid | $300k | $300k |
| | | **Subtotals** | $1,225k | $1,540k |

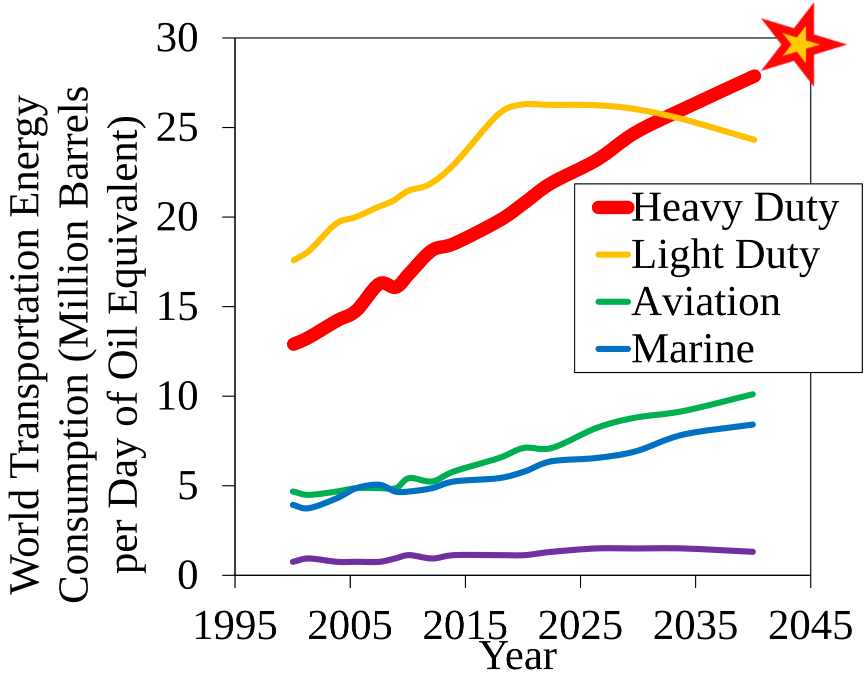
## Partners

- Program Lead Lab
  - Oak Ridge National Lab (ORNL)
- Partners
  - Thrust 4A: Advanced Characterization
    - Argonne National Lab (ANL)
      - Advanced Photon Source (APS)
- ARMY Ground Vehicles Systems Center (GVSC), informal

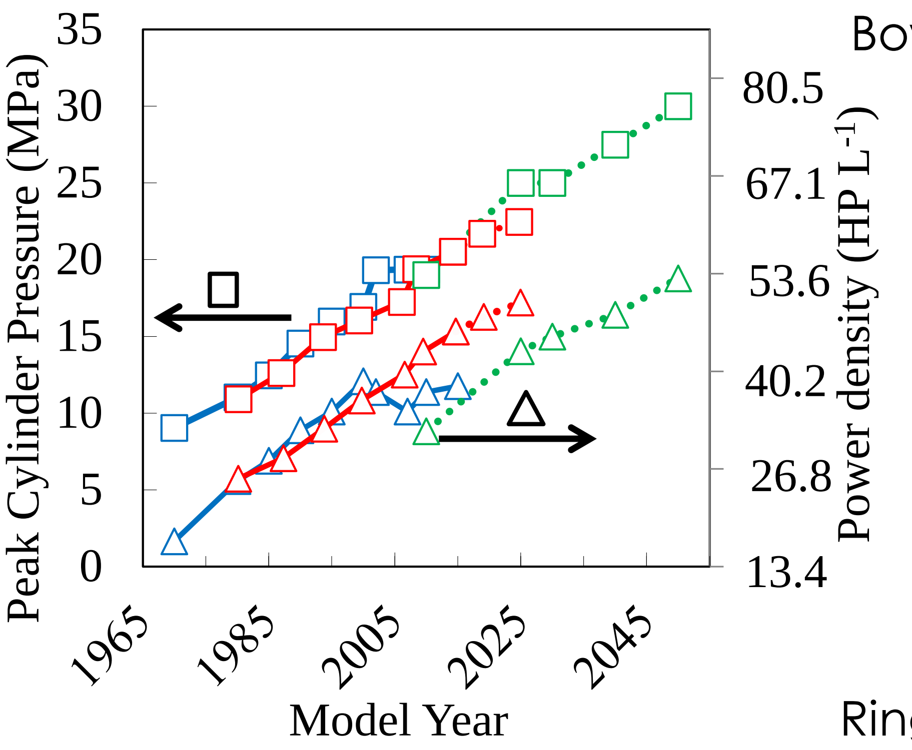
RELEVANCE

# Relevance

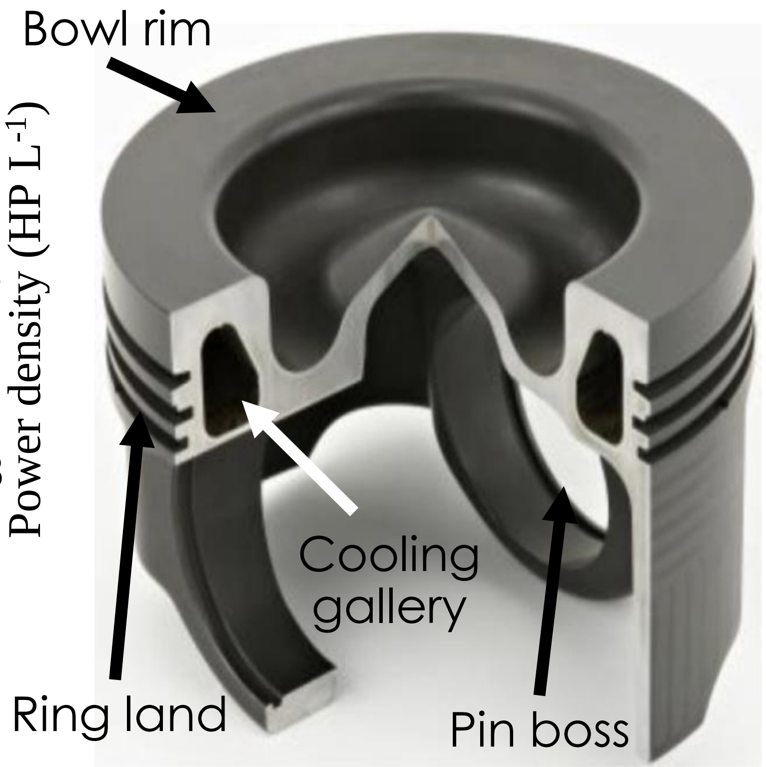
- Challenge to electrify heavy duty line haul freight due to battery power density
- Higher cylinder pressures and temperatures = higher efficiency.
- Current heavy duty diesel (HDD) piston steels (4140 & micro alloyed steel (MAS)) not suitable for temperatures ≥~500°C (low oxidation & fatigue resistance).
- Objective: develop affordable, innovative, higher temperature piston alloys




Exxon Mobil. 2018 outlook for energy: a view to 2040; 2017




Pierce et al., Prog. Mat. Sci. 103 (2019) p. 109.



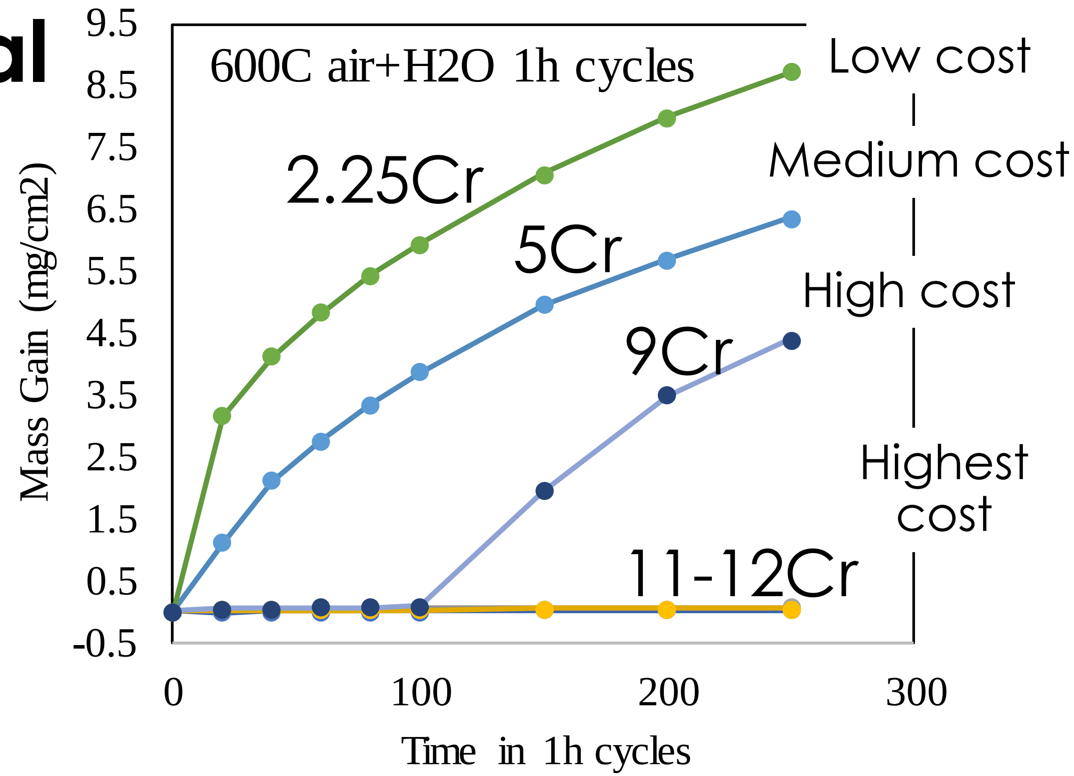
# Milestones for Task

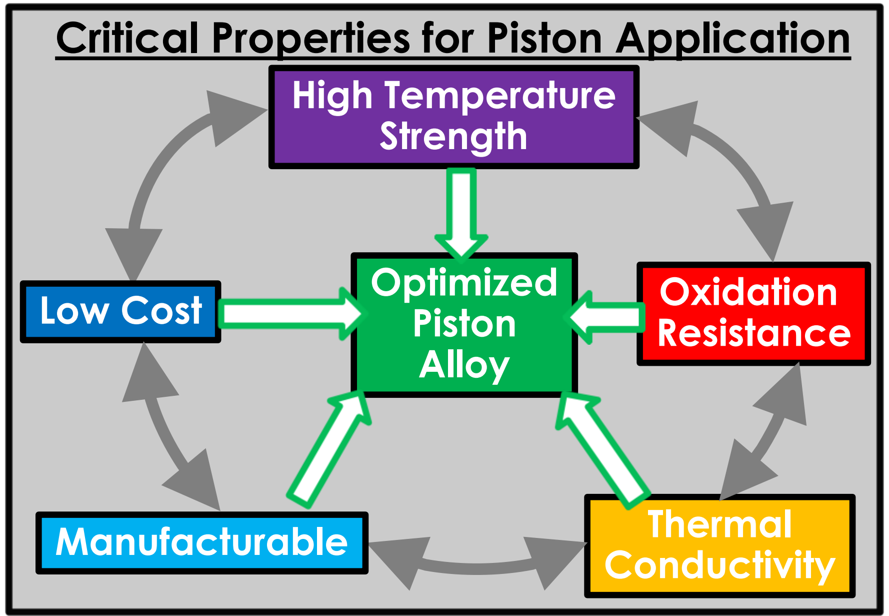
| 2021 | Task 2A2: Higher Temperature Heavy-Duty Piston Alloys |
|---|---|
| Q2 | Milestone: Longer term oxidation testing and mechanical testing of optimized low and medium Cr developmental alloys in the aged condition<br><br>Status: **COMPLETE**, longer term oxidation testing and mechanical testing of ages specimens complete. |
| Q4 | Milestone: : Establish industrial partnerships to commercialize new 600-650 °C capable piston materials<br>Status: **Continuing to explore potential industrial partnerships.** |

# Investigating Three Developmental Martensitic Steel Concepts

- Evaluate existing, higher-temperature commercial steels
  - Two 12Cr martensitic steels (12Cr-A and 12Cr-B)
    - High alloy content = Good performance but high cost
  - 4140 (1Cr-1Mn wt.%)

- **Low chromium (Cr) alloys (0-3 wt.%):** Lowest cost, high strength, 550-600°C.
- **Medium Cr alloys (3-8wt.% Cr):** Moderate cost, high strength, good oxidation resistance, 600-650°C
- **High Cr (8-15 wt.% Cr):** Highest cost and oxidation resistance,650-700°C.



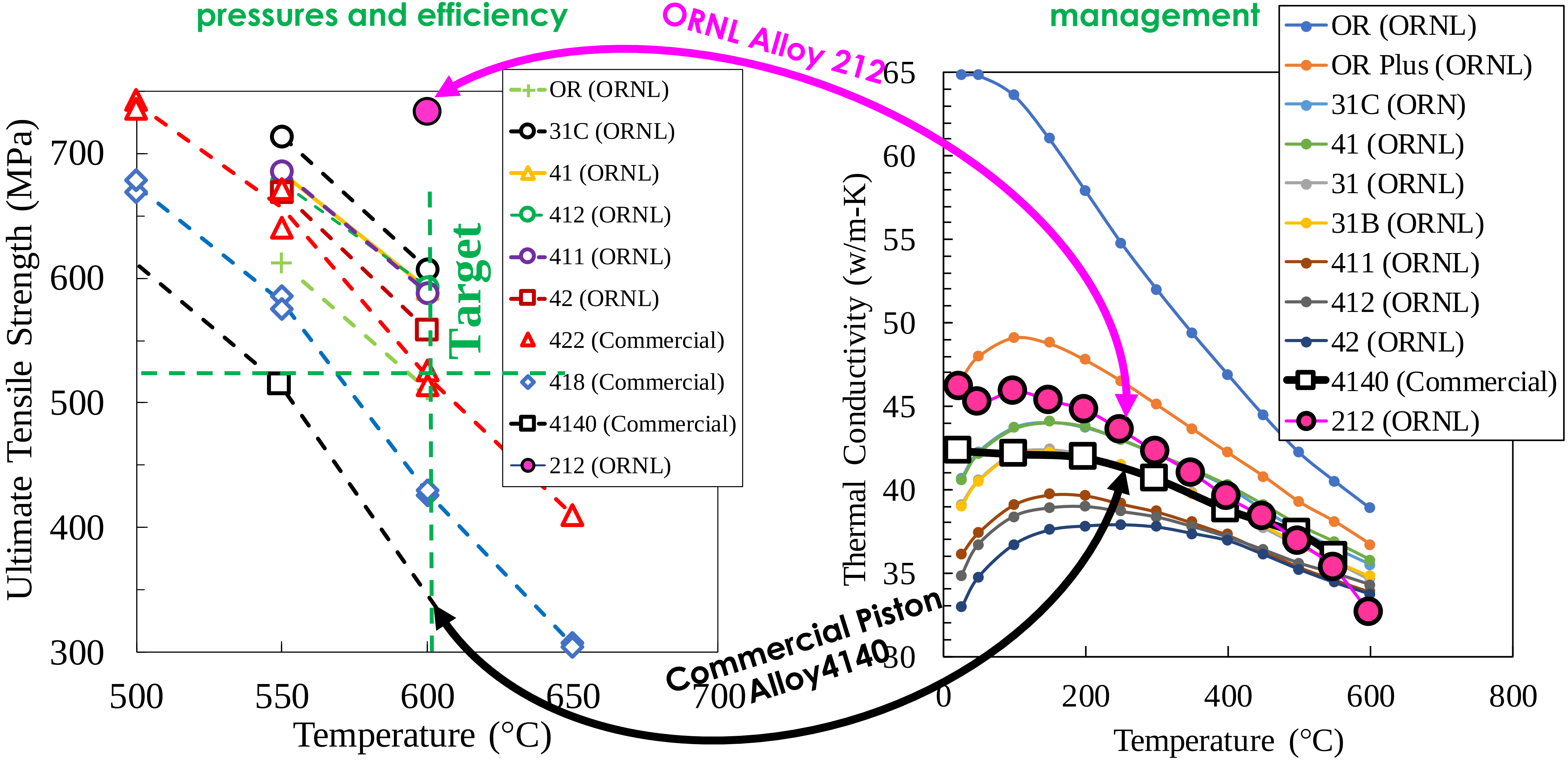


OAK RIDGE National Laboratory

# ORNL Low-Cr Developmental Alloys: 100% Increase in Strength at 600 °C and 10% Increase in Thermal Conductivity vs. alloy 4140

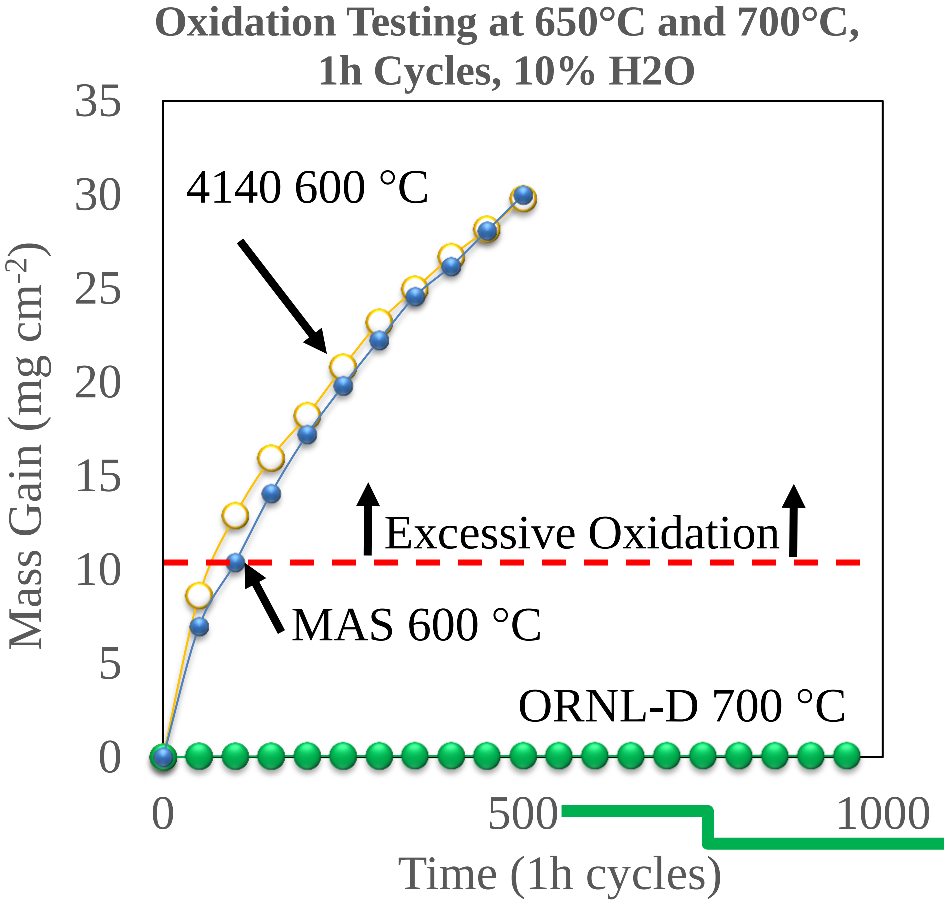
**Potentially enabling higher cylinder pressures and efficiency**

**Potential for improved thermal management**



# Low-Cost Medium Cr Alloys With Oxidation Resistance to 700 °C

- Commercial piston alloys 4140 and Micro alloyed steel (MAS) oxidation limited to 500 °C
- ORNL developmental alloys exhibit low oxidation mass gain and 200C increase in oxidation limit
- New alloys enable higher temperature, more efficient engine operation



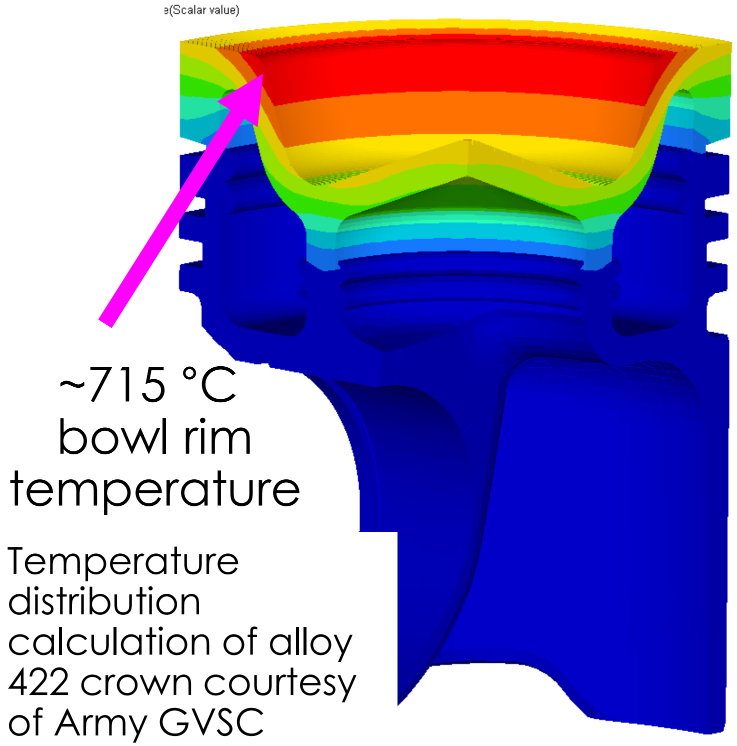

**ORNL Alloy**

**MAS Piston Alloy Oxidation Tested 500h at 600 °C, Excessive Oxide Spallation**

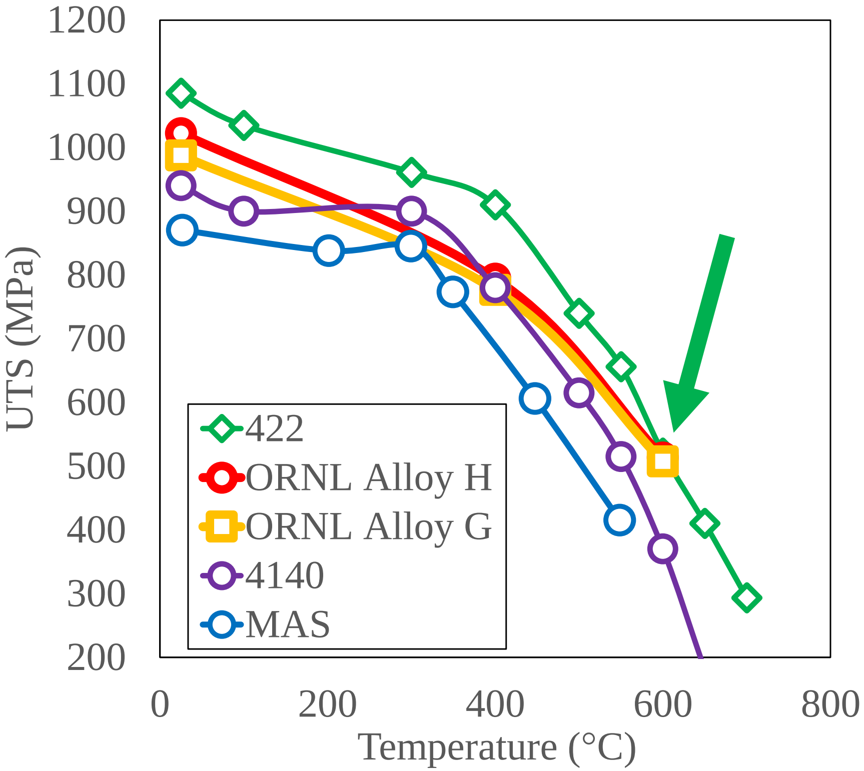
**ORNL Alloy-D Oxidation Tested 500h at 700 °C, Thin Adherent Oxide**

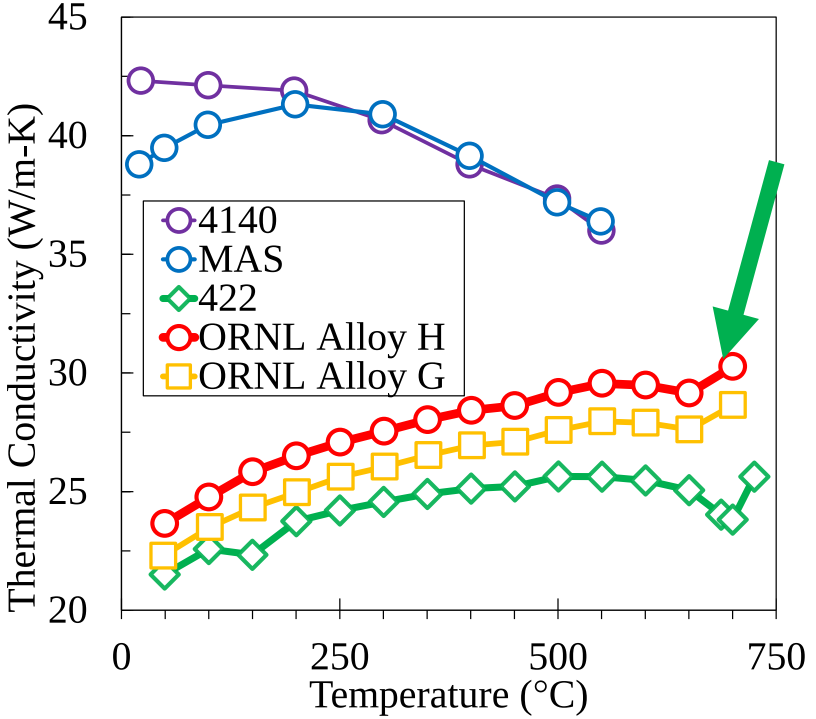
# Oak Ridge High Cr Alloys: Breakthrough in Overcoming Strength, Oxidation, and Thermal Conductivity Tradeoff

- ORNL alloys (ORNL-H and –G) show 10-15% increase in thermal conductivity with equivalent 600 °C strength relative to 422.
- Reduces peak temperatures and oil cooling loads (lower parasitic losses)
- High strength and oxidation resistance at bowl rim needed.



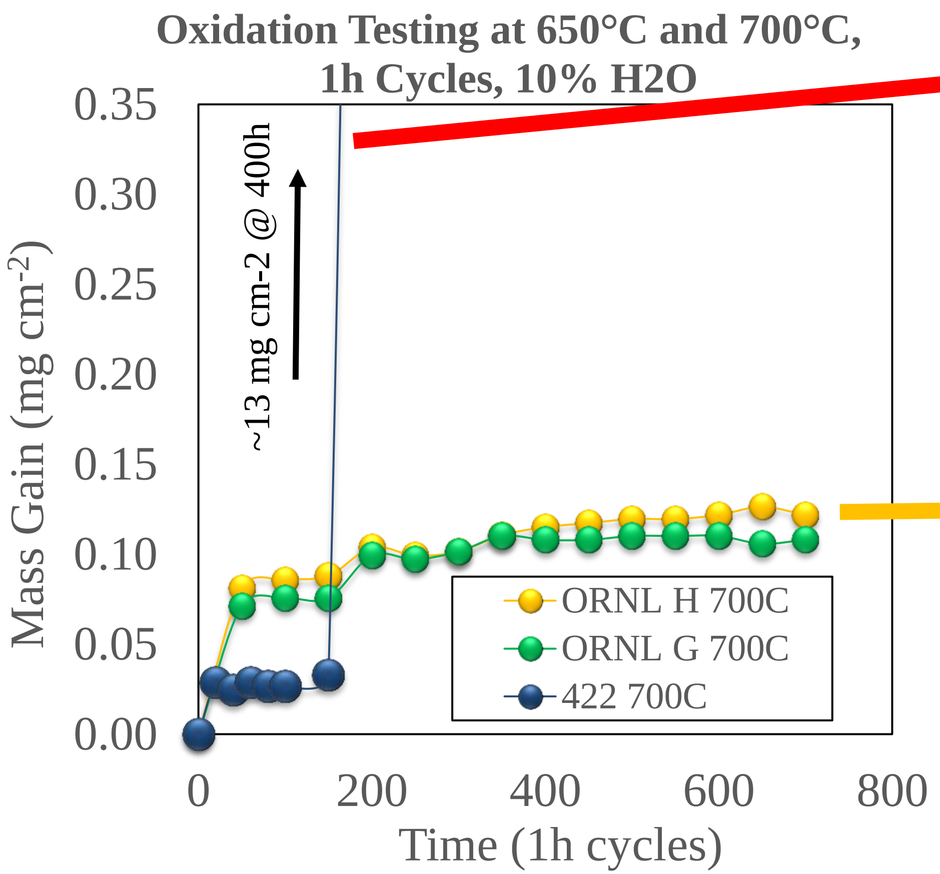

Temperature distribution calculation of alloy 422 crown courtesy of Army GVSC
- Red hottest
- Blue coolest

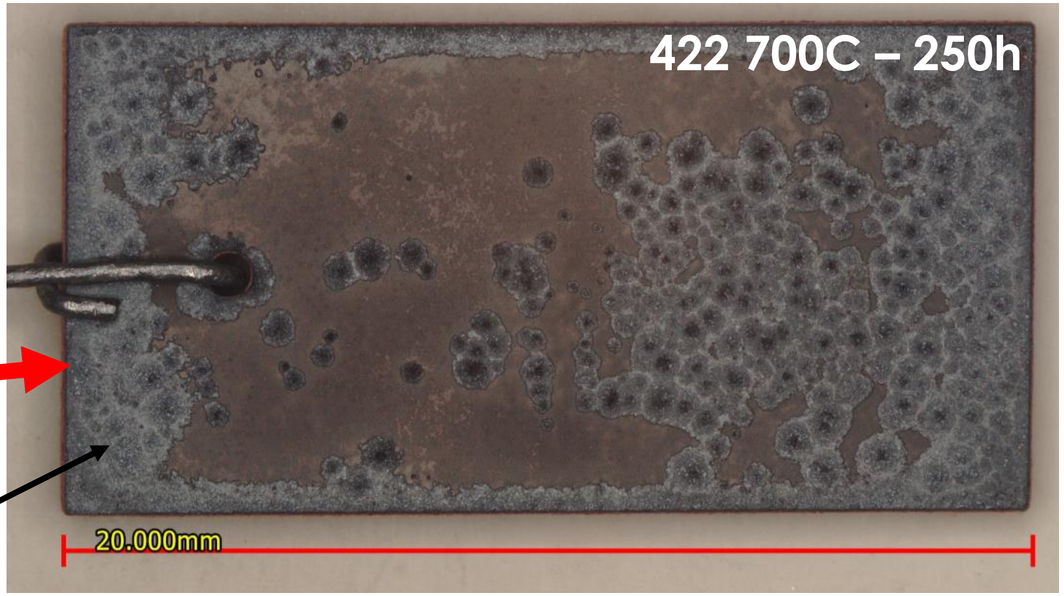


# ORNL High Cr Alloys H & G Exhibit Improved Longer Term Cyclic Oxidation Resistance to 700°C Over Commercial 12Cr Steels

- Commercial 422 alloy shows break away Fe oxidation formation at 700 C°.
- **Exceptional results prompting interest in scaling up**




Break away Fe oxide formation

# Responses to Previous years Reviewer's comments

- *Question: Relevance—Does this project support the overall DOE objectives? Why or why not?*
  - *Response: Yes, focused on improving efficiency of HD line haul freight vehicles, which is a* ***highly challenging segment to electrify****. The EPA is projecting that U.S. freight will double from 2019 to 2040.*
- *Question: Resources—How sufficient are the resources for the project to achieve the stated milestones in a timely fashion?*
  - *Response: Resources are optimal for lab scale development. Additional resources will be needed for scale up of material without significant contribution from industry.*

# Remaining Challenges and Barriers

- Optimizing balance of strength, oxidation resistance, and thermal conductivity.
- Industrial collaboration and scaling up of developmental alloys

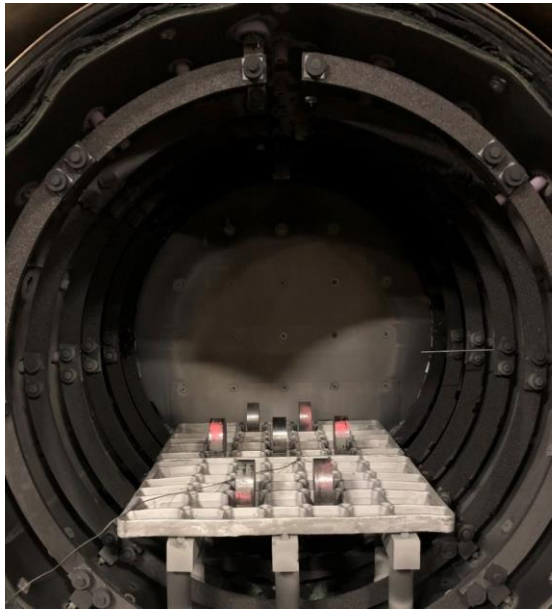
# Collaboration and Coordination

- **Task Partners**
  - Thrust 4A – Advanced Characterization (ORNL)
    - Microstructural Characterization via **Transmission Electron Microscopy** &**Atom Probe Tomography**
- **Other Collaborations**
  - Ground Vehicles Systems Center (GVSC), US Army
    - Manufacturing Prototype Pistons of Commercial Alloys.
    - Working with piston supplier.
    - Working with metals and processing, forging, and heat-treating facilities.

CNMS

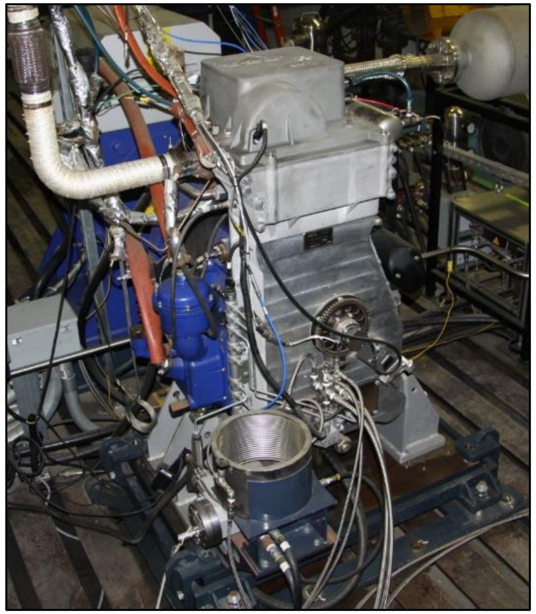
Argonne NATIONAL LABORATORY

DEVCOM GROUND VEHICLE SYSTEMS CENTER



Industrial vacuum furnace showing 12Cr pucks prior to heat treatment for manufacture of protype pistons

GVSC Single Cylinder Test Engine



# Proposed Future Research

- FY22 and beyond:
  - Perform remaining optimization of developmental alloys prior to scale up (6-12 months).
  - Initiate partnerships to scale up material for prototype piston manufacturing with supplier.
  - Identify Electric Vehicle (EV) applications, such as gear trains for electric trucks, where ORNL's capabilities in rapid development of new alloys with targeted property sets can offer high impact.





*Any proposed future work is subject to change based on funding levels*

# New Oak Ridge Developmental Alloys Show Improved Properties Relative to Current Commercial Alloys

## Commercial Alloy Evaluation

- Evaluated12Cr steels and thermal processing methods relative to current piston steels.
- 12Cr alloys evaluated in this task are being made into prototypes with Army GVSC collaboration.

## High Cr Developmental Alloy Evaluation

- Novel alloys with good strength, excellent oxidation resistance to 700 °C , and higher thermal conductivity than commercial 12Cr steels.

## Medium Cr Developmental Alloy Evaluation

- Novel alloys with improved strength, similar oxidation resistance, and 20-40% lower material cost relative to 12Cr commercial alloys have been developed

## Low Cr Developmental Alloy Evaluation

- Low-cost low-Cr  alloys demonstrated with  higher strength than commercial 12Cr alloys and good oxidation resistance from 500 to 575°C.