Project ID: mat221

Lightweight and Highly-Efficient Engines Through Al and Si Alloying of Martensitic Materials*

*Funded by VTO LightMAT Program, managed by PNNL

Dean Pierce (PI, Presenter),
Govindarajan Muralidharan (Co-PI)
Hsin Wang, Artem Trofimov, Allen Haynes,
Oak Ridge National Laboratory
Yong-Ching Chen (PI)
Corey Trobaugh (Co-PI)
Quancang Ma, Jian Zhou, Howard Savage,
Ben Wang, Cummins Inc.

2023 DOE Vehicle Technologies Office
Annual Merit Review

June 13, 2023

Timeline/Budget

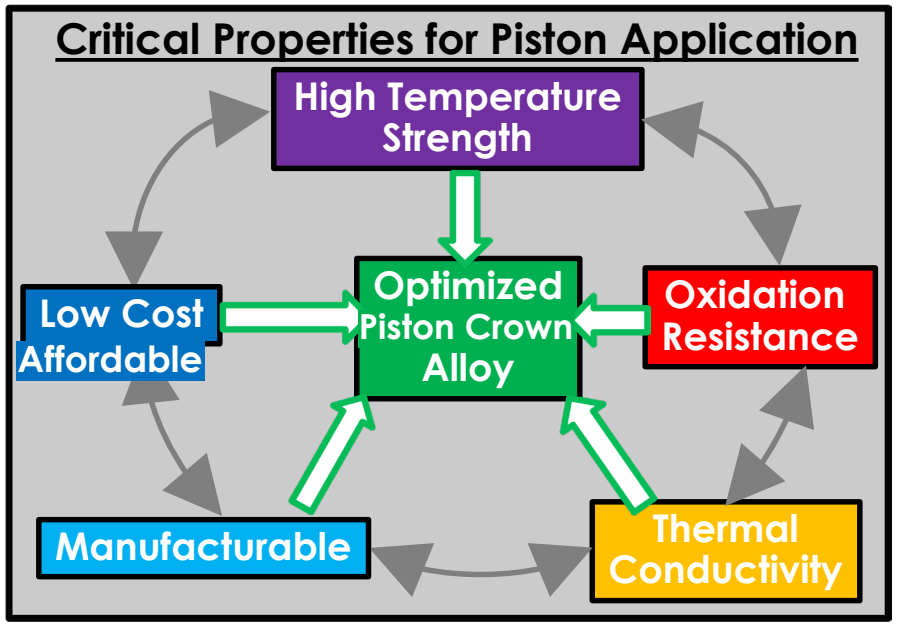
- Program Start: May 2019
- Program End: October 30, 2023
- FY23: $150k
- FY23 Industry cost share: $350K
- 90% Complete

Partners

- Cummins
- Mahle

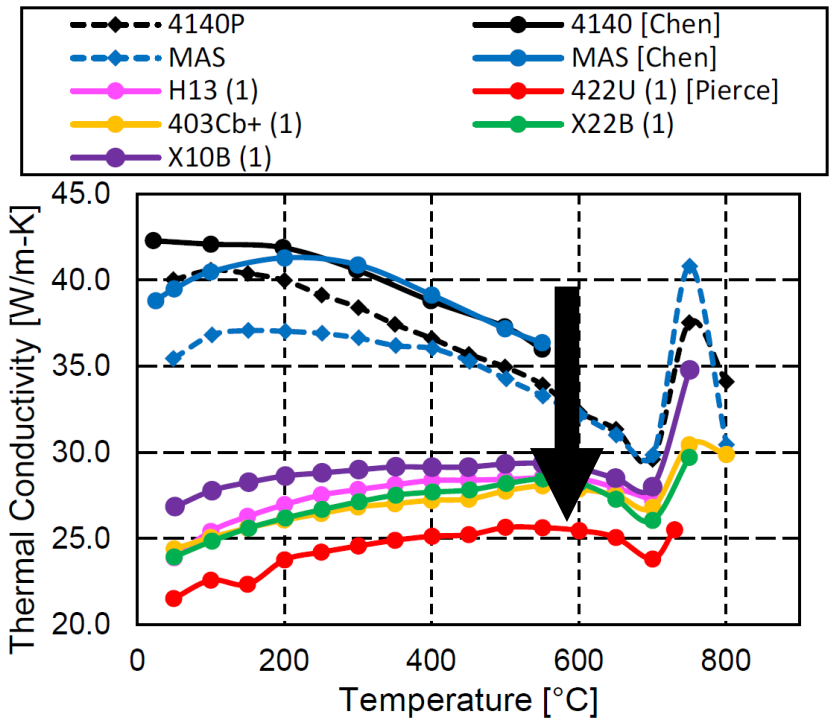
Barriers

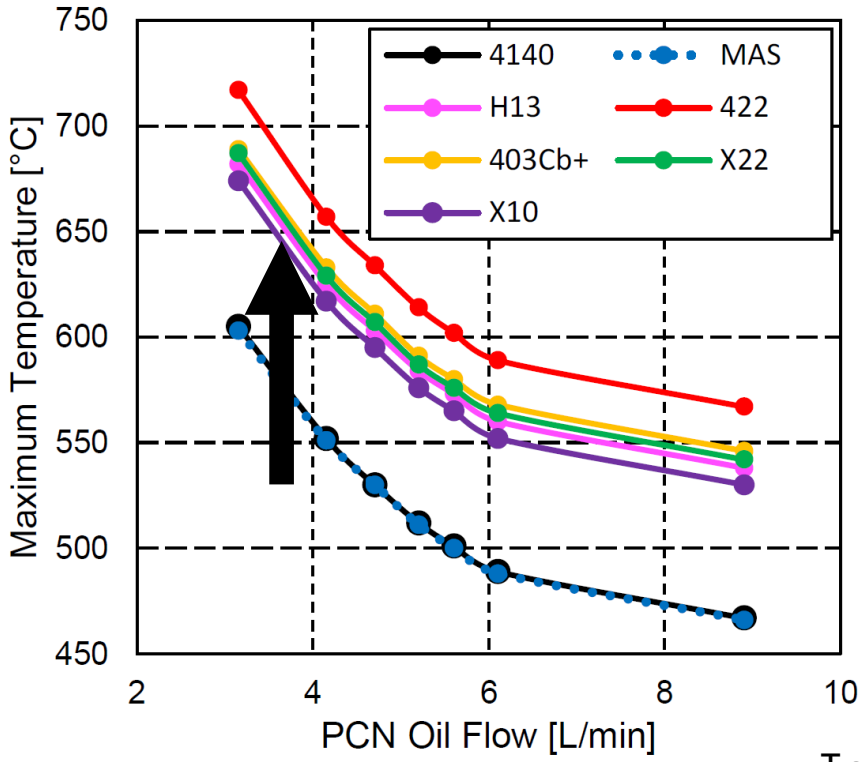
- Optimization of properties of piston crown steels
- Machinability/weldability/Affordability
- Scaling steel to larger sizes
- Achieving higher power density



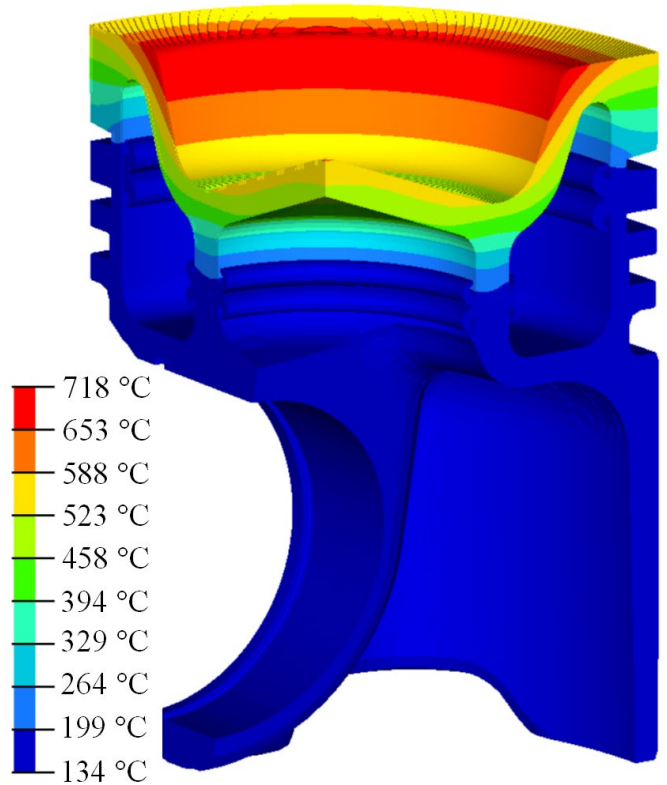
Metallurgical Trade-off: Higher Alloy Content Increases Strength and Oxidation Resistance but Decreases Thermal Conductivity Which Raises Piston Temperature

Black arrows indicate increasing alloy content



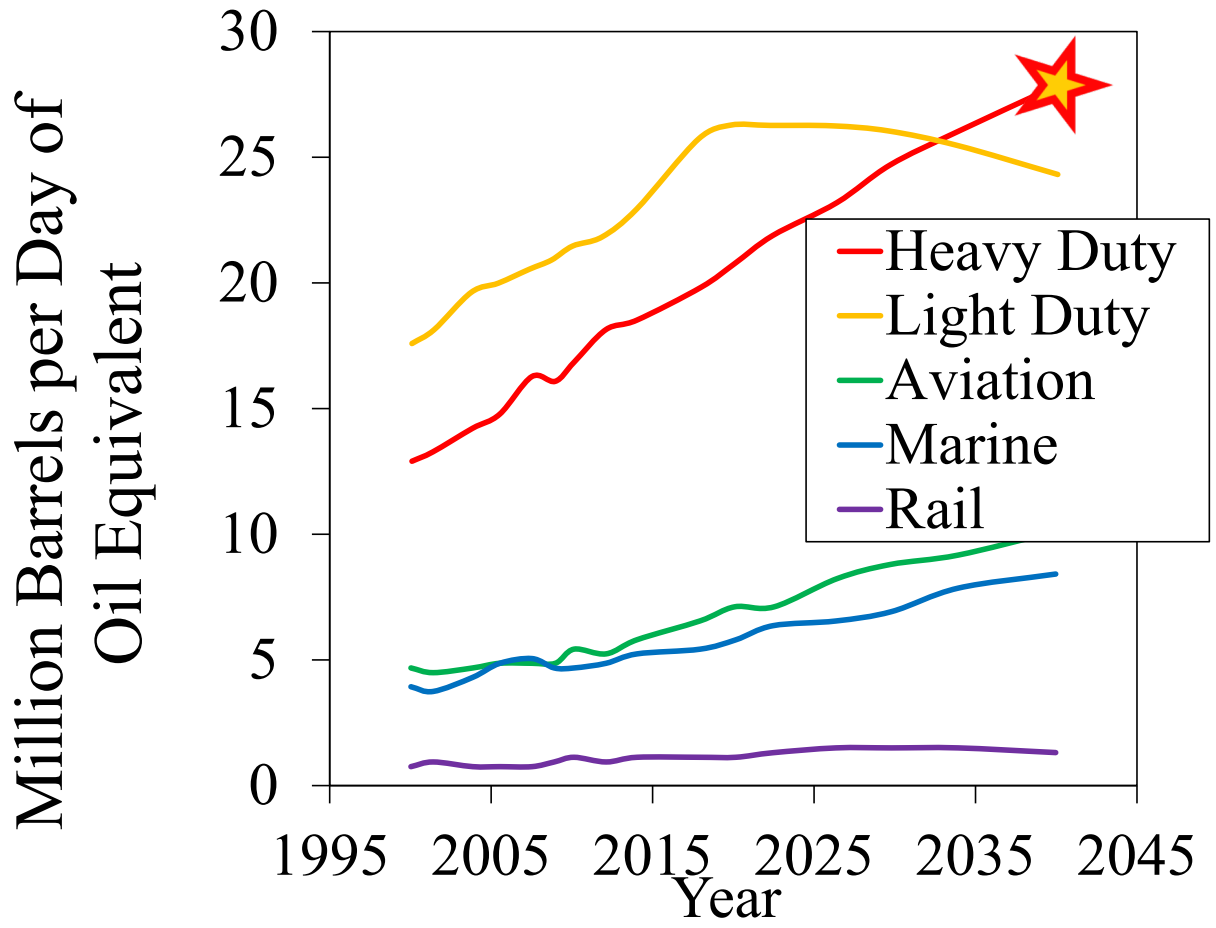


Gingrich et. al, SAE, 2022



Temperature distribution on 422 steel piston
(Pierce et al., materials and design, 2022)

Heavy Duty Freight Vehicles Will Become Top Energy Consumer as Electrification Remains Challenged



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

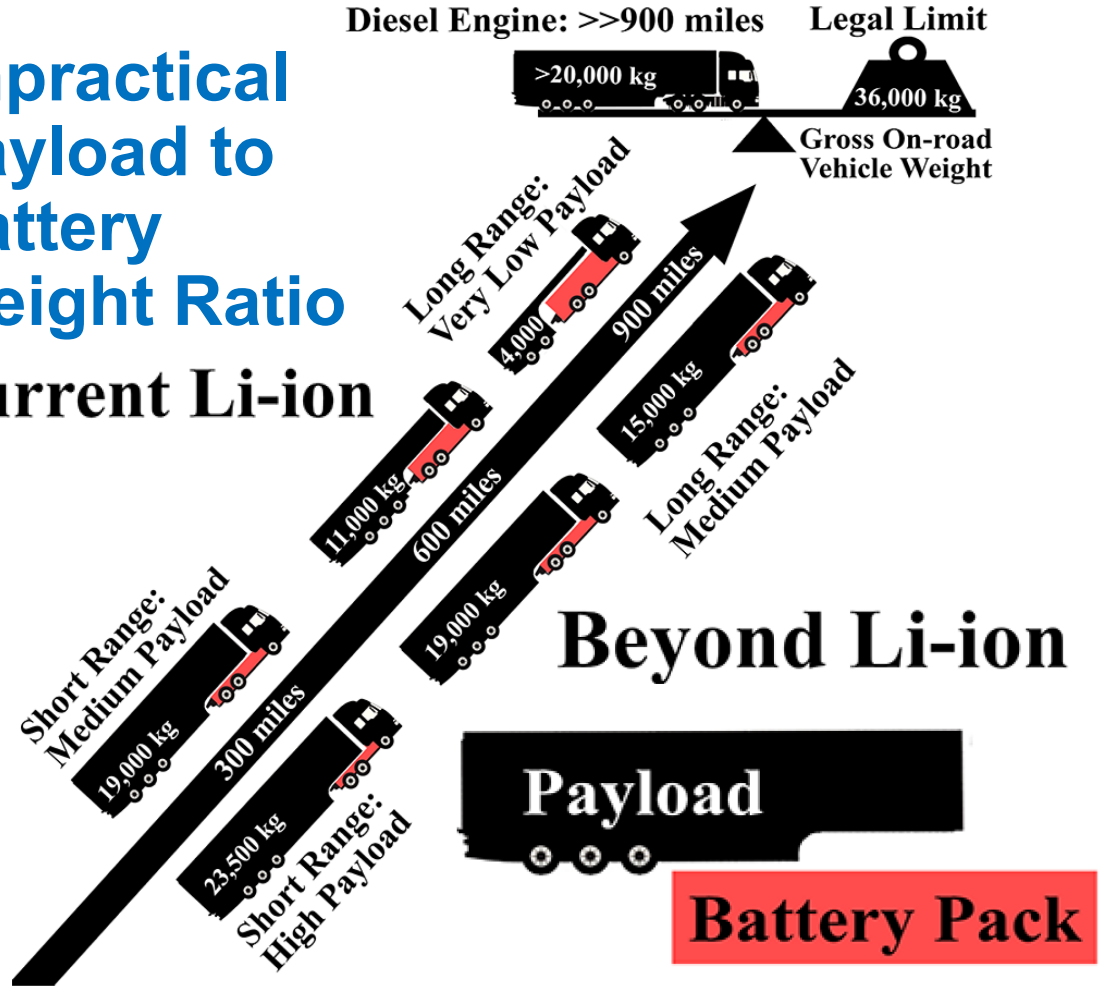
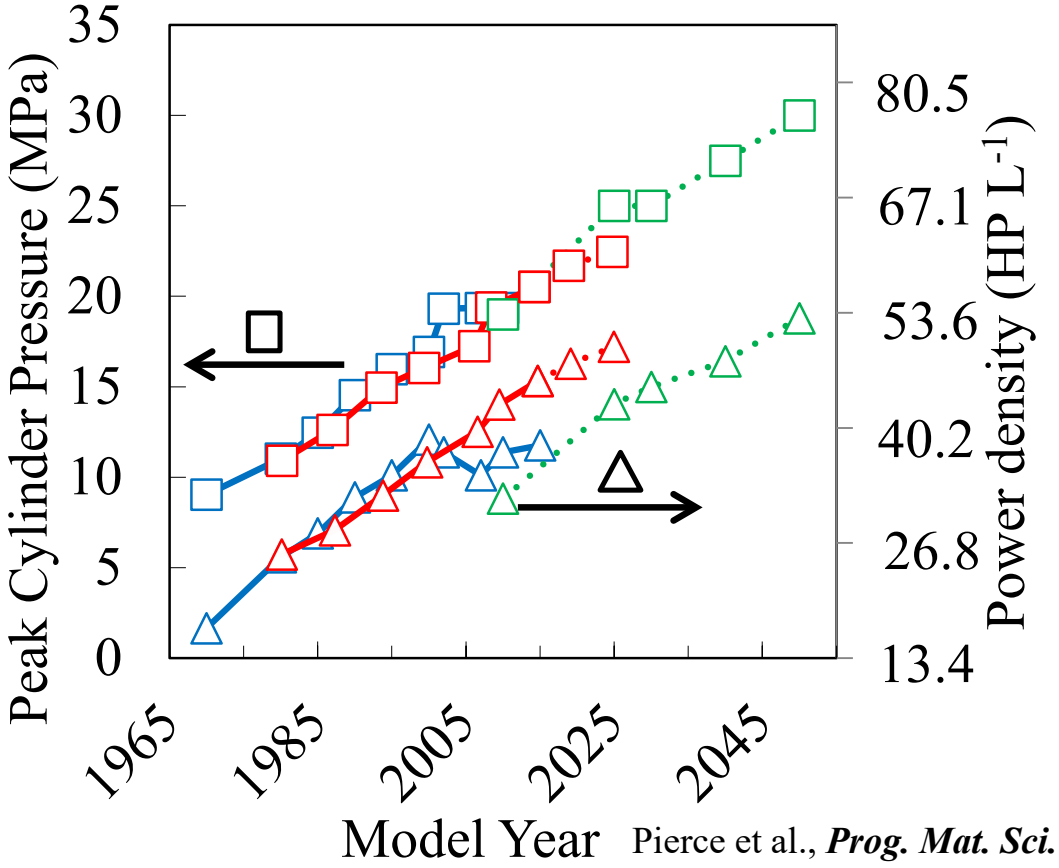


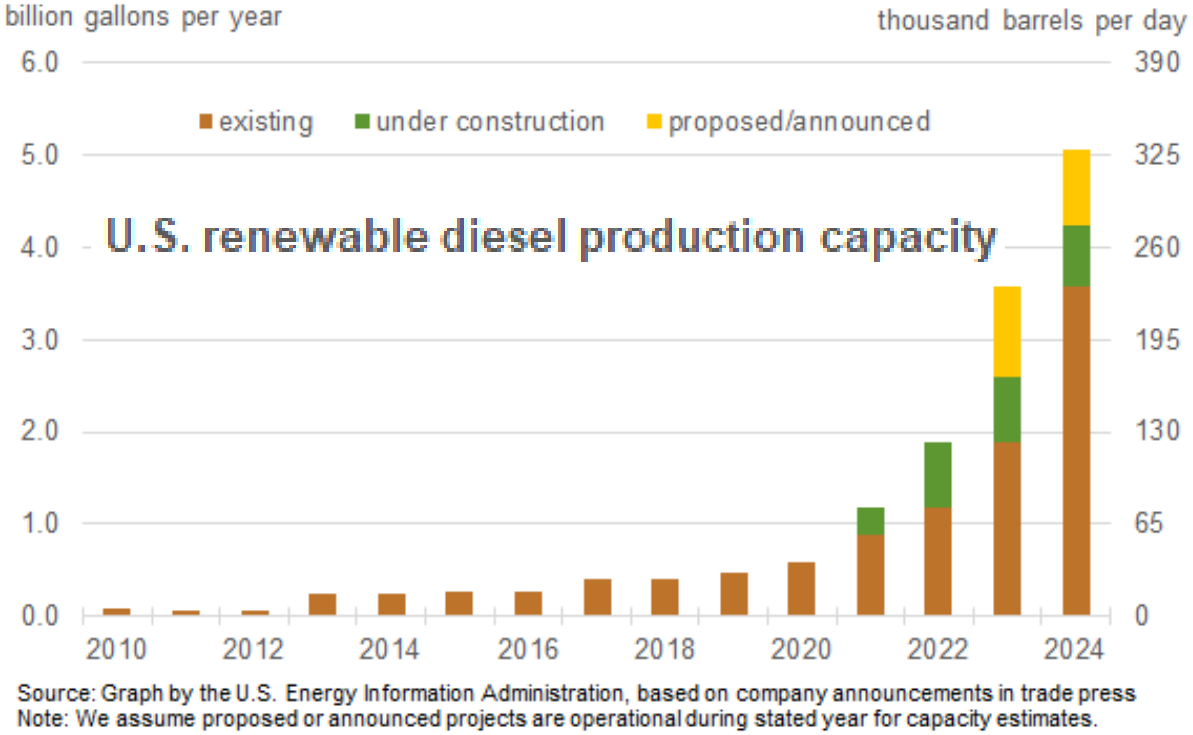
Figure 1. Summary of a comparison between current and beyond Li-ion batteries for electrifying semi trucks DOI: 10.1021/acsenergylett.7b00432 *ACS Energy Lett.* 2017, 2, 1669−1673

Increasing peak cylinder pressures and temperatures require new piston materials

- Current piston materials 4140 and Microalloyed steel not suitable above 500 °C
- New steels to increase efficiency and reduce emissions



- Increasing demand for greener fuels for ICE: green hydrogen, bio-diesel, renewable diesel, natural gas, etc.

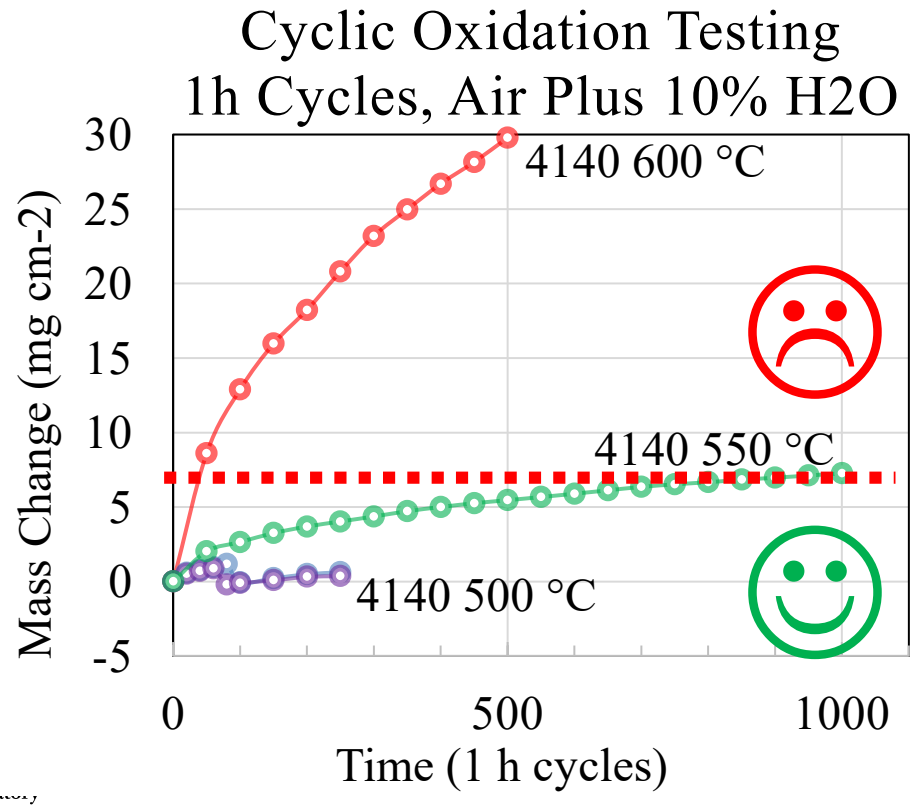


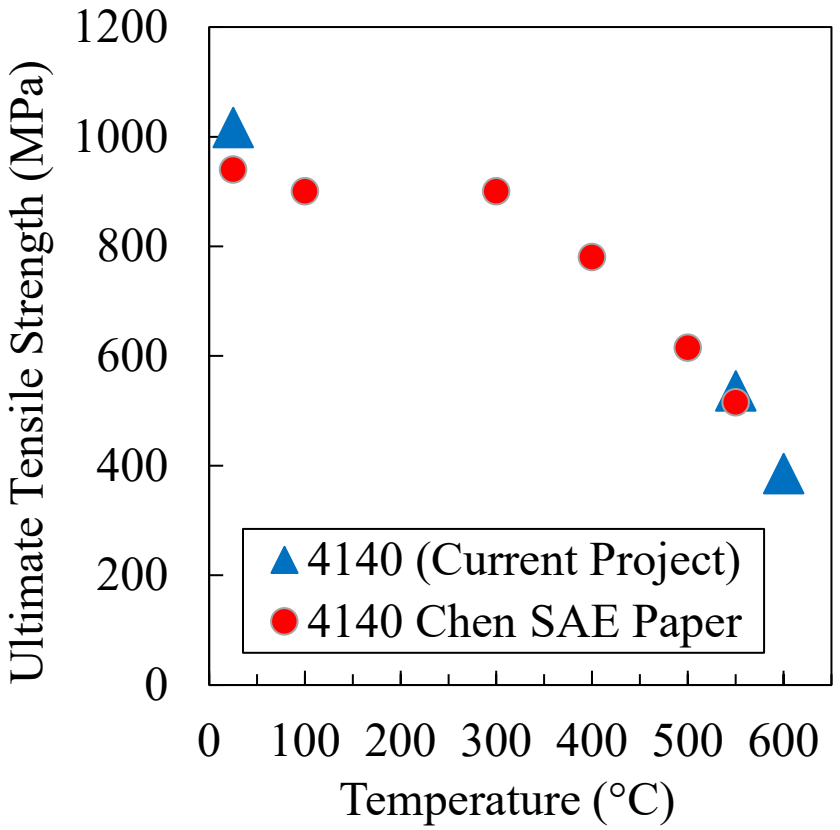
Pierce et al., ***Prog. Mat. Sci.*** 103 (2019) p. 109).

Commercial Steel Piston Alloy 4140 is Currently at Limits of Temperature and Strength in Heavy Duty Diesel Engines (HDDE)

- 4140 is limited to peak temperatures near 500°C.
- Major barrier to increasing engine efficiency.
- Challenge is to significantly improve properties at low cost

Composition (wt.%)						
Alloy	Mn	C	Cr	Si	Mo	Fe
4140	0.9	0.4	1	0.3	0.2	97.6





Milestones for Task

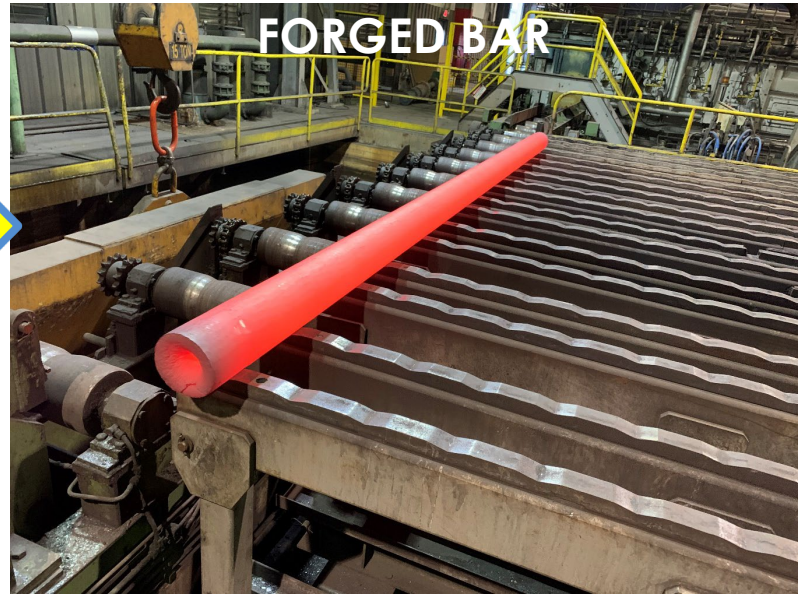
- **FY21 Milestone 1:** Bars are forged into pancakes for piston machining: **Complete.**
- **FY21 Milestone 2:** Heat treatment of pancakes: **Complete.**
- **FY22 Milestone 1:** Develop Report Detailing ORNL Work. October 31st, 2023. **On Track.**

Alloy Development to Piston Prototype and Engine Test

1. Computationally designed, melted, processed ~35 different alloy compositions
    1. maximize strength, thermal conductivity, and oxidation resistance with limited cost increase.
2. Performed evaluations
    - Elevated temperature tensile and fatigue testing
    - Cyclic oxidation testing at 550 and 600 °C
    - Thermal properties: Diffusivity, heat capacity, thermal Expansion
    - Computational fluid dynamics analysis

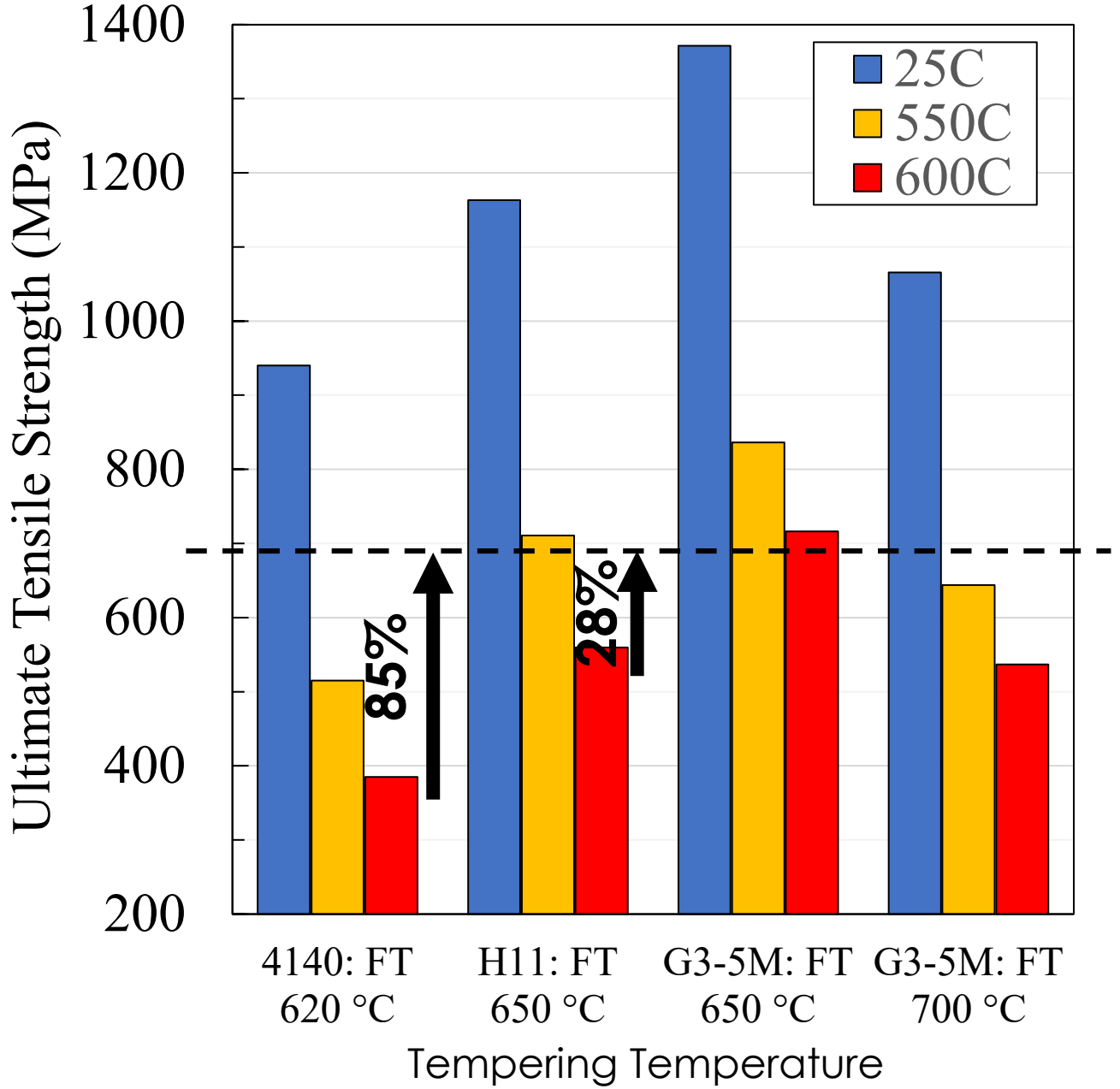
3. **Submitted joint world-wide patent application**
4. **Down selected promising alloy with remarkable properties**
5. **1500+ lb industrial heat successfully melted and forged**
6. **Industrial heat treat process refinement**
7. **Mechanical properties testing on scaled up alloys**
8. **Prototype pistons manufactured!**
9. **Engine testing of Full Scale Pistons of New Alloy Completed!**

Cummins and ORNL Led Casting, Forging, and Annealing of Industrial Scale Ingot of New Alloy



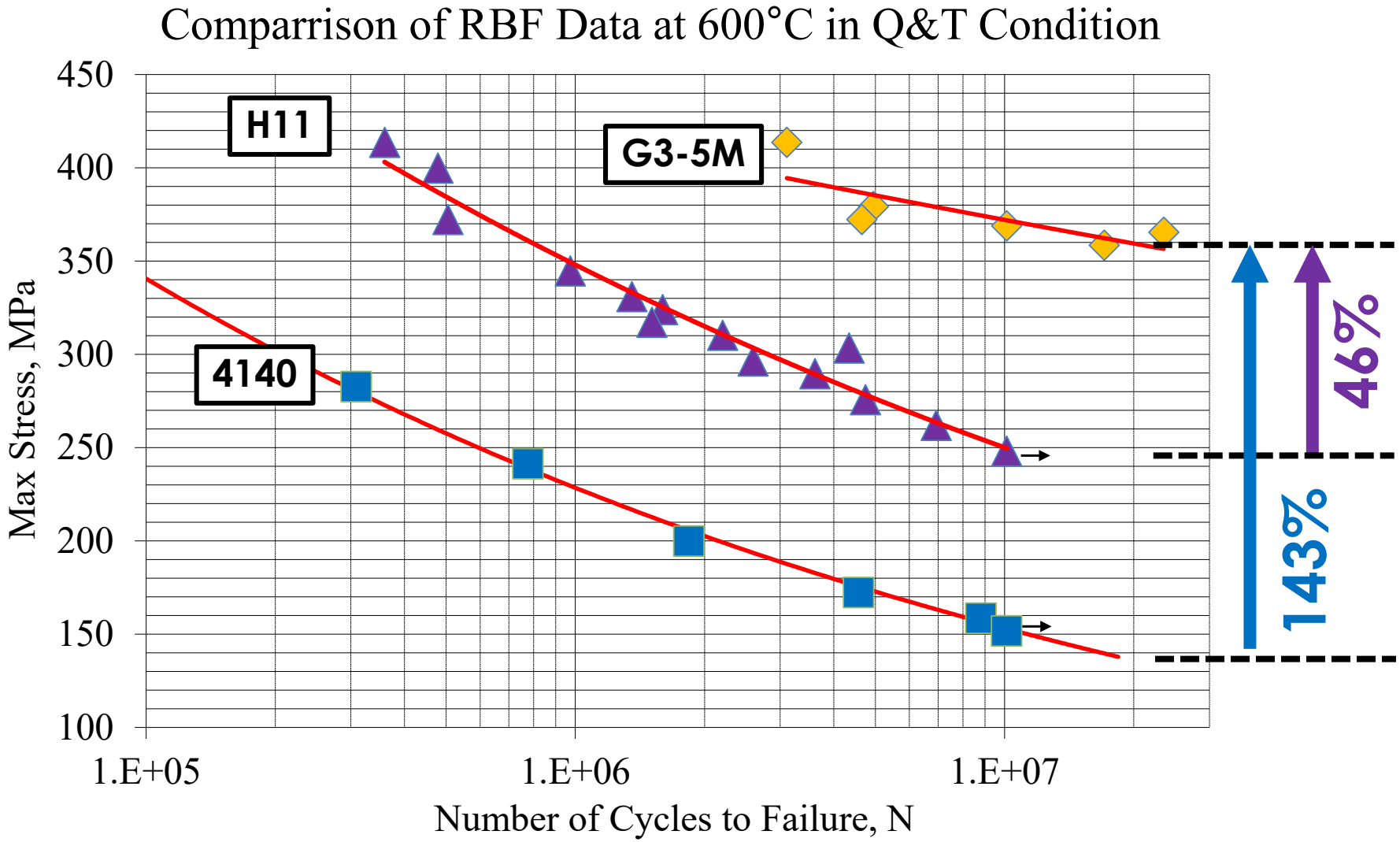
G3-5M Exhibits 85% Increase in Strength Over 4140 Steel at 600°C

- 28% increase over H11 (5Cr tool steel), despite significantly lower alloy content



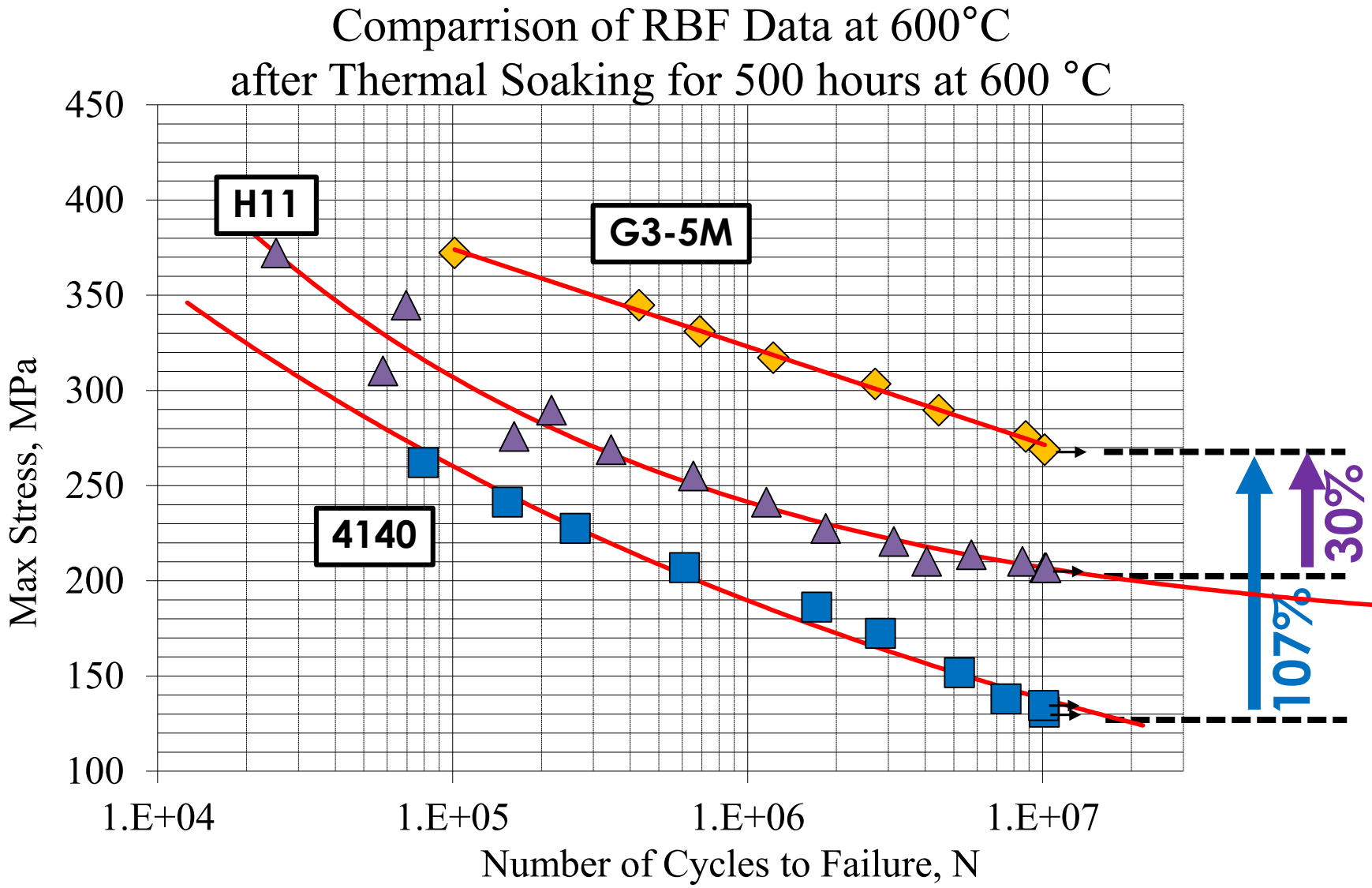
G3-5M Exhibits 143% Increase in Rotating Beam Fatigue Strength over 4140 Lab at 600 °C

- Fatigue strength at 600 °C 365 MPa
- 46% increase over H11
- Can we achieve fatigue strength in scaled up alloy?

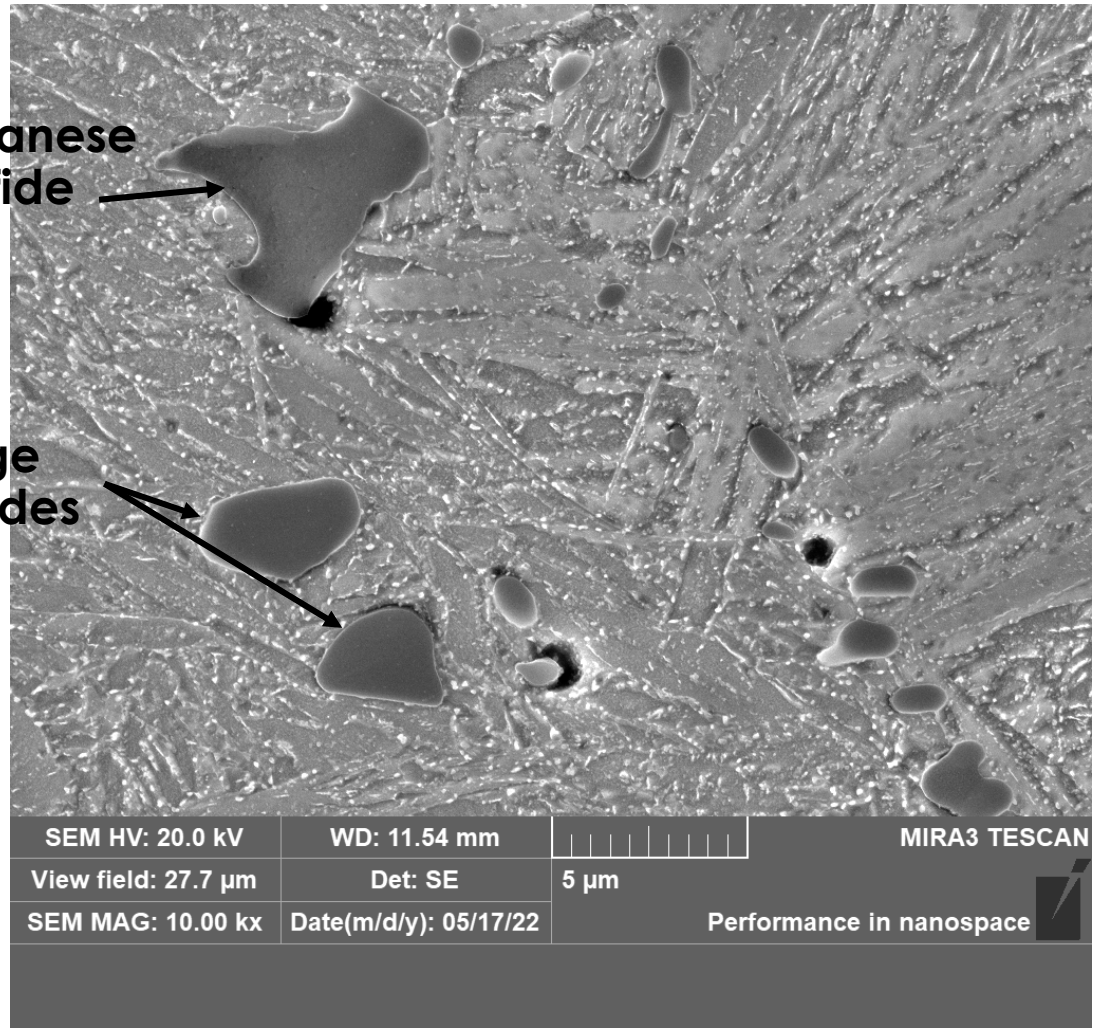


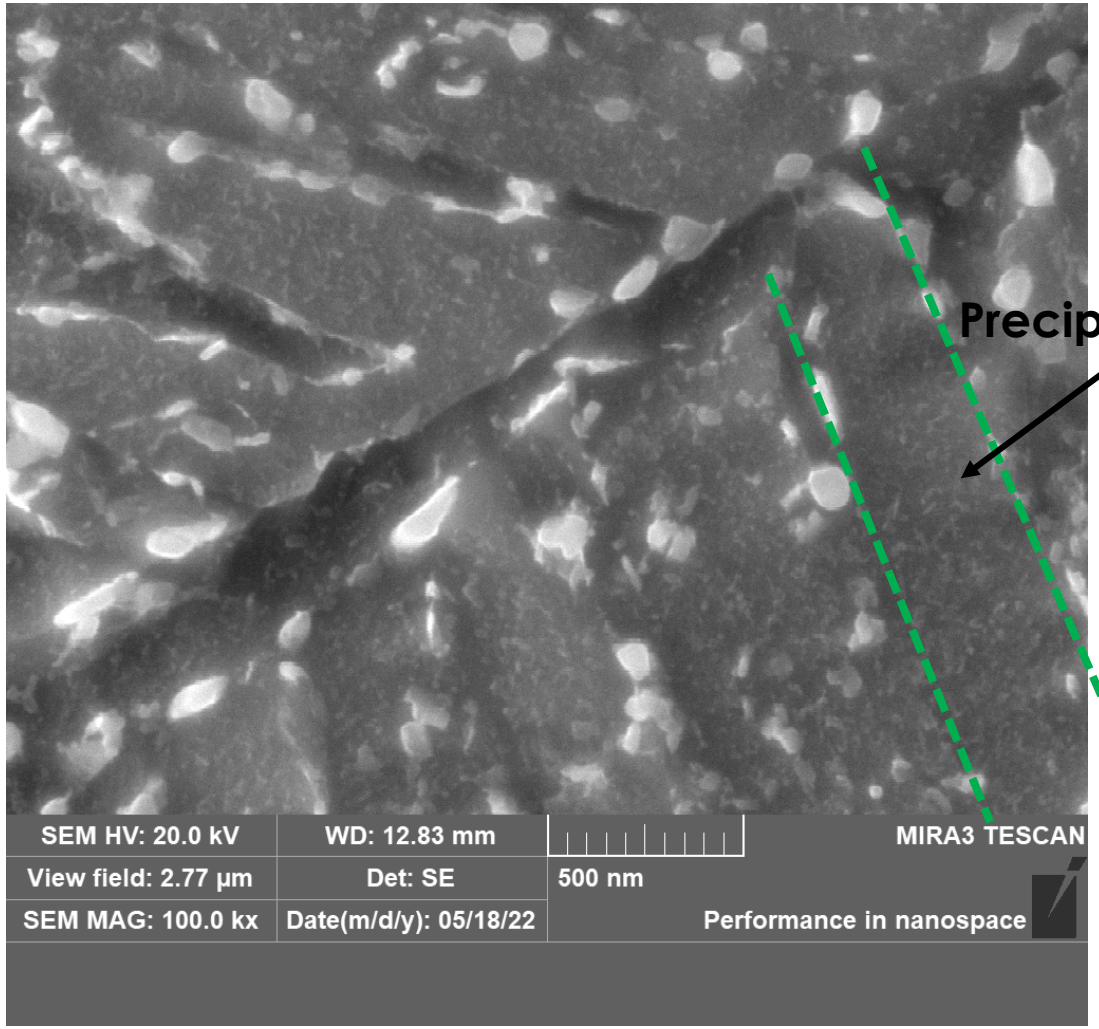
Industrial Heat Exhibits 107% Increase in Fatigue Strength at 600 °C Over 4140 After Aging at 600 °C for 500h

- 30% increase over H11

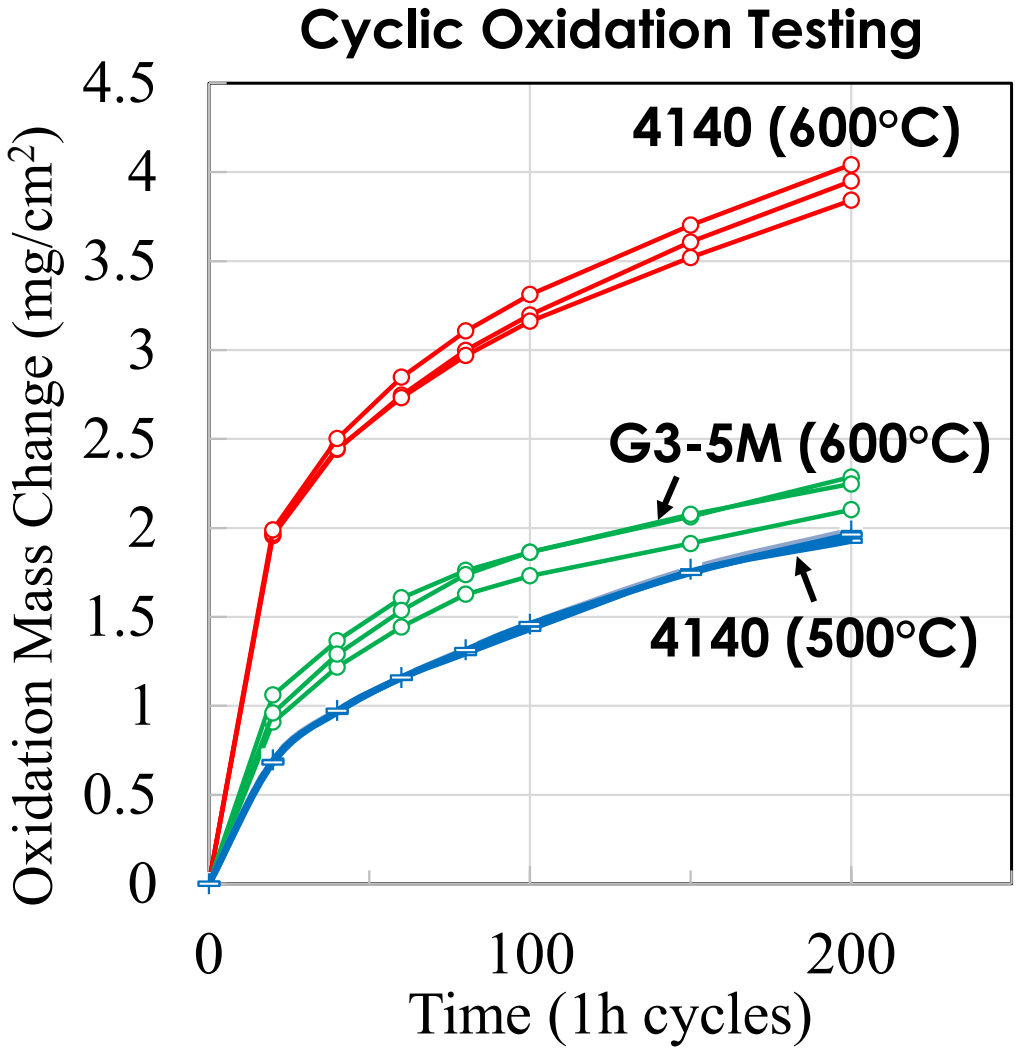


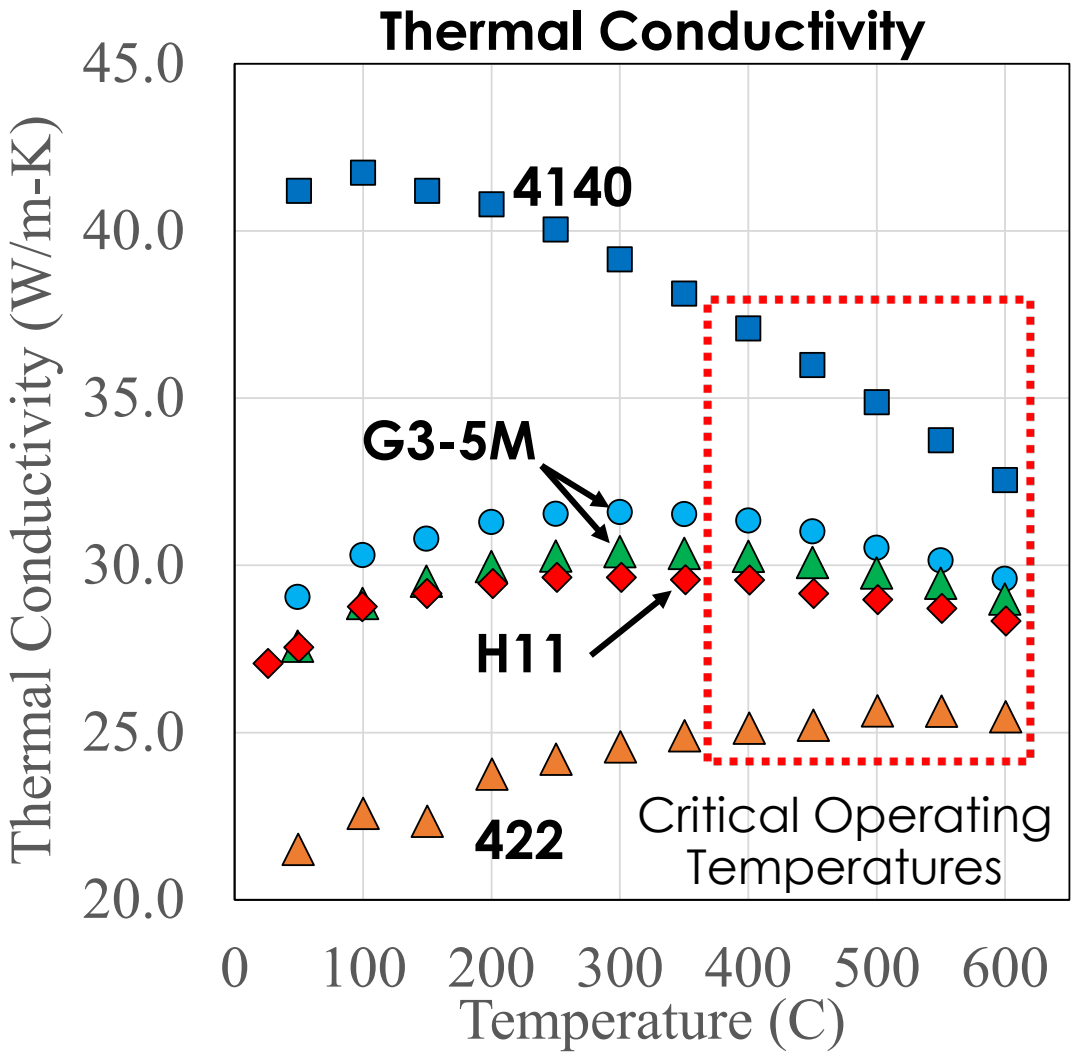
Novel Thermal Processing Route Produces Wide Distribution of Precipitates from 5 um to <50 nm





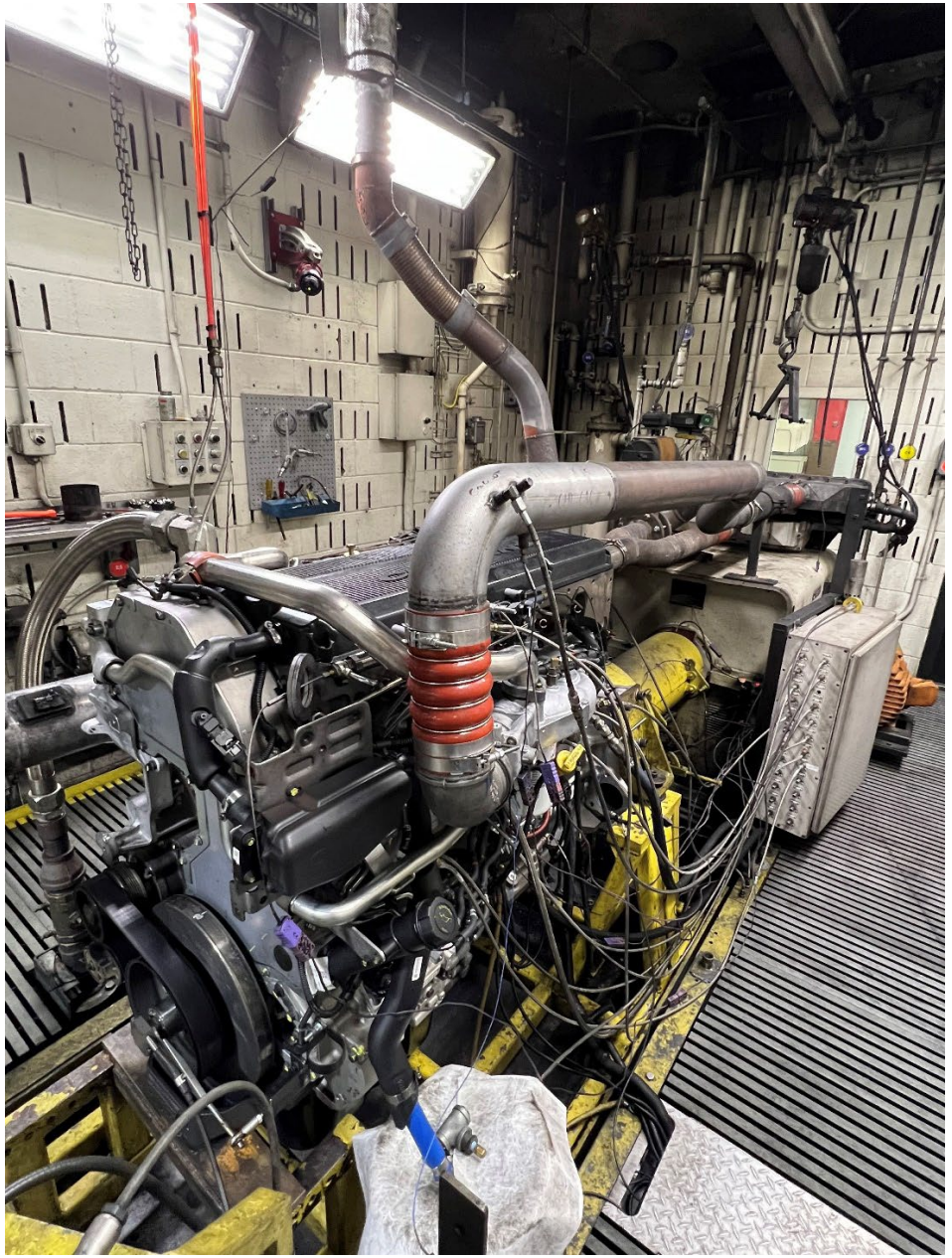
G3-5M extends the oxidation resistance to 575 or 600°C Over 4140, Modest Increases in Thermal Conductivity over H11





G3-5M Piston Survived Modified Peak Power Output Test With Enhanced Severity

- X15 X600 Production Engine
- 500h Modified PPO (peak power output) test to further increase severity
- Split test (4140 and G3-5M pistons)
- Surface/oxidation characterization remains to be completed



Cummins X15 X600 Production Engine at Jamestown, NY Engine Plant

Responses to Previous years Reviewer's comments

- Project scored 3.47 out of 4, compared to Materials Tech. average of 3.23
- Lowest criteria was "Tech Accomplishments" 3.33
- Challenge with electrifying HD Freight transport makes project well aligned with VTO goal
- Oxidation tests of scaled up alloy deemed important.
  - *We are in process of oxidation testing scaled up alloy*
- Limited fatigue data, lack of baseline data
  - Showed more extensive fatigue data this year in scaled up alloy, along with 4140 and H11
- Modeling in future work?
  - Modeling was conducted on G3-5M and 4140 to illustrate temperature increase
- This reviewer believes that the key barrier to the subject technology is thermal fatigue. The project needs to include testing for thermal fatigue with samples that have sharp corners.
  - Thermal fatigue is important but challenging to replicate in lab environment.

Remaining Challenges and Barriers

- Decision on suitability for next engine development
- Commercialization with steel mill

Collaboration and Coordination

- CRADA between Cummins and ORNL
- Melting, Processing and Forging Shops
- Partnered with Mahle to manufacture prototype pistons
- Collaborating with Thrust 4 on STEM and APT

Proposed Future Research

- Characterization of engine tested pistons
- Complete fatigue and wear testing
- Complete lab scale oxidation testing on scaled up alloy
- Identify if any small changes to alloy chemistry are warranted
- Evaluate suitability of alloy for other applications and fuels, including: injectors, dies, valves, high temperature fasteners, and for low C fuels (e.g., hydrogen, ammonia, natural gas, etc.)

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

SUMMARY

Developed, Scaled Up, and Engine Tested a Novel Cost-Effective Piston Alloy With Improved Properties in 4 Years

- Global patent filed
- 143% fatigue strength increase over 4140 at 600°C
- New steel enables more efficient engine designs
- Apply to alternative fueled engines (hydrogen, renewable/synthetic diesel, natural gas)
- Other applications
  - Injectors, tooling, etc.
- Improved trade-off between thermal properties, strength, and oxidation resistance over state of the art steels