



# U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – GROUND VEHICLE SYSTEMS CENTER

Engine Testing and Evaluation of Commercially Available Steels  
for Next Generation Diesel Engine Pistons: Update #1

Michael Tess

Research Engineer

Ground Vehicle Power and Mobility (GVPM)

DISTRIBUTION A. Approved for public release; distribution unlimited.  
OPSEC #: 5449



# MULTI-DISCIPLINARY PROJECT TEAM



## GVSC – Army Ground Vehicle Technology Experts

*(M. Tess, E. Gingrich, K. Sebeck, G. Byrd, V. Korivi)*

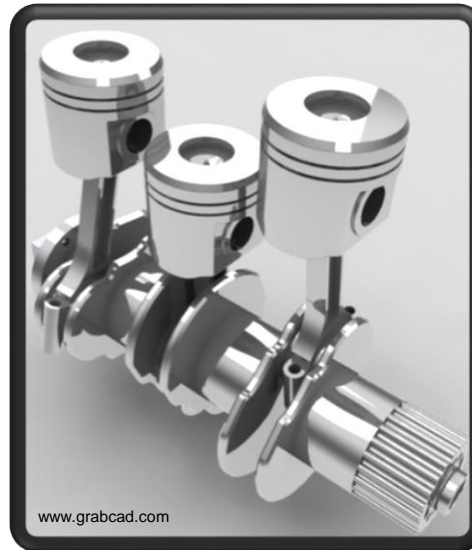
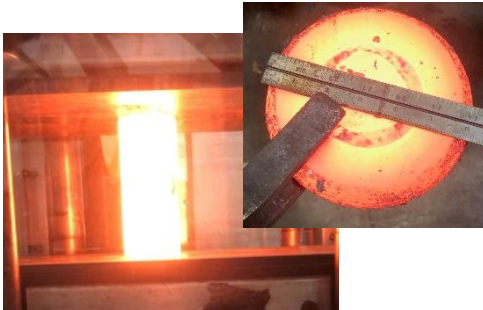
- Project sponsor
- Propulsion labs (single-cylinder research engine)
- Materials research & characterization labs
- Modeling and simulation (CFD and FEA)



## ORNL – Materials Scientists

*(D. Pierce, G. Muralidharan, A. Haynes)*

- Oxidation testing
- Mechanical properties
- Thermophysical properties
- Metallography



## Tenneco – Piston OEM

- Prototype manufacturing
- Application engineers
- Materials engineers
- Perspectives on HD diesel market

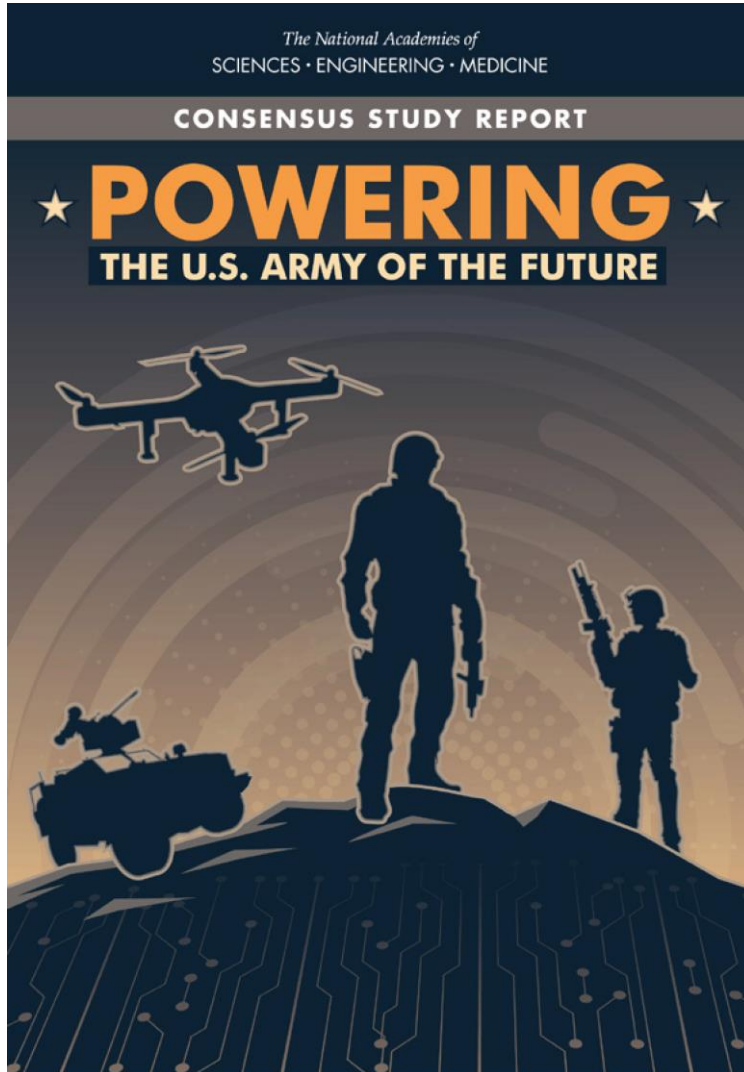




# RESEARCH VISION AND CONTEXT



*Hot Off the Press!* 9 JUN 2021



## Expert Committee's Recommendations:

- Liquid hydrocarbon fuels “should serve as the primary sources of power and energy ... for the foreseeable future” (*through 2035*)
- Engine Efficiency: Continue investing in technology to improve the tank-to-wheel conversion efficiency of a vehicle, to include high efficiency diesel engines
- Electrification: Develop hybrid electric vehicles with internal combustion (IC) engines, and/or partial vehicle electrification concepts, not battery electric vehicles
- Multi-fuel engines: Use diesel and biodiesel to supplement jet fuel (e.g. JP-8, F-24) as the mission allows

National Academies of Sciences, Engineering, and Medicine. 2021. Powering the U.S. Army of the Future. Washington, DC: The National Academies Press. <https://doi.org/10.107226/26052>



# MOTIVATION



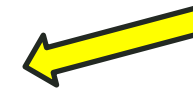
- Performance requirements: Military ground vehicles must operate in all climates – arctic to desert – with the propulsion system under armor (engine, transmission, intake, exhaust, cooling, etc)
- IC engine development: trends toward higher in-cylinder gas pressures and temperatures, which are ultimately limited by maximum piston temperatures and piston durability
- Traditional steel piston alloys: Current piston alloys (4140 and microalloyed steel [MAS], 38MnSiVS5 or equivalent) are constrained by temperature limits (~500 °C max)



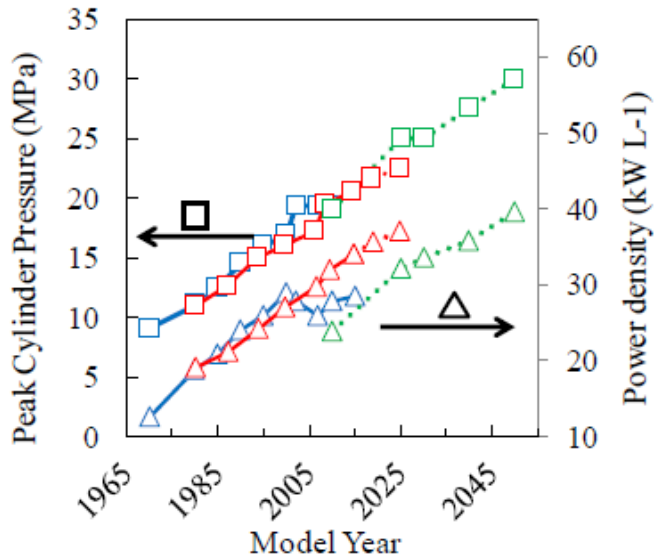
High power density, low heat rejection



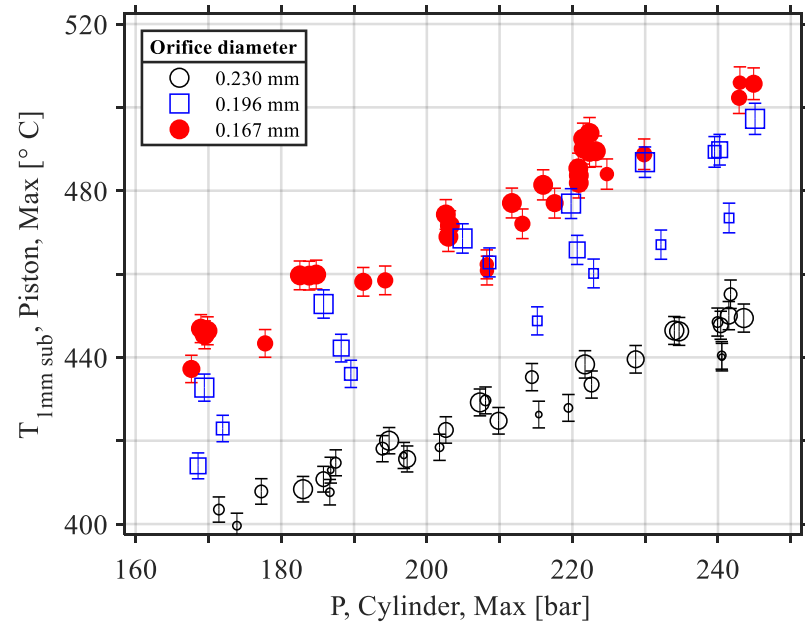
Pathways to higher efficiency force a materials solution



Requires strength & oxidation resistance at high temperature



Pierce et al., Prog. Mater. Sci, 2019



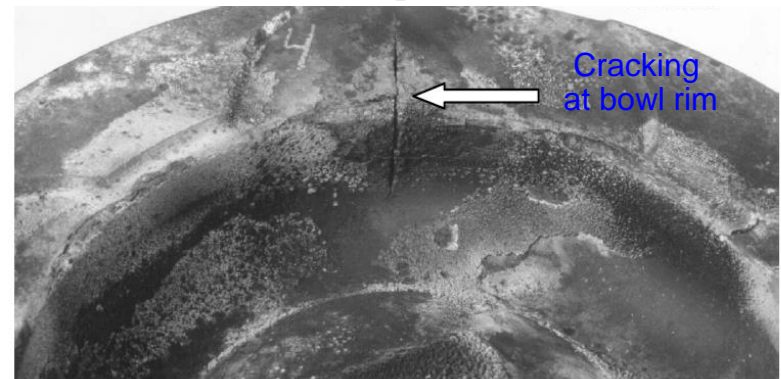
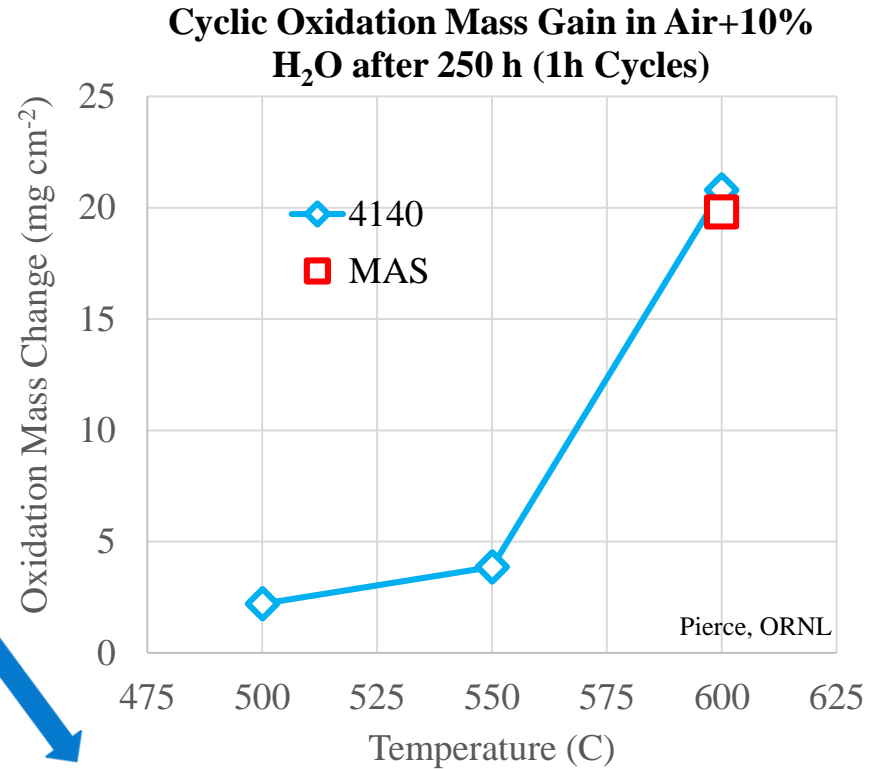
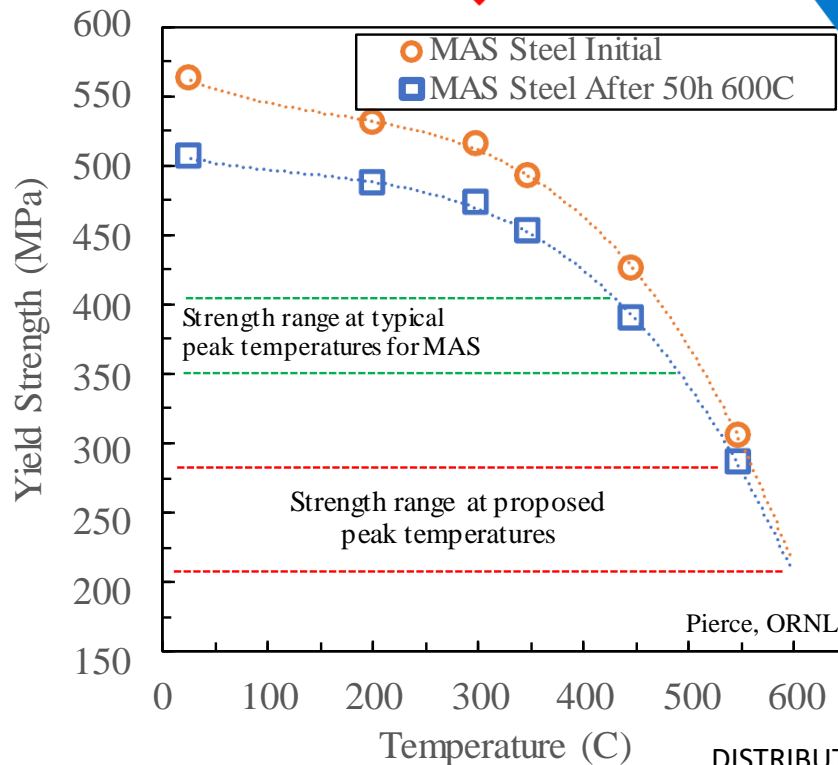
Tess et al., unpublished



# CHALLENGES WITH EXISTING MATERIALS



- Higher temperatures and pressures in next generation HD diesel engines
- Higher temperatures leads to:
  - Much higher oxidation rates
  - Significant loss of strength



Chen and Worden, SAE 2000-01-1232



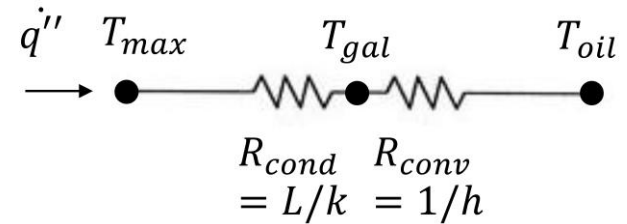
# GOALS AND DIRECTION



- How do we solve the diesel piston thermal management problem?

Higher risk? → High-temperature piston alloy ←

- Piston crown coatings (thermal / oxidation barrier coatings)
- Novel piston cooling architectures (e.g. unique geometry, phase change materials, sealed coolant chamber)



Two primary goals:

1. +600°C operating temperature
2. 30 MPa cylinder pressure

Materials Selection → Engine Evaluation → Post-Mortem Characterization

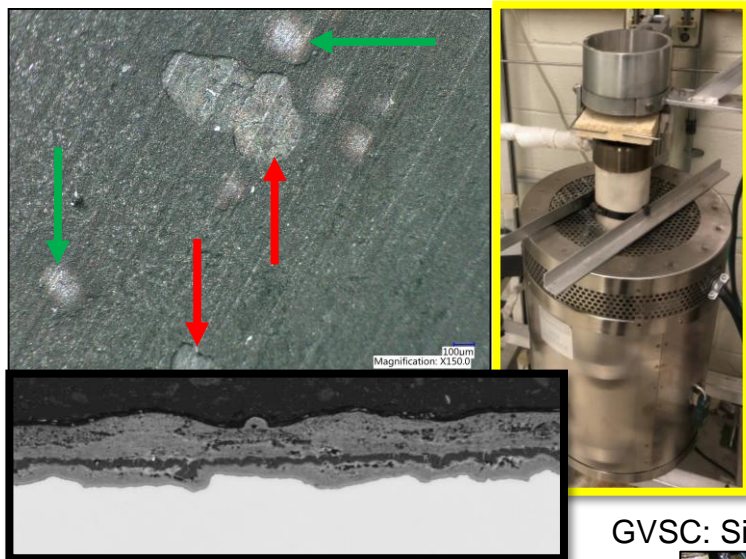
- Years 1-2: Initially focus on commercially available steel alloys
- Year 3: Analyze & publish results, pursue alloy development *if necessary*
  - Targeted alloying improvements
  - Leverage DOE-VTO Powertrain Materials Core Program for MD/HD vehicles



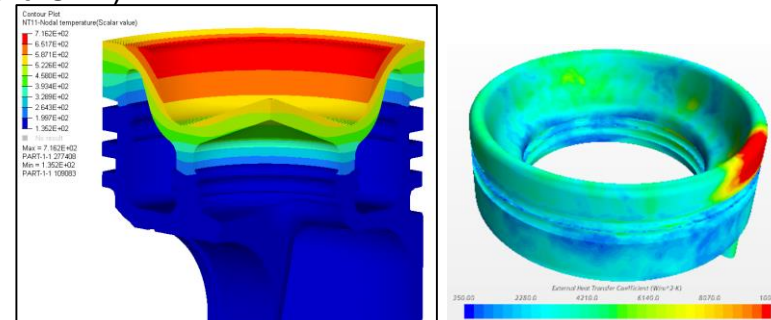
# PROJECT SCOPE / APPROACH



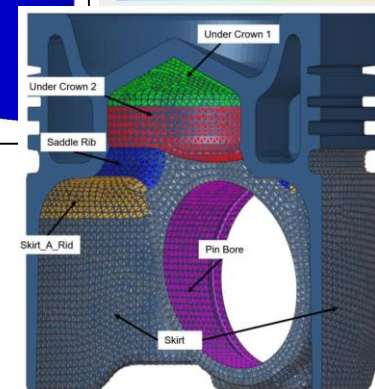
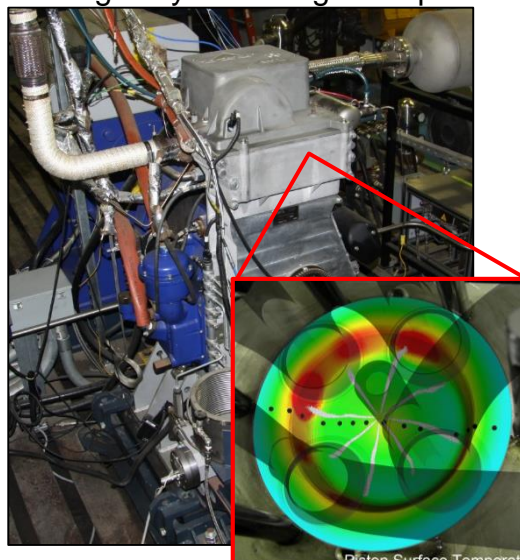
ORNL: Alloy screening, oxidation testing, material property data, and post-mortem analysis



GVSC M&S: Piston thermal and structural analysis (FEA and CFD)



GVSC: Single-Cylinder Engine Experiments



Manufacture prototype pistons



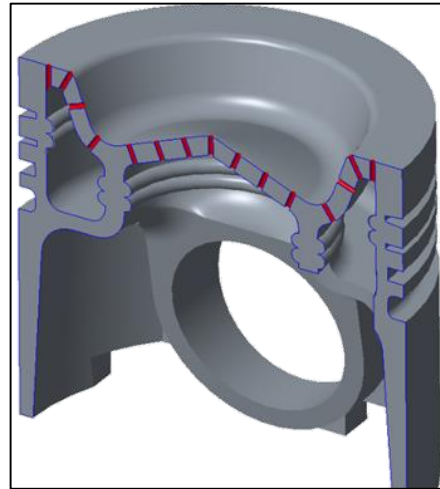
# SINGLE-CYLINDER RESEARCH ENGINE (SCRE)



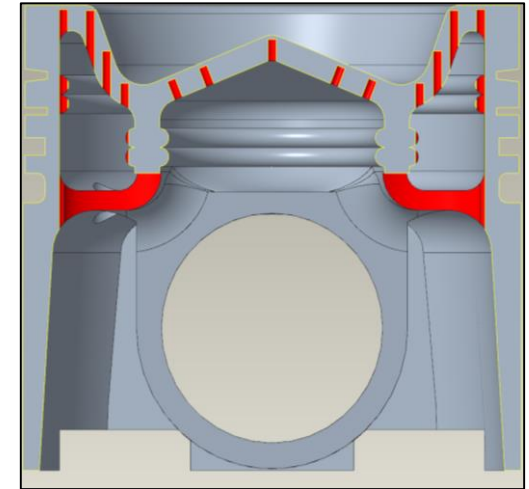
Full engine instrumentation and piston telemetry system supports thermal survey of piston → boundary conditions for piston FEA

- Subsurface piston temperatures
- Surface heat flux

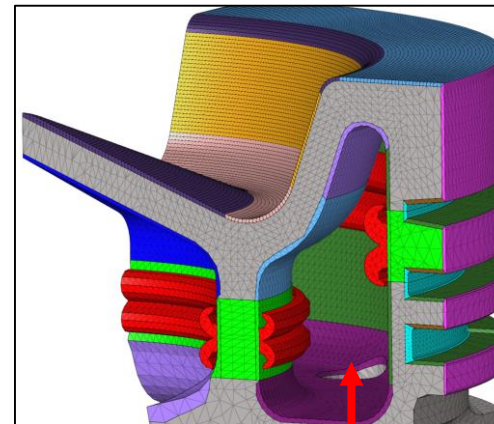
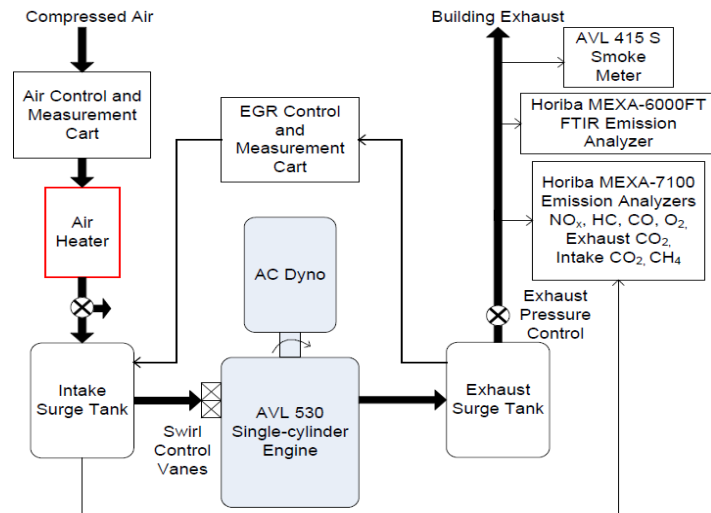
Displacement (L)	1.49
Bore (mm)	122
Stroke (mm)	128
Number of Valves (-)	4
Compression Ratio (-)	14.5
Swirl Ratio	0-3.5 (variable)
Peak Firing Pressure (bar)	250
Max. Injection Pressure (bar)	2000
Injector Nozzle Geometry (mm)	8 hole x 0.167



surface mounted TCs



subsurface mounted TCs



Cooling gallery inlet/outlet

### Piston Construction:

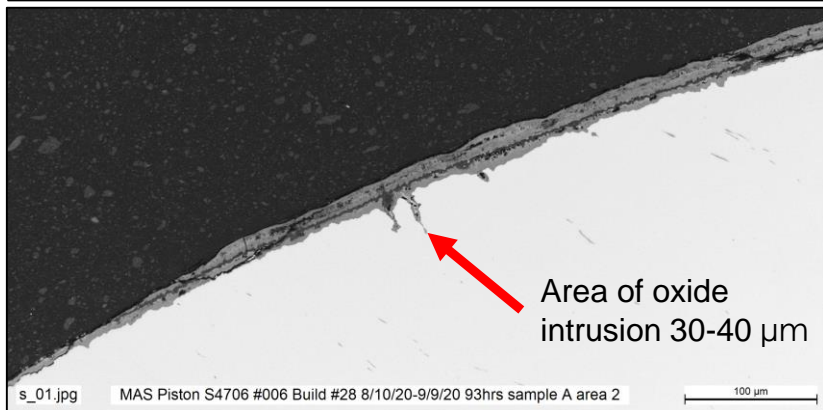
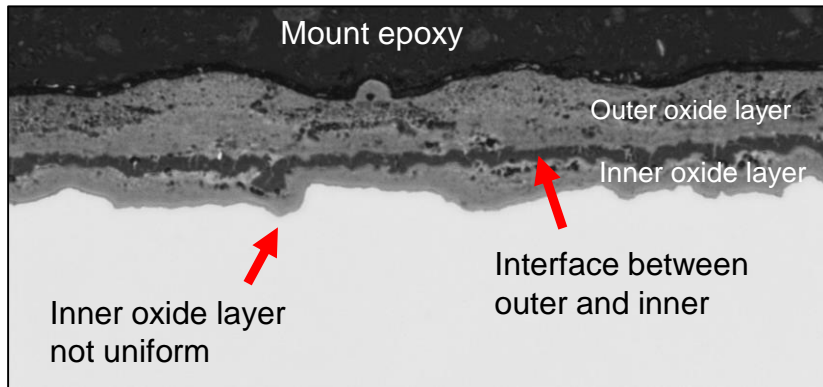
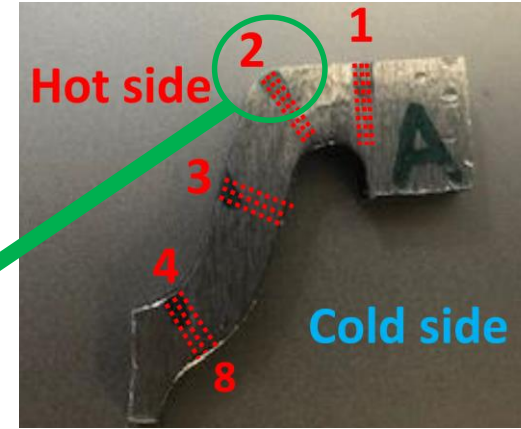
- Machined crown
- Forged skirt/bottom
- Rotary friction weld
- Bushingless design
- Manganese phosphate coating



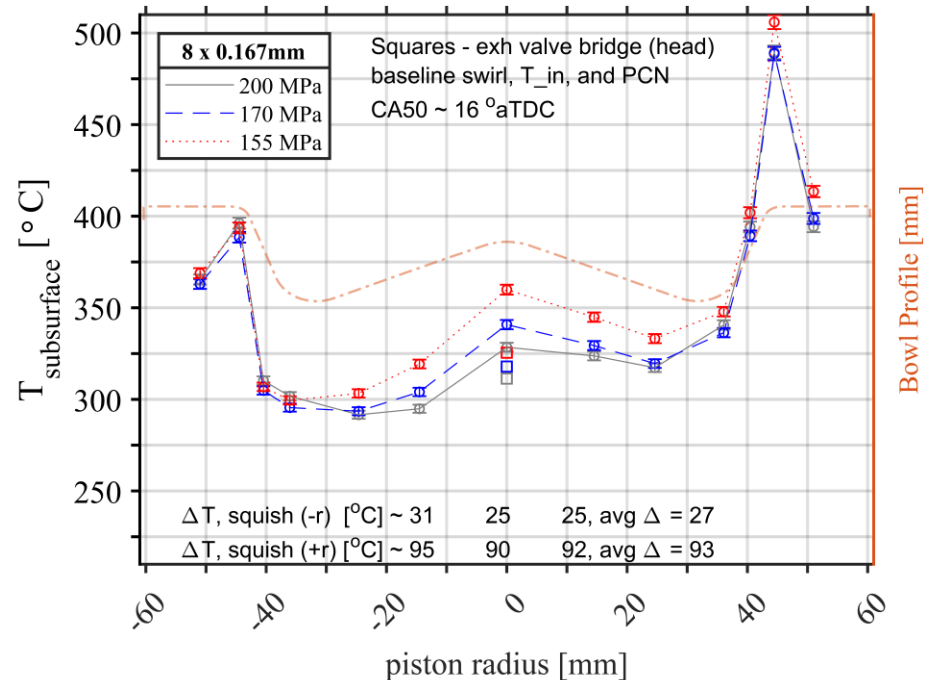
# BASELINE 1: MAS PISTON @ 530 °C BOWL RIM TEMPERATURE



- Oxide thickness at piston bowl rim region ~20  $\mu\text{m}$
- Multi-layer iron oxide
- Localized areas of oxide intrusion noted - *crack nucleation sites*
- Adherent oxide (no major spallation observed)
- Hardness traverses suggest moderate softening (6-7%) at surface due to thermal exposure



\* Example subsurface piston temperature distribution – not representative of actual 530°C test



DISTRIBUTION A. See first page.



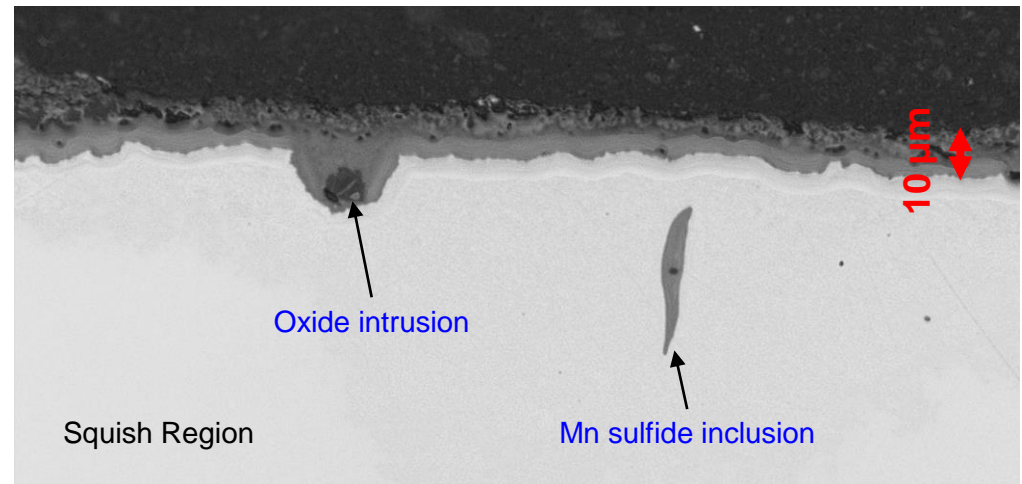
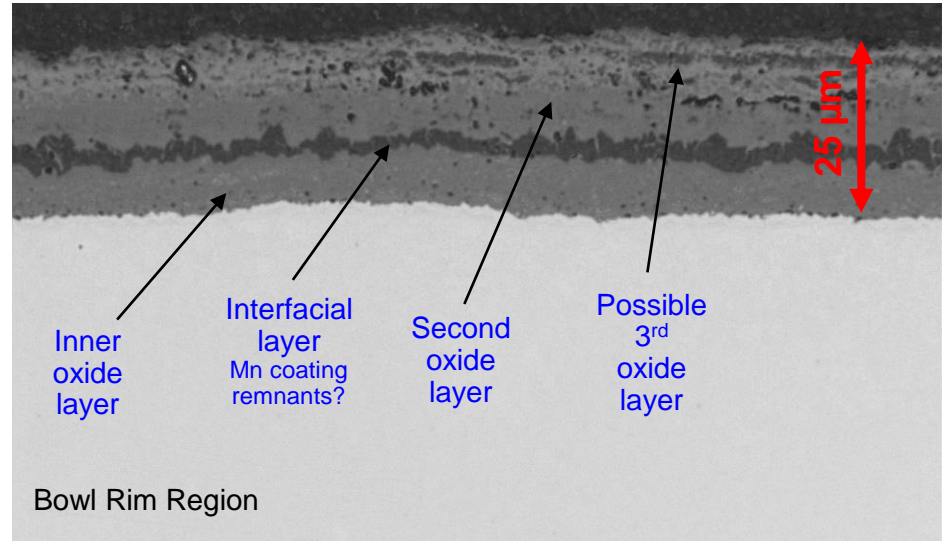
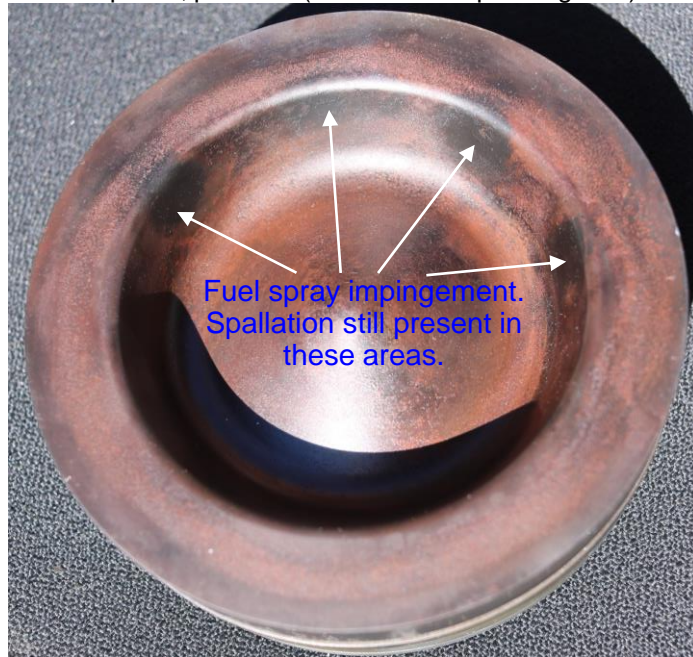
# BASELINE 2: 4140 PISTON @ 600 °C BOWL RIM TEMPERATURE (1 OF 3)



Example of new piston, pre-test (note Mn phosphate coating)

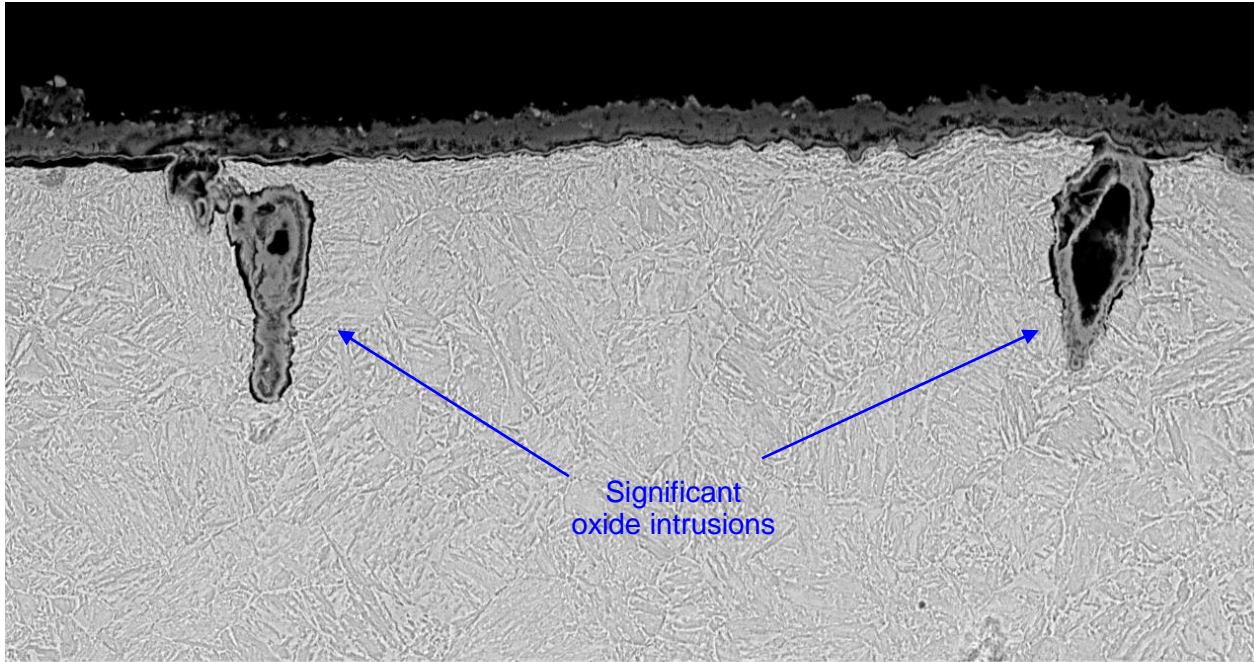


Build 34 piston, post-test (100 hrs total operating time)





# BASELINE 2: 4140 PISTON @ 600 °C BOWL RIM TEMPERATURE (2 OF 3)



HT Piston\_0046

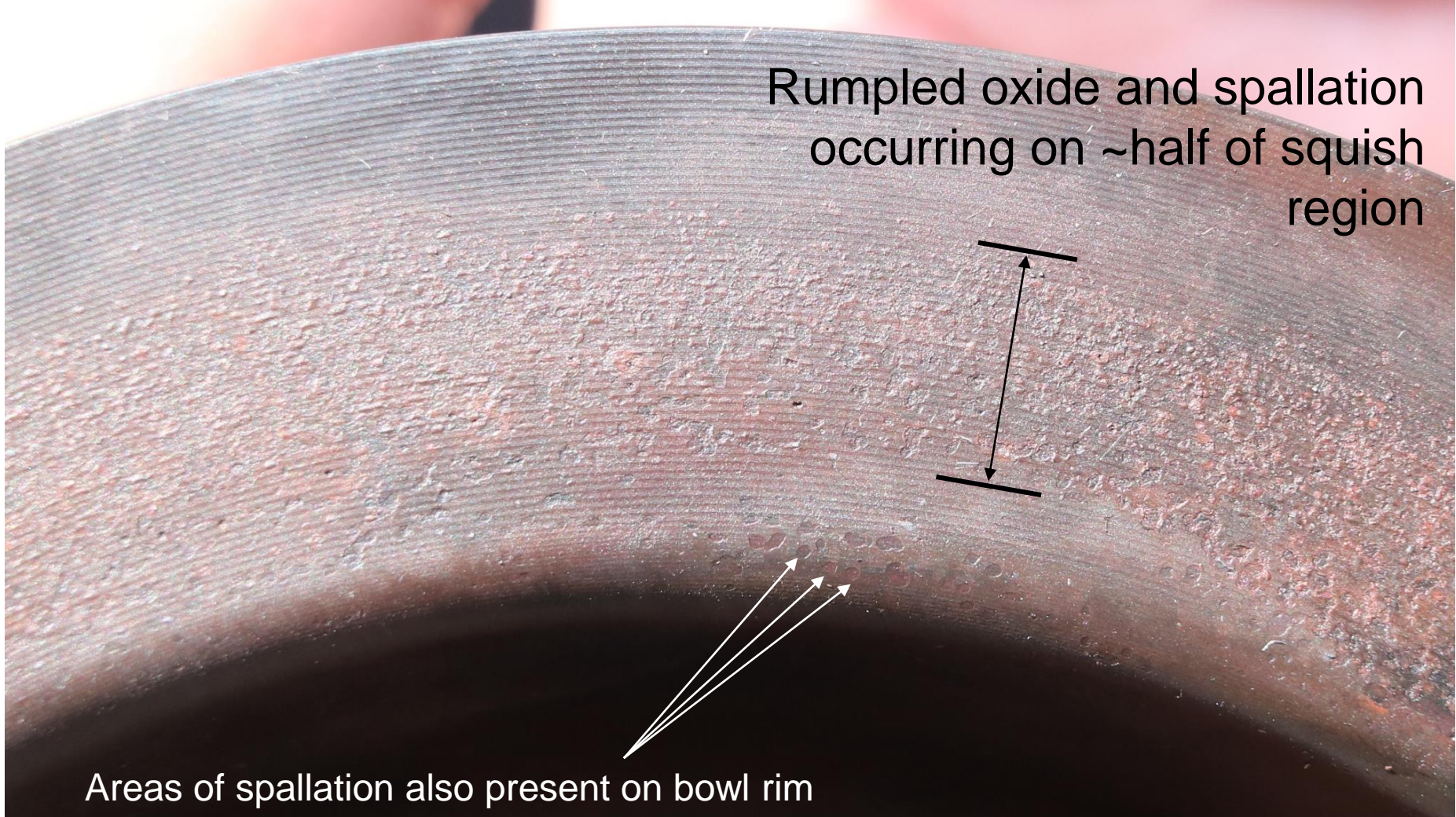
2021/06/07

HL D4.9 x1.0k 100 um

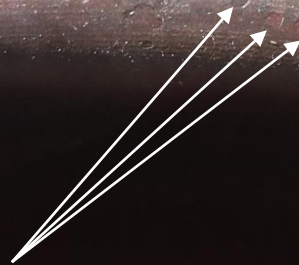
4140 Piston Abuse Test



# BASELINE 2: 4140 PISTON @ 600 °C BOWL RIM TEMPERATURE (3 OF 3)



Rumpled oxide and spallation  
occurring on ~half of squish  
region



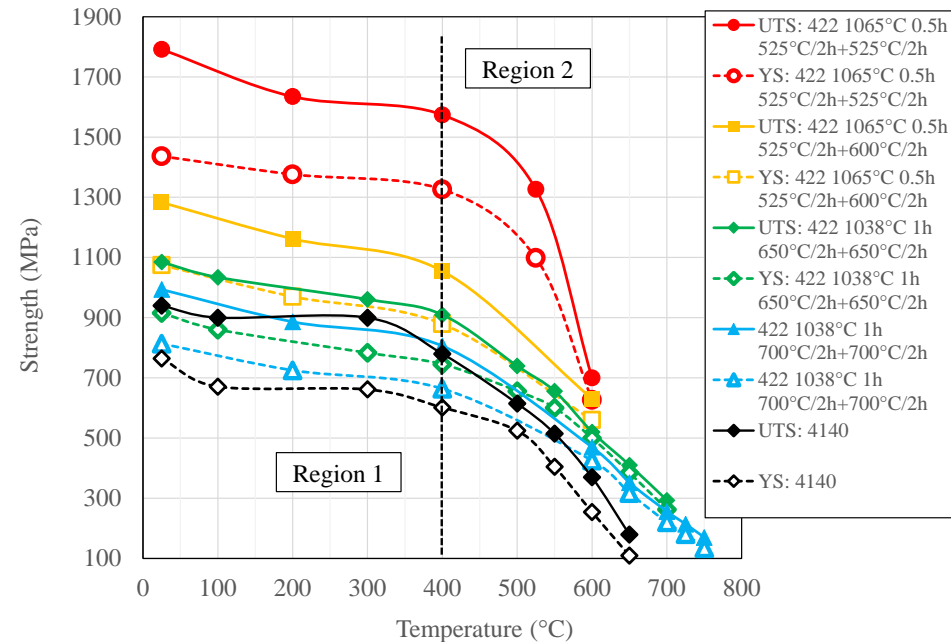
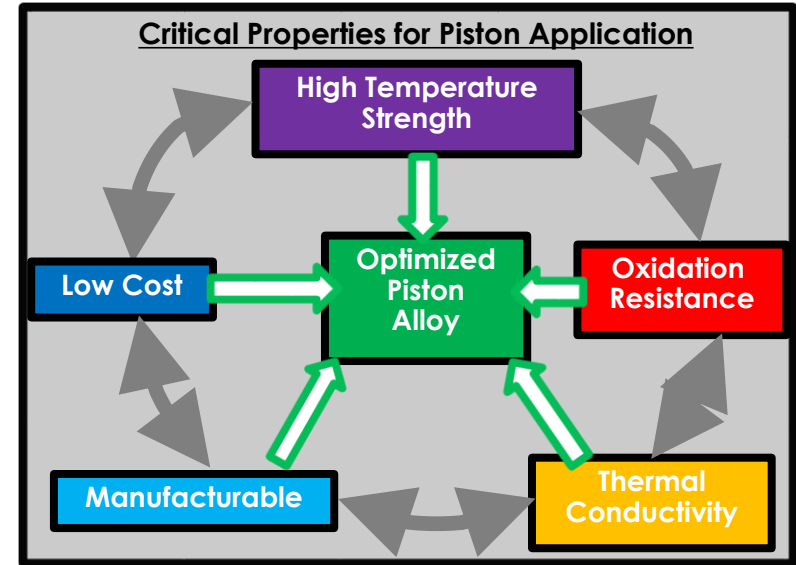
Areas of spallation also present on bowl rim



# SELECTION CRITERIA FOR CANDIDATE COMMERCIAL ALLOYS



- Significant increase in oxidation resistance (relative to MAS and 4140)
  - Acceptable oxidation kinetics
  - Resistance to spallation
  - Resistance to oxide intrusion
- Mechanical properties
  - Hardness, strength and elastic properties
  - Must also pass fatigue life assessment
- Thermal properties
  - Conductivity,  $k = \alpha \rho c_p$
  - Thermal expansion
- Manufacturability
  - Rotary-friction weldable to 4140 bottom forging (constraint for prototyping effort)
- Machinability (35 HRC)
- Affordability: ~ \$4/lb
- Service life
  - Military qualification purposes
  - 250-500 hrs at peak piston temperature (rated power condition)





# COMMERCIAL STEELS OF INTEREST



- Green: Strong candidates to meet future performance requirements
- Orange: Improved properties over 4140 and MAS, but unlikely to meet all requirements
- Red: Existing commercial steels used in HD pistons (not suitable for next generation)
- Continuing to update/refine matrix as research progresses

Table: Weight percent elemental composition of candidate alloys

Composition (wt.%)															
Alloy	Crystal Structure	Ni	Mn	C	Cr	Si	V	Mo	W	S	P	Fe	Ti	Co	Nb
MAS (Tess)	BCC	0.4	1.4	0.41	0.15	0.52	0.09	0.036	-	0.045	0.013	96.836	<0.0005		<0.002
4140	BCC	0	0.9	0.4	1	0.3	0	0.2	0	0.024	0.01	97.559			
H10 modified	BCC	0	0.55	0.4	3.25	1	0.4	2.5				89.9		2	
1.2367	BCC	BCC	0.35	0.36	5.07	0.25	0.65	2.8				90.52			
DHA-HS1	BCC														
DH31-EX	BCC	0.14	0.92	0.33	5.43	0.34	0.53	2.36		<0.002	0.011	89.879			
422U (Universal Stainless)	BCC	<b>0.8</b>	0.66	0.21	<b>11.22</b>	0.3	0.24	0.98	1	<0.0005	0.016	84.42			
422C (Crucible Materials)	BCC	<b>0.79</b>	0.78	0.23	<b>12.09</b>	0.36	0.22	1.08	0.96	0.006	0.019	Bal.			
418	BCC	<b>2</b>	0.37	0.17	<b>12.3</b>	0.23	0.04	0.08	2.78	<0.0005	0.016	81.829			
Inc625	FCC	Bal.	0.5 max	0.1 max	21.5	0.5 max		9					0.4 max	1.0 max	3.75

**\*\*Prototype 422/4140 pistons in progress\*\***

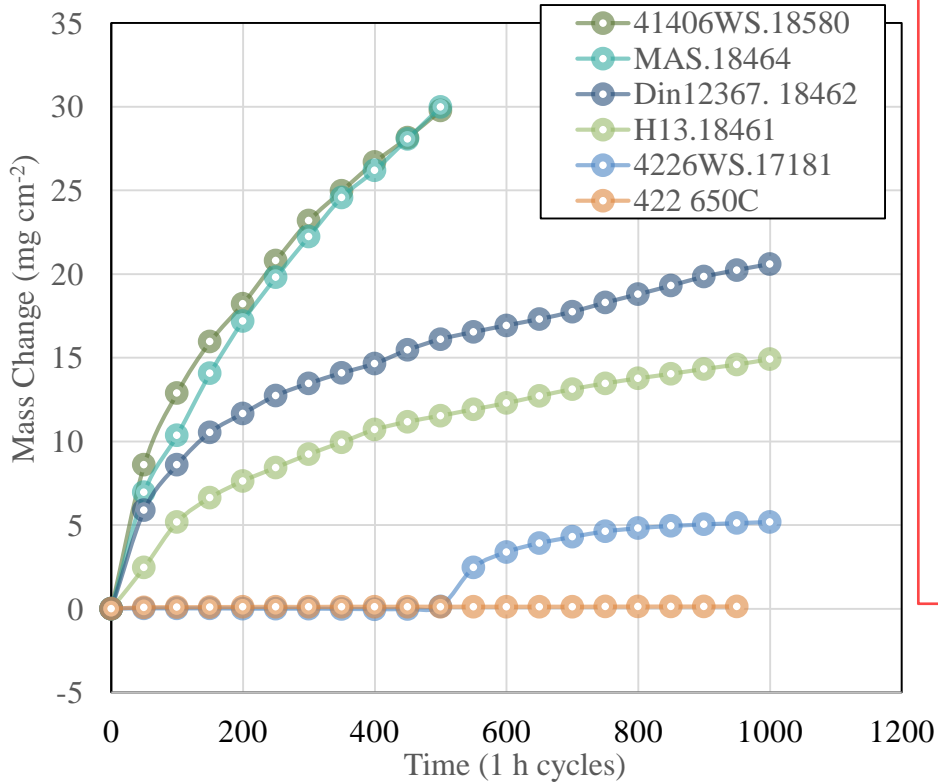


# LONG-TERM CYCLIC OXIDATION TESTING



- Air + 10% H<sub>2</sub>O
- Severe spallation in MAS at 600 °C
- Thick oxide scale in 4140
- 422 performs well

Cyclic Oxidation Testing at 600°C in air  
Plus 10% H<sub>2</sub>O, 1h Cycles

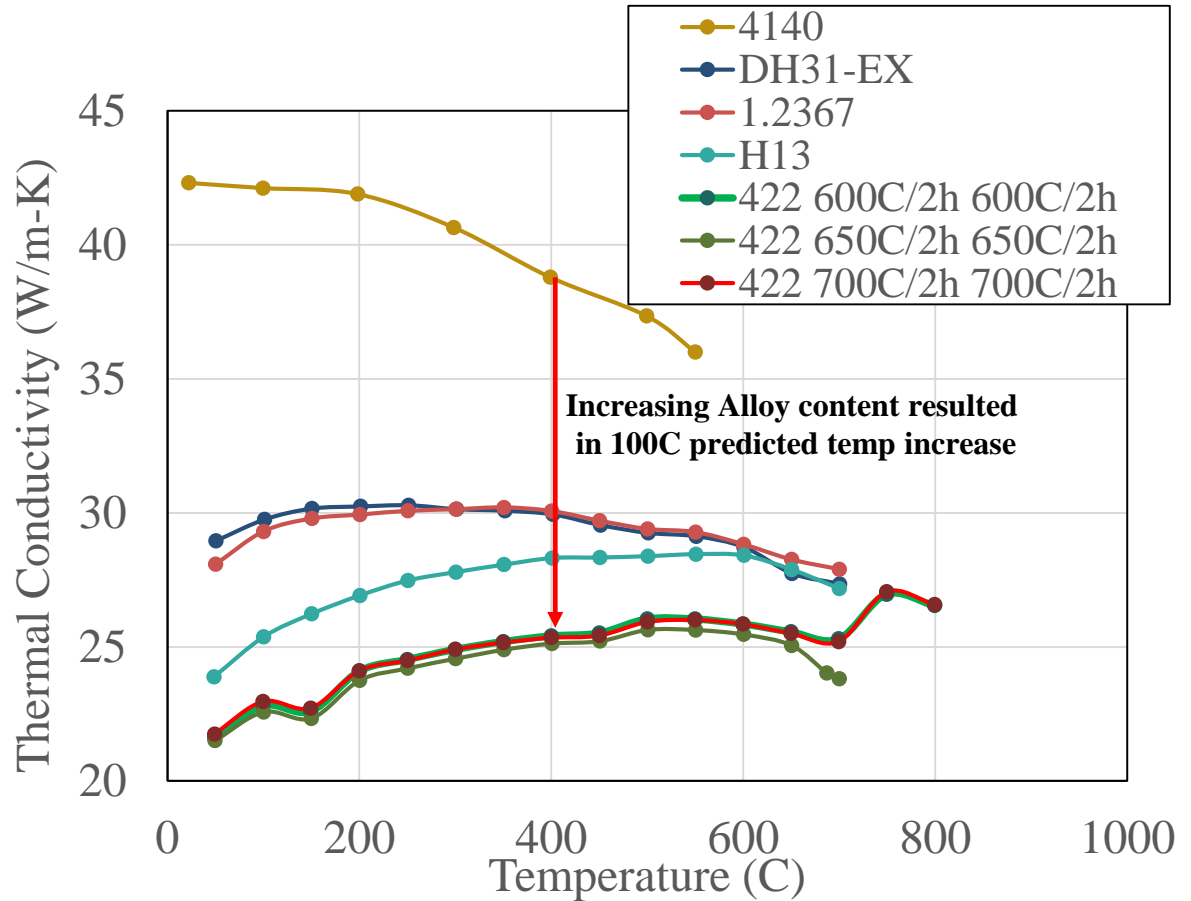




# THERMAL PROPERTIES



- Heat is conducted by electrons and phonons (lattice vibrations)
- Alloying elements scatter electrons and phonons
- Higher alloyed steels have:
  - Lower thermal conductivity
  - Operate at higher temps, partially negating strength and oxidation benefits





# 422 CROWN / 4140 SKIRT PISTON DISPLACEMENT



- Operating condition 3 (2500 rpm, 20 bar IMEPg)
- Displacement Scaled 40x
- Significant thermal arching about upper flank root of friction welds

Contour Plot  
Displacement(Y)  
Analysis system

4.441E-04
3.454E-04
2.467E-04
1.480E-04
4.934E-05
-4.934E-05
-1.480E-04
-2.467E-04
-3.454E-04
-4.441E-04
No result

Max = 4.441E-04  
PART-1-1 1298139  
Min = -4.441E-04  
PART-1-1 16444





# 422 CROWN / 4140 SKIRT STEADY-STATE TEMPERATURE AND STRESSES



## Signed VonMises Stress (Pa)

Bowl Wall  
Temperature = 711 C  
Compressive Stress = -283 MPa

Bowl Top  
Temperature = 698 C  
Tensile Stress = 239 MPa

Friction Weld 1  
Temperature = 160 C  
Tensile Stress = 344 MPa

Gallery 5  
Temperature = 372 C  
Tensile Stress = 355 MPa

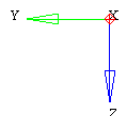
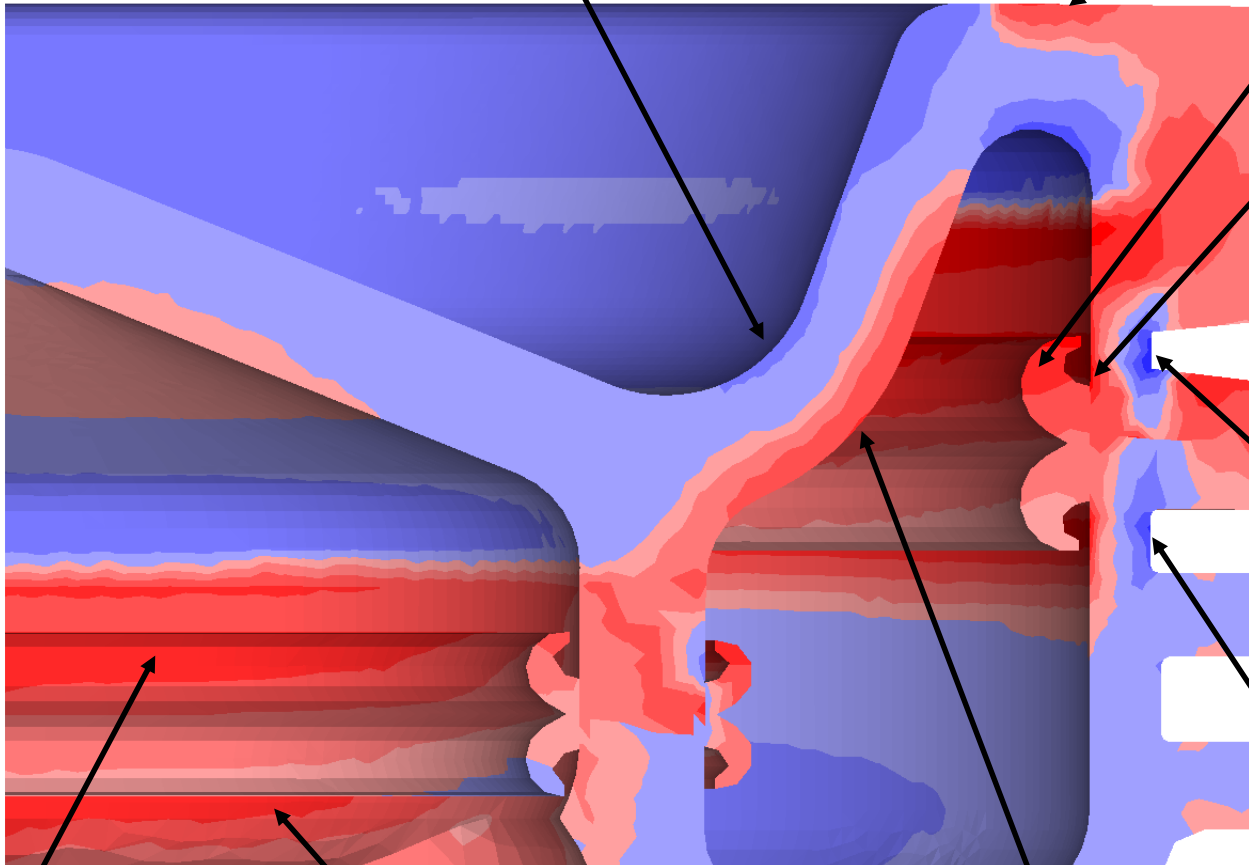
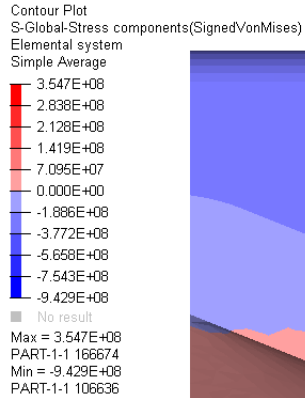
Grv 1<sup>st</sup> RT  
Temperature = 244 C  
Compressive Stress = -822 MPa  
@ HAZ  
Temperature = 209 C  
Compressive Stress = -943 MPa

Grv 2<sup>nd</sup> RT  
Temperature = 149 C  
Compressive Stress = -714 MPa  
@ HAZ  
Temperature = 154 C  
Compressive Stress = -766 MPa

Gallery 1  
Temperature = 546 C  
Tensile Stress = 245 MPa

Under Crown @ HAZ  
Temperature = 175 C  
Tensile Stress = 316 MPa

Friction Weld 2  
Temperature = 185 C  
Tensile Stress = 273 MPa






# OXIDATION TEMPERATURE LIMITS



- **Challenge:** Steels with higher oxidation resistance exhibit lower thermal conductivity, causing higher operating temperature, partially negating improved oxidation resistance
- “Usable temperature increases” are obtained based on material oxidation limits

- 12Cr 422 forms slow growing, adherent, chromia scale, with high oxidation resistance to ~700°C
- 3-5 wt.%Cr DH31-EX and H10 form fast growing Fe oxide scale, result in lower “usable temp” increase
- HTCS-130 high thermal conductivity steel exhibits excellent usable temperature increase, despite Fe oxide formation, but potential oil coking

Oil Flow Rate, lpm	A286	422	DH31-EX	H10	MAS	HTCS-130 (estimated)
8.9	619	550	528	494	466	391
6.1	638	571	550	516	488	413
5.6	649	584	562	528	500	425
5.2	659	595	573	539	511	436
 4.7	676	614	592	557	530	455
4.15	695	636	614	579	551	476
3.15	746	690	669	632	604	529
Oxidation Limit	704	760	600	585		550
Usable Temp increase over MAS (oxidation limited)	28	146	8	28		95
<div style="border: 1px solid blue; padding: 5px; display: inline-block;">Relative to predicted piston temperature at 4.7 lpm oil flow rate</div>						
Only minor oxidation expected at these temperatures for 250-500h						
Modearte Oxidation, likely acceptable for 250-500h						
Rapid Oxidation, not recommended for 250-500h						
Above manufacturers recommendation of 704C. Testing at ORNL recommended						



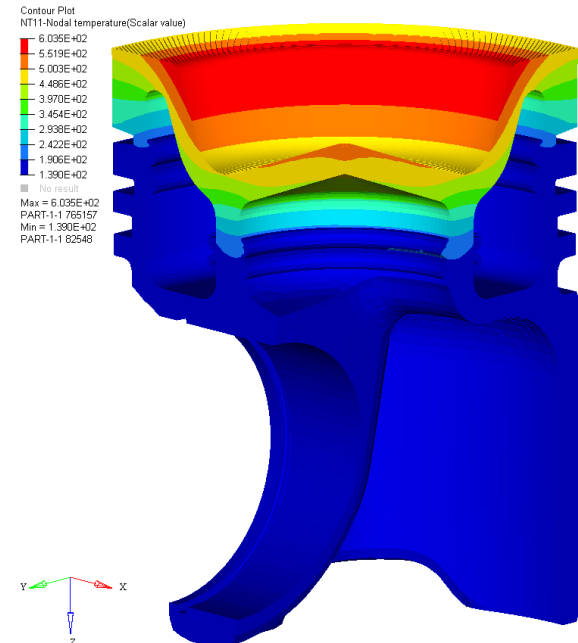
## SUMMARY / FUTURE WORK



- **GVSC is committed to improvements in IC engine efficiency, heat rejection, and power density**
- **Cross-functional and multidisciplinary team actively engaged in high-temperature piston alloys**
- **Several commercially available alloys were identified with potential increases in the oxidation temperature limit**
- **Significant metallurgical challenge to balance strength, oxidation resistance, thermal conductivity, manufacturability, and cost**

### Future Work

- **Down-select four commercial alloys (ORNL)**
- **Prototype piston manufacturing (Tenneco)**
  - Alloy 422 in progress
- **Engine testing (GVSC)**
- **Post-mortem analysis**
- **Longer-term multi-cylinder engine testing**
- **Alloy development**





# Thank You!

Questions?



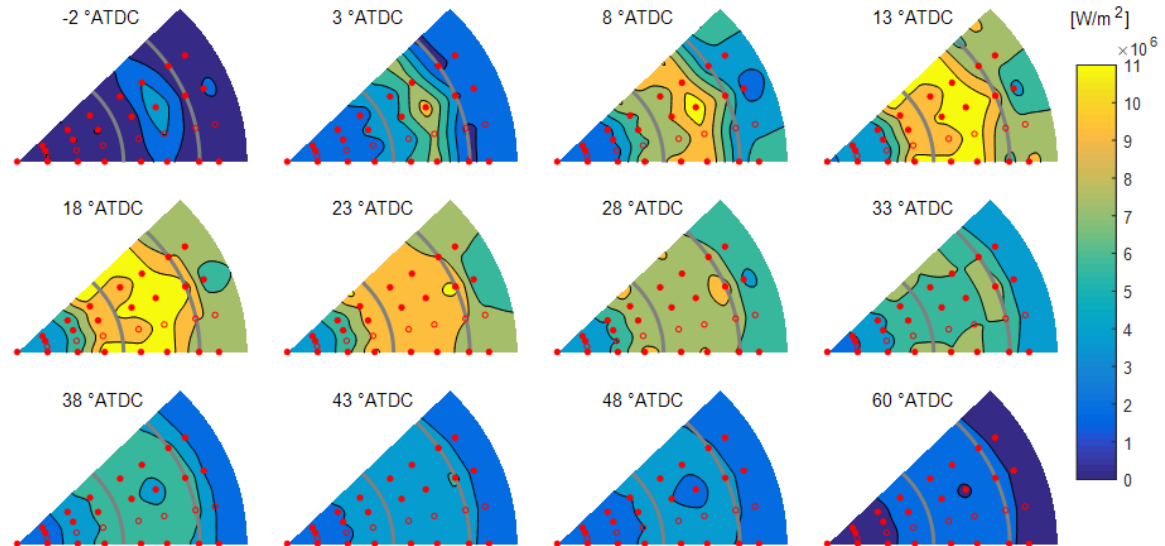
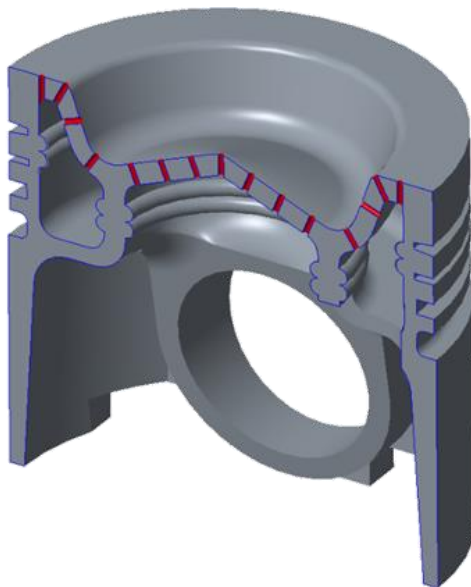
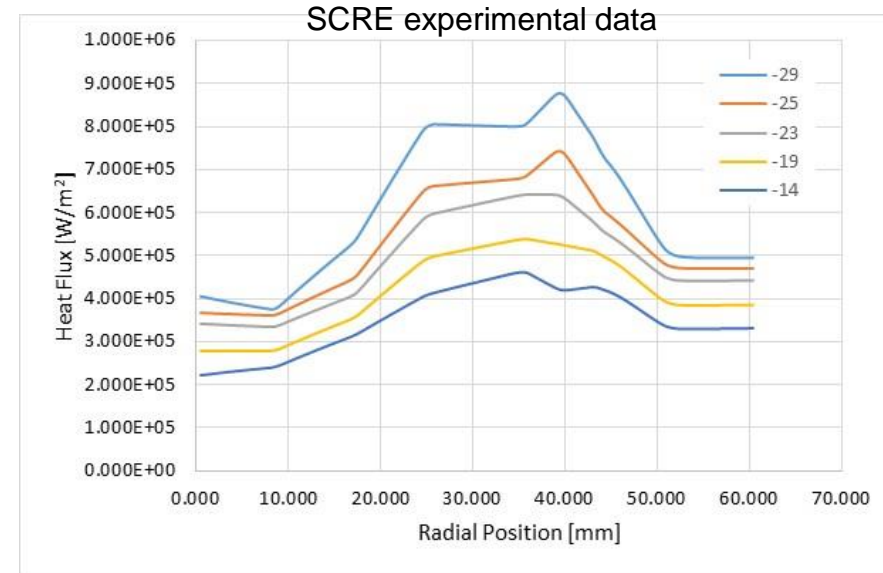
# Backup Slides



# PISTON CROWN HEAT FLUX BOUNDARY CONDITION



- Model rated power operating condition
  - 2500 rpm,  $IMEP_g = 20.3$  bar
  - Start of injection command (SOIC)  $-25^\circ$  aTDC
- Assume heat flux only a function of radius (constant in azimuthal direction)
- Heat flux generated from surface fast-response thermocouple measurements in a single-cylinder research engine (SCRE)
  - Gingrich, Eric, *High-output Diesel Engine Heat Transfer*. PhD dissertation, University of Wisconsin - Madison, 2020.



DISTRIBUTION A. See first page.



# PISTON OIL GALLERY BOUNDARY CONDITION



- Operating condition:
  - 2500 rpm, 20.3 bar mean effective pressure
  - Peak cylinder pressure ~ 200 bar
- Surface heat flux on piston crown based on surface-mounted, fast-response piston thermocouple measurements in SCRE
- Calibrate the FE model heat transfer coefficients on the under-crown surfaces to match embedded (subsurface) thermocouple (TC) measurements of an MAS piston in SCRE

