



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

Center for Thermal Spray Research:
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Michael Tess and Eric Gingrich
Research Mechanical Engineer
Ground Vehicle Power & Mobility

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OUTLINE



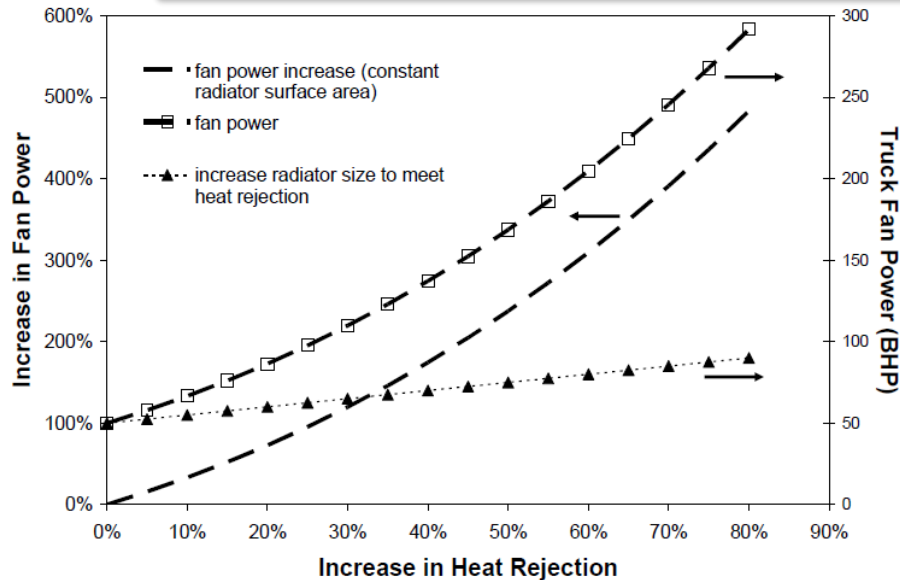
- Motivation
- TBC Piston Experimental Matrix
- Engine Results
 - YSZ thickness effects
 - TBC thermal property effects
 - TBC surface effects
- Build 17 Postmortem
- Final Thoughts



ARMY MOTIVATION



- Army ground vehicles are subject to a range of vehicle-level requirements that impact the design and selection of the power plant
 1. **Duty cycle**- The combat vehicle duty cycle is more heavily weighted toward low-load when compared to on-road commercial trucks.
 2. **Reliability versus durability**- The lifetime of a combat vehicle is significantly less than a commercial truck. In peacetime combat vehicles cover less than 1,000 miles per year whereas commercial trucks accumulate up to 250,000 miles annually. Additionally, the inability of a combat vehicle to operate in the critical moment may be fatal.
 3. **Extremes of operating conditions**- Combat vehicles are required to operate at extreme ambient temperatures from -60 to 120F while maintaining vehicle propulsion requirements (e.g top speed, gradeability, acceleration, etc.). Additionally, the terrain that these vehicles operate over are extreme and may include paved roads, snow, ice, sand or mud.
 4. **Armor enclosure**- The entire propulsion system is enclosed in armor for combat vehicles. Ballistic grilles are used on air inlets and outlets which can drive up the cooling system fan power to as much as 10 to 15 percent of propulsion system power.



Thermal barrier coating may offer a way to:

- Reduce heat rejection to cooling system
- Increase engine durability (lower piston substrate temperatures at extreme operating conditions)
- Increase engine efficiency



TBC PISTON EXPERIMENTAL MATRIX



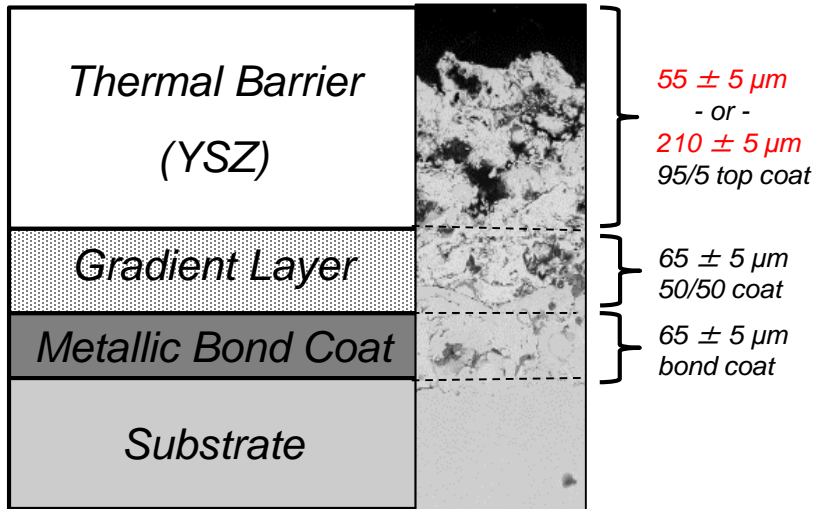
TBC ID / Engine Build	Architecture	As-Sprayed Thickness [mm]	Installed Thickness [mm]	Thermal Conductivity [W/m-K]	Surface Roughness, Ra [μm]	Purpose	
Previously reported	TBC1 / EB2 S-3652#5	YSZ	0.185	0.21	0.85	Ra ~ 12 μm	Thin TBC
	TBC2 / EB3 S-3652#2	YSZ	0.325	N/A (reused-TBC10)	0.85	Ra ~ 12 μm	Thick TBC
	TBC3 / EB5 S-3652#3	YSZ	<0.325 (sanded)	0.31	0.85	Ra ~ 6 μm	Lower Ra
	TBC4 / EB9 S-3652#8	YSZ	<0.295 (sanded)		0.85	Ra ~ 6 μm	Same as TBC4, instrumented with thermocouples at metal surface (subsurface to coating)
	TBC5 / EB12 S-3652#13	Cordierite/YSZ	<0.295 (sanded)	N/A (reused-TBC11)	0.39	Ra ~ 11 μm	Thermal swing
	TBC6 / EB13 S-3652#14	Cordierite/YSZ	<0.295 (sanded)	0.18	0.39	Ra ~ 7 μm	Thermal swing, lower Ra
New since fall 2018	TBC7 / EB14 S-3652#6	YSZ	<0.185 (sanded)	0.14	0.85	Ra ~ 4 μm	Thin TBC with lower Ra
	TBC8 / EB15 S-3652#4	Cordierite/YSZ	0.21-0.23 (final)	0.35	0.50	Ra ~ 10 μm	Improved process (F4MB-XL torch), microstructure, and thermal properties
	TBC9 / EB17* S-4706#007	Porous YSZ + dense sealing layer	0.30 (final)	0.60	1.3-1.5 (effective)	Ra ~ 2 μm	Sealing layer to minimize Ra *Head interference
	TBC10 / EB18 S-3652#2	Porous YSZ + dense sealing layer	0.18 (final)	0.21	1.3-1.5 (effective)	Ra ~ 3 μm	Thin sealing layer *Currently on test
	TBC11 / TBD S-3652#13	Porous YSZ + residual sealing layer	0.30	TBD	N/A	TBD	Heavy sanding to remove sealing layer Goal: surface cavities



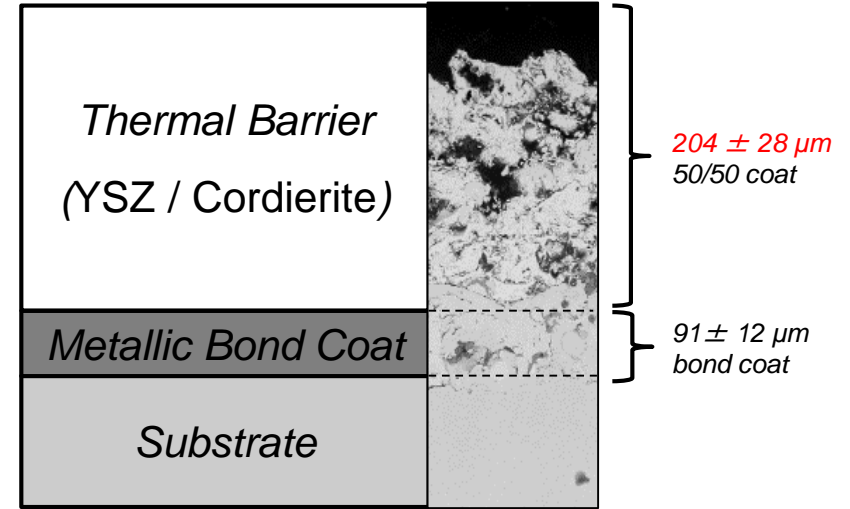
REVIEW OF PREVIOUS WORK (1 OF 2): TBC ARCHITECTURE



YSZ



Blended YSZ / Cordierite

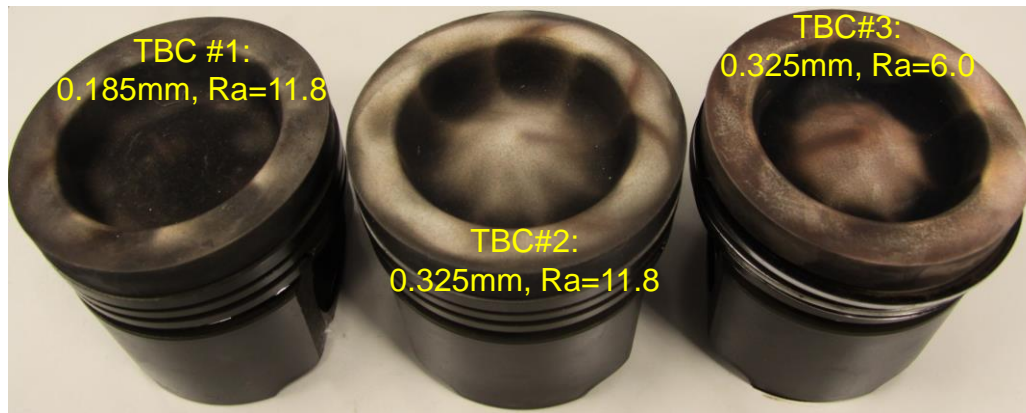
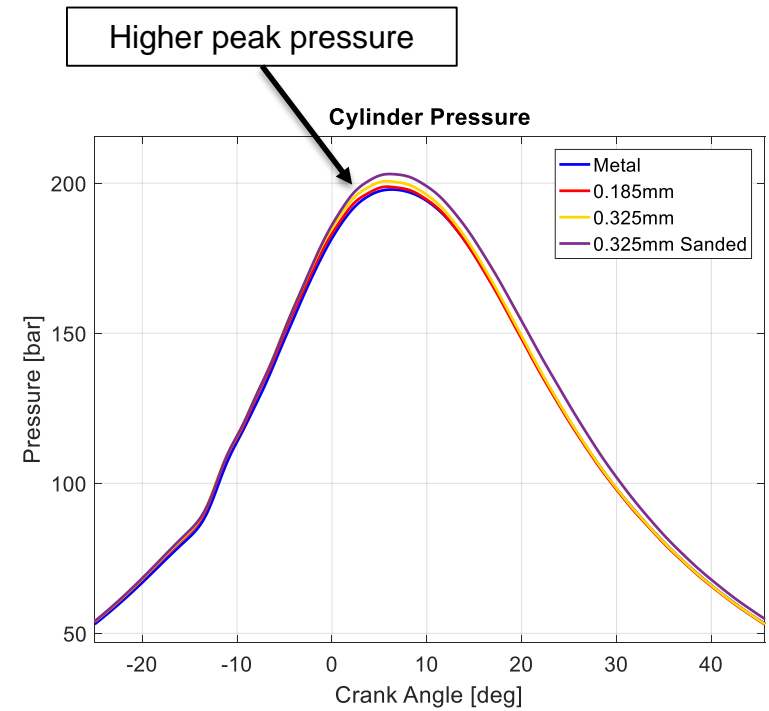
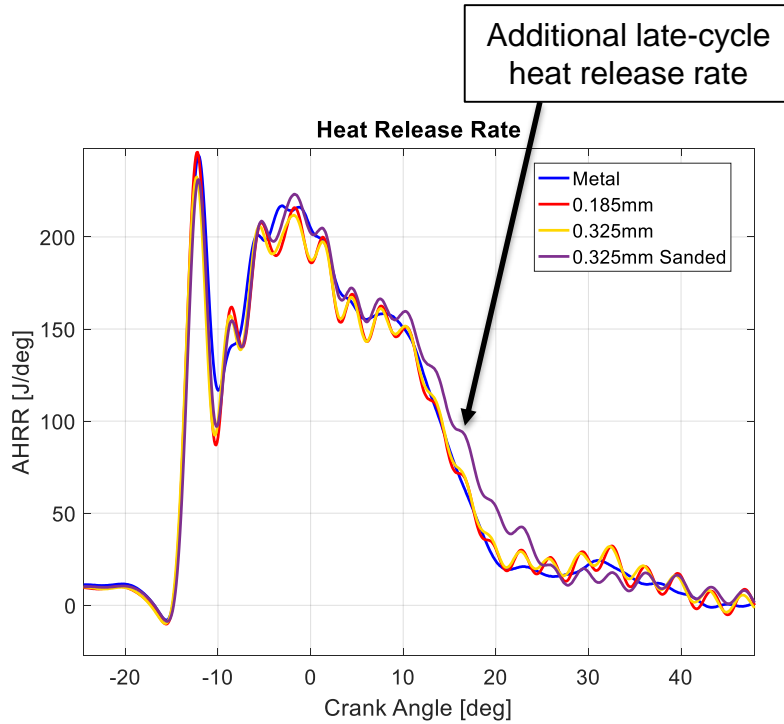


Piston	As-Sprayed Thickness [mm]	Roughness, Ra [um]	Material
Metal	0.0	~2.0	Steel
TBC 1	0.185	11.8	YSZ
TBC 2	0.325	11.8	YSZ
TBC 3	0.325	6.0	YSZ

Piston	As-Sprayed Thickness [mm]	Roughness, Ra [um]	Material
Metal	0.0	~2.0	Steel
TBC 5	0.325	10.5	YSZ / Cordierite
TBC 6	0.325	7.3	YSZ / Cordierite



REVIEW OF PREVIOUS WORK (2 OF 2): ENGINE DATA





THICKNESS EFFECTS – TBC 7 BUILD 14

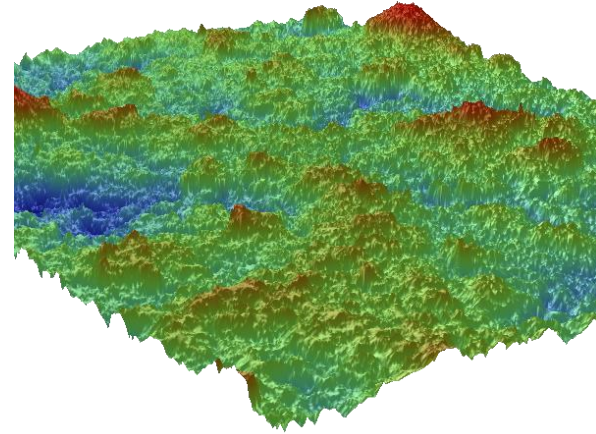


Circles: Optical profilometry measurement locations (12, 3, 6, and 9 o'clock positions of squish region)

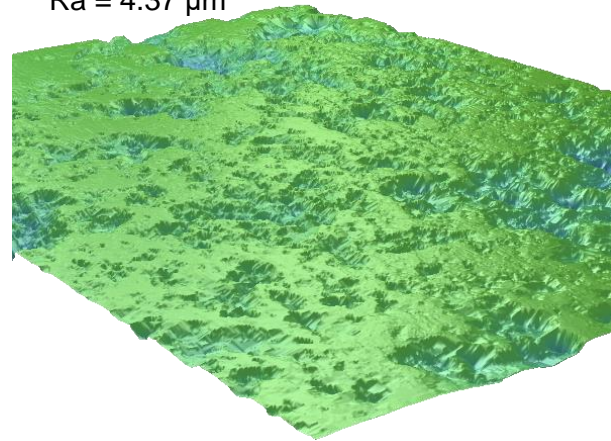
- Piston before installation in engine



- After 15 hours of engine firing time, 75% at high load



Optical profilometry @5x magnification:
unsanded (top) and sanded (bottom)
Ra = 4.37 μm





THICKNESS EFFECTS – TBC 7 BUILD 14



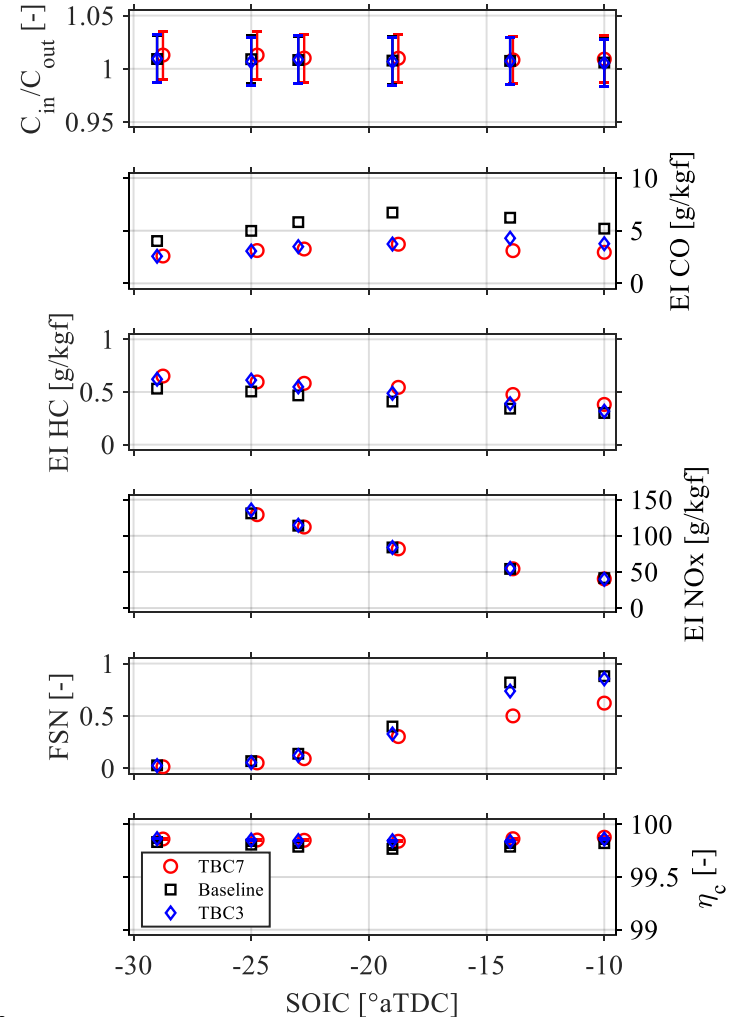
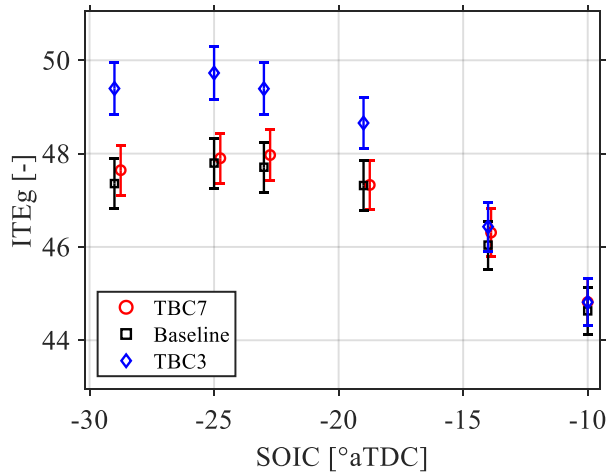
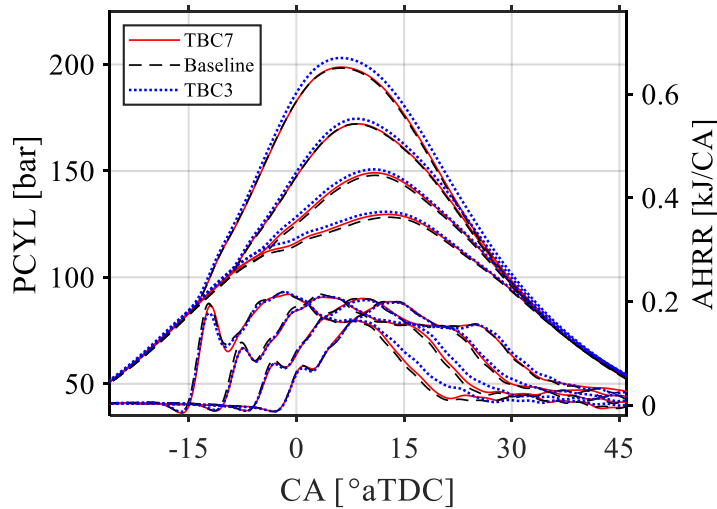
- Piston before installation in engine



THICKNESS EFFECTS – TBC 7 BUILD 14



- Cylinder pressure (PCYL) and apparent heat release rate (AHRR) similar to the baseline case
- Similar emissions for all cases
- Gross indicated thermal efficiency (ITE_g) for the thin coating is less than the thick coating, equivalent to the metal baseline

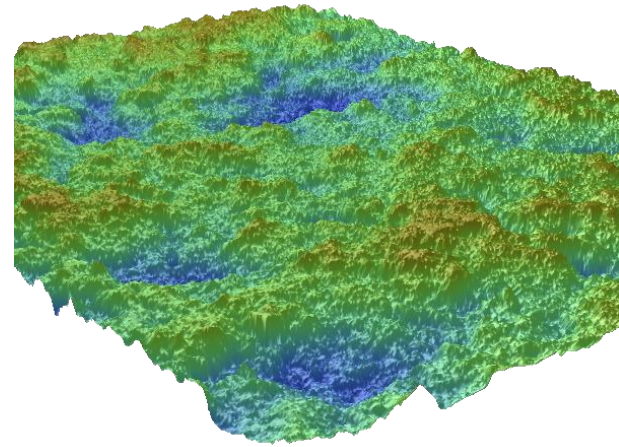




- Piston before installation in engine



- After 25 hours of engine firing time, 90% at high load



Optical profilometry @5x magnification after sanding

Ra = 10.84 μm



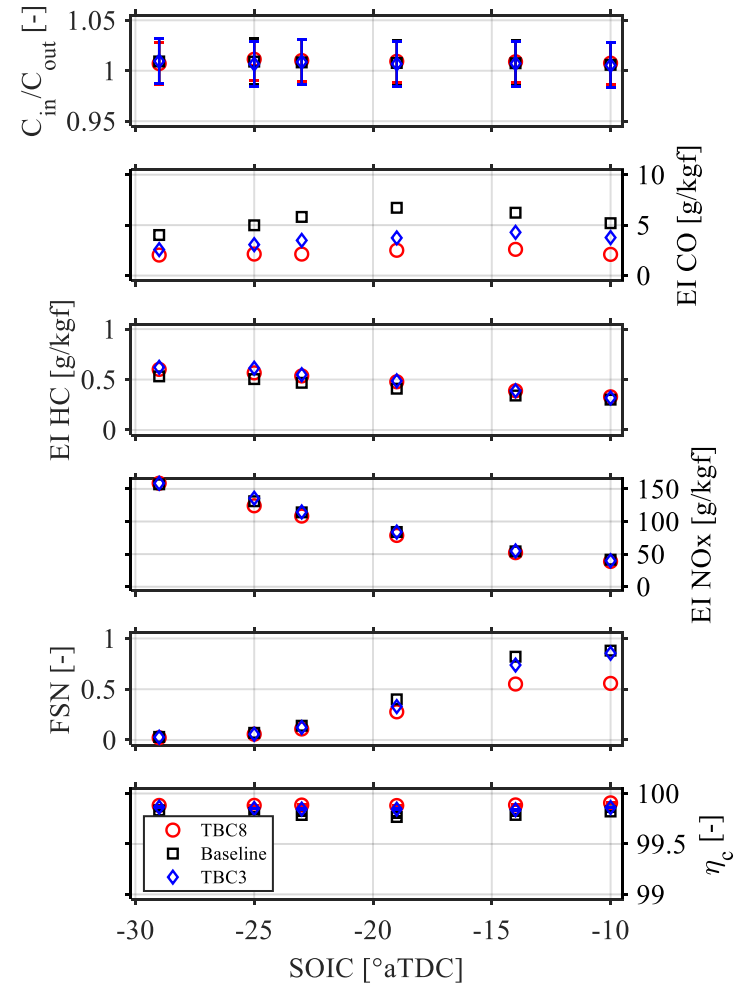
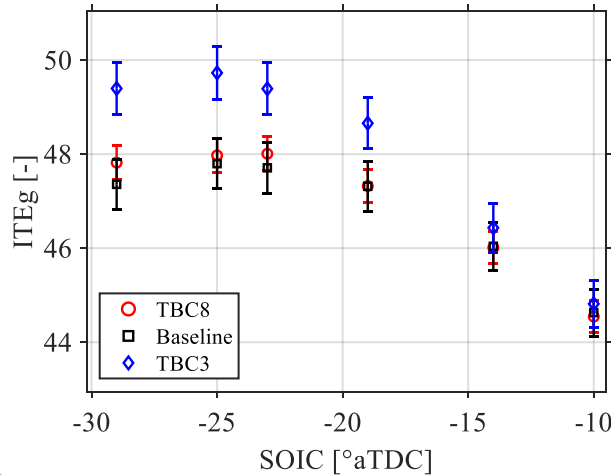
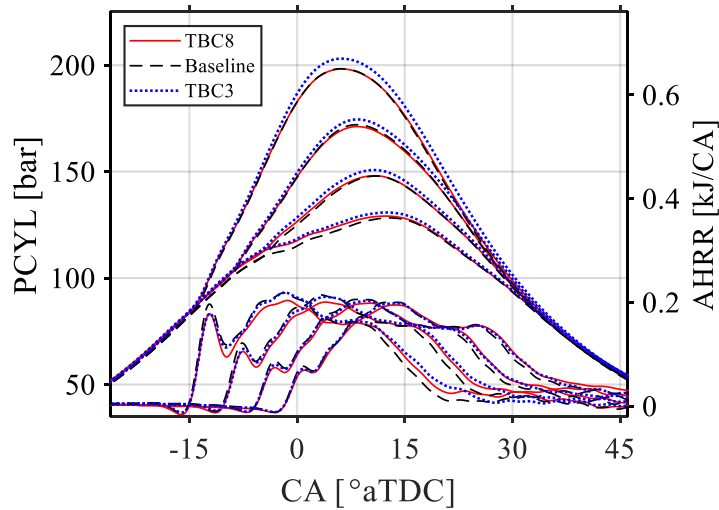
- Piston before installation in engine



CONDUCTIVITY EFFECTS – TBC 8 BUILD 15

GROUND VEHICLE
SYSTEMS CENTER

- Similar cylinder pressure and heat release rate profiles
- Similar emissions for all cases
- Efficiency for the lower conductivity coating less than the 0.325mm sanded YSZ, equal to the baseline





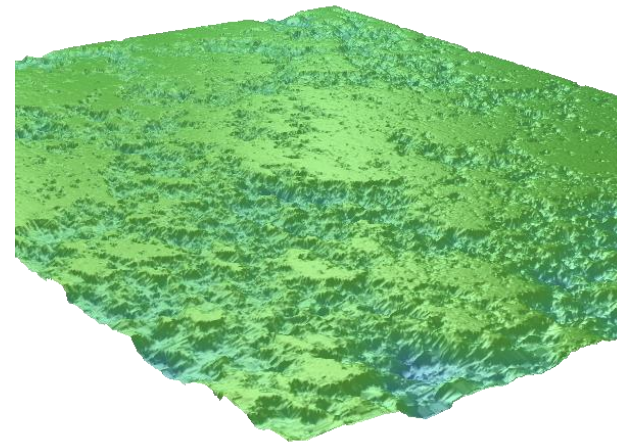
SURFACE EFFECTS – TBC 10 BUILD 18



- Piston before installation in engine



- Borescope of piston in engine (current engine build)
- 15:19 total engine firing time to date, all at high load



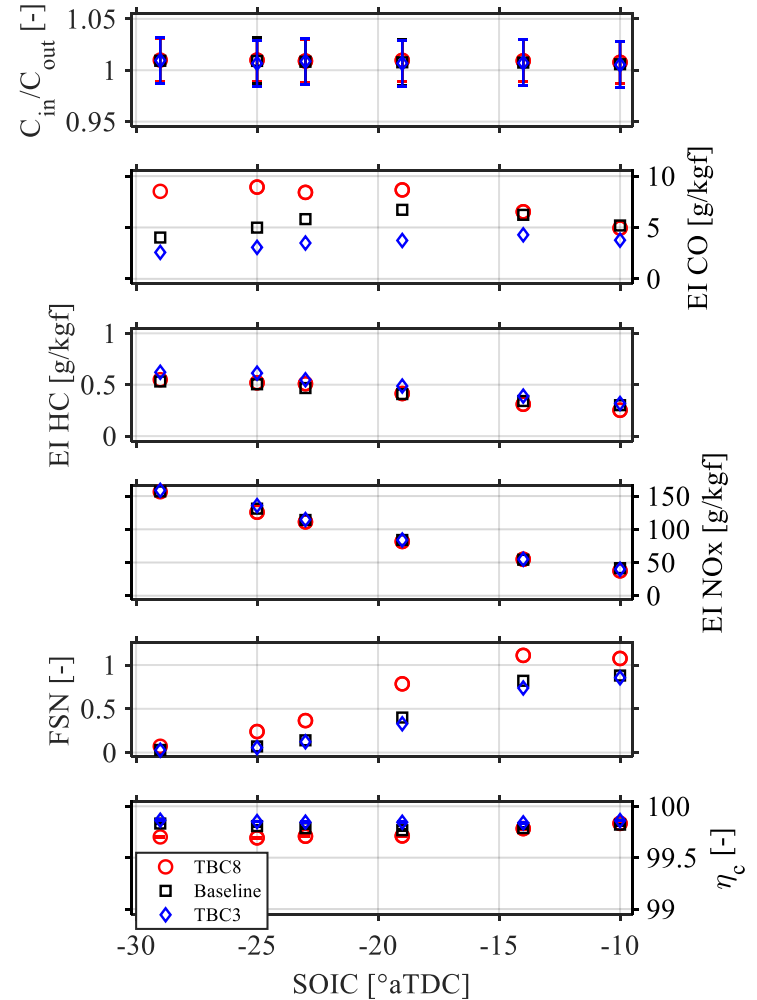
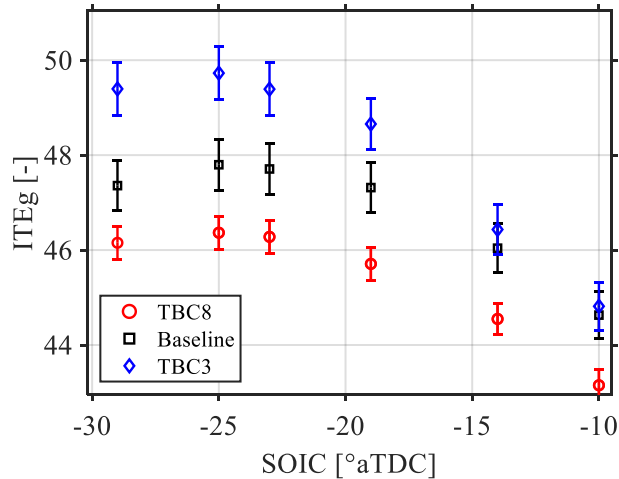
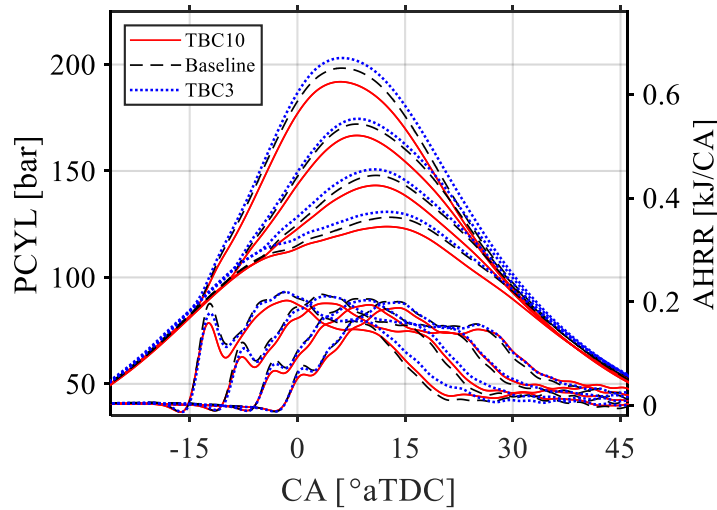
Optical profilometry @5x magnification after sanding
Ra = 3.58 μ m



SURFACE EFFECTS – TBC 10 BUILD 18

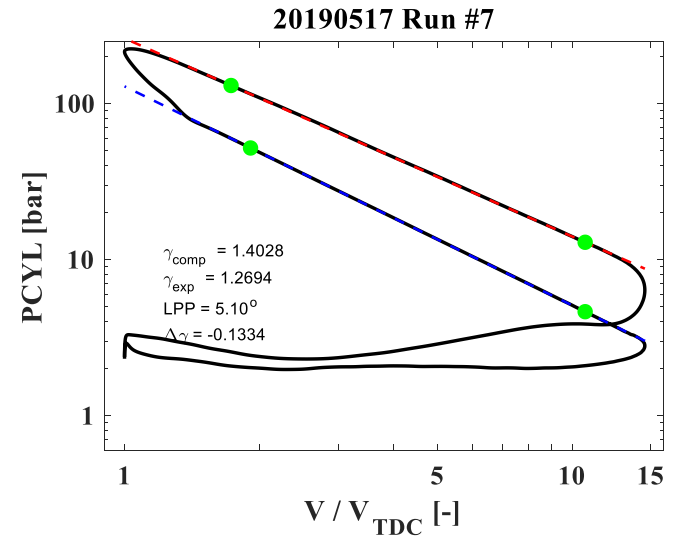


- Cylinder pressure and heat release rate for TBC10 significantly less than baseline case
- Carbon monoxide emissions for TBC 10 slightly higher at most advanced injection timings
- Efficiency significantly less than the baseline for all timings, despite a higher compression ratio

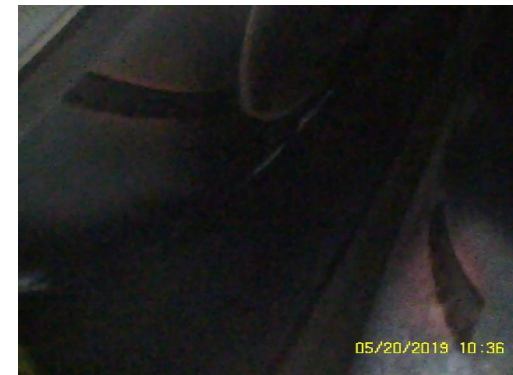




BUILD #17 – THIN DENSE SEALING LAYER

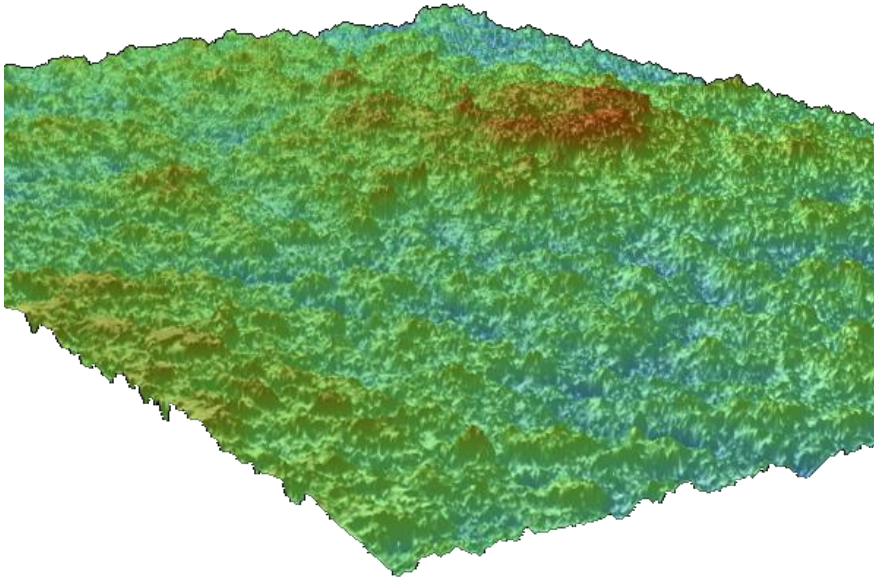


- Day 0 (break-in) engine test plan - 3:19 of engine firing time
- At the end of Day 0, conducted routine diagnostics of a new engine build, including:
 - Check cylinder leakage rate: 7% of 100 psig input pressure (good)
 - Inspect combustion chamber via borescope camera: probable interference between piston and cylinder head

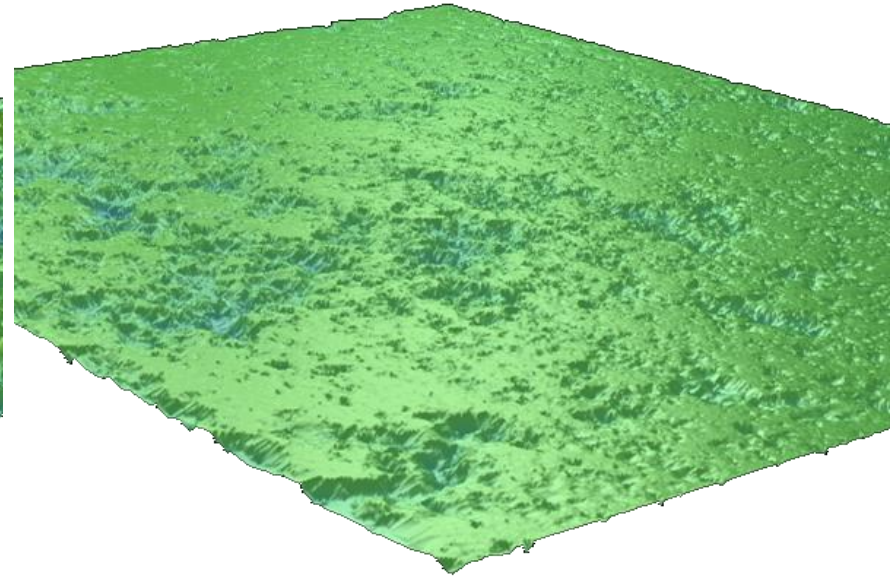




BUILD #17 – THIN DENSE SEALING LAYER



TBC11
Unpolished



TBC9
Polished

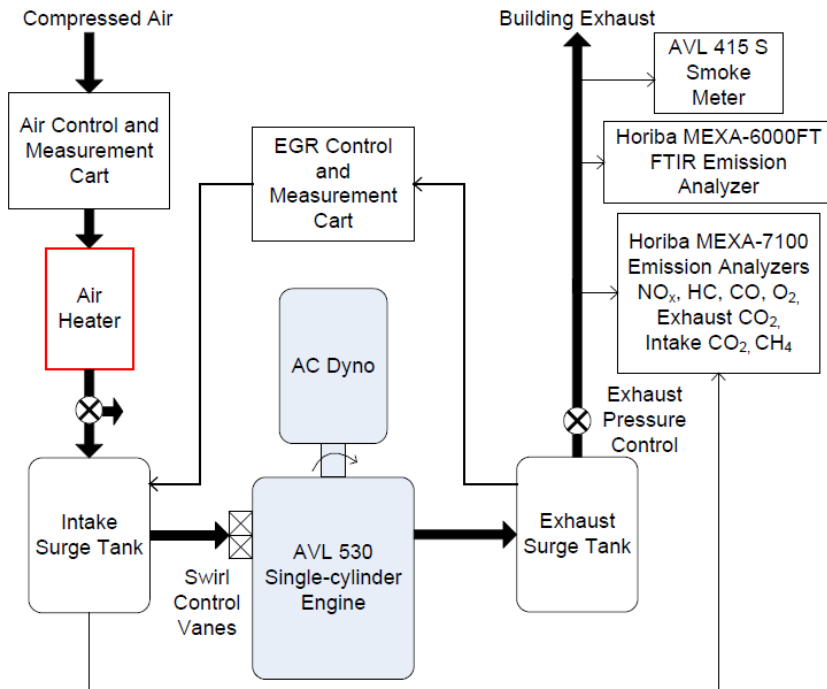
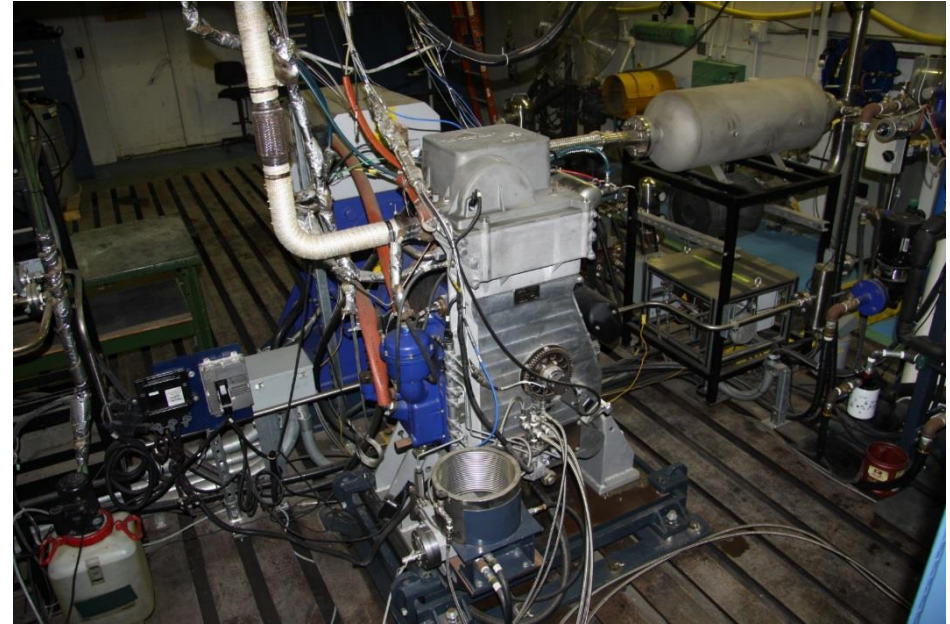
- Optical profilometry @ 5x magnification



SINGLE-CYLINDER RESEARCH ENGINE



Displacement (l)	1.49
Bore (mm)	122
Stroke (mm)	128
Maximum Injection Pressure (bar)	2000
Number of Valves	4
Swirl Ratio (variable)	0-3.5
Peak Firing Pressure (bar)	250



Combustion bowl profile

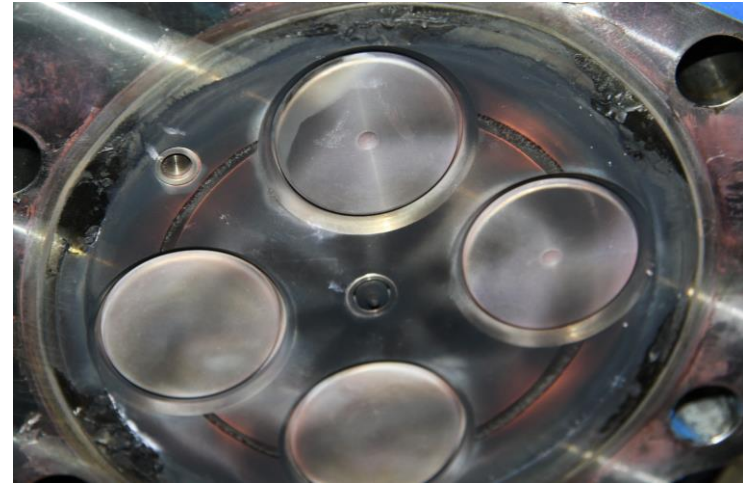


CYLINDER HEAD





BUILD #17 – TEARDOWN PHOTOS



- Piston-to-head clearance:
 - Static: 0.48mm (near bowl, piston rocked up) - 1.04mm (near edge, piston rocked down)
 - Dynamic: < 0mm
 - Cylinder head depression: ~0.1mm
- Coating integrity: no spalling or delamination
 - Vertical micro-cracks around the bowl lip



BUILD #17 – TEARDOWN PHOTOS



- Different images of same witness mark
- Minor-thrust side of piston



FINAL THOUGHTS



- Cylinder pressure data integrity
 - Extraordinarily large pumping loop for TBC9 and initial results for TBC10, although brake torque also decreased
 - Thermal efficiency very sensitive to TDC determination
 - Compression ratio also affects thermal efficiency
- Next steps
 - Further technology development (what to optimize?)
 - Surface characteristics
 - Thermal property, e.g. Toyota thermal swing concept
 - Patterning, e.g. Toyota only coats the squish region
 - Considerations for manufacturing development
 - Three different TBC pistons procured from a piston manufacturer, on hand and ready to test
 - More complex bowl geometries will pose greater difficulties in achieving uniform thickness



Questions?

Contact:

michael.j.tess.civ@mail.mil

eric.m.gingrich.civ@mail.mil



BACK-UP SLIDES



SURFACE PROFILOMETRY HISTORGRAMS

