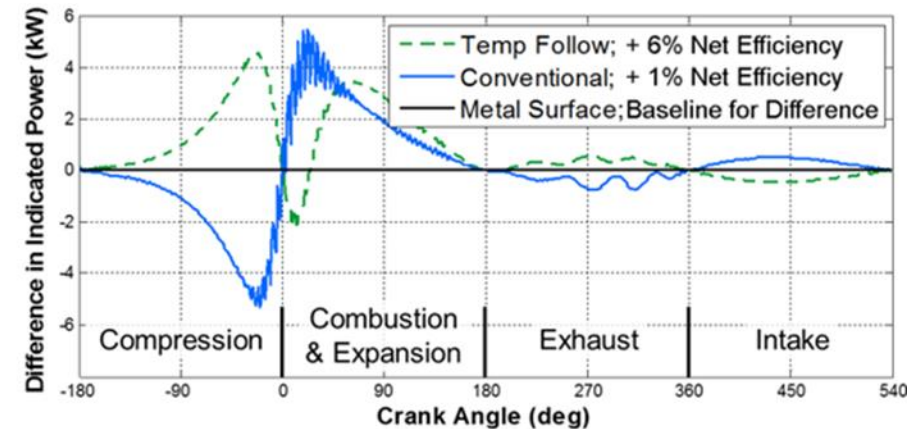
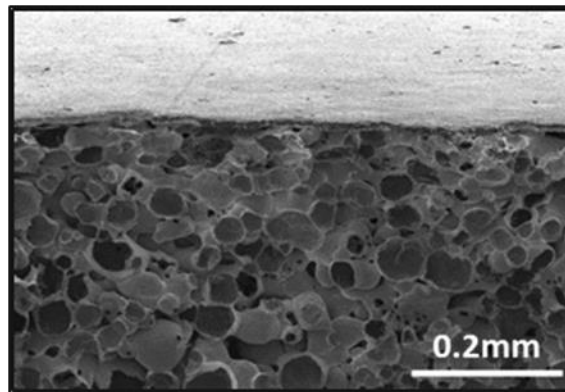
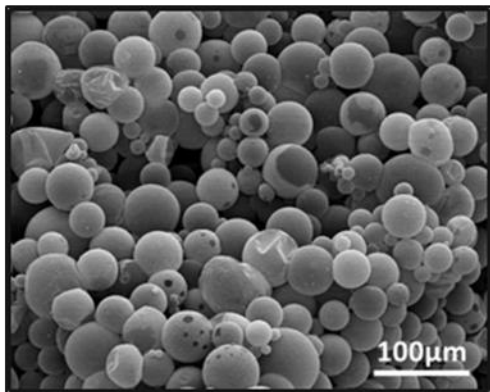
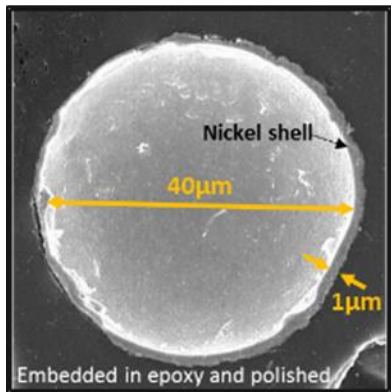


Temperature-Following Thermal Barrier Coatings for High-Efficiency Engines

June, 2020 : Project ID: ace123

Tobias Schaedler - Principal Investigator
 Peter Andruskiewicz - Presenter



Team:

Tobias Schaedler, Patrick Webb
 Peter Andruskiewicz, Russ Durrett, Paul Najt, Mike Potter

- HRL
- GM

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Timeline

1/1/2017 – 12/31/2020

- 3 budget periods of 12 months with go/no-go milestone after BP1 & 2
- No-cost extension on BP2 for 12 months (through 12/31/2019)
- Currently 75% Complete

Budget

\$2.8M Total Budget, including 50% cost share provided by GM

- \$730k in 2017 incl. cost share
- \$1,137k in 2018 incl. cost share
- \$0 in 2019 (No-cost extension)
- Remaining in 2020, pending closures

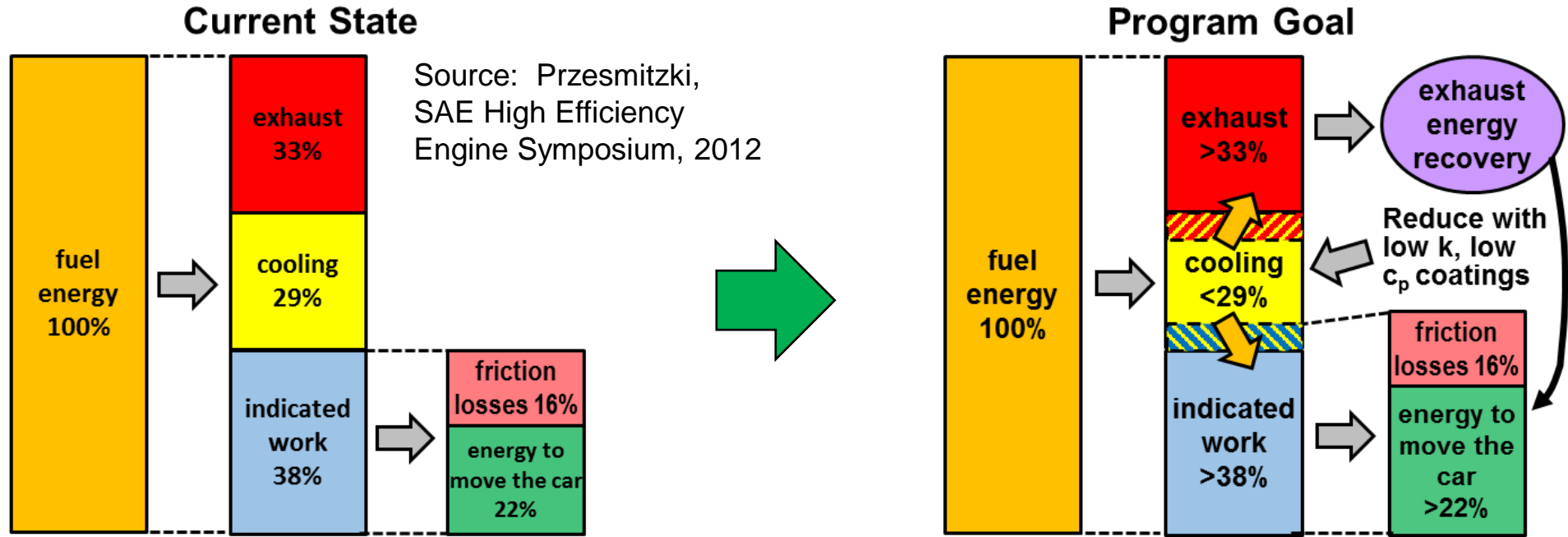
Barriers and Technical Targets

- Dilute Gasoline Combustion – Thermal Management
- Parasitic Loss Reduction
- Waste Heat Recovery

Partners

HRL Laboratories is Prime Awardee, GM Research & Development is Sub

- Commercial Partner for Ceramic Sealing Layer Application
- Commercial Partners for Microsphere Production
- Commercial Partner for Insulating Exhaust Port Inserts



The objective of this project is to increase the efficiency of internal combustion engines by 4% to 8% with thermal barrier coatings within the cylinder and exhaust ports that add less than ~\$250 in cost to a 4-cylinder engine.

Benefits will be derived from:

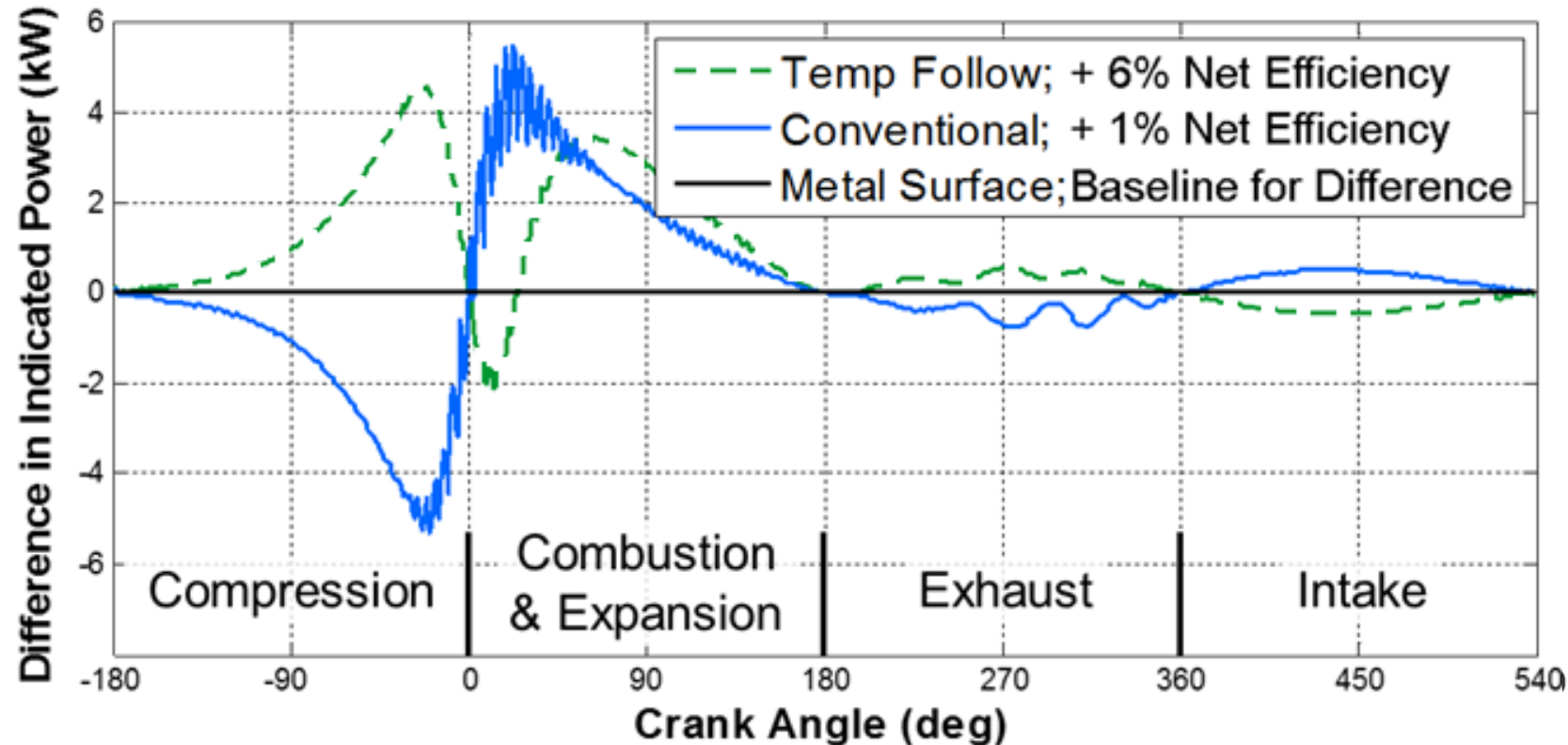
- In-Cylinder Efficiency improvements through lower heat losses
- Increased effectiveness of exhaust energy recovery and aftertreatment with higher exhaust temperatures under highly dilute conditions

Improved Efficiency in hydrocarbon-fueled engines supports the VTO Technology Integration Goals of National Security, Affordability for Businesses and Consumers, and Reliability/Resiliency

Temperature-following low-heat-capacity (low- c_p) insulation allows surfaces to stay cool during the intake and compression stroke, which will help volumetric efficiency and compression work in comparison to a high-heat-capacity conventional insulation with the same thermal resistance. During combustion, the Temperature-following coating surface can increase rapidly to provide similar insulation benefits during this stroke to a conventional coating.

Conventional insulation's expansion benefits are negated by the increased compression work, while Temperature-following shows improvements over the baseline Metal in compression & expansion.

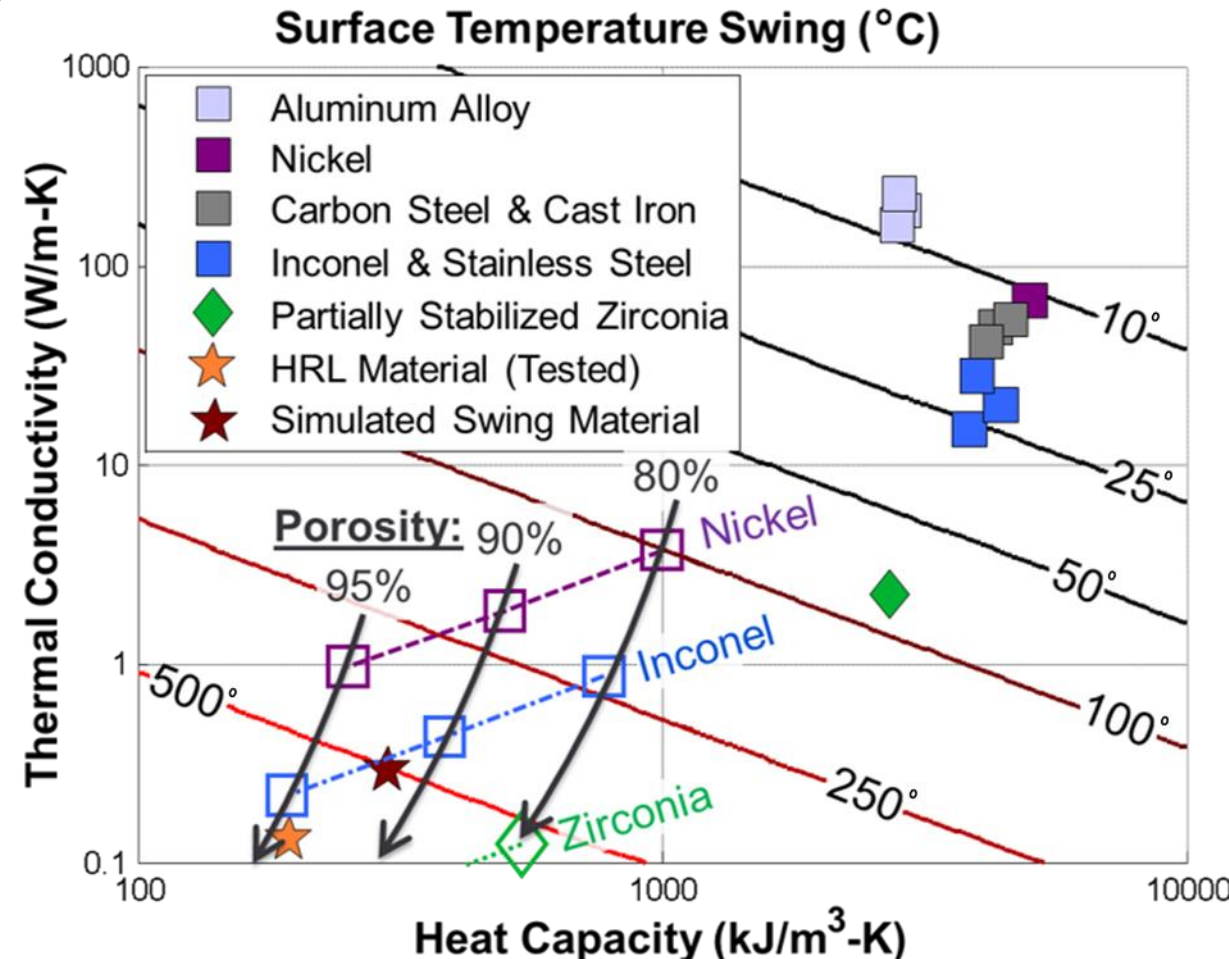
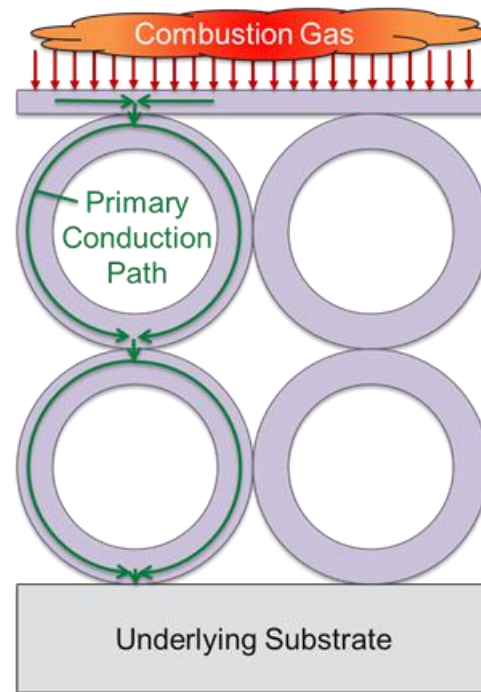
This allows the low- c_p TBC to provide the benefits of lower heat rejection, but without the volumetric efficiency or SI pre-ignition drawbacks.

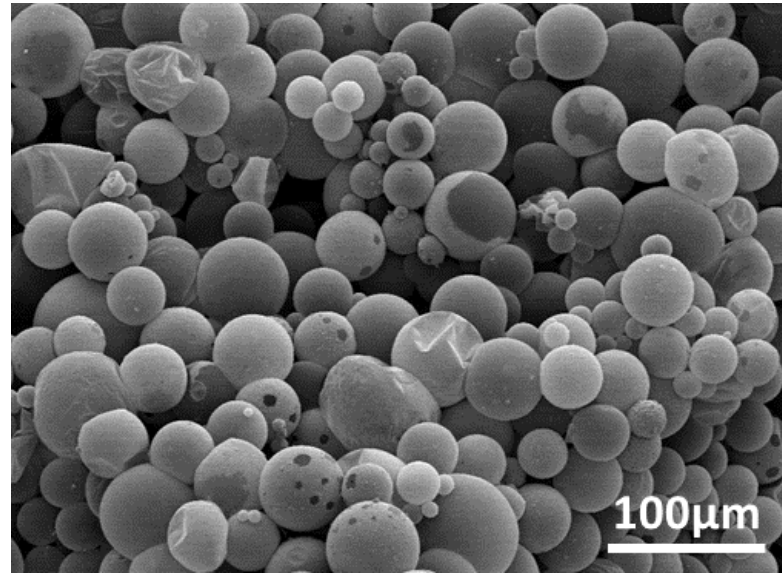
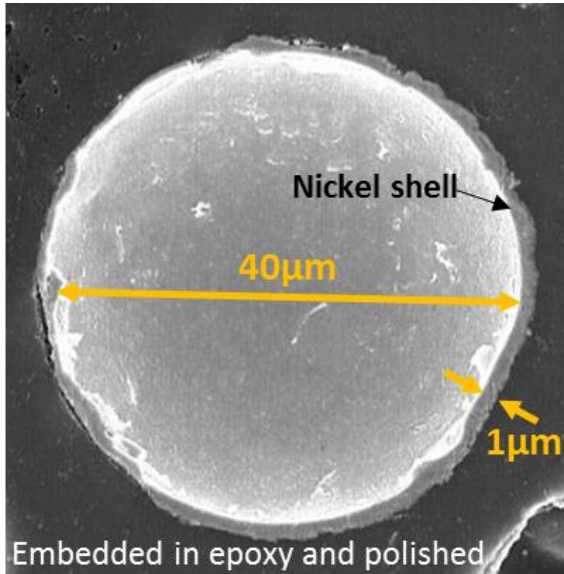


Large amounts of surface temperature swing could be achieved with a combination of low thermal conductivity (k) AND low volumetric heat capacity (c_p). High levels of porosity were determined to be necessary to decrease both the k and c_p by making the conduction area thinner and conduction path more convoluted while reducing the density, thereby reducing the mass of material that would need to swing in temperature.

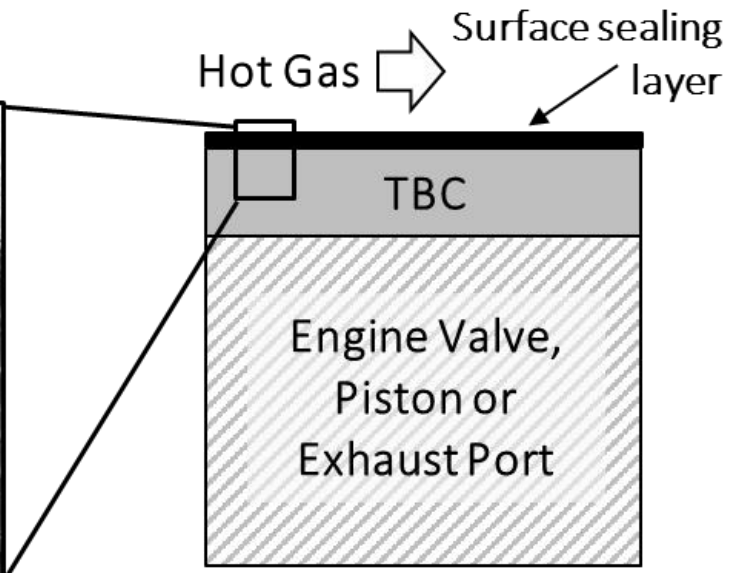
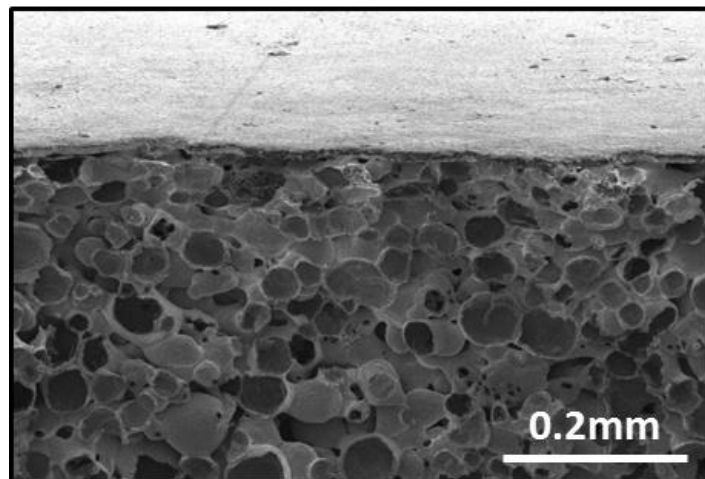
Estimated material properties for various solid materials and levels of porosity are overlaid on the plot.

90 - 95% porosity is necessary to achieve large enough surface temperature swing. Approximately half the porosity volume is within microspheres, while half is interstitial.





HRL has developed hollow nickel-alloy microsphere TBCs with an average diameter of 30 - 50µm and 1 - 2µm shell thickness. These microspheres can be sintered together to form ductile, high-temperature metal matrices with over 90% porosity.

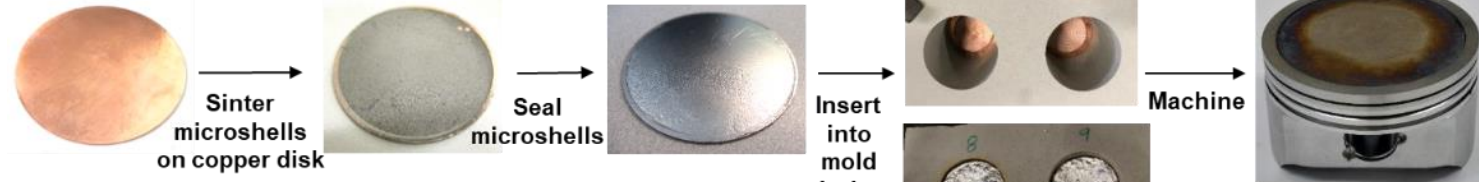


Microsphere TBCs can be applied to parts using dry molds, slurries, air spraying, and other techniques.

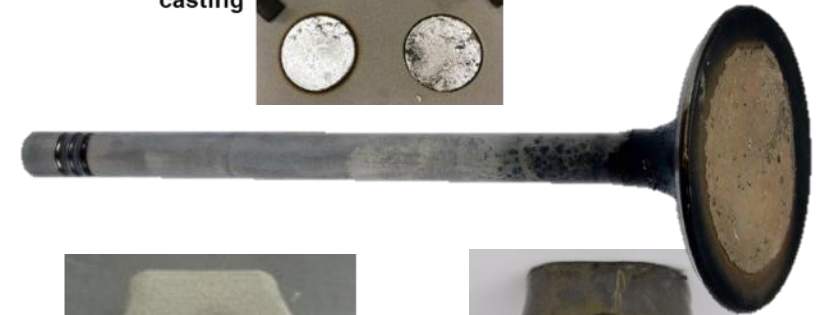
The surface must be sealed to avoid ingress of hot combustion gasses and unburned fuel vapor into interstitial porosity volumes.

The process for applying the microspheres is dependent on the material that the TBC is applied to.

- For aluminum or other materials with a low melting temperature, such as those in many pistons and cylinder heads the Ni microsphere matrix would need to be sintered at $\sim 850^{\circ}\text{C}$ separately. The microspheres could be sintered onto intermediate bonding material that could survive those temperatures like a copper form to provide structure to the matrix and protect the microspheres while bonding to aluminum during casting.



- For steel, stainless, or many high-temperature alloys used in valves and heavy-duty diesel pistons, the nickel microspheres can be sintered directly to the substrate.



- Exhaust port inserts could be made with a thicker high-temperature alloy forming the inner surface, coated with microspheres followed by a protective layer, and inserted into the cylinder head casting.



Task	Subtask (Budget Period is first digit in WBS)	Budget Period 1				Budget Period 2 with No Cost Extension				Budget Period 3							
		2017				2018				2019				2020			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
0. PM	0 Program Management	D1 D12															
1. Modeling	1.1 Simulation of Coating Performance	[Timeline bar from Q1 2017 to Q4 2018]															
	1.2 Simulation of Engine Performance	[Timeline bar from Q1 2017 to Q4 2019]															
2. Coating Development	2.1 Microshell Development	M1.2.1 [Timeline bar from Q2 2017 to Q4 2018] M2.2.1															
	2.2 Coating Process Development	M2.2.2 [Timeline bar from Q2 2017 to Q4 2019]															
	2.3 Coating Surface Sealing	M2.2.3 [Timeline bar from Q3 2017 to Q4 2019]															
3. Testing, Charact. & Analysis	3.1 Thermal Properties of Coating	M1.3.1 [Timeline bar from Q2 2017 to Q4 2019] M3.3.1															
	3.2 Permeability & Mechanical properties	M1.3.2 [Timeline bar from Q2 2017 to Q4 2019] M3.3.2															
	3.3 Single Cylinder Engine Testing	M1.3.3 [Timeline bar from Q2 2017 to Q4 2019] M2.3.3 [Timeline bar from Q3 2018 to Q4 2019] M3.3.3 M3.3.4															
4. Manufact. Readiness and Scale-up	4.1 Develop Supplier for Microshells	M3.4.1 [Timeline bar from Q3 2018 to Q4 2019]															
	4.2 Develop Supplier for Coated Pistons	[Timeline bar from Q3 2018 to Q4 2019]															
	4.3 Develop Supplier for Exhaust Ports	[Timeline bar from Q3 2018 to Q4 2019]															
	4.4 Develop Supplier for Coated Valves	[Timeline bar from Q3 2018 to Q4 2019]															

= Milestone = Go/No Go = Deliverable

Milestones

- M3.4.1. Supplier manufactured microshells for <\$10/engine
- M3.3.1 and M3.3.2 Properties of production coating demonstrated
- M3.3.3 Fuel economy improvement demonstrated with 3rd Gen prototype parts
- M3.3.4.3 Fuel economy improvement demonstrated with supplier manufactured parts

Prototype steel pistons were procured to enable us to test the TBC performance without the variability associated with bonding to aluminum. These started as steel pucks, upon which foil-sealed and unsealed TBCs (intended for ceramic sealing layers) were sintered around March 2019. Final machining was to be performed at the supplier because the sintering temperature would cause some material creep and affect the piston dimensions.

The pistons were sent back to the supplier after the TBC was applied, but machining issues and other delays at that supplier resulted in many of the pistons getting damaged beyond usability, while the few that remained viable only getting returned to us by November 2019.

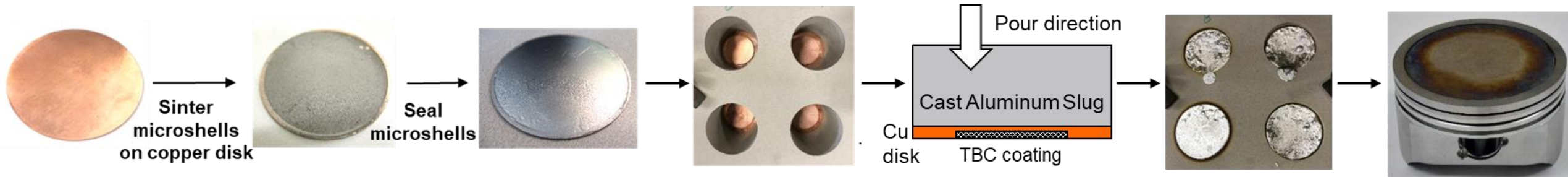
This was the primary reason for the continued no-cost extension.



Challenge: low melting point of aluminum piston prohibits sintering of TBC directly on piston

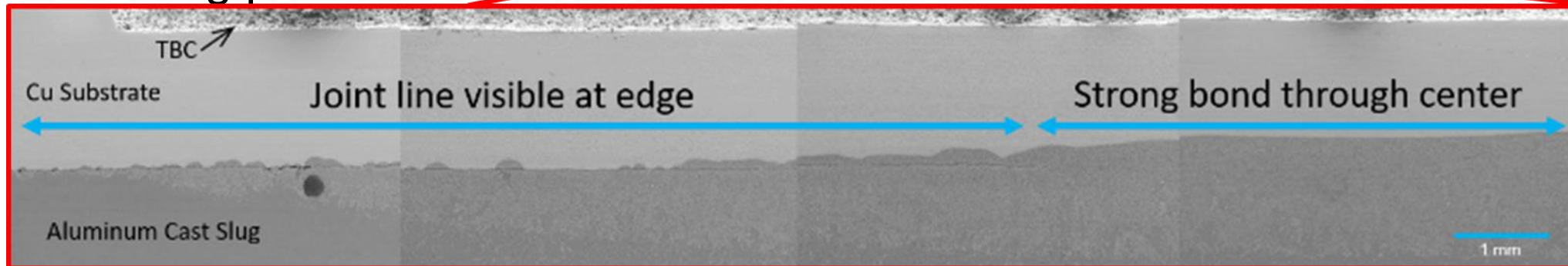
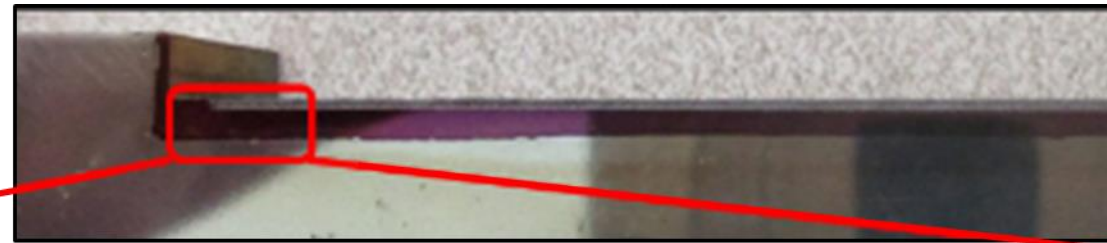
1st Approach: sinter TBC on Cu disk and braze to Al piston → braze bond failed in engine testing

2nd Approach: sinter TBC on Cu disk and cast Al over disk to form bond after TBC is sintered



First set of cast aluminum pistons showed a strong bond through the center of the sample, with the outer ~7mm not bonded. Changes are being made to the casting procedure

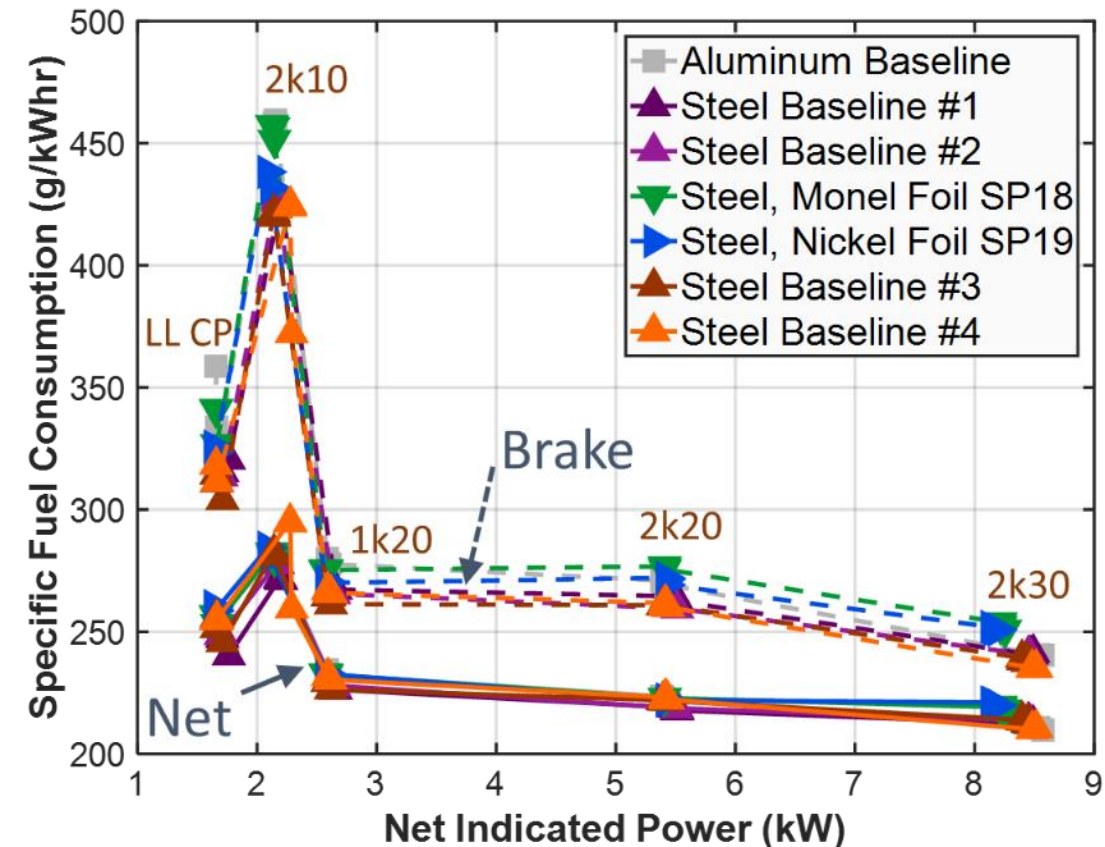
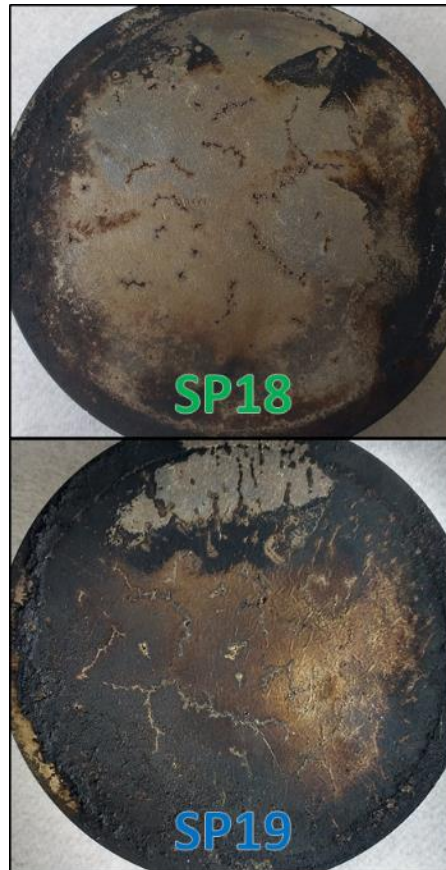
to control pour parameters to increase the bonding area.



The baseline steel pistons showed **~5% improvement** over Al baseline due mostly to higher combustion efficiency and reduced friction. Both of these are likely due to the decreased piston-bore clearance & better dimensional stability of steel.

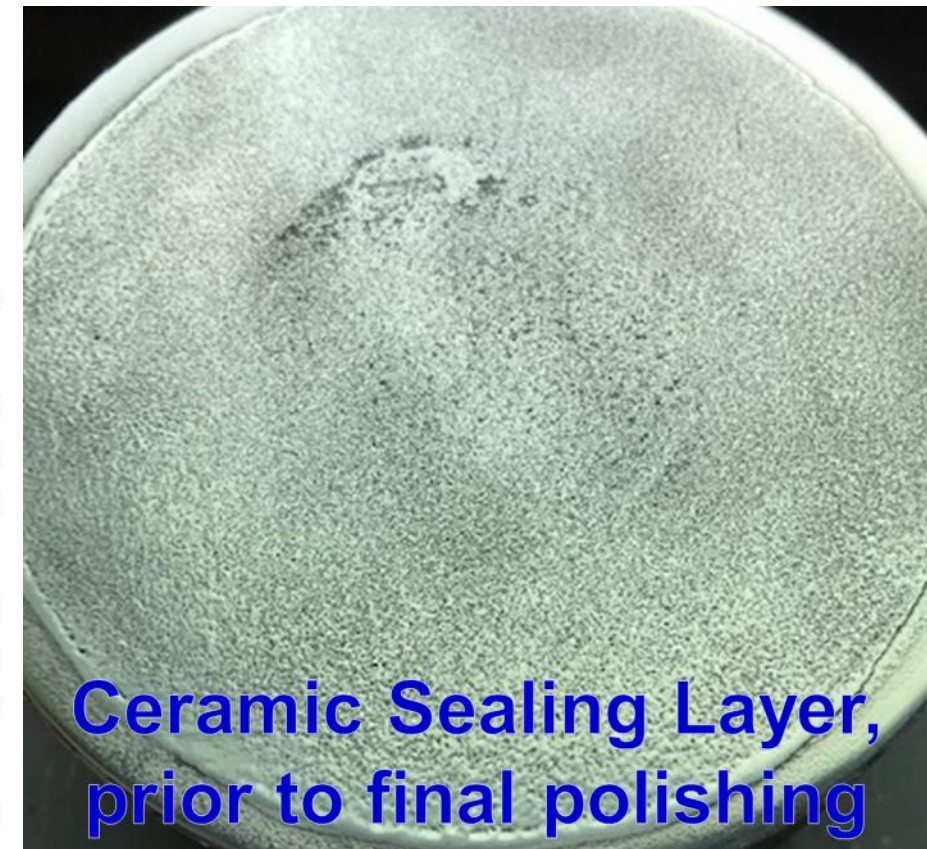
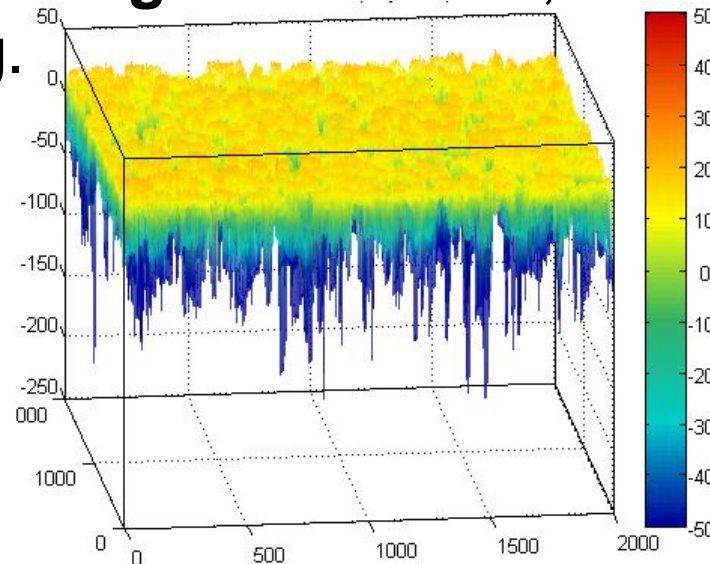
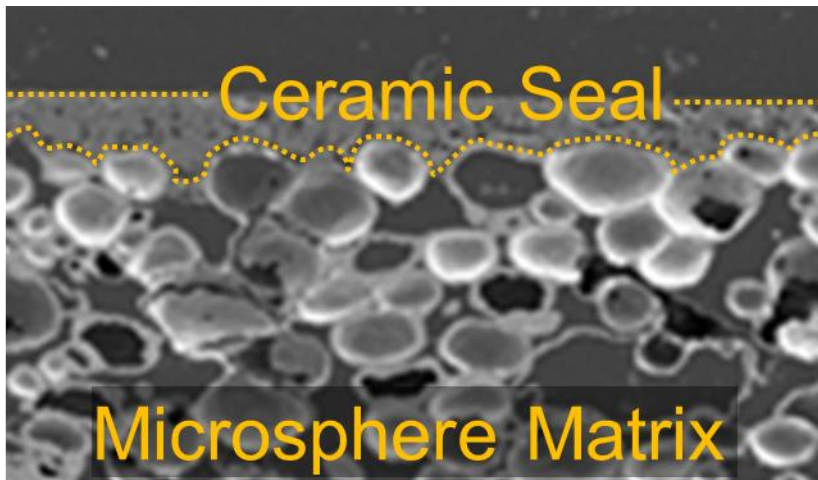
The foil-sealed pistons showed a **2-5% decrease** in fuel efficiency from the steel baseline. Primary loss mechanisms were incomplete combustion and heat losses, both of which are indicative of a perforated sealing layer. This was confirmed by visual inspection in-situ and post-test examination.

Despite tested variations in foil alloy and thickness, the foil strength is inadequate given the mass and thus thickness constraints. Future efforts will focus on Ceramic.



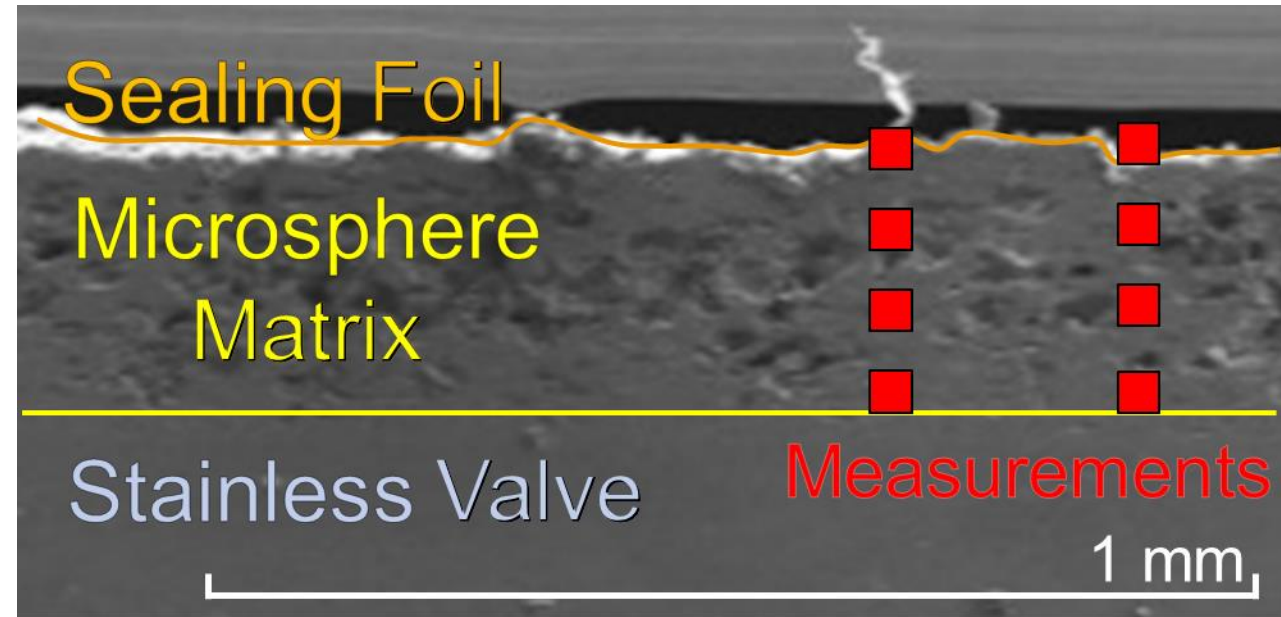
Two un-damaged steel pistons without sealing layers were delivered for ceramic sealing. The precise surface profile was measured in multiple locations for these pistons to determine the roughness and other metrics. These measurements drove the targeted minimum ceramic sealing layer thickness of $15\mu\text{m}$ since the ceramic fills the gaps between the top layer of microspheres.

The pistons were then cleaned & sent to the ceramic supplier for application of their **low-T process that does not impact final machining dimensions**, followed by surface polishing.



Experiments have been performed on foil- and ceramic-sealed components with a sulfur-doped fuel as a tracer element. After 32 hours of testing, the component is sectioned and the sulfur concentration measured at multiple points by EDS to determine the extent of combustion gas penetration.

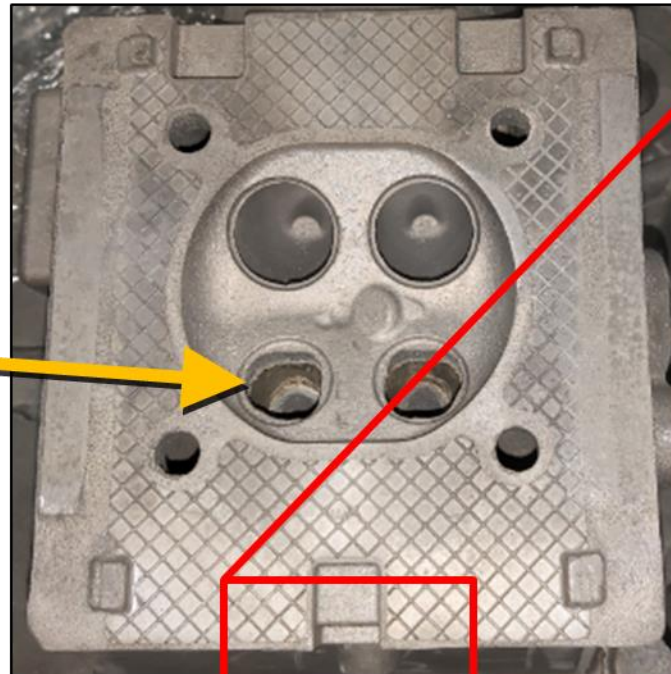
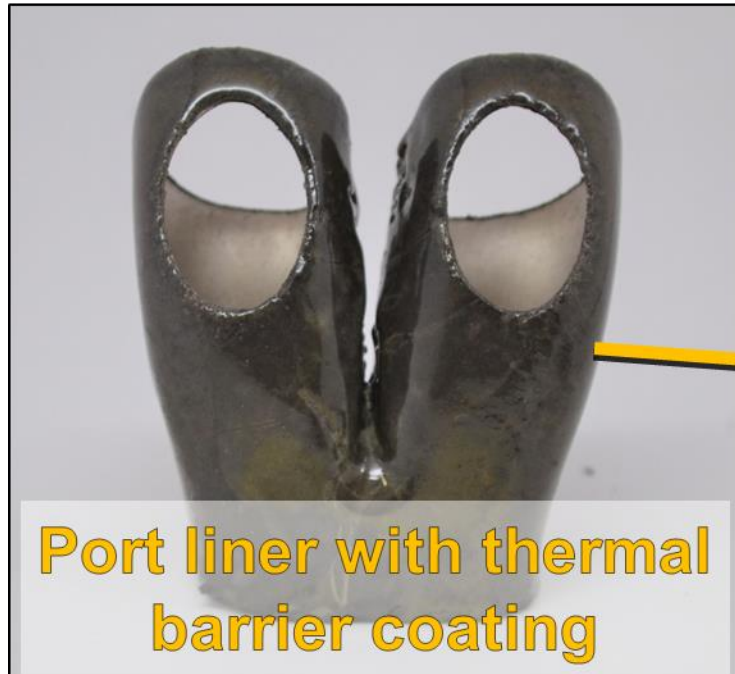
Shown here, significant concentrations of sulfur were detected under a visibly observable defect, but they fell off fairly rapidly when sampled away from the foil perforation.



Sulfur Concentration

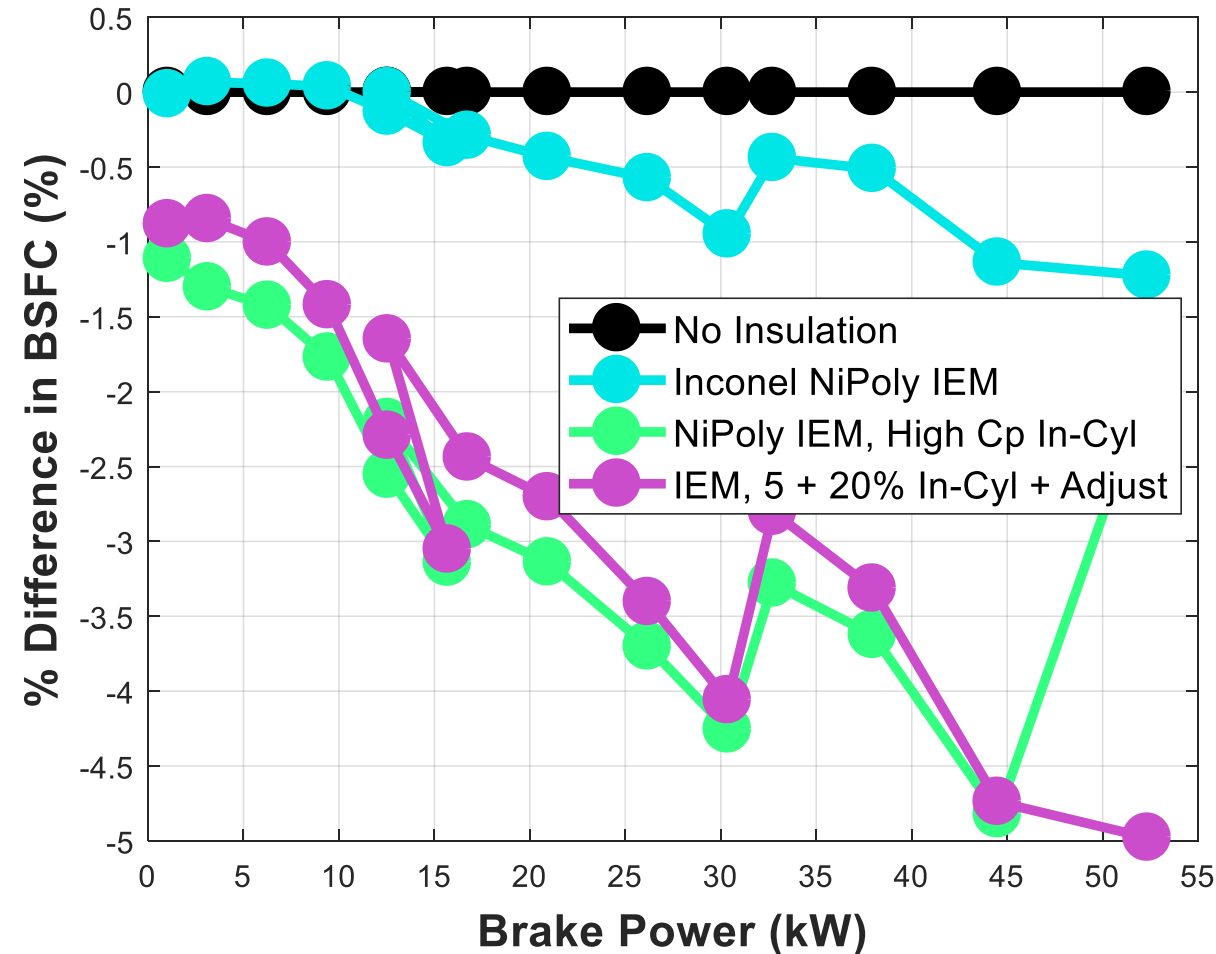
Under Perforation	Next To Perforation
0.75%	1.4%
0.71%	0.21%
0.34%	0.08%
0.30%	0.02%

The prototype exhaust port inserts have been created with approx. 1mm of our microsphere-based insulation between a smooth sealing layer exposed to the exhaust gas and a porous protective ceramic layer to prevent dissolution when exposed to molten aluminum while casting. Three of these ports have been cast into cylinder heads; two for our own engine testing and the last for structural analysis at the casting supplier.



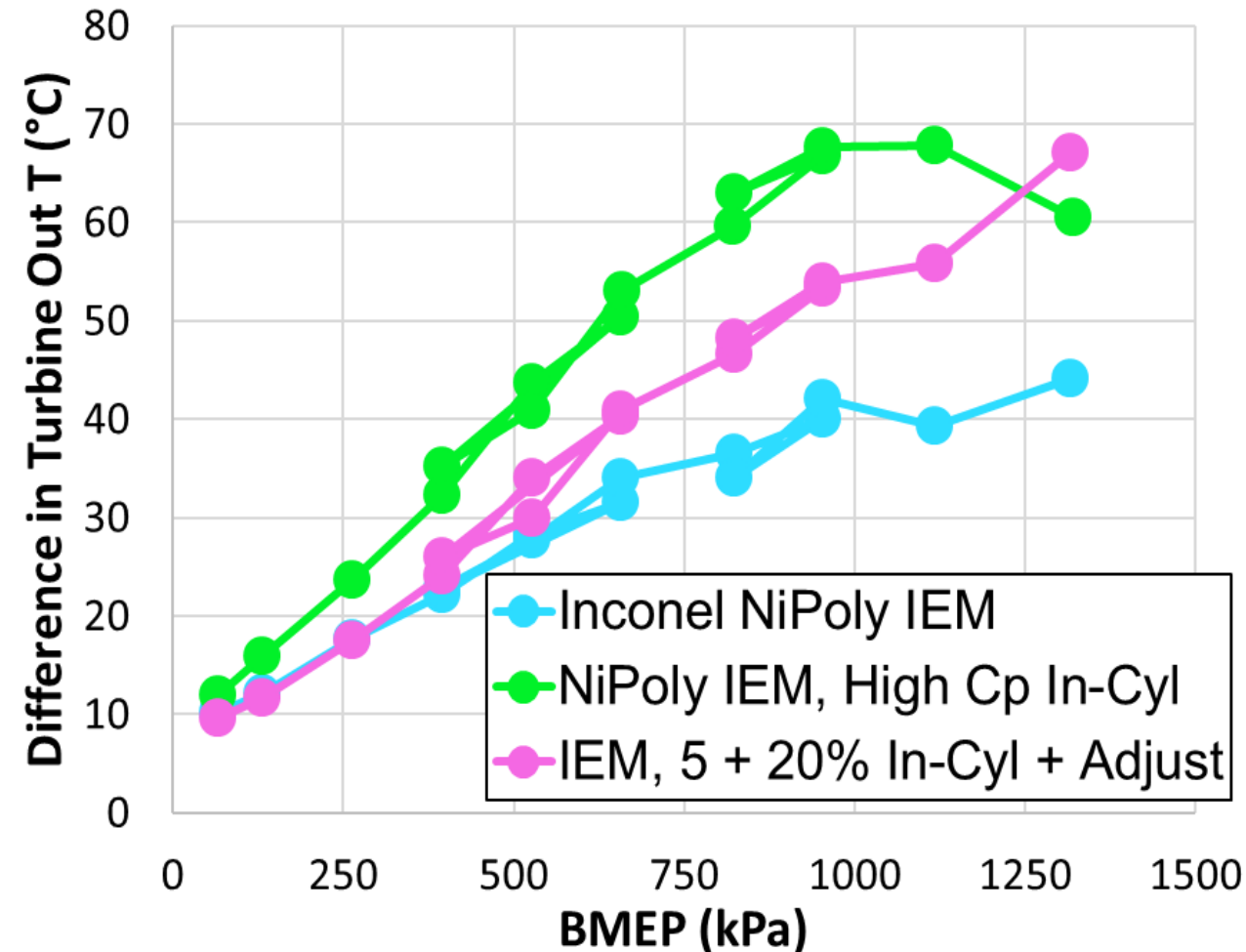
The expected benefits from TBCs originate from multiple sources. In-cylinder gains in efficiency are the most obvious source, with steady-state improvements between 1 and 5% over an uninsulated baseline.

Taking these points over the FTP75 for a 110 kW turbo-diesel drivetrain in a mid-size CUV, the result is a **2.3% gain for High c_p + IEM**, which is the greatest steady-state insulation case with our unique microsphere matrix technology, and **2.0% for insulation maximizing the T-swing potential**.



Increases in insulation, both in-cylinder and in the exhaust, increase the exhaust temperature by 10 – 70°C depending on load and insulation strategy. The uninsulated baseline engine would need changes to the calibration (AFR, late-post injection etc) to increase steady-state exhaust temperature at the lowest 4 points, which could be eased with insulation. These calibration changes **improve cycle efficiency by 0.7-0.9%.**

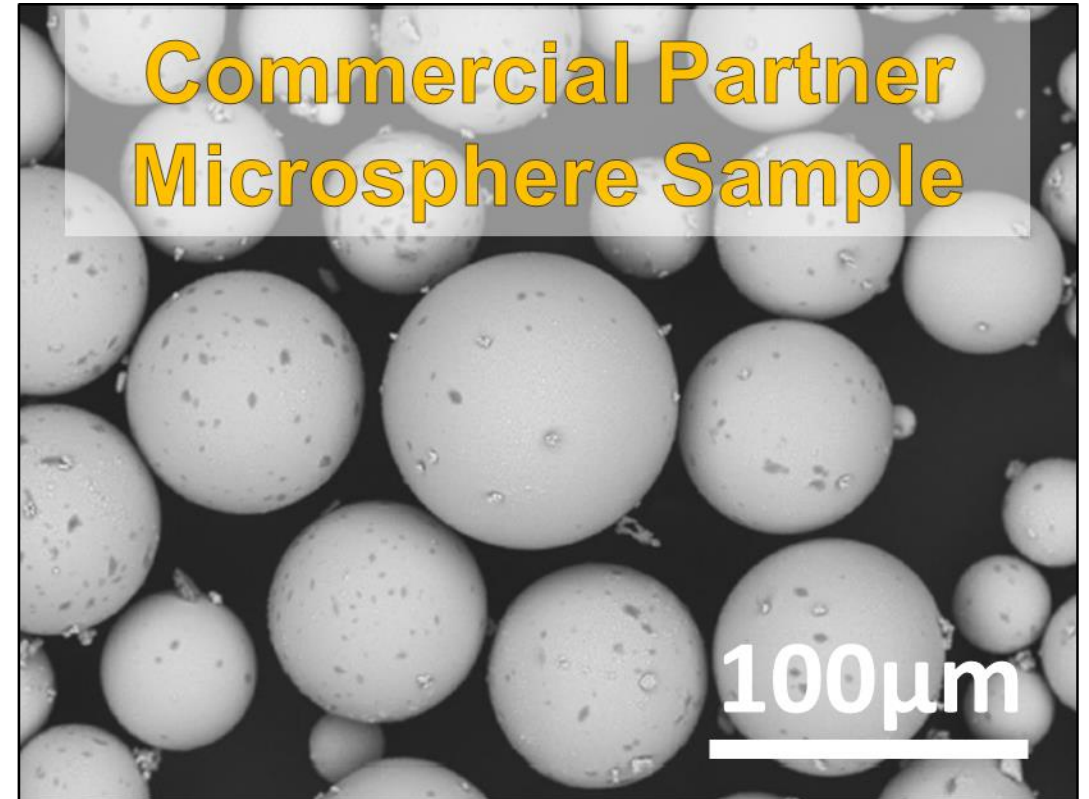
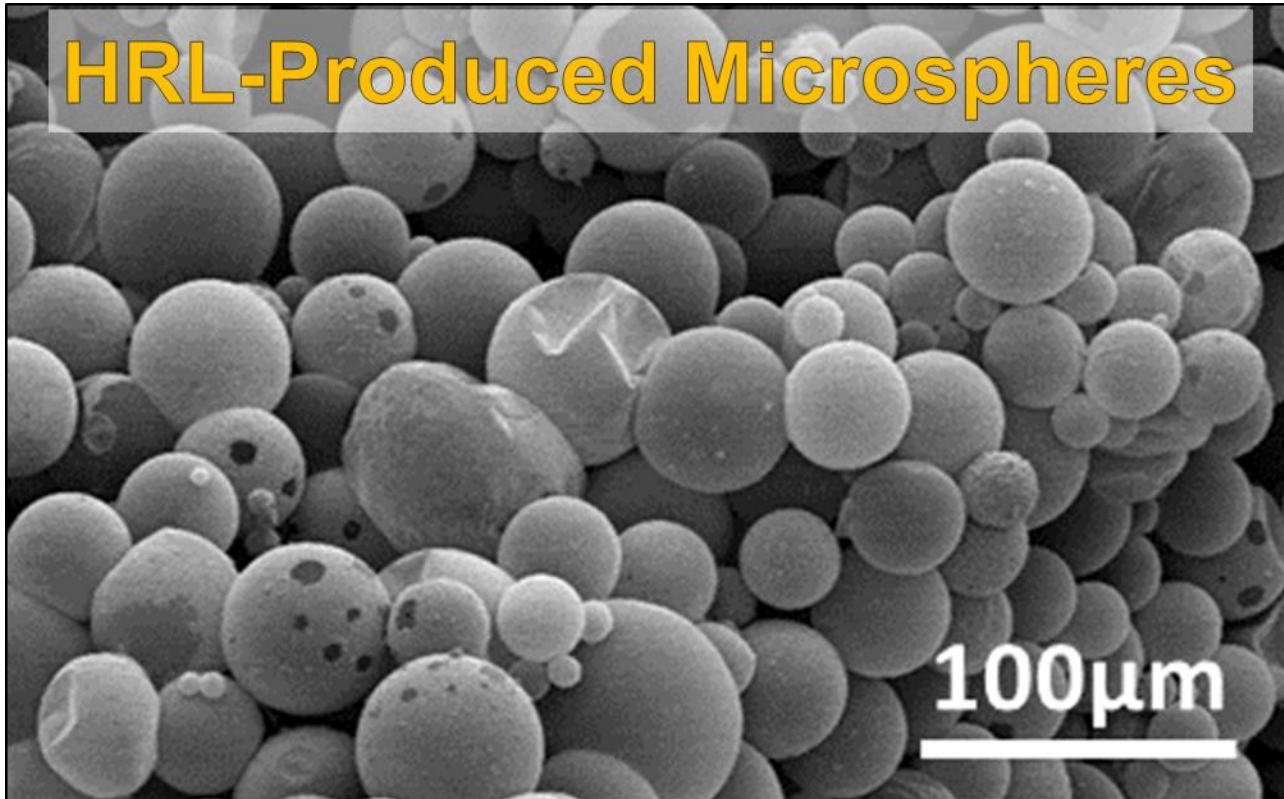
Beyond this, insulation helps aftertreatment warmup during a cold-start. Applying these temperature increases to a production-calibrated aftertreatment model, reductions in post-DOC & SCR CO₂ emissions from hotter Exh T were equivalent to **over 2% BSFC improvement** by reducing specific warm-up routines beyond those mentioned above. Experimental benefits suggested up to 5% improvement for this increase in Exh T.



HRL Laboratories - Primary Investigator (Malibu, CA)

GM Research - Subcontractor (Warren, MI)

Multiple industry partners have been engaged for the production of Ni-plated microspheres for use in coatings and exhaust port inserts.

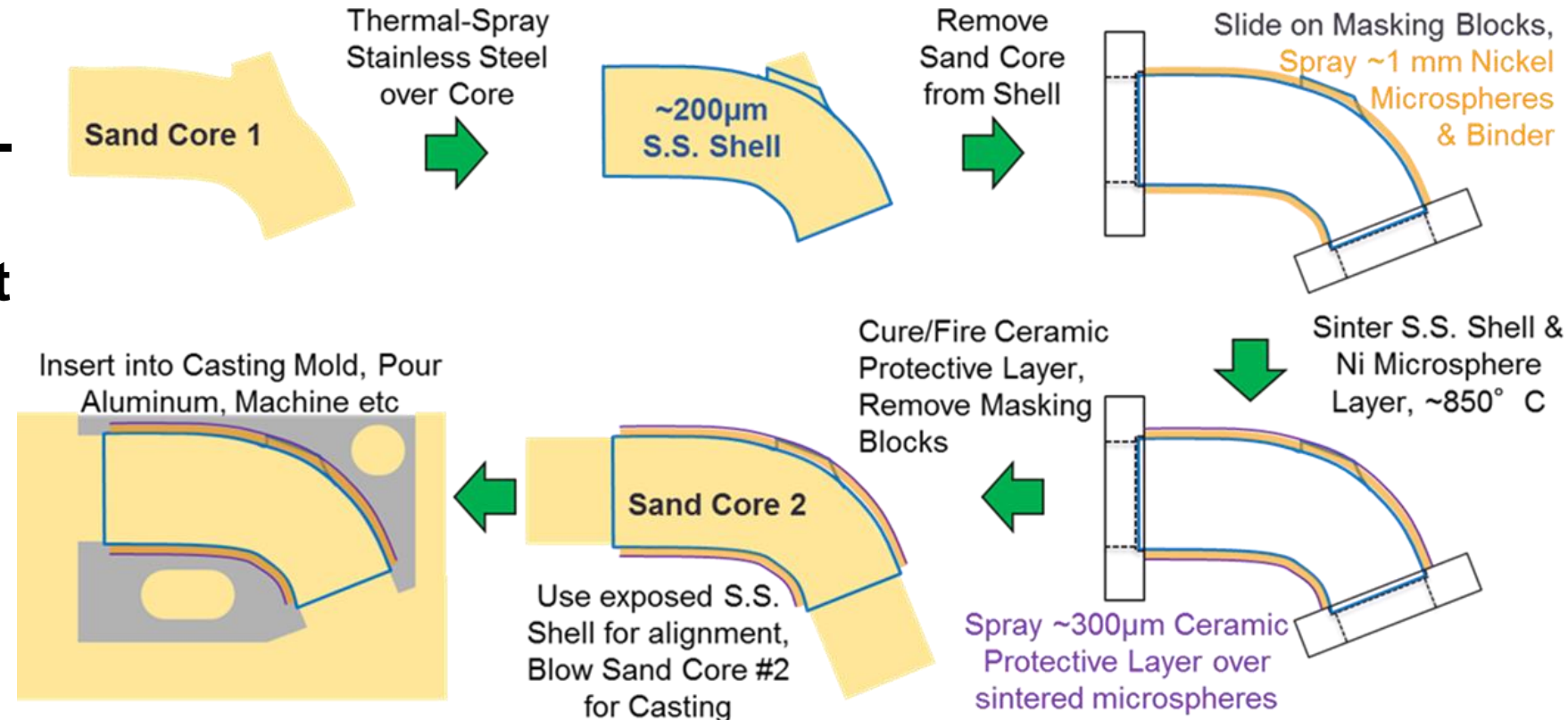


Suppliers have been engaged for complete exhaust port inserts for cylinder head casting. One proposed process is shown below for low-cost mass-production.

An automotive Tier-1 supplier is involved in design and production of steel pistons.

Discussions are ongoing for ceramic sealing layer application.

GM diesel programs, Tier-1 suppliers & heavy-duty OEMs are showing interest in using our port and in-cyl insulation technology in their own programs, providing more paths for mass commercialization and cost reduction.



- Exhaust port insulation based upon the research and structures from this work is included as a possibility in future GM diesel engine applications to ease or eliminate catalyst heating penalties.
- Our expertise in temperature-swing coatings is being pursued by multiple non-competitive OEMs and Tier-1 suppliers for overall engine efficiency gains to promote reductions in global CO₂ productions.
- Benefits in vehicle cost, mass, coolant pump losses, and aerodynamic drag are also possible with reduced heat losses, although these have not been quantified as part of this work.
- Further improvements in application and durability could enable more GM internal developments and applications.

- The microsphere-based insulating material meets target material properties for surface T-swing effects (targets of 0.2 W/m-K Conductivity and 0.2 MJ/m³-K)
- Drastic improvements in impermeability of the sealing layer have been made & the ceramic sealing layer survived in-cylinder environment with minimal damage.
- Promising bonding results when Al pistons are cast over TBC coated substrate.
- TBC coated exhaust ports were successfully fabricated and cast over without destroying the microsphere layer or macro-scale distortion.

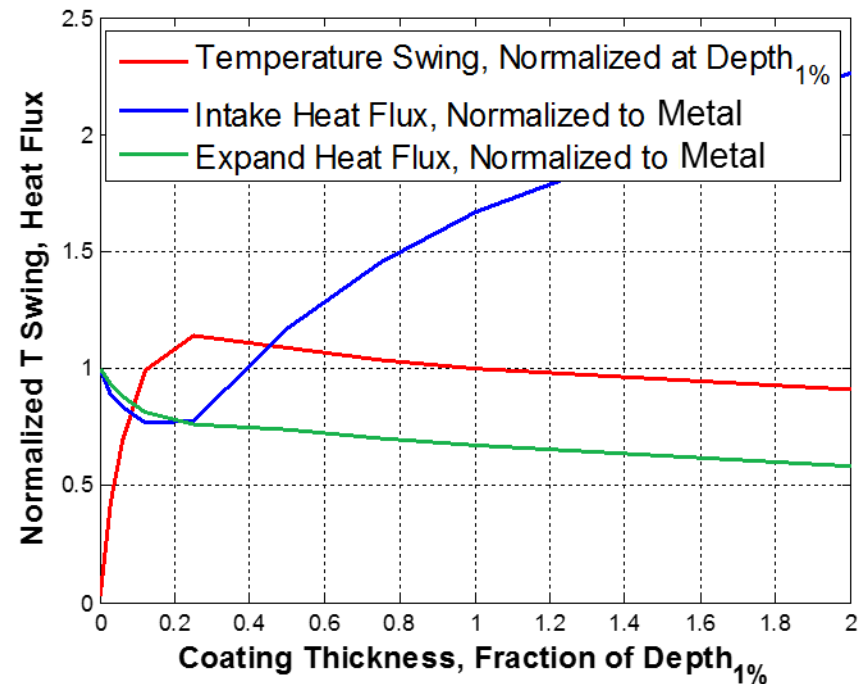
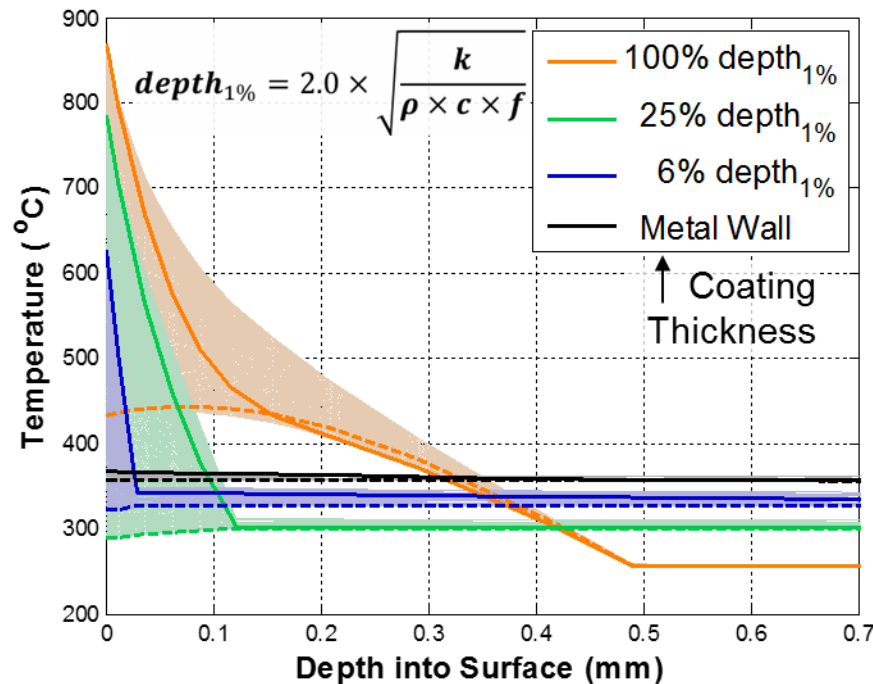
- Analytical tools have been developed and validated allowing accurate assessment of potential design solutions.
- Potential benefits for effective thermal barrier materials is at least 2.7% for exhaust applications, which will be our first path to production.
- Further benefits are on the order of 2% for strictly thermodynamic in-cylinder applications, and substantially more when accounting for the applicability to end-gas autoignition for SI engines.
- Commercialization of the microspheres and exhaust port inserts is progressing well

Technical Backup Slides

Ideal Coating Depth

A representative “Depth_{1%}” was defined based on the material properties and cyclic engine frequency to describe the depth into a material at which the inter-cycle temperature swing has decayed to 1% of it’s surface value.

The ideal coating thickness is 25% of the depth_{1%} to minimize heat loss during expansion and the intake stroke, effectively balancing heat losses off the front and back of the coating to allow maximum temperature swing while minimizing the intake heat transfer in comparison to the baseline metal wall.



Influence of Sealing Cap

Highly porous coatings, especially with a large portion of open-cell porosity such as the void spaces between packed microspheres spheres, will require an impenetrable sealing layer to prevent permeable porosity losses, which impacts the surface temperature swing by concentrating mass where it is most detrimental.

Thicker metal sealing caps substantially dampen the surface T swing while increasing the wall temperature during intake and compression; These effects are somewhat mitigated by adjusting the insulating layer thickness beneath the sealing layer

Ultimately a very thin or low-mass sealing layer is critical to the overall coating performance

