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Several variants of thermal management coatings for high-output diesel engines were produced by an atmospheric plasma spray process. A large database of thermal and mechanical properties of these coatings was developed for materials selection. Coat.ngs from this database were screened for potential in engine use by novel laboratory tests, deposited on piston crowns, and tested in a single cylinder research engine. Coatings appear very durable, even under the highest load conditions tested, while limited direct benefits to thermodynamic efficiency were observed. Potential strategies to use coatings to enable systemic benefits are briefly explored and are elaborated on in this works follow-up proposal.

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1. Introduction

Improving performance and thermal efficiency of combustion engines through higher operating temperature is an age-old concept. In addition to providing improvements in direct engine operational efficiency, the higher temperature exhaust gas also provides an excellent source for auxiliary heat recovery concepts.

To address this emergent opportunity, the Center for Thermal Spray Research (CTSR) at Stony Brook University (PI: S. Sampath) has supported a DoD wide initiative aimed at developing advanced high-performance diesel engines. In this effort, CTSR proposed to develop several variants of a novel, low thermal inertia (TI, combined low thermal conductivity and volumetric specific heat) coatings through an iterative design, evaluation and optimization loop. Over the last four years, the CTSR group has spent considerable efforts at understanding the past efforts and the challenges entailed in incorporating thermal insulation coatings with diesel engine piston crowns, valve surfaces, cylinder liners and exhaust ports.

The team, CTSR and CCDC-GVSC, integrated the initial development efforts with engine performance modeling and comprehensive testing efforts at US Army CCDC-GVSC. Over the second year of this period, CTSR coated several variants of its materials system for evaluation in US Army's test engine. During the third year, these engine tests results were used as feedback control for further refinement of coating architectures and refined material selection. The final, fourth year of this project again utilized previous successes to better understand the role of coating in increasing efficiency in these systems.

2. Background

As noted earlier, there is significant past efforts aimed at developing adiabatic or LHR diesel engines. Much of this past work was focused on addressing conductive heat losses through the piston, and as such sought to extend conventional thermal barrier coatings developed for gas turbines. Due to diesel engine's lower operating temperatures and vastly different duty cycles it is unclear if the coating material, architecture, microstructure and thicknesses of these coatings are appropriate to extend from gas turbine experience. The presence of the coating can thus affect the in-cylinder heat transfer and combustion processes, and hence the engine design and calibration (including associated turbomachinery) needs to be re-optimized as a system. In particular, the heat transfer rates from the combustion gas to the surfaces of the various engine combustion chamber components depends on the instantaneous difference between the gas and wall temperatures. The substantial variation in gas temperature and heat transfer coefficient associated with the rapid succession of thermodynamic events and fluid motion during the cycle imposes a time-dependent heat flux at the component surfaces.

It has long been appreciated that the benefits of thermal insulation are best realized when the engine can experience a so called "temperature swing" where the temperature within the chamber follows the combustion temperature cycle. In many cases the TBC tends to keep the surface "hot" resulting in non-optimal temperatures during the air-intake cycles. Modifications to engine parameters to some extent mitigate some of these challenges, but the exact formulation of the strategy has not been fully developed in the past decades. Past technologies also did not benefit from recent innovations with multipoint and pulsed fuel injection as well as more effective computer control of the engine operational cycles. Invariably any improvements in operational temperatures have also resulted in concomitant increases in exhaust NO_x.

3. Project objective and overview

The Center for Thermal Spray Research at Stony Brook University, in partnership with US Army Combat Capabilities Development Command, Ground Vehicle Systems Center, proposed to evaluate novel multilayer, multifunctional overlay coating concepts that capture the concepts of temperature swing heat insulation for ICEs and it is practical to implement from a materials and manufacturing points of view. The temperature swing depends on the properties of the combustion chamber and is given by $\Delta T \sim 1/(kc\rho)^{1/2}$, where k is the thermal conductivity, c is the specific heat, ρ is the density. The skin depth of the thermal wave penetration is an important parameter, which is given by $\delta \sim (k/c\rho N)^{1/2}$, where N is the engine speed. Clearly, no single material can readily provide the requisite thermal inertia and surface thermal properties to adequately address all these transient requirements. The idea here is that rather than rely on a single material (such as the Toyota example), to use available manufacturing derived concepts and material architecture to impart location specific thermal characteristics. Essentially, the concept will rely on strategically utilizing, thermal barrier materials (various types of low conductivity ceramics), incorporating process induced porosity as an effective thermal barrier and also provide the requisite low heat capacity to enable temperature swing and strategically depositing high conductivity heat spreaders to allow more effective temperature swing and remove residual heat from the air intake locations.

The proposed thermal management coating concept builds on a similar system demonstrated by Prof. Sampath (PI) at CTSR Stony Brook University for an entirely different thermal-management application developed for the US Navy under an Office of Naval Research contract (2010-12).

The proposed research effort integrates:

(i) Engine requirements and thermal modeling/simulation effort at Army CCDC-GVSC and Cummins that provides detailed thermal management requirements for ICEs;

(ii) design of the layered coating system with appropriate location specific thermal inertia and mechanical considerations;

(iii) selection of materials for the low thermal inertia and heat dissipation layer, as well as any bond coat layers to provide requisite thermal cycling durability;

(iv) processing of coatings system on coupons and actual ICE components;

(v) analytical characterization of the coatings system, thermal/mechanical properties measurements, and process optimization;

(vi) actual engine testing with and without coating at Army TARDEC, and measurement of temperature distributions, exhaust composition and efficiencies

(vii) analysis and characterization of tested coatings for thermo-mechanical damage; and

(ix) analysis of results and iterations for optimization. An auxiliary task will also include consideration of embedded temperature sensors within the coating enabled by Direct Write Thermal Spray Technology.

4. Project objective and approach

The proposal is structured in two parts. Part- 1 will be focusing on the materials selection and coating design, while Part- 2 will be the engine testing of the coated piston heads (in association with Army) with the final coating solutions emerged from Part- 1. Although the two parts complement each other, they have different requirements: Specific task plans and objectives, summarized below.

Part 1 of the proposal is defined to have three primary objectives:

1. Develop multilayer thermal barrier coating architecture which can address the following material property requirements
    a. **Low thermal inertia** - enables material to efficiently follow the combustion chamber temperatures in all the stroke cycles.
    b. **High durability** - from changes in material due to oxidation and from propagation of damage during service
    c. **Low thermal conductivity** - thermal insulation to the metal component to facilitate high engine operating temperature
    d. **Reduced in-plane thermal gradient** - minimize the hotspot and hence, minimizing risk of localized failure due to high stress mismatch. A novel metallic pattern layer on topcoat with ability to diffuse the localized heating will be employed
2. Deposit the optimized thermal barrier coating architecture on the pistons for engine test. The piston crown profile will be decided by TARDEC.
    a. Two different bowl-design of piston crown for **different compression ratios**
    b. Multiple trials to ensure **minimum coating thickness variation** along the diameter of the crown
    c. Cross section of either piston heads or a metal-strip (discussed in later section) will be polished for **microstructure optimization.**
3. Materials analysis of coated piston after engine test performed under Part- 2 of the project. The analysis will be based on
    a. Chemical changes in individual layers of the multilayer coatings after engine test
    b. Physical health of coating, such as sign of chipping and delamination

Objectives of the Part-2 of the proposal are as follows.

1. Coupon level evaluation of multilayer coatings using heat flux and infrared transmissivity
2. Conduct single cylinder test with pistons coated with various architectures (coating 1, 2, 3 and 4), and perform detailed engine performance analysis. These pistons will be analyzed for the coating material performance under Part- 1 of the project.
3. Conduct multi-cylinder (eight cylinder) test on the pistons coated with optimal coating (coating- 5) architecture

5. Task-wise summary for Part 1

5.1 Materials selection

Various sprayed ceramic coatings were characterized for their thermal and physical properties. Figure 1 below is the thermal inertia vs thermal conductivity characteristics of plasma sprayed oxide coatings measured at room temperature. All of the coatings were measured as free-standing forms following separation from the substrate. For each coating, a number of different parametric conditions were investigated. Figure 1 provides overview information this data so as to provide contextual information on properties of sprayed oxides. This shows a large range of both materials and processing conditions, covering a large range of thermal swings. Of interest are the coatings that have low specific heat and thermal conductivity. Materials that show promise include yttria stabilized zirconia and cordierite with high porosity. These materials will be investigated in further detail in the subsequent sections.

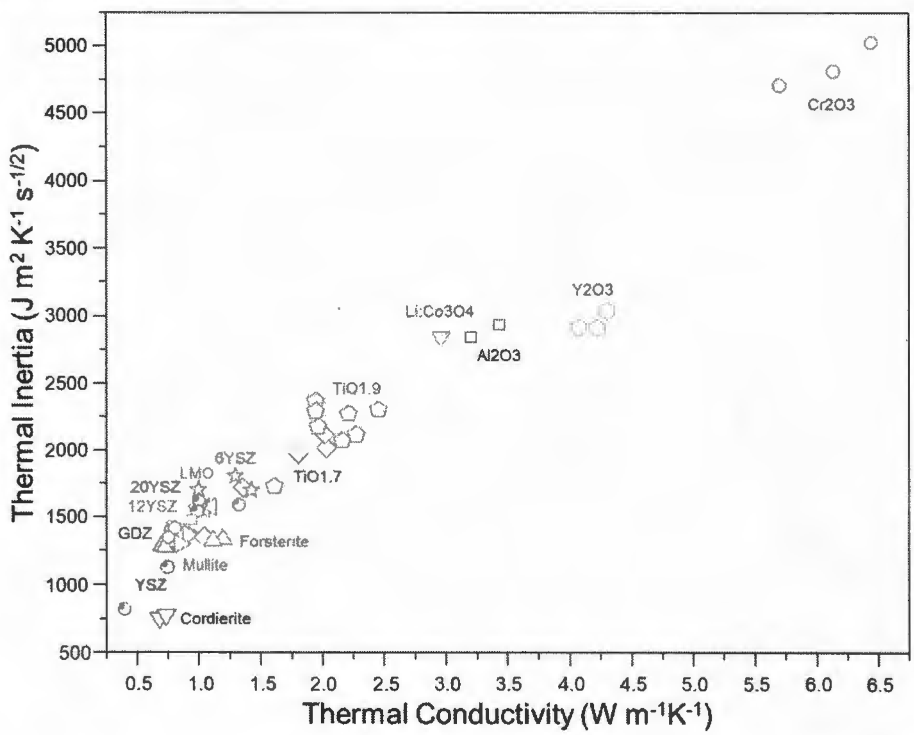


Figure 1. Thermal conductivity vs. Thermal inertia of the various thermal sprayed coatings

5.2 Deposition of various architectures and patterns for coupon level testing

Coupon level testing and parametric studies was performed with in-house spray processing on standard 9" x 1" substrates (steel, Al, and stainless steel). Functional test specimens were fabricated on 3" x 3" low carbon steel substrates.

5.3 Materials characterization and functional testing

A task-wise breakdown of characterization and functional testing are shown below. General results are presented following the specific tasks under the part 1 objectives.

Task P1.1: Thermal Conductivity measurements

Thermal conductivity measurements were made on free-standing coatings using a combination of characterization tools. Thermal diffusivity was measured using laser-flash technique over a temperature range of 25°C – 500°C. Density was measured using Archimedes method at room temperature. Specific heat capacity was measured using laser-flash technique and differential scanning calorimetry. The results from these tests were used to calculate thermal inertia.

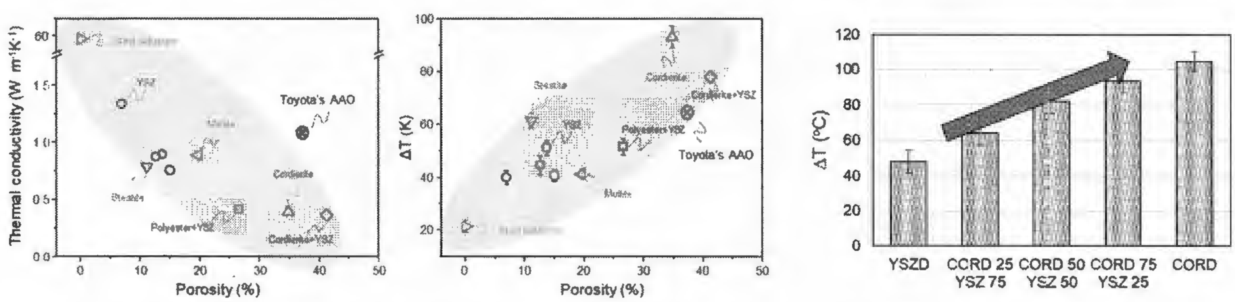


Figure 2. Measurement of thermal conductivity and thermal swing of various thermal sprayed samples at room temperature.

The thermal conductivity of Atmospheric Plasma Spray (APS) materials are highly dependent on morphological characteristics. The APS process used to produce these coatings results in inter-splat pores roughly aligned parallel to the substrate surface and accompanied by fine features such as microcracks and relatively small grain sizes. The exact composition of these features can easily be tailored though process controls which greatly influence the microstructure and pore morphology. In the case of Yttria Stabilized Zirconia (YSZ) these process variations can push the thermal conductivity can from 0.37 to 1.1 W/(mK). Alternatively the thermal conductivity of cordierite, the primary material of interest in this investigation, was manipulated between 0.25 to 0.60 W/(mK) by mixing cordierite and YSZ feedstock powders by volume fraction.

Task P1.2: Adhesion test

Evaluation of coating adhesion with the substrate was measured according to ASTM C633. Coatings were sprayed on standard metal adhesion buttons, and bonded together using specified adhesive agents. Specimens then underwent controlled strain loading until failure. All samples were found to be on the order of 30 to 40 MPa. Continued testing and further location of failures is being undertaken, specifically for the cordierite-YSZ system previously mentioned.

Task P1.3: Thermal expansion coefficient measurements

To facilitate the calculation of thermal stresses, which originate due mismatches in thermal expansion, the Coefficient of Thermal Expansion (CTE) of the materials discussed earlier were measured using standard dilatometric techniques. All measurements were made on thick (>1 mm) free-standing coatings single layer coatings. Multilayers were excluded from this test, as thermal expansion mismatch causes them to undergo bending during testing, which leads large instrumental errors.

Table 1. Coefficient of Thermal Expansion of thermal sprayed coatings $(10^{-6})/°C$

	Cordierite	Cr_2O_3	*Forsterite*	$La_2Zr_2O_7$	$Mn_{1.5}Co_{1.5}O_4$	*Mullite*	$TiO_{1.9}$	Y_2O_3	$Yb_2Si_2O_7$	*YSZ*
50 °C	2.2	5.8	8.3	8.1	10.5	4.2	6.6	7.1	5.2	8.4
500 °C	3.7	7.6	11.8	9.4	12.5	6.5	8.3	8.2	5.5	10.9

Dilatometry was performed between 25 and 1000 °C with CTE evaluated at 50 and 500 °C, with results summarized in Table 1. CTE can be seen to gradually increases as a function of temperature. Large thermal mismatches between the coating layers will cause large thermal stresses that will can result in the cracking or delamination of the coating. Generally, thermal expansion can be taken to follow a rule of mixtures type behavior which leads to graded or mixed materials reducing the propensity for failure in these systems.

Task P1.4: Fracture toughness and flexural strength measurements

Both fracture toughness and flexural strength measurements was performed using a standard three-point bend setup. The measurements were performed on thick specimens with at least three repeats for each case. These two measurements will be used to scrutinize the materials in terms of their strength to withstand high compressive pressures and or their resistance to any pre-existing cracks. Below figure shows a standard YSZ coatings with nominally 0.78 $MPa*m^{1/2}$ fracture toughness. The standard YSZ powder can be blended with metallic powder (here, a nickel bond coat mixture) and deposited to disperse metallic particles throughout the coating. This was done with a 95/5 vol.%, and showed a slight increase in the measured toughness of the blended material. The nickel particles act to blunt crack propagation or act as obstacles that force a propagating crack along a more energetically costly route. Both result in a higher toughness.

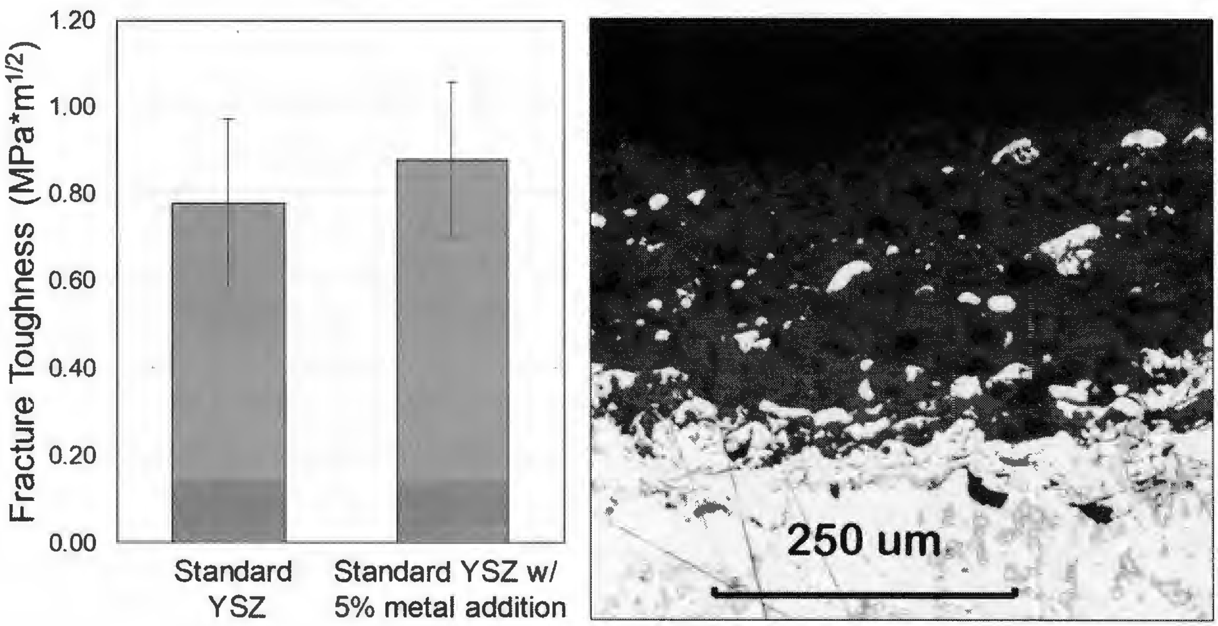


Figure 3. Fracture toughness of various YSZ by different processes and with different compositions. On the right, slight increase in toughness of the blended YSZ – Nickel mixture over the standard YSZ.

Task P1.5: Elastic modulus calculations using curvature measurements

Bi-layer curvature technique, which has been extensively used at CTSR-Stony Brook to characterize non-linear elastic properties of sprayed ceramic coatings, was used to measure in-plane elastic modulus for single layers and an overall elastic modulus of multilayer coatings. These measured values will be utilized in the thermal stress profile calculations for multilayer coatings under gradient temperature conditions. For the 5 different thermal inertia variants, using pure YSZ, there is a steady increase in coating elastic modulus, expected as the coating structure densifies. In Figure 6, scanning electron microscopy (SEM) of the cross-sections of those samples is shown, with increasing density seen in the microstructures. This results in a severe crack at the highest density/thermal inertia sample.

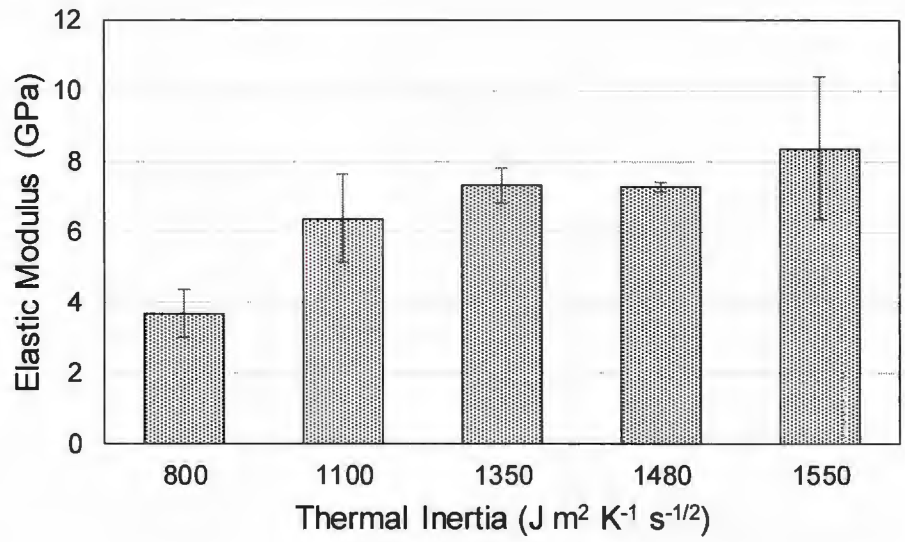


Figure 5. Elastic modulus results of 5 different thermal inertia materials.

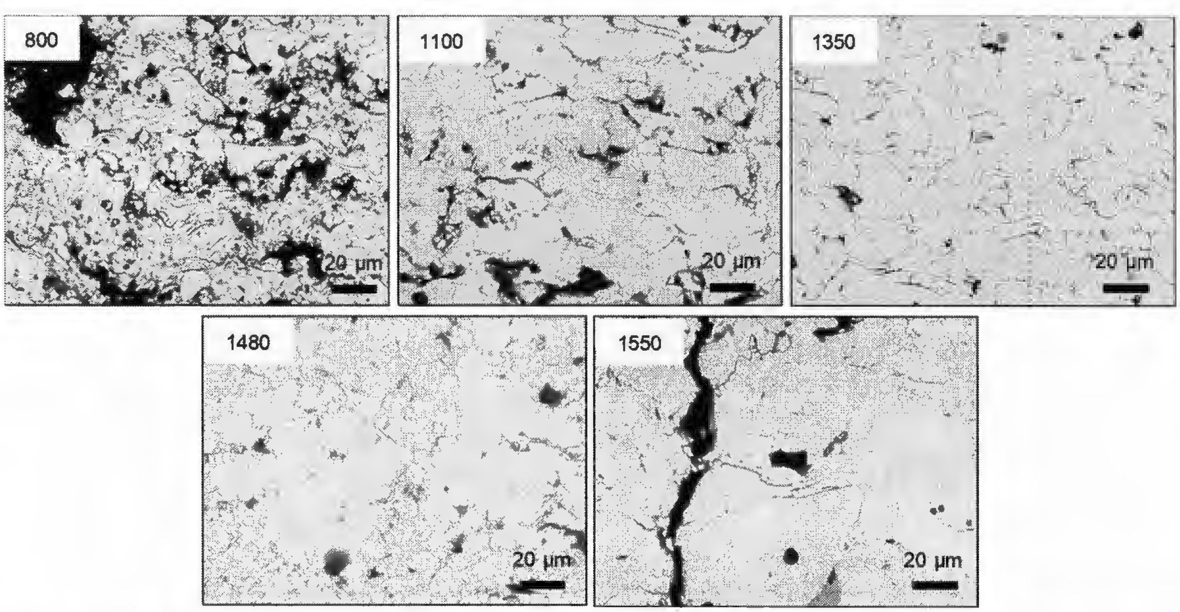


Figure 6. SEM microstructures of the varying YSZ materials, as a function of increasing thermal inertia.

5.4 Simulated testing to estimate thermal inertia and temperature swing

Samples were tested by directing a high heat flux oxy-kerosene flame through a rotating shutter. As the flame passes through the shutter and is subsequently removed the surface temperature fluctuations are recorded using a high-speed thermal imaging camera. This test is performed to simulate the transient thermal exposure that a coating may experience in its operating environment.

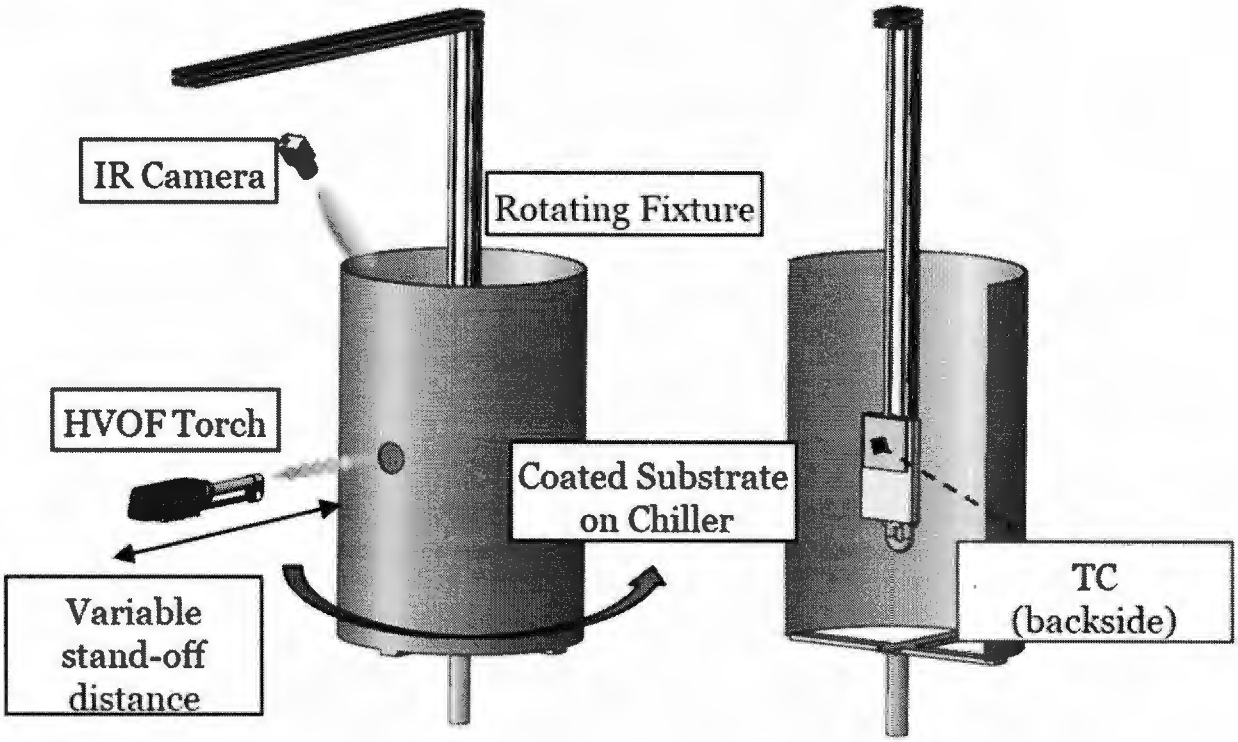


Figure 7. Schematic test setup of pulse testing for simulated engine performance.

The figure below shows the sample before and after thermal exposure with the surface thermal transience illustrated as a false color temperature reproduction. Backside water cooling was used to manage the overall temperature and prevent overheating of the fixturing components.

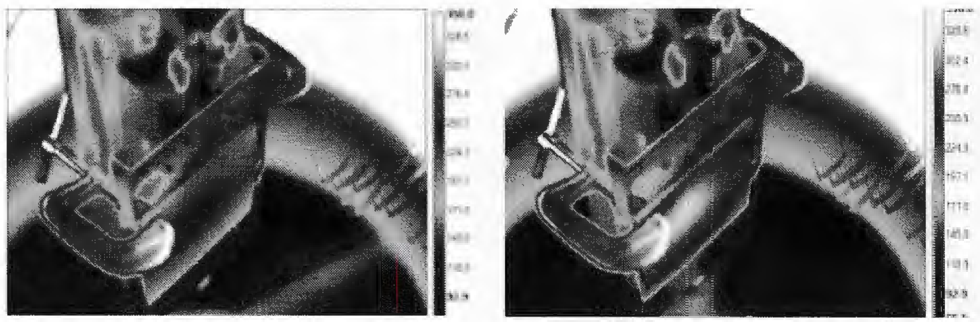


Figure 8. FLIR infrared camera view of sample surface. The simulated cyclic transience can be seen fluctuating in the center of the image.

Temperature swings were measured using a fixed region of interest after approaching a time invariant response, which generally developed around one minute into the test. The difference between high and low surface averaged temperature values was then assessed by taking the average of three minutes of cycles. Coatings for these tests were produced on 3" x 3" x 3/32" plates with samples for microstructure and material comparisons produced to a fixed 0.200 mm thickness. Further tests were performed on coatings ranging from 0.025 mm to 1.6 mm in thickness to probe the effects of thickness on thermal swing, which has been identified as a critical parameter for effective insulation.

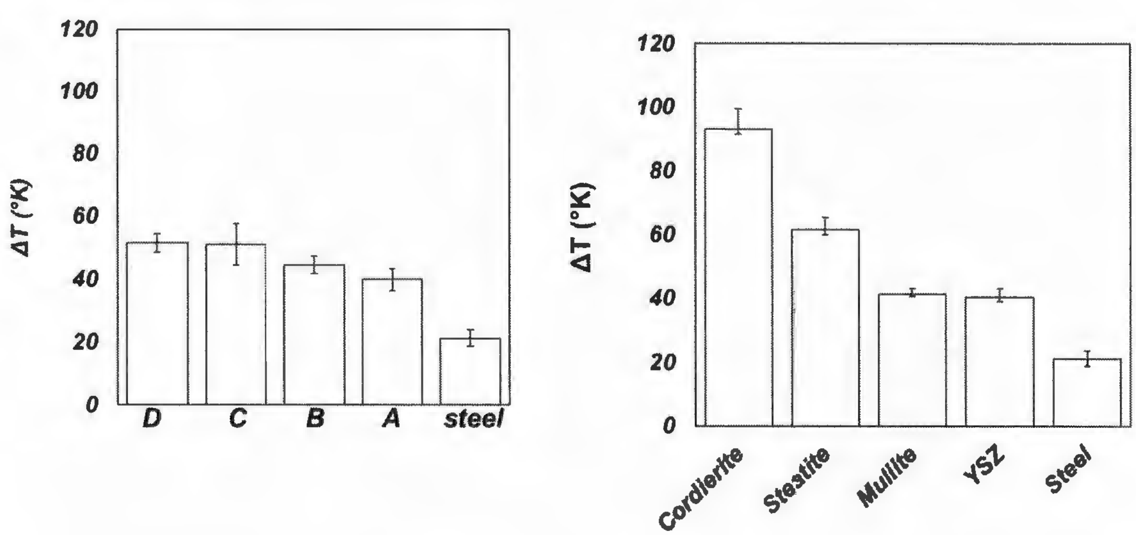


Figure 9. Thermal swing for both microstructure (left) and material variations (right) with baseline steel provided of the right of each plot.

The results from this test suggest that microstructure induced thermal property reduction increases thermal swing to a certain point, where thermal swing saturates. The results from material variation suggest that cordierite should provide ideal thermal behavior for this application.

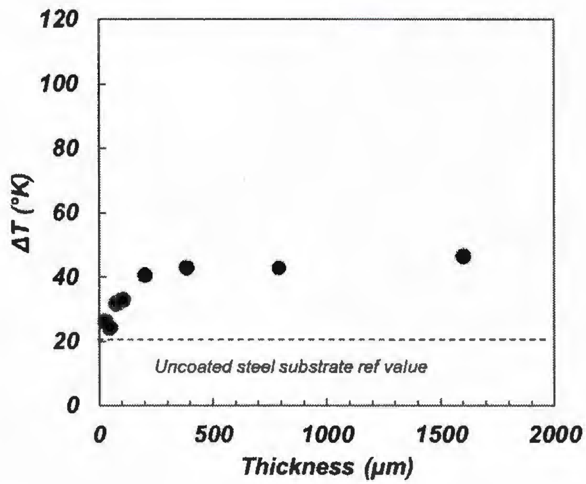


Figure 10. Thermal swing is plotted against thickness for coatings ranging from 0.025 to 1.6 mm for a standard YSZ coating, with thermal swing saturating at thicknesses above 200um.

5.5 Finalize the optimum coating architecture for engine test

The use of layered structures in this work is based on their successful implementation in gas turbine architectures widely reported in past literature. For this application, this includes a bond coat layer, ranging from 40 to 65 μm, a transition layer of blended 70/30 vol% ratio of YSZ and bond coat and a top coat of 95/5 vol% blend YSZ and bond coat to meet the remaining thickness requirement, which varied based on TARDEC requirements from 70 to 250 μm. The below figures show both SEM and optical microscopy of the coating cross-section. Modified architecture of the coating was applied on the piston with total of 265 μm thickness of 50/50 atomic weight% ratio of cordierite/YSZ and bond coat.

In addition, two alternative architectures have been provided to the CCDC-GVSC to probe the effects of material properties and surface roughness. Cordierite-YSZ coated pistons were provided with target architectures of 280 μm, cordierite-YSZ top coat, with 40 to 65 μm bond coat. Finally, a dense YSZ sealing layer was applied to a coating similar to the first pistons provided.

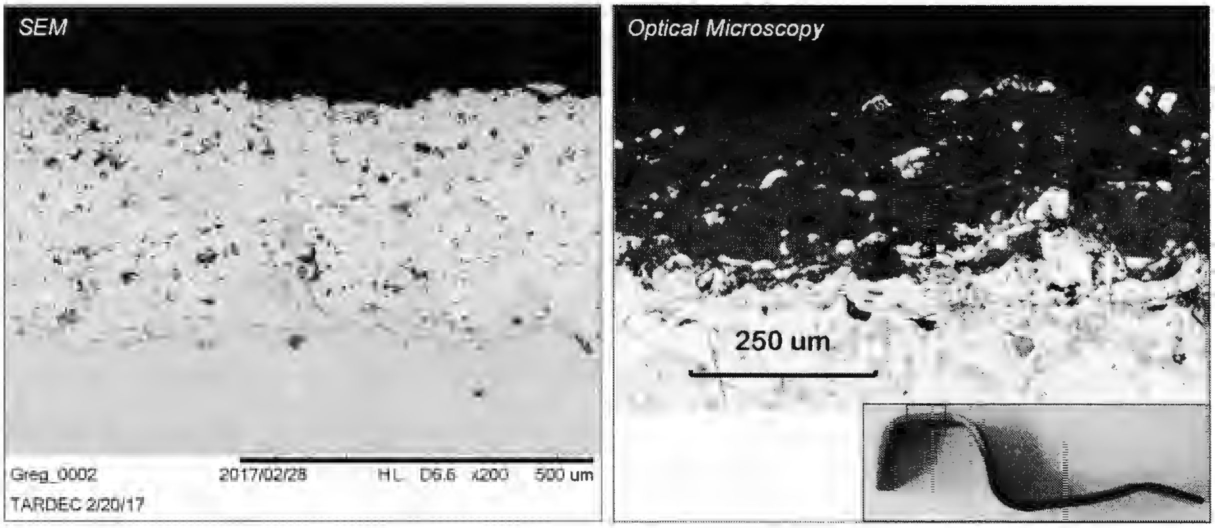


Figure 10. First coating architecture on pistons sent to CCDC-GVSC. Coatings were optimized on test strips, and then on a mock piston, before final coating on the provide test pistons.

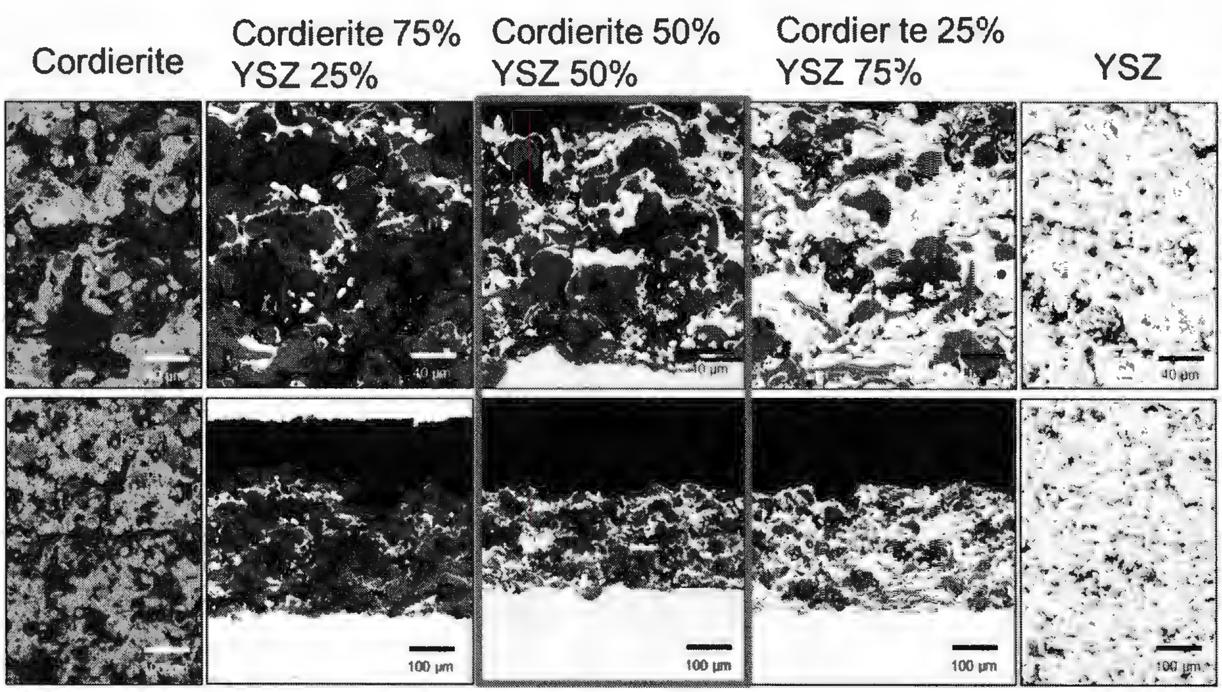


Figure 11. Second coating architecture on pistons sent to CCDC-GVSC. Coatings were optimized on test strips, and then on a mock piston, before final coating on the provide test pistons.

5.6 Improved manufacturing process for piston thermal barriers

The manufacturing process used to provide the first samples provided to the CCDC-GVSC has greatly been greatly improved through further process optimization, toolpath development, and alternative hard masking strategies. The development process has been split into three distinct development stages: toolpath development on strips mocking the piston bowl geometry, toolpath refinement and spray program development on mock parts, and final part production.

Process development has included upgrading the plasma spray hardware from the 3MB plasma spray torch a F4MB, which provides a smaller deposition footprint that allows for finer control over thickness and microstructure on the complex bowl geometry.

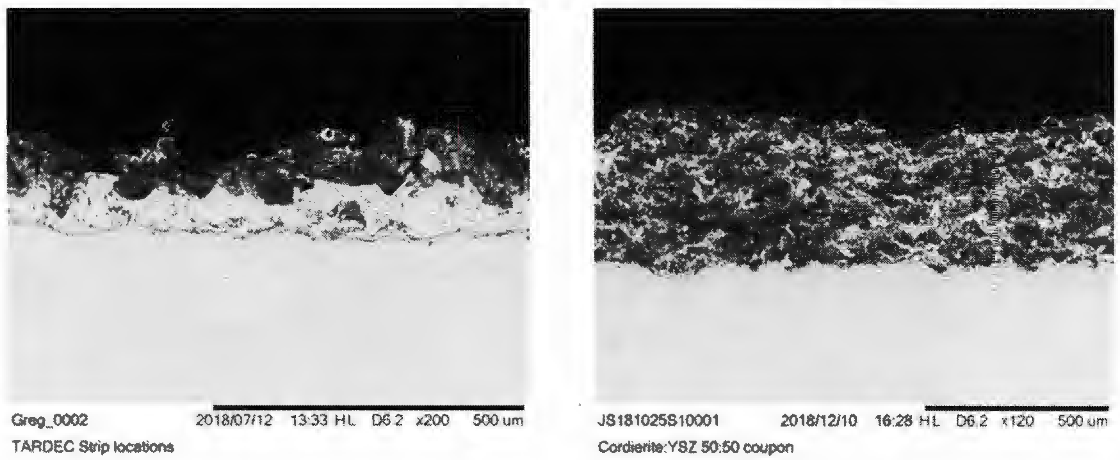
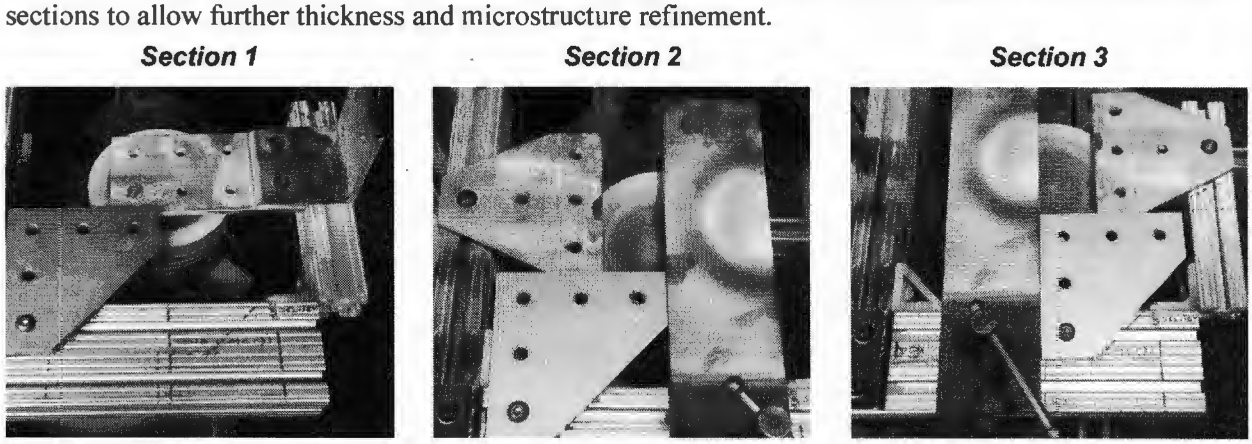


Figure 12. The improved microstructure provided by the F4MB. The image on the left is a SEM micrograph of the microstructure developed on parts of the piston geometry using the 3MB, while the image on the right shows the improved control of reproducing coupon level microstructures on the piston geometry using the F4MB.

Toolpath development has centered on splitting the continuous spray program into three distinct sections to allow further thickness and microstructure refinement.



6. Task-wise statement of work for Part- 2: Engine testing of coated piston

6.1 Single-cylinder Research Engine – SCRE

Alongside material development and optimization at CTSR, concurrent work was also undertaken at CCDC-GVSC. The focus of this work was going to be on their single-cylinder research engine (SCRE) rig, which allows for testing of actual pistons under operation conditions. This potentially could include additions of coating and other variables. As part of this work, pistons were provided by CCDC-GVSC to CTSR for coating, which was detailed above. At this point, preliminary results are available from CCDC-GVSC on YSZ and cordierite coated piston testing.

After minor changes the first YSZ pistons have shown a benefit to Indicated Thermal Efficiency gross (ITEg) upwards of 2%, while maintaining all other critical engine metrics (emissions and measured temperatures) equivalent to or better than the baseline uncoated piston. However, initial tests showed reduced performance in terms of ITEg and the Filtered Smoke Number (FSN). Researchers at the CCDC-GVSC suggested that the increase in FSN was likely due to poor air fuel mixing caused by the TBC's increased surface roughness. To mitigate this the first set of pistons was surface finished using SiC polishing paper from an as sprayed surface roughness of 12 um R_a to a 6 um R_a.

In addition, the cordierite YSZ mixture coated pistons, which have greatly reduced thermal properties, have shown little improvement to any engine metric. The results of the YSZ coated piston engine tests suggest that this may in part be the result of the coatings greatly increased surface roughness. Due to limitations in available powder feedstocks, these coatings were only surface finished to an average roughness of 10 um R_a.

To probe these effects a finer cordierite feedstock was obtained and used to spray coatings with higher density and a lower as sprayed surface roughness. These coatings were additionally surface finished to a 2 um R_a surface finish. Alongside these coatings were produced on varying sections of the piston crown by selectively masking radial sections. The resulting patterned piston coatings were selected to remove the coating interactions with the combustion process. Three variations were produced and tested in the SCRE: a fully coated cordierite-YSZ piston crown, a piston crown with only the "squish" region coated, and a piston crown with only the bowl coated. Initial tests reveal no apparent change to any measurable engine metric, however by creating a denser and smoother coating the thermal properties of these coatings were significantly penalized.

6.2 Government furnished material

Once initial testing at CCDC-GVSC locations has been completed, the material and coating that performs closes to their prescribed requirements will be then deposited onto the same series of pistons for evaluation in the SCRE and MCE rigs.

7. Project Schedule and Milestones

As the project has evolved over its course, significant progress has been made at CTSR in fulfilling the targets laid out in the proposal. This can be summarized under specific tasks, as how data was reported above, or in more broad deliverables, as outlined below.

7.1 Deliverables of Part 1

The deliverables for Part- 1 have all been fulfilled of the projects are as follows, with comments below each item on the status. Part 1 also included a task-wise breakdown of specific focus points.

1. *Develop a comprehensive database for metallic and ceramic sprayed coating for their thermo-physical characteristics based on their a) density, b) thermal conductivity and c) specific heat.*

This has been well completed and continues to be built upon for this works succeeding proposal. A range of materials, process conditions, etc. have been tested. A database of more than 13,000 thermophysical property measurements of actual prayed coatings has been established that can be used for materials selection.

2. *Design and establish robust setups for thermal inertia measurements, based on both heating and cooling pulse.*

Robust setups have been designed and evaluated for heating pulse testing. Results have pointed to distinct trends that alight with results from the base material thermal inertia measurements. Testing has focused on different thickness coatings and different temperature ranges of the test platform. Further focus was placed on developing a method to test to simulate a higher RPM range, which has been designed based on a variable speed rotating fixture. This was used to screen candidate materials identified from the CTSR thermal property database for the engine tests conducted within the scope of this work

4. *Multilayer architecture coating deposition on nineteen sets of piston heads provided by TARDEC for engine test.*

A large number of pistons, more than nineteen, have been provided by CCDC-GVSC. These have been coated with materials ranging from traditional TBCs to novel thermal swing materials and metals at the CTSR. Several patterning studies have also been conducted to probe coating-combustion interactions. Additionally, thermocouple instrumented telemetry pistons have also been provided that will serve to aid in the understating of heat transfer though these systems. Knowledge gained from these telemetry tests will provide feedback into strategies for realizing efficiency gains though the use of coatings.

7.2 Deliverables for Part 2

The project schedule is setup for the government to receive up to five sets of optimized coatings. Each subsequent coating iterations will leverage engine data generated from the previous set. Each subsequent iteration may include changes to:

1. *Piston bowl shape*
2. *Coating application patterns*
3. *Coating thickness*
4. *Coating thermal properties including thermal capacitance and conductivity.*
5. *Roughness*

Changes made for each iteration will be primarily directed by CCDC-GVSC when additional engine performance is sought after. If a coating fails during testing, failure analysis should be conducted by the contractor. At this stage, preliminary results from pistons with YSZ coating have been provided. A new set of pistons with cordierite/YSZ mixture coating have been sent for the next test runs. Also, continued development and measurement of the new materials is in progress and will be used in ongoing coating deposition and to target future performance improvement.

7.3 Current status

At the current time a range of materials development, testing, and observation has been achieved. Deliverables for parts 1 and parts 2 are currently met. Supplemental work has also been enabled with project support. Work on thermal inertia measurement, material development, process development, and engine testing has been presented at the June 2019 CTSR Consortium meeting, Nov. 2019 CTSR Consortium meeting, May 2019 ITSC, April 2019 SAE WCX, May 2020 ITSC, June 2020 CTSR Consortium meeting, and Dec. 2021 TICS symposium with feedback from industrial partners being well received. The project has also enabled several graduate and undergraduate students to be involved in various positions of coating manufacture, testing, and evaluation.

In addition, key points from this work have been disseminated though four publications. These include: "Thermal Swing Evaluation of Thermal Barrier Coatings for Diesel Engines", published in the Journal of Thermal Spray Technology in 2020; "A Comprehensive Experimental Investigation of Low-Temperature Combustion with Thick Thermal Barrier Coatings", published in Energy in 2021; "The Effects of Thick Thermal Barrier Coatings on Low-Temperature Combustion", published in SAE International in 2020; "The Impact of Piston Thermal Barrier Coating Roughness on High-Load Diesel Operation" , published in the International Journal of Engine Research in 2021. The first publication listed here was also the recipient of the Journal of Thermal Spray Technologies 2020 runner up best paper award.

The 3 main objects of Part 1 included, 1) developing a multilayer thermal management architecture which is able to address the issues of low specific heat, low thermal conductivity, reduced in-plane thermal gradient, and high durability; 2) deposition of these architectures on actual pistons for CCDC-GVSC; 3) material analysis after engine test performance. In the first regards, this has overall gone well in the case of characterizing materials with low specific heat and low thermal conductivity. Durability and in-plane thermal gradients have been assessed through both traditional and novel laboratory experiments as outlined in this report. CTSR was successful in optimizing and depositing these architectures on the provided pistons, ensuring thickness consistency across the piston. In addition, the pulse heating tests, which have showed a strong relationship between thermal inertia and actual thermal swing in a simulated engine test environment.