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Further Industrial Tests of Ceramic Thermal-Barrier Coatings

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Summary

Manufacturers of aircraft, missile, automotive, and military-vehicle gas turbine engines and diesel and spark-ignition reciprocating engines and manufacturers in other diverse industries have continuously expressed interest in thermal-barrier coatings (TBC). Because of this interest and the need to continue to evaluate the use of the coating, the NASA Lewis Research Center made technical assistance arrangements (contracts) with several commercial organizations under which Lewis designed plasma-sprayed, yttria-stabilized-zirconia TBC's for their products. Lewis was then furnished with the test conditions and evaluations of coating usefulness. These systems were sprayed at Lewis and incorporated the two-layer ceramic-bond coating concept. Coating thickness and chemical composition were varied to fit the application. All of the systems incorporated yttria-stabilized zirconia as the ceramic thermal-insulating coating. This coating lowered metal temperatures, protected metal parts, and increased metal part life. In some cases burning, melting, and warping were eliminated. For example, the uncoated leading edges of the first-stage turbine vanes for an advanced gas turbine engine fatigued and melted after short test times in full-scale engine cyclic tests, but the satisfactory performance of the TBC resulted in the meeting of major program objectives with no cracking or melting of the air-cooled metal walls. Also, the thermal protection provided by the coating system on the flame impingement surfaces of combustor transition sections eliminated metal cracking during accelerated mission testing with no deleterious effects to the coating. The results of the tests on coated diesel engine parts showed that the NASA-applied coating reduced heat losses by 5 percent and that it exhibited excellent adherence. Based on these early results the manufacturer sees a future potential for ceramic-insulated adiabatic diesel engine parts.

Additional benefits were realized from these endeavors. First, hands-on experience with TBC's was provided to industry. Second, the success of these endeavors encourages these and other organizations to accelerate the implementation of TBC technology.

Introduction

Interest in thermal-barrier coatings (TBC) has been continuously expressed by manufacturers of aircraft, missile, automotive, and military-vehicle gas turbine engines and diesel and spark-ignition reciprocating engines and by manufacturers in other diverse industries. Because of this interest and the need to continue to evaluate the use of such coatings, the NASA Lewis

Research Center made technical assistance arrangements (contracts) with several commercial organizations under which Lewis designed and sprayed TBC's for their evaluation. In return Lewis was furnished with the conditions and test results.

The first such series of tests is described in reference 1. In that reference it is established that a two-layer TBC system with a bond coating of nickel-chromium-aluminum-yttrium (NiCrAlY) and a ceramic coating of yttria-stabilized zirconia substantially reduces the temperature of air-cooled metal parts operating in the hot-gas paths of aircraft and ground-based-vehicle gas turbine engines. It is also shown in reference 1 that this two-layer TBC increases part life and eliminates burning, melting, and warping.

The results reported herein are a continuation of the technology/data exchange program. All of the systems incorporated yttria-stabilized zirconia as the ceramic coating. The coating systems used were based on recent research at Lewis (refs. 2 and 3) and incorporated the two-layer coating concept, but coating thickness and chemical composition were varied to fit the application. Also, the chemistry of the arc gas used to spray the bond coatings was varied for some cases, as suggested in reference 4.

To protect proprietary interests, test conditions are not always described in great detail. The information presented, in addition to a discussion of test results, includes (when available) photographs of coated parts before and after tests. Based on the results of these tests, conclusions are drawn about the usefulness of TBC's in industrial applications.

Arc-Plasma-Sprayed Procedures

Before spraying was done at Lewis, all of the metal surfaces were vapor degreased and grit blasted with 99.5-percent-pure (white) aluminum oxide. The inlet supply pressure to the commercial grit-blasting equipment was 5.5×10^5 N/m² (80 psia). The alumina grit size was 250 μ m (0.01 in.). Within 15 min after the grit blasting, the bond coatings were arc plasma sprayed onto the roughened metal surfaces with a commercial hand-held gun. The particle size of the bond coating powder fed into the plasma spray gun was 44 to 74 μ m (0.002 to 0.003 in.). Within 30 min after the bond coating was applied, the ceramic was arc plasma sprayed onto the bond coating. The particle size of the ceramic powder fed into the gun was 44 to 74 μ m (0.002 to 0.003 in.). Pure argon was used as the arc gas for spraying all of the zirconia ceramic coatings. In two cases argon arc gas with 3.5-vol% hydrogen was used to spray the bond coatings; for the other case pure argon was used.

Research Turbine Vanes for Advanced Gas Turbine Engine

Objectives and Specimens

Prior to the use of thermal-barrier coatings (TBC) many first-stage-vane leading edges were destroyed after only a few cycles of engine operation (fig. 1). This resulted in premature termination of the tests. To achieve better vane durability and longer engine test times, TBC's were sprayed onto the leading edges of 40 turbine vanes of identical design. The leading edges of these vanes were fabricated from thoria-dispersion-strengthened nickel chromium. Leading edges of 33 of these vanes, which cracked from previous tests, were refurbished by laser welding. Representative uncoated vanes after the cracks were welded shut are shown in figure 2. A coated vane is shown in figure 3. Thirty of these vanes were sprayed with a Ni-16Cr-6Al-0.6Y bond coating to a thickness of 0.015 cm (0.006 in.) and then with a ceramic coating of $ZrO_2-12Y_2O_3$ to a thickness of 0.030 cm (0.012 in.). To increase durability and to maintain good aerodynamic

performance, the ceramic was faired into the uncoated vane profile aft of the leading edge and was smoothed to a roughness of 1.6 to 3.0 μm rms (6.3×10^{-5} to 1.2×10^{-4} in.) with silicon carbide cloth. Roughness was measured with a commercial surface roughness indicator. It was necessary to end the coating abruptly at the hub and tip of the leading edges. The tests at high pressures and temperatures discussed in reference 1 show that the coating would probably deteriorate near these exposed sharp corners. Redesign of the vanes for more durable coating application was not feasible, but the investigations described in reference 1 indicate that the metal walls of the vanes could still survive for the duration of the tests because there would be conduction cooling from a wall exposed by a spalled coating to a cooler coated metal wall adjacent to the spalled area. Five other vanes were sprayed with a Ni-25.7Cr-5.6Al-0.3Y bond coating, and five more vanes were coated with a Ni-18Cr-12Al-0.3Y bond coating. These 10 vanes were then coated with $ZrO_2-7.9Y_2O_3$ ceramic coatings. Incorporating the results of reference 4, the bond-coating spraying was done at 20 kW using argon arc gas with

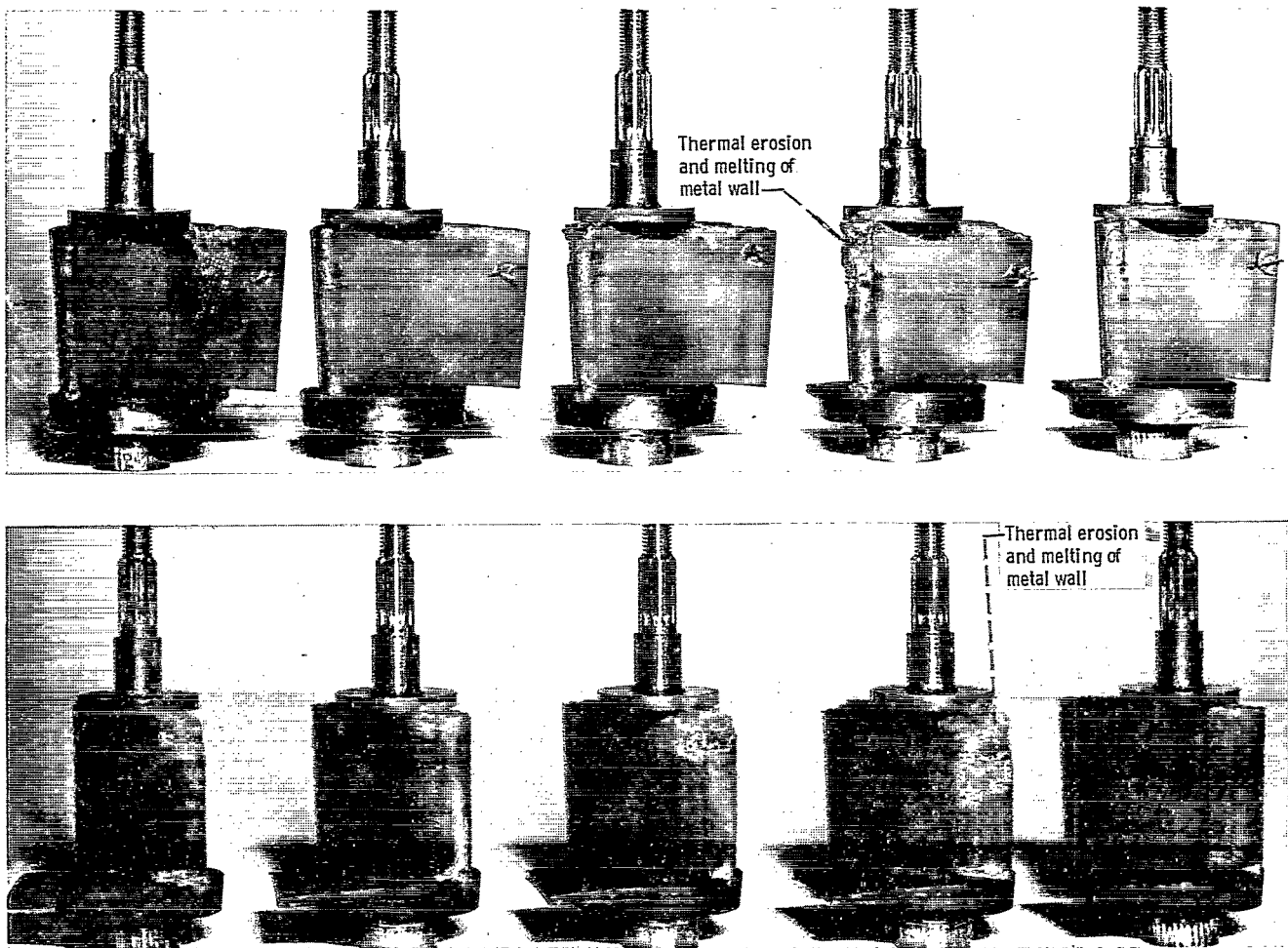
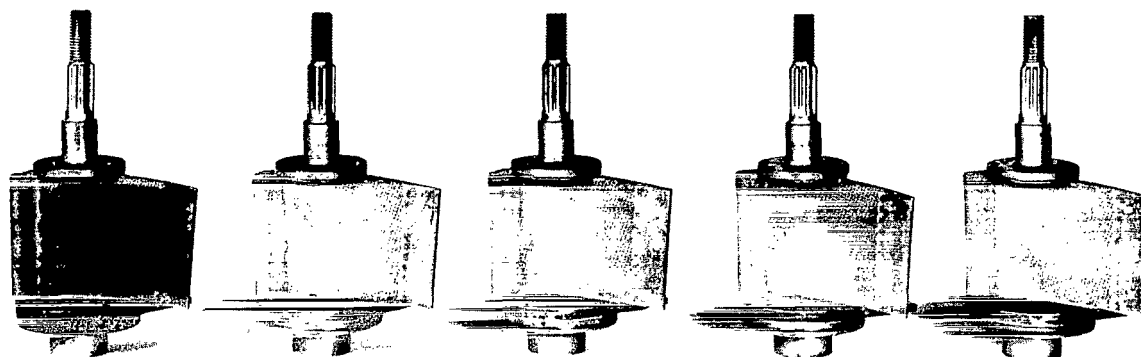


Figure 1. - Premature first-stage-vane leading-edge metal wall distress before use of thermal-barrier coatings.



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Figure 2. - First-stage vanes of advanced gas turbine engine before coating.

3.5-vol% hydrogen rather than at 11 kW using only argon. The ceramic profiles, thicknesses, and roughnesses of these 10 vane specimens were identical to those maintained on the other 30 vanes. Because of masking problems compounded by time and materials limitations, the gas turbine manufacturer recoated some of the vanes at the hub and tip regions with a NiCrAlY bond coating and an Al_2O_3 ceramic coating.

Experimental Conditions and Results

Accelerated, full-scale engine cyclic tests were performed. Cycling was done from idle to maximum temperatures of about 1255 K (1800° F) to above 1870 K (2900° F).

After 69 major cycles and 4½ hours at temperatures above 1870 K (2900° F) the engine was shut down for borescope inspection of the leading edges of the first-stage vanes coated with TBC. This inspection showed no evidence of coating or vane deterioration. The engine was then run for 18 more cycles. The condition of the vanes when they were removed from the engine after a total of 87 major cycles is shown in figure 4. Some coating cracking and spalling from the bare metal surfaces was noted at the base of most of the vanes coated either with Al_2O_3 , $\text{ZrO}_2\text{-}12\text{Y}_2\text{O}_3$, or $\text{ZrO}_2\text{-}7.9\text{Y}_2\text{O}_3$ ceramics. There was some pitting of the bond coating from which the ceramic coating had spalled, but the metal walls nevertheless remained intact. Visual inspection of all 10 of the $\text{ZrO}_2\text{-}7.9\text{Y}_2\text{O}_3$ -coated vanes at the central or midspan regions showed that the ceramic surfaces were in excellent condition. However, in this central region 6 of the 30 $\text{ZrO}_2\text{-}12\text{Y}_2\text{O}_3$ -coated vanes were spalled or cracked. Nevertheless, the meeting of major engine program objectives was largely attributable to the good durability and thermal insulation qualities of the ceramic thermal-barrier coatings.

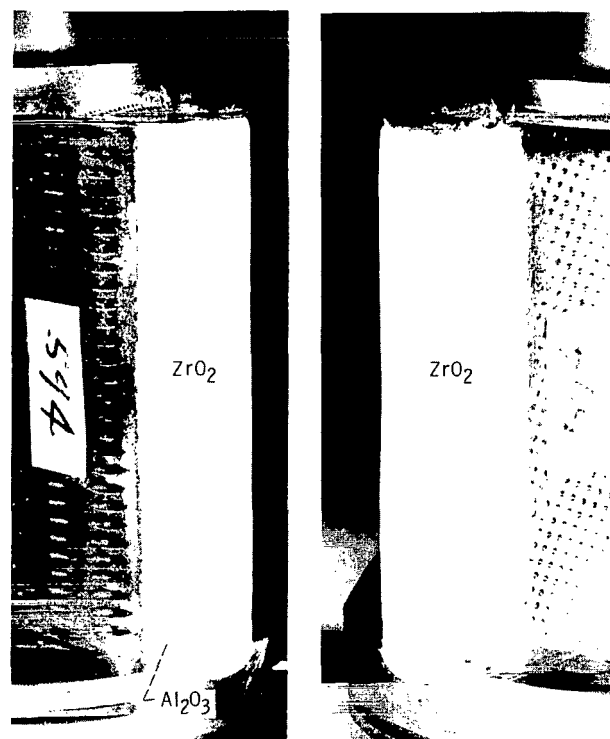


Figure 3. - Leading edges of advanced gas turbine engine first-stage vanes after coating and before testing.

Combustor Transition Section for Production Gas Turbine Engine

Objectives and Specimens

Prior testing revealed evidence of warping and cracking of uncoated combustor components and premature deterioration of commercially available

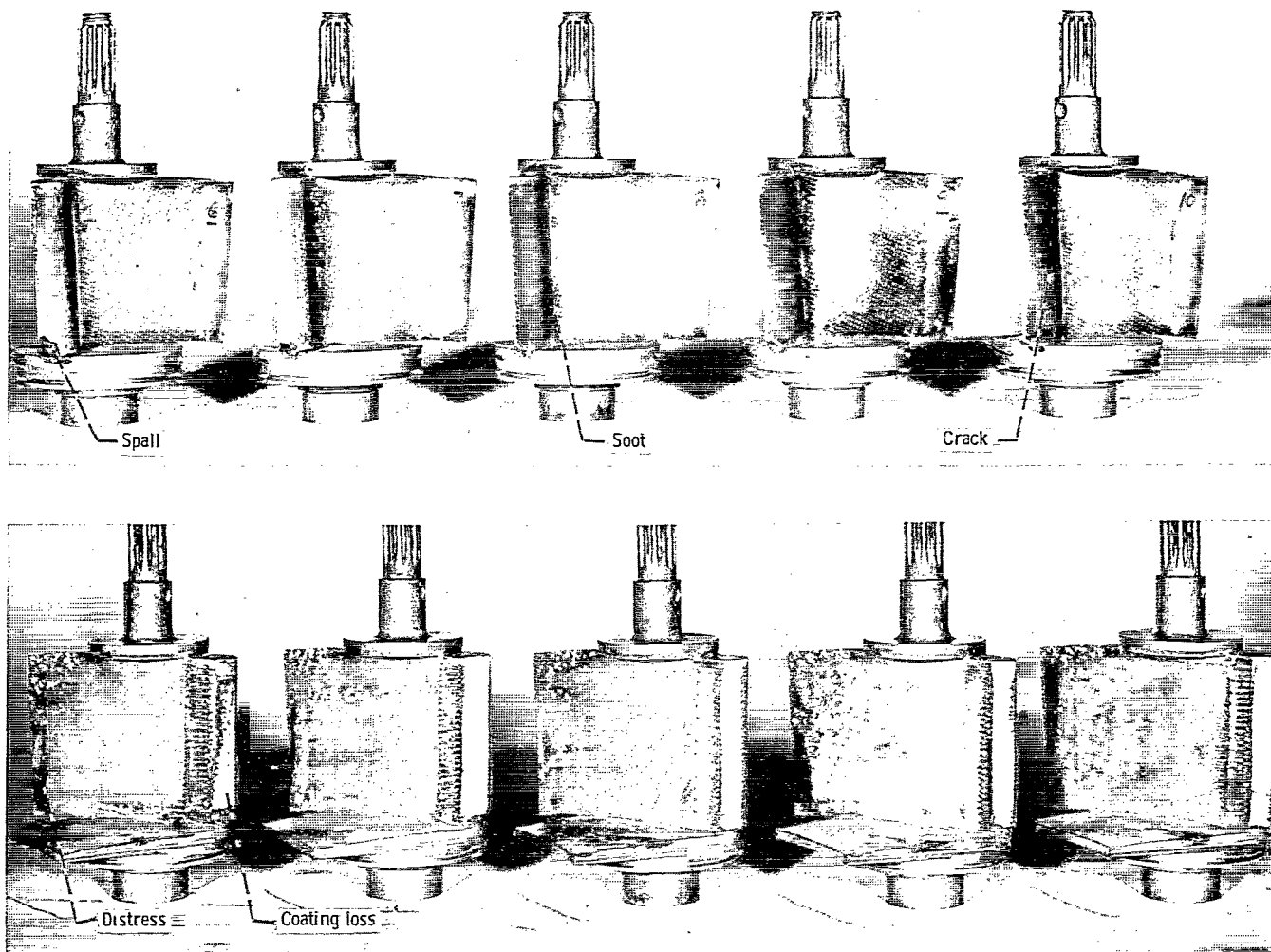


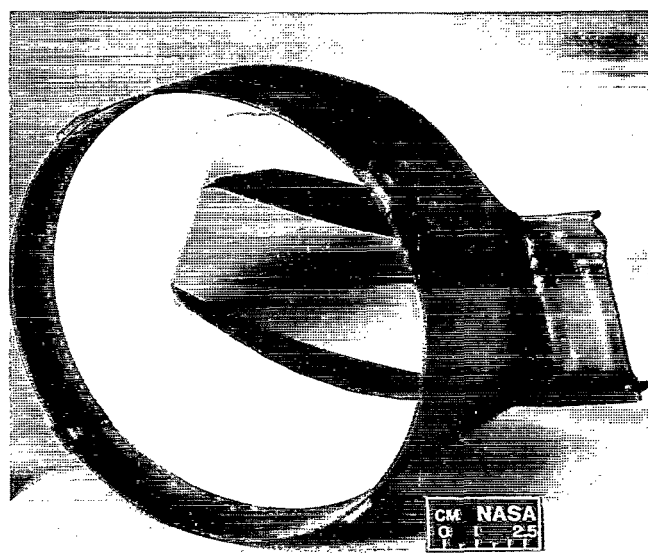
Figure 4. - First-stage vanes of advanced gas turbine engine after testing.

coatings. Therefore tests were done to evaluate the use of recent Lewis coating technology that could improve the durability of these parts.

A two-layer TBC system was used that consisted of a bond coating of Ni-16Cr-6Al-0.3Y sprayed to a thickness of 0.015 cm (0.006 in.) and a ceramic coating of $\text{ZrO}_2\text{-}8\text{Y}_2\text{O}_3$ sprayed to a thickness of 0.003 cm (0.012 in.) onto the interior flame impingement surfaces of the transition sections shown in figure 5. The ceramic was not smoothed after deposition. The bond coating was sprayed at 20 kW using argon arc gas (ref. 4) rather than at 11 kW using only argon. Then the cooling holes (fig. 6), which had been covered during deposition, were punched open.

Experimental Conditions and Results

Accelerated full-scale engine cyclic mission tests were performed according to the cyclic details shown in figure 7. Cycling was done from about 1500 K (2240° F) and about $21 \times 10^5 \text{ N/m}^2$ (300 psia) to 800 K (980° F) shutoff conditions.



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Figure 5. - Coated combustor transition section of production gas turbine engine before tests.

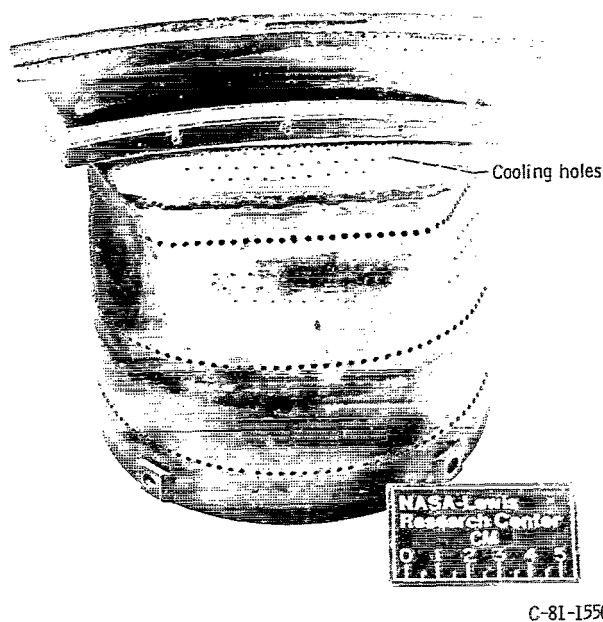


Figure 6. - External view of combustor transition section of production gas turbine engine.

Five coated transition sections and five uncoated transition sections of identical design were run simultaneously for 236 hours and 944 major cycles (fig. 7) of accelerated testing and for 300 hours overall in the same engine. Two of the five uncoated combustors cracked during the tests. No failure of coating or metal was observed with the coated sections. The tests were successful, and it was concluded that the coating has a high potential for improving the durability of this engine model, which currently is in service in large numbers.

Diesel Engine Head and Valves

Objectives and Specimens

There is interest in coatings for diesel components to reduce heat loss and thus enhance efficiency. The research objectives were to determine the in situ structural integrity of the coating and to determine the insulative effects of the TBC on engine performance. Good coating structural integrity is especially important on the valves, which deflect considerably when they slam into the seat.

The engine was a single-cylinder version of a water-cooled production engine with a 116-mm (4.6-in.) bore and a 121-mm (4.8-in.) stroke and was rated at 34 kW at 2100 rpm, which equates to a brake mean effective pressure of 1550 kPa (225 psi). This is a high output by today's standards. Figure 8 shows uncoated valves inserted into position in the head before spraying. Head, intake valve, and exhaust valve base materials were cast iron, SAE-HNV-6, and SAE-V-12, respectively. The head and valves (figs. 8 and 9) were coated with Fe-25Cr-5Al-0.6Y bond coating to a thickness of 0.015 cm (0.006 in.) and then sprayed with $ZrO_2 \cdot 8Y_2O_3$ for a total coating thickness of greater than 0.1 cm (0.040 in.). Then the ceramic coatings on the valve and head were ground to thicknesses of 0.075 and 0.1 cm (0.030 and 0.040 in.), respectively. Zirconia sprayed onto diesel engine valves and heads ground very well. Some glazing occurred at low workpiece speeds, but the glazing problem was solved by redressing the wheel and increasing the workpiece speed. Once the head was machined, a special piston was prepared that maintained a standard piston-to-head-deck clearance.

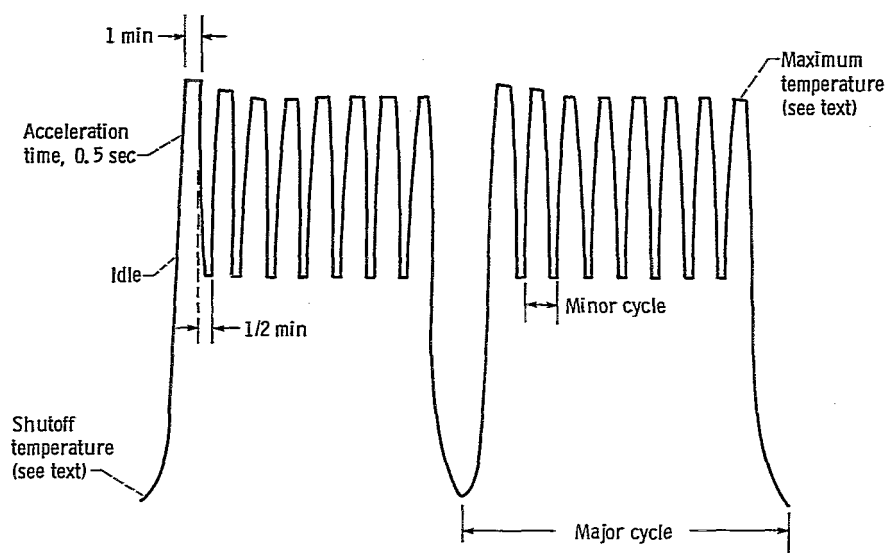


Figure 7. - Representative engine cycles for accelerated, full-scale tests.

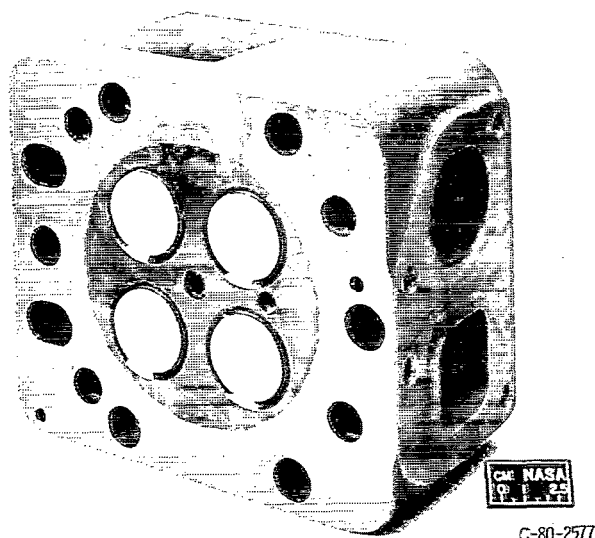


Figure 8. - Diesel engine head and valves before coating.

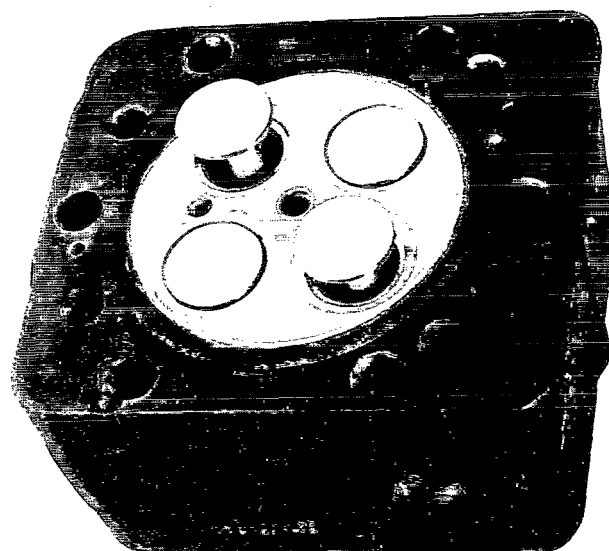


Figure 10. - Diesel engine head and valves after coating and before testing.

Experimental Conditions and Results

The water-cooled diesel engine with the ceramic-coated parts (fig. 10) was run for 10 hours at full load conditions. The uncoated parts had shown wear and sometimes even destruction after a 10-hour run at these conditions. After the engine was run for 5 hours, the head was removed and inspected. Because the coated parts were in excellent condition, the test was continued for another 5 hours. The parts were then removed from the engine, and visual inspection showed that they were in excellent condition. Photographs of these parts after running are shown in figures 11 and 12. All of the coatings were intact and there was a light coating of carbon on the ceramic surface. The distress in the cylinder pressure transducer region (fig. 11) resulted from

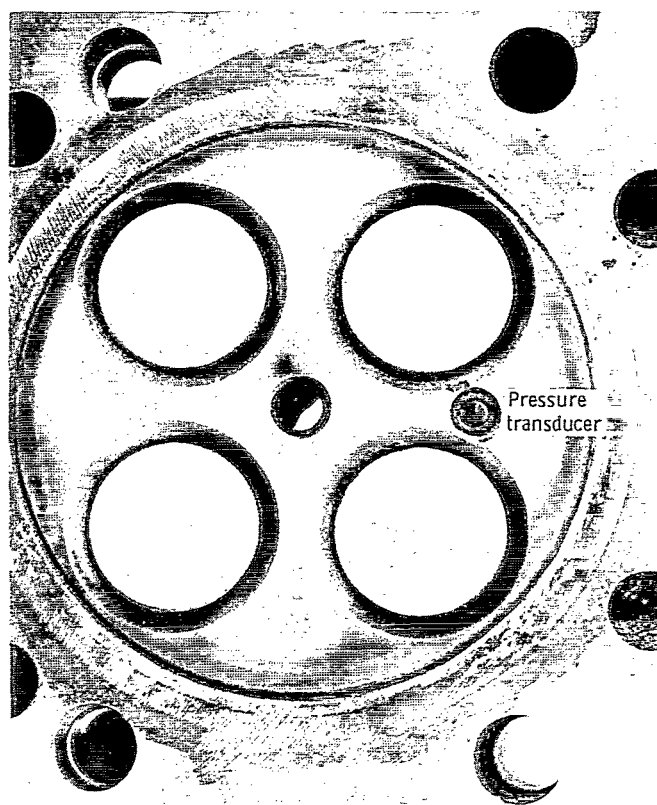


Figure 11. - Diesel engine head and valves after coating and testing.

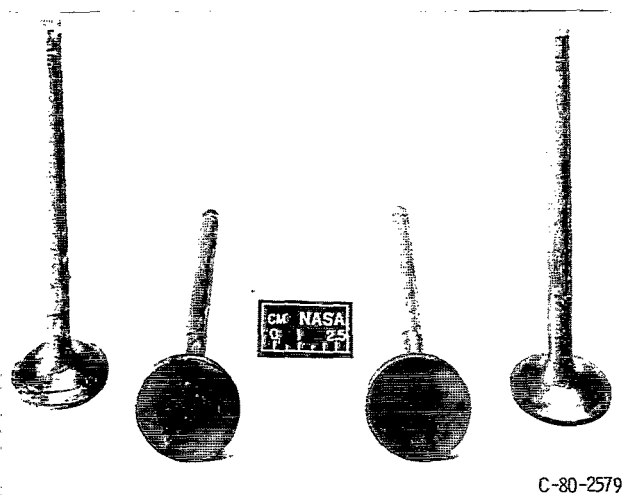


Figure 9. - Diesel engine valves before coating.

pretest handling and not from testing.

The TBC appeared to have adequate strength to withstand the thermal and mechanical loading incurred in this high-output diesel engine and apparently was instrumental in reducing distress on uncoated parts.

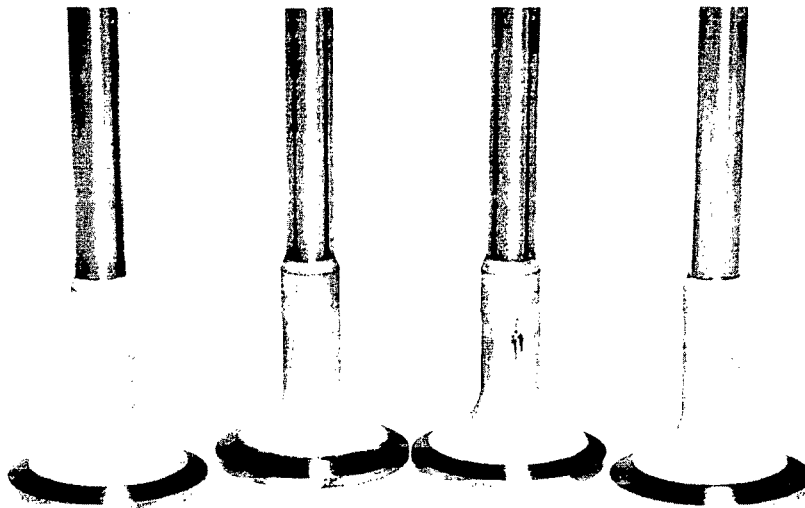


Figure 12. - Diesel engine valves after coating and testing.

Exhaust temperatures were increased from 880 K (1124° F) to 920 K (1196° F) when the engine was run with the insulated parts. Because of the higher combustion chamber gas temperatures, engine volumetric efficiency was, as expected, reduced by 5 percent at rated conditions. The amount of smoke exhausting from the engine was the same. Measurement of total heat rejection to the coolant showed a 5 percent reduction with the insulated components. Considering the limited surface area that was coated, these results indicated to the manufacturer that insulating all heat paths would have resulted in significant heat loss reduction.

Concluding Remarks

Various two-layer thermal-barrier coating systems incorporating yttria-stabilized zirconia for thermal protection and bonded to the base metal wall with various bond coatings were investigated. All systems lowered metal temperatures, protected metal parts, increased metal part life, and eliminated metal burning, melting, and warping. For example the uncoated leading edges of the hot-section turbine vanes for an advanced gas turbine engine fatigued and melted after short test times at full-scale accelerated testing, but the improved durability of the coated vanes resulted in the meeting of major program objectives with no cracking or melting of the air-cooled metal walls. Also, the thermal protection provided by the zirconia on the flame impingement surfaces of combustor transition sections for a production gas turbine engine eliminated metal cracking during accelerated mission testing with no deleterious effects to the coating. It was concluded that the coating

has a high potential for improving the durability of this production engine. The results of the tests on coated diesel engine parts showed that the NASA-applied coatings exhibited excellent durability. Based on these early results the manufacturer sees good future potential for ceramic-insulated diesel engine parts, provided that they can be made cost competitive with uncoated parts. This could be done by using less costly base metal materials.

Several other benefits were realized from these endeavors. First, hands-on experience with thermal-barrier coatings was provided to industry. Second, the success of these endeavors encourages these and other organizations to accelerate the implementation of thermal-barrier coating technology.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, May 6, 1982

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