JTTEE5 1:27-31

Ceramic-Coated Components for the Combustion Zone of Natural Gas Engines

L. Holloman and A.V. Levy

The use of ceramic coatings on the combustion zone surfaces of large, natural gas-fueled, internal combustion engines is discussed. Unique handling and quality control systems are required for plasma spraying thin (0.25 mm, 0.0010 in.) coatings on up to 48.25-cm (19-in.) diameter piston crowns and cylinder heads weighing up to (1200 lb). The in-service performance characteristics of two types of natural gas-fueled combustion engines powering natural gas compressors that had thin zirconia ceramic coatings applied to their combustion zone surfaces are presented. Their performance was measured in the field before and after coating. It was determined that the durability, power output, fuel consumption, exhaust emissions, and other operating characteristics all improved due to ceramic coating of the flame side surfaces of cylinder heads, power pistons, and valves.

1. Introduction

THIN, yttria-stabilized zirconia ceramic coatings are being applied to the combustion zone surfaces of natural gas-fueled combustion engines that power natural gas compressors. The resulting improvements in engine durability and performance that have been experienced are significant and are prompting ever increasing interest. The use of the coatings was based on the success achieved when the same coating was applied to the combustion zone surfaces of a medium-speed diesel engine that propelled a towboat on the U.S. inland waterways for a 2-year test period.[1] The use of thin coatings in diesel engines rather than the thicker, up to 2.5-mm (0.10-in.) thick thermal barrier coatings that are under development for diesel engines, was based on the ceramic coating technology that has been used for several years on combustor cans and other components in aircraft gas turbines where a three- to four-fold increase in life has been achieved through the use of coatings.[2]

The coating used was prealloyed, partially stabilized zirconia (ZrO_2) containing 8 wt.% Y_2O_3. It was manually plasma sprayed 0.25 mm (0.010 in.) thick over a 0.12-mm (0.005-in.) thick NiCrAlY bond coat on the piston domes, cylinder head fire decks, and valve faces.[3] In the towboat diesel engine, its use resulted in lower fuel consumption, increased power, modified emissions, faster pickup, smoother overall operation, and less deterioration of the coated surfaces, compared to operation of the same engine uncoated, and the operation of a companion, uncoated engine in the same towboat. The use of the ceramic coatings in the natural gas-fueled engines has resulted in improved performance in excess of that observed in the towboat diesel engine.

At the time of preparation of this article, over 1200 parts have been coated and are operating in different size engines burning various grades of natural gas—from dirty gas that has just exited the ground to gas that has been prepared for entry into the national pipeline distribution system. Coated parts have served for as long as 16,000 hr of almost continuous operation to date without showing any signs of deterioration.

Key Words: diesel engine applications, engine performance, fuel efficiency, technical note, thermal barrier coatings, yttria stabilized zirconia

L. Holloman, Hanover Energy Services Comapny, Odessa, Texas 79764 USA, and **A.V. Levy**, Lawrence Livermore Laboratory, M62-203, 1 Cyclotron Road, Berkeley, California 94720 USA.

2. Engine Operating Experience

Letters describing engine operating changes that have occurred as the result of using ceramic coatings have been received from several engine operators. Although they do not constitute properly documented engine performance data, the consistency of the operating improvements in the letters makes it of value to report some of the data herein. Well-controlled and instrumented comparative engine performance tests, in addition to the two reported herein, are underway. The companies that sent the letters have requested anonymity.

One operator reported lowered fuel consumption of 7 to 10%, extended spark plug life due to a cleaner, more complete burn, lowered mid-engine noise due to a more even burn in the cylinders, lower cooling water temperature of 6 °C (10 °F), lower oil consumption, and reduced crankcase pressure. All of the operators reported no carbon deposits at any of the locations where they normally occur, which is evidence of modification of the combustion process.

Another operator reported fuel pressure lowered from 4.3 bar (62 psi) to 2.9 bar (42 psi) on an engine carrying a 93% load. A measurable reduction in unburned hydrocarbons in the exhaust was observed. The engine ran smoother and was able to pick up load surges better. Another engine had a measured reduction in NO_x emissions from 800 g uncoated to 1272 g coated. The fuel consumption on this engine was reduced from 3400 m^3 daily to 2700 m^3.

The use of thin ceramic coatings on combustion zone parts has been introduced on older gas-fired engines of several designs and sizes, one by one, as they were taken out of service for periodic maintenance. Because of the relatively wide range of part configurations and sizes and intermittent arrival for overhaul and coating, the use of robotics has not been economical, and therefore, a manual coating operation has been used to date. Physical handling of the large and various configured natural gas engine parts required special lifting, rotating, and precoat surface preparation equipment. This equipment has handled parts weighing up to 909 kg (2000 lb) and as much as 0.56 m^2 (6 ft^2) in area.

3. Experiments

A controlled evaluation of the effects of using the ceramic coatings was conducted in two types of natural gas-fueled engines. The first type was a processing and compression engine that used processed methane gas for fuel. The second type of engine was a high-speed, field gathering engine that typically used unprocessed field gas for fuel.

The data presented in this article is, essentially, raw data directly from the in-service engines obtained using instrumentation that did not interfere with engine operation. In this regard, it is not refined test stand data.

3.1 *Test Engine No. 1*

Test engine No. 1 is a slow-speed reciprocating engine with the characteristics shown in Table 1. Both the cylinder head and power piston dome surfaces had large deposits of unburned hydrocarbon when disassembled for overhaul after 4916 hr of noncontinuous service. The deposits were removed by a sand blast operation prior to nondestructive testing (NDT). The surfaces to be coated were roughened with an Al_2O_3 grit blast immediately prior to coating. The piston dome was coated with an average thickness of 0.28 mm (0.011 in.) and the cylinder head with an average thickness of 0.25 mm (0.0098 in.) of 8 wt.% Y_2O_3-ZrO_2. Figure 1 shows a typical coating cross section.

Some of the operating characteristics of the engine were measured before and after coating and compared. After coating, the peak firing pressure of the engine was lower and The combustion burn was notably improved, as indicated by the shape of the engine reference cylinder operating pressure curve and vibration trace. The detonation that had occurred in the uncoated engine was eliminated. The vibration traces indicated that the power piston ring vibration had been reduced and, in fact, the sensitivity of the analyzer to record vertical vibration had to be doubled to pick up any vibration. The ignition timing was set to see if detonation would occur, as it did in the uncoated engine, and none occurred. The improved burn allowed the power piston to be pushed down smoother so that, at reversal, vibration of the bearings and bushing were virtually nonexistent. The improved behavior was measured periodically to 5700 hr of operation.

Figure 2 is a comparison of the curve of the peak pressures and indicated horsepower of each of the ten cylinders in the engine in the three conditions measured, *i.e.*, uncoated with 4900 hr of service, coated with 400 hr of service, and coated with 5700 hr of service. The comparison of peak pressure to indicated horsepower (IHP) indicates that the lower peak pressures in the coated engine produced more horsepower, which equates to an increase in engine operating efficiency and durability of the combustion zone components.

A summary of engine operation changes that occurred as the result of coating the combustion zone surfaces with a ceramic coating is listed in Table 2.

Table 1 Characteristics of Test Engine No. 1

Manufacturer	Clark Brothers
Engine model and type	HBA-10 gas engine, driven compressor
Horsepower	2500 BHP (69 MW) at 300 rpm
Power cylinders	
Number	10
Bore	43.2 cm (17 in.)
Stroke	43.2 cm (17 in.)
Operating cycle	Two-cycle scavenging air
Compressor configuration	Two 56-cm (22.0-in.) cylinders One 29.2-cm (11.5-in.) cylinder Two 20.3-cm (8.0-in.) cylinders Three scavenger air cylinders
Pressure differential	0.2 MPa (33 psi) suction 3.5 MPa (510 psi) discharge
Gas pumping capability	2.8×10^4 m^3/day (10^6 ft^3/day)
Engine run time prior to coating	4916 hr
Fuel gas	Methane (sweet), 9.7 to 9.8×10^5 J (925 to 930 BTU)

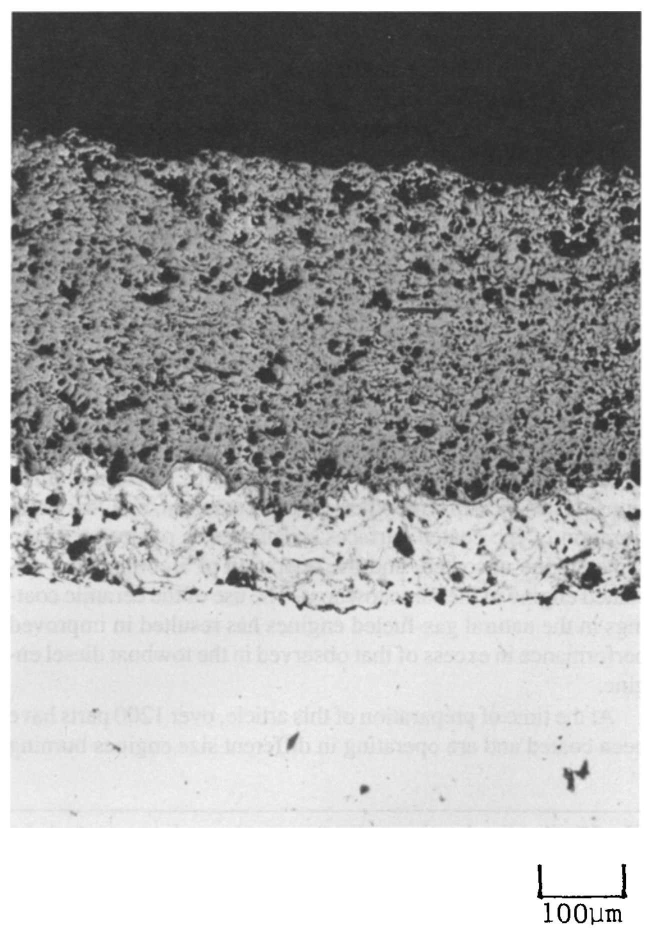
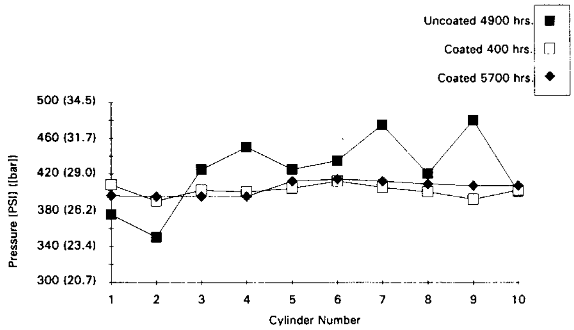


Figure 1 Plasma spray ceramic coating over NiCrAlY bond coat on cast iron substrate.



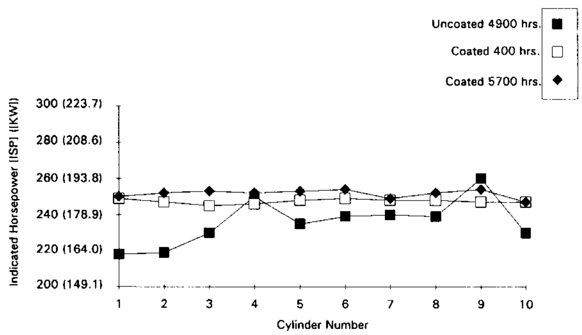


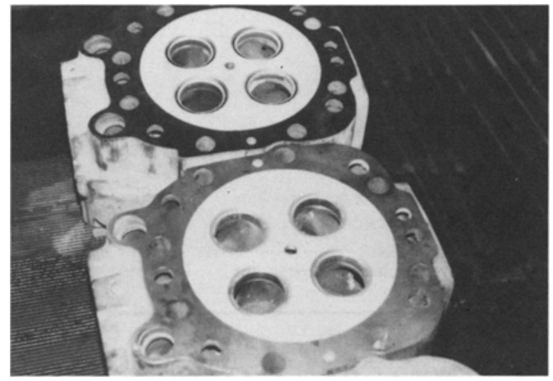
Figure 2 Engine No. 1 peak pressures and indicated horsepowers uncoated after 4900 hr of service and coated after 400 and 5700 hr of service.

3.2 *Test Engine No. 2*

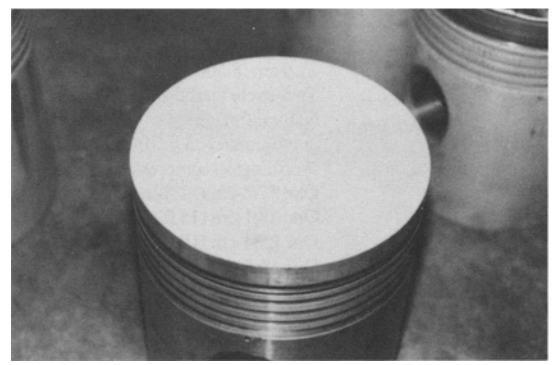
Test engine No. 2 is a commonly used, high-speed, field gas gathering and compression engine. In most cases, these types of engines are located in remote field locations, and the fuel gas is substandard compared to the fuel gas used in test engine No. 1. The uncoated and coated parts performance analysis of this engine was conducted with an ultrasonic engine analyzer. The combustion zone pressure stream data were inaccessible; therefore, peak firing pressures and indicated horsepowers were not available. Figure 3 shows the three types of parts that were coated.

Test engine No. 2 was analyzed prior to shutdown. Vibration traces on the cylinders indicated excessive noise in the exhaust valves, excessive noise in the power piston rings, knocks at bottom dead center of the piston stroke indicating wrist pin bushing wear, connecting rod bearing wear, and piston slap due to worn power rings. The ultrasonic patterns indicated roughness in the piston stroke and piston ring leakage.

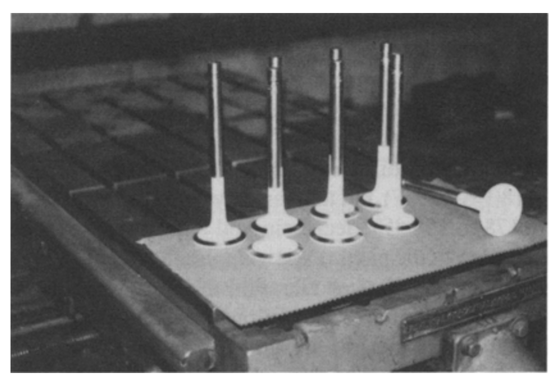
Test engine No. 2 was disassembled, removing all combustion zone components for complete NDT inspection. Large amounts of carbon deposits were present on the tops of the power pistons and on the power valves. The power piston rings had excessive wear, as indicated by the piston ring leakage. New original equipment manufacturer power pistons and power valves along with the fire deck of the cylinder head were ceramic coated to an average thickness of 0.25 to 0.28 mm (0.0098 to 0.011 in.). The engine was reassembled to manufacturer's specifications and placed back in service. Like engine No. 1, test engine No. 2 seemed to start more easily.



Cylinder head



Power piston



power valves

Figure 3 As-coated components from test engine No. 2.

After 30 days of operation, the engine was again analyzed. The vibration trace of the reference cylinder indicated a much smoother running engine. After 8000 hr of service, the vibration level was still minimal. As reported by the operator, an average of 40 to 50% increase in spark plug life was experienced.

Table 2 Engine Operation Changes

Parameter	Effect
Peak firing pressure	Smoother
Vertical vibration of the piston rings	Lowered
Vertical vibration of the cylinder head	Reduced
Indicated horsepower	Higher
Indicated horsepower at lower peak pressures	Greater
Fuel injection valve temperatures	Reduced from 75 to 49 °C
Crankcase oil temperatures	Lowered by 10 to 11 °C
Engine cooling water discharge temperatures	Reduced by 10 to 12 °C

Table 3 Characteristics of Test Engine No. 2

Manufacturer	Waukesha
Engine model and type	L7042G
Rated brake horsepower	550 HP (0.4 MW)
Power cylinders	
Number	12
Bore	23.4 cm (9.375 in.)
Stroke	21.6 cm (8.500 in.)
Operating cycle	Two-cycle (carburetor)
Fuel gas	Natural field gas, 1148 BTU (1.2 MJ) at approximately 3.4 GPM liquid (12.9 lpm)
Compressor configuration	Worthington compressor package One 57.2-cm (22.5-in.) cylinder One 38.1-cm (15.0-in.) cylinder One 25.4-cm (10.0-in.) cylinder One 14.6-cm (5.75-in.) cylinder
Pressure differential	34.5 kPa (5 psi) suction 6.9 MPa (1000 psi) discharge
Gas pump capability	(2×10^6 ft^3/day) $5.6 \times 10^4 m^3$/day

A summary of engine operation changes that occurred as the result of using the ceramic coating is as follows. Piston rings seated quicker than normal, possibly due to a smoother burn in the combustion zone, which allowed the piston to be pushed down evenly rather than in a zig-zag motion. Mid-engine noise levels at piston reversal were greatly reduced, probably because of the smoother burn.

Cooling water discharge temperature dropped from 83 to 70 °C (180 to 160 °F). Oil temperatures were reduced from 80 to 70 °C (178 to 158 °F), decreasing oil breakdown and allowing better cooling of the piston. Vertical vibration at the cylinder top was reduced, and vertical vibration of the power piston rings was also reduced. Fuel consumption was reduced by 10 to 12%. Manifold vacuum increased from 15 to 23 cm (6 to 9 in.), indicating that the engine had less load on it to move the same amount of gas.

A comparison of exhaust gases from the ceramic-coated field engine No. 2 and an uncoated similar unit using processed gas fuel is shown in Table 4. The exhaust gas samples were taken from the exhaust streams of both engines using a vacuum pump. It was observed that the exhaust from the coated engine contained more condensation than that from the uncoated engine. As seen in Table 2, instead of an increase in the level of undesirable emissions, the NO_x level was reduced in the coated engine by approximately 60% compared to that of the uncoated, clean fuel, gas-burning engine. The role of the coating in reducing the NO_x level and the water contents of the two exhaust gases needs to be further investigated.

Table 4 Composition of Engine Exhaust Gas

	Exhaust analysis	
	Uncoated engine	Coated engine
Hydrocarbons	0.02%	0.08%
NO_x	331.5 ppm	119 ppm
CO	150 ppm	150 ppm
O_2	7.54%	6.97%
Nitrogen	83.84%	83.40%
CO_2	8.6%	9.63%

4. Discussion

The thin ceramic coatings applied to the combustion zone components of test engines 1 and 2 appeared to have enhanced engine performance and potentially reduced engine maintenance. The engine analysis of the ceramic-coated combustion zone components implies that a probable reduction in ignition delay and improved burn could increase the service life of such components as power pistons, power piston rings, power cylinder heads, fuel injection valves on the two-cycle engines, and power valves and spark plugs on the four-cycle engines.

The improved burn could also allow the piston to move down the cylinder more smoothly, enhancing the service life of the rod bearings, wrist pins, and bushings. The lower fuel injection valve temperatures on the two-cycle engines should extend the life of the valves and, at the same time, allow the fuel gas to enter the combustion zone at a lower temperature, thereby reducing the possibility of detonation. The lower oil temperatures on both engines decreased oil breakdown and vaporization. The lower cooling water discharge temperature indicates a longer service life of the cylinder head.

Figure 4 illustrates two GMVH Cooper power cylinder heads. The uncoated cylinder head had large deposits of unburned hydrocarbons throughout, whereas the coated head shows only a trace after 16,000 hr of service.

5. Conclusions

From the observations and test results reported herein, applying thin ceramic coatings to the combustion zone components of natural gas fuel combustion engines may result in a significant reduction in overall maintenance cost, lower fuel cost, increased engine efficiencies over the overhaul life of the engine, and other benefits. The decrease in fuel consumption and increase in manifold vacuum suggest a reduction of engine load and a significant increase in engine efficiency. It is recognized that other on-coming technologies in the field of advanced engine systems, *i.e.*, advanced fuel injection, piston configurations, and turbocharger design, may collectively produce equivalent results. However, most of these innovations are designed for use in new engine designs, whereas the application of the ceramic coatings can be retrofitted into any engine.

Acknowledgments

The authors would like to acknowledge the support of Ray Smith Imperial Energy Limited, Adobe Gas Pipeline, Yingjie

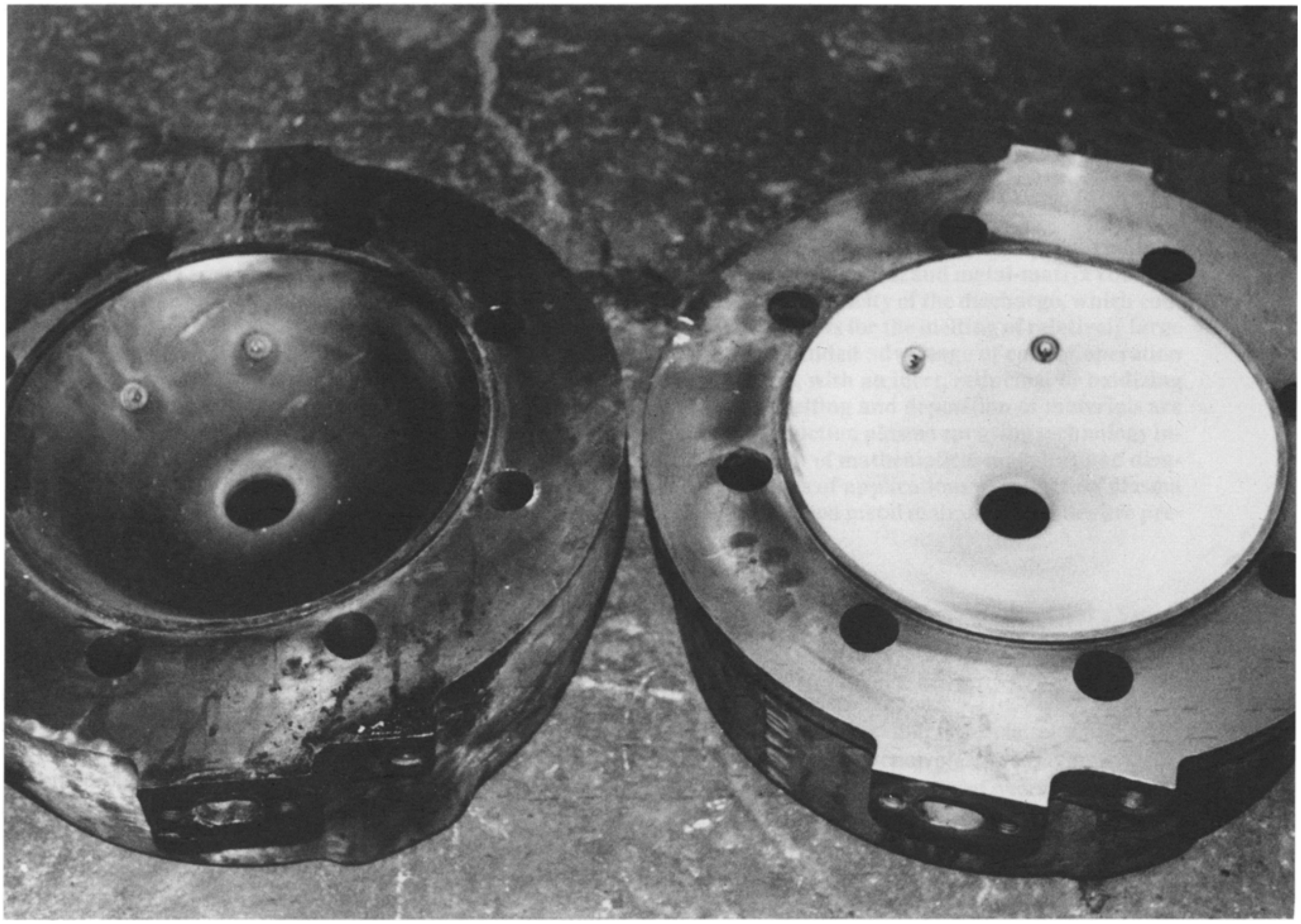


Figure 4 Power cylinder head after 16,000 hr of service. The left head is uncoated and the right head is coated.

Liu, and Bu Qian Wang at the Lawrence Berkeley Laboratory and Walter Reid-Mobile Analytical Laboratories in the preparation of this paper.

References

1. "Enhanced Marine Diesel Engine Performance and Component Durability Towboat Field Test and Evaluation," Final Report No. MA-RD-760-87038, MARAD Contract No. DTMA 91-84-C-4105, Seaworthy Systems, Inc.
2. K.T. Scott and J.E. Restall, "Some Aspects of the Development and Performance of Ceramic Thermal Barrier Coatings for Gas Turbines," Proceedings of ASM Thermal Spray Technology Conference, Cincinnati, Oct (1988) 255-262.
3. A.V. Levy and S.S. McAdam, "Durability of Ceramic Coatings in 14,000 Hours Service in a Marine Diesel Engine," ASM Paper No. 88-ICE-19, Jan (1988).