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OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

ORNL/Sub/90-SG151/1

THE DEVELOPMENT AND TESTING OF CERAMIC COMPONENTS IN PISTON ENGINES

FINAL REPORT

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Norton Company

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TRW, Inc.

CERAMIC TECHNOLOGY PROJECT

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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The Development and Testing of Ceramic Components In Piston Engines

I. Abstract.

Within the past 10-15 years, ceramic hardware has been fabricated and tested in a number of piston engine applications including valves, piston pins, roller followers, tappet shims, and other wear components. It has been shown that, with proper design and installation, ceramics improve performance, fuel economy, and wear and corrosion resistance. These results have been obtained using rig and road tests on both stock and race engines. Selected summaries of these tests are presented in this review paper.

II. Introduction.

Over the past decade, considerable interest has been generated in the application of advanced materials to both standard and high-performance piston engines. Technological development in ceramic materials has enabled components to be fabricated and evaluated in a wide variety of rig-tests or actual engines. Most of this effort has focused on valve-train hardware. Ceramic valves, roller followers, tappets, wear pads, piston pins, and other hardware have significant potential for improvement of engine performance and durability. Their light weight, high strength, and corrosion and wear resistance are clear advantages.

For gasoline engines, the major benefit of these components is reduced mass. Light-weight components allow for: (1) changes to be made in cam profiles for quicker valve or injector events and improved combustion, (2) higher operating speeds for greater power density, and (3) reduced spring forces for better fuel economy. Typical mass reductions of between 20% and 70% are possible in comparison with titanium and steel valves, respectively. Testing in standard production engines has demonstrated ≈ 20% improvement in maximum engine speed, ≈ 14% reduction in engine friction, and an increase in average fuel economy of up to 7%. Ceramic hardware has performed admirably, surviving extended rig testing and road trials ranging between 50,000 miles and 300,000 miles. Significant achievements have also been made in racing engines. Ceramic valves have been installed in state-of-the-art Formula 1 race cars, and have endured track-trials under race conditions for in excess of 250 kilometers at engine speeds up to 14,000 revolutions per minute (RPM). Valves have also been tested in other racing circuits, from Formula 3 to NASCAR, also with considerable success.

For diesel and alternative fuel engines, the major advantages of ceramics are wear and corrosion resistance. Corrosion and erosion become significant problems with more aggressive cam profiles, or when using less refined fuels, waste fuels, natural gas, or coal. Reductions in valve train wear of up to 80% have been observed. Laboratory tests have shown that silicon-nitride ceramics are preferred due to lower coefficients of friction. When using corrosive fuels, valves and related components have endured extended tests (over 700 hours of continuous operation) in highly corrosive environments, outlasting comparable metal parts by factors of 4 to 5 in life.

Included in this paper is a summary of selected test results for ceramic hardware in various applications ranging from standard gasoline and diesel engines, to high-performance race engines. Some of these experiences are summaries of earlier published results, while others represent more recent, unpublished findings. They are presented together in this paper to demonstrate both the breadth and depth of ceramics experience.

III. Applications Experience.

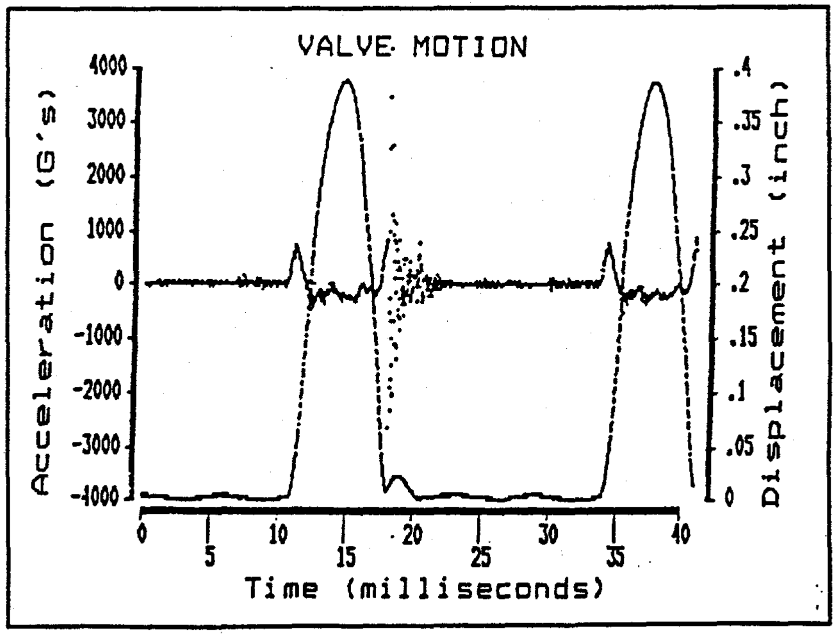
Applications experiences are broken down into three categories: (1) standard gasoline engines, (2) diesel engines, and (3) racing engines.

- Standard Gasoline Engines - For conventional vehicles, the substitution of silicon nitride (Si_3N_4) or SiAlON (a form of Si_3N_4) valve-train components for metal hardware can result in significant reductions in inertial forces. The density of these ceramics is approximately 40% of the metal hardware they replace, which improves valve-train stability, lowers frictional losses, and increases performance and fuel economy.

  - Dynamics - To evaluate the dynamic benefits of ceramic hardware, a 2.5-liter push-rod engine was iteratively outfitted with standard production metal and ceramic valves. Testing of these two sets of hardware was then conducted on a dynamometer stand under identical conditions, except for a 26% reduction in spring forces on the ceramic hardware. Valve motion was measured in real-time using an Optron electro-optical comparator.[1] Shown in Figures 1 and 2, respectively, are motion and acceleration traces for the metal and ceramic valves. The respective masses of these two components were 112 grams and 51 grams. Note in Figure 1 that, for the metal valve, considerable bounce occurs during valve closure. The metal valve hits the seat under a primary impact load of ≈5564 N. The inertia of impact, coupled with the elasticity of the material, results in bounce and a secondary impact of < 1000 N, along with decaying additional smaller impacts. With the ceramic hardware, initial seating impact loads of ≈1100 N were observed. In Figure 2, no secondary bounce conditions are seen for the ceramic hardware. Elimination of bounce leads to improved efficiency, reduced emissions, and lower wear.

  - Fuel Economy - To characterize the effect of light-weight hardware on fuel economy, a 1.6-liter Quad-Four engine was tested as part of a cooperative program between TRW, Norton, and AC Rochester.[2] A series of valve-train components was installed in several identical engines for the purpose of measuring changes in friction and fuel economy as a function of valve-train mass and spring force. Three hardware configurations were selected: (1) all metallic hardware with mechanical tappets, (2) a mixture of steel and titanium components, and (3) a mixture of ceramic, titanium, and steel components. These hardware configurations are presented in Table I. Level I valves were steel, but had a 1 mm smaller stem diameter than the production valves, with some mass removed from the head area. The exhaust valves had material removed from the head area as well. Level II intake valves were titanium, and had the same geometry as the Level I valves. The exhaust valves were steel with 1 mm removed from the valve stem diameter and head regions. Level III valves were ceramic. After successive installations of these configurations,dynamometer motoring torque tests were conducted. Three runs were made for each configuration. Following motorized testing, the cylinder heads were installed into vehicles for fuel economy testing. The U.S. EPA Federal Test Procedure was run, and fuel economy measured. Vehicles were equipped with five-speed manual transmissions, and each test was run at least three times. The results of

Figure 1 - Exhaust Valve Motion, Metal Valve At 5200 RPM



these tests are presented in Table II. Significant reductions in frictional torque loss were measured for all test levels. The most pronounced changes were observed at lower RPM ranges, and for the lowest mass configuration. At an engine speed of 1800 RPM, motoring torque was reduced by 4.5%, 8.3%, and 14.0% for Levels I through III hardware, respectively. As engine speed increased, the percent of engine friction caused by the valve train decreased. Fuel economy improvement between Levels I and III increased substantially. Due to reduced mass and lighter spring forces, an overall improvement of ≈7% was observed. These test data show that

Figure 2 - Exhaust Valve Motion, Ceramic Valve At 5200 RPM

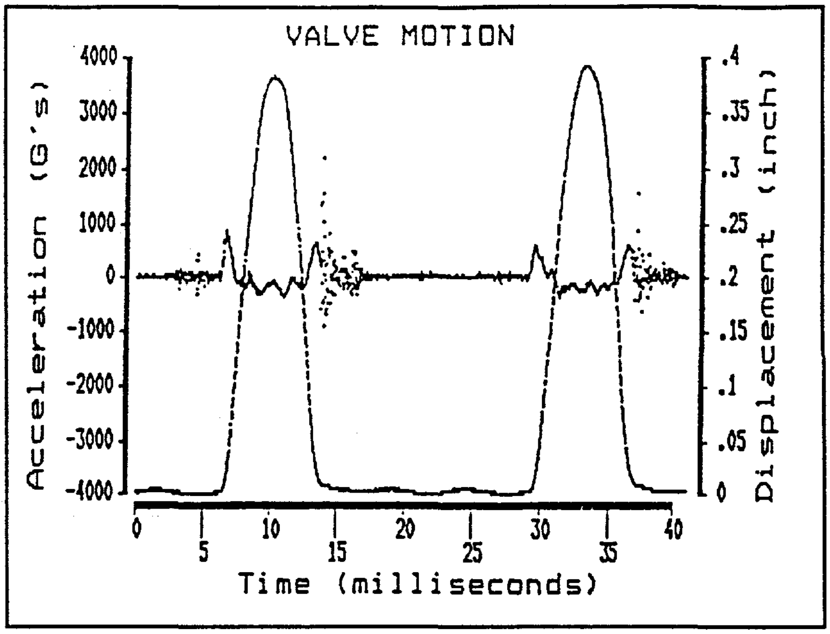


Table I - Quad-Four Light-Weight Valve Train Configurations

Intake Position	Current Material & Mass (g)	Level I Material & Mass (g)	Level II Material & Mass (g)	Level III Material & Mass (g)
Valve	Steel - 70.4	Steel - 50.9	Titanium - 30.9	Ceramic - 23.7
Cap	Steel - 16.4	Steel - 8.9	Steel - 8.9	Titanium - 4.9
Keys (2)	Steel - 1.9	Steel - 1.5	Steel - 1.5	Steel - 1.5
Spring	Steel - 55.7	Steel - 43.1	Steel - 37.3	Steel - 32.7
Tappet	Hydraulic - 81.1	Mech. - 56.1	Mech. - 37.1	Mech. - 17.5
Exhaust Position	**Current Material & Mass (g)**	**Level I Material & Mass (g)**	**Level II Material & Mass (g)**	**Level III Material & Mass (g)**
Valve	Steel - 59.6	Steel - 56.3	Steel - 46.8	Ceramic - 21.5
Cap	Steel - 16.4	Steel - 10.0	Steel - 8.9	Titanium - 4.9
Keys (2)	Steel - 1.9	Steel - 1.9	Steel - 1.5	Steel - 1.5
Spring	Steel - 55.7	Steel - 44.4	Steel - 44.5	Steel - 32.6
Tappet	Hydraulic - 81.1	Mech. - 56.1	Mech. - 37.1	Mech. - 17.5
Overall Mass (g)	**Current**	**Level I**	**Level II**	**Level III**
Intake	188.4	131.8	90.8	58.5
Exhaust	176.3	139.1	109.1	56.3

important benefits can be obtained by reducing valve-train reciprocating mass. Similar results have been demonstrated with other engine configurations.[3] Improvements in almost all piston engines can be expected.

- Wear - Valve face and seat wear has been an on-going concern in standard spark-ignition engines ever since the elimination of lead from gasoline. Induction-hardened steel seats are acceptable solutions, but their wear can be variable. To characterize improvements in wear using ceramic hardware, iterative engine tests were conducted using SiAlON valves on TP15 seats (austenitic stainless steel), steel valves on SiAlON seats, or a combination of SiAlON valves and seats. Seat and valve recession rates were measured for these components.[4] Tests were conducted in two separate engines, a 5.7 liter V-8 truck engine, and a 1.6 liter Quad-Four engine. Results are shown in Figures 3 and 4. In Figure 3, the effects of valve face wear and seat wear were measured for two seat materials (i.e., TP-15, and SiAlON). The data provide three interesting conclusions which correspond to the three sets of histograms in Figure 3: (1) When SiAlON seats are substituted for TP-15 seats, wear on the metal valve face actual increases slightly. (This is to be expected, due to the fact that stainless steel valve is now impacting a harder, and more abrasive material.); (2) However, seat wear rates are significantly reduced by the substitution of SiAlON for TP-15; and (3) The combined wear of the two components is substantially lower for SiAlON seats. In Figure 4, data from a 100 hour durability test of SiAlON valves in the Quad-Four engine are shown. For these tests, a comparison was made between stainless steel and SiAlON valves on TP-15 seats. Tests were run with induction hardened and non-hardened seats. Note that for the standard metallic hardware, significant wear of valve stem and guide are observed. In comparison, after 100 hours of operation, SiAlON valves on metal seats showed little wear. Seat recession, valve stem and guide wear were reduced between ≈50% and ≈97% for SiAlON valves, depending upon whether the seats were hardened or not. Even with non-hardened seats, the wear rate was improved over the base metals. These improvements are believed to be due to a combination of effects. First, spring forces were reduced for the ceramic valve. Consequently, there was significantly lower impact stress. Frictional forces between the seat and the valve were thereby decreased. Second, under lower spring forces and with the lighter mass of the ceramic, there is less bounce. This results in lower abrasive action between the two components. Third, the SiAlON material has better surface finish and intrinsically lower sliding friction. Fourth, the Young's modulus of SiAlON is substantially higher than for the metal it replaced. Therefore, there was less flexing of the valve within the stem and at the head regions. Reduced flexing also translates to lower wear. Finally, due to the chemical inertness of the SiAlON, lower combustion deposits were observed. In fact, after extensive testing, soot was easily removed from the SiAlON valves with a dry cloth. The lack of deposits reduces frictional build-up between the seat, stem, and guide, resulting in reduced wear. For metal valves, an extensive chemical reaction and bonding occurred between the surface of the valve and the combustion products. This reaction

Table II - ACR Quad-Four Light-Weight Valve Train Results

	% Reduction In Reciprocating Mass	% Reduction In Valve Full Open Spring Force	% Reduction in Engine Friction (2400 RPM)	% Increase In FTP Fuel Economy
Level I	26	20	3.20	1.9
Level II	45	50	6.53	3.9
Level III	69	67	11.81	7.0

Figure 3 - Average 100 Hour Wear Rates For Valve Train Components

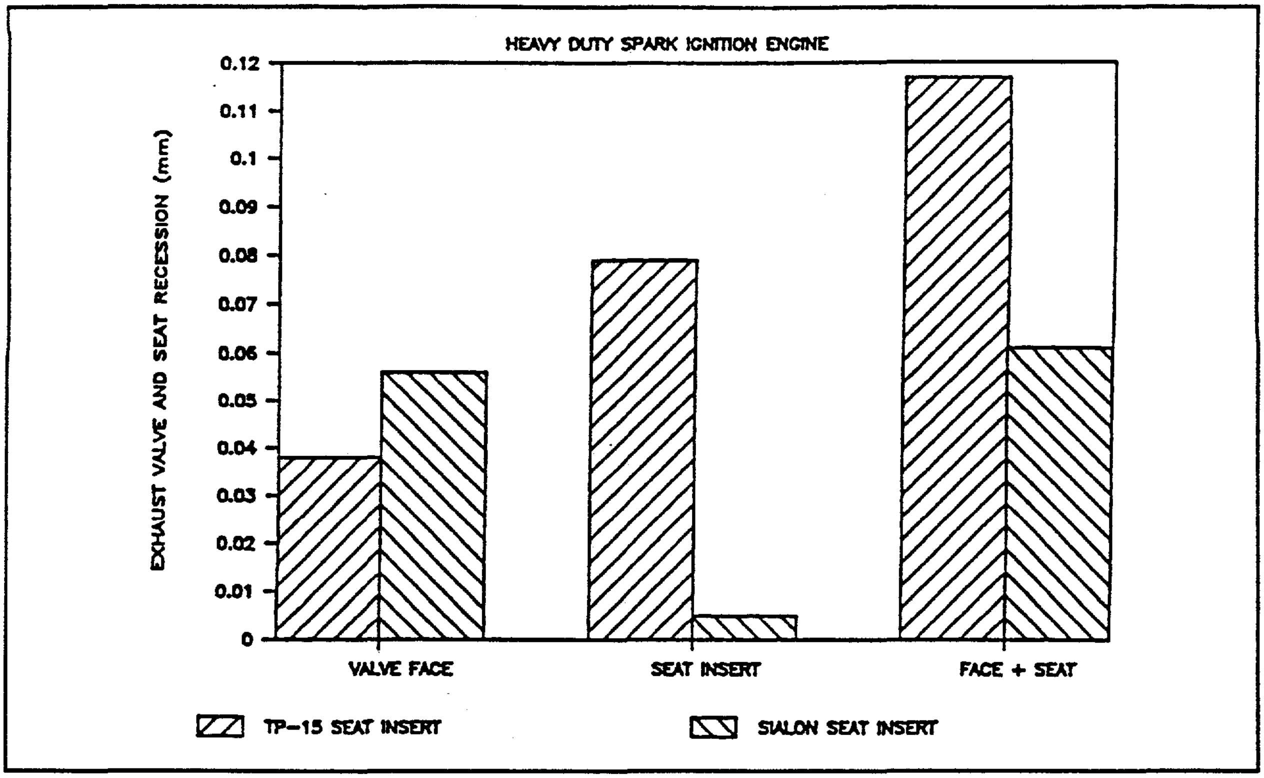
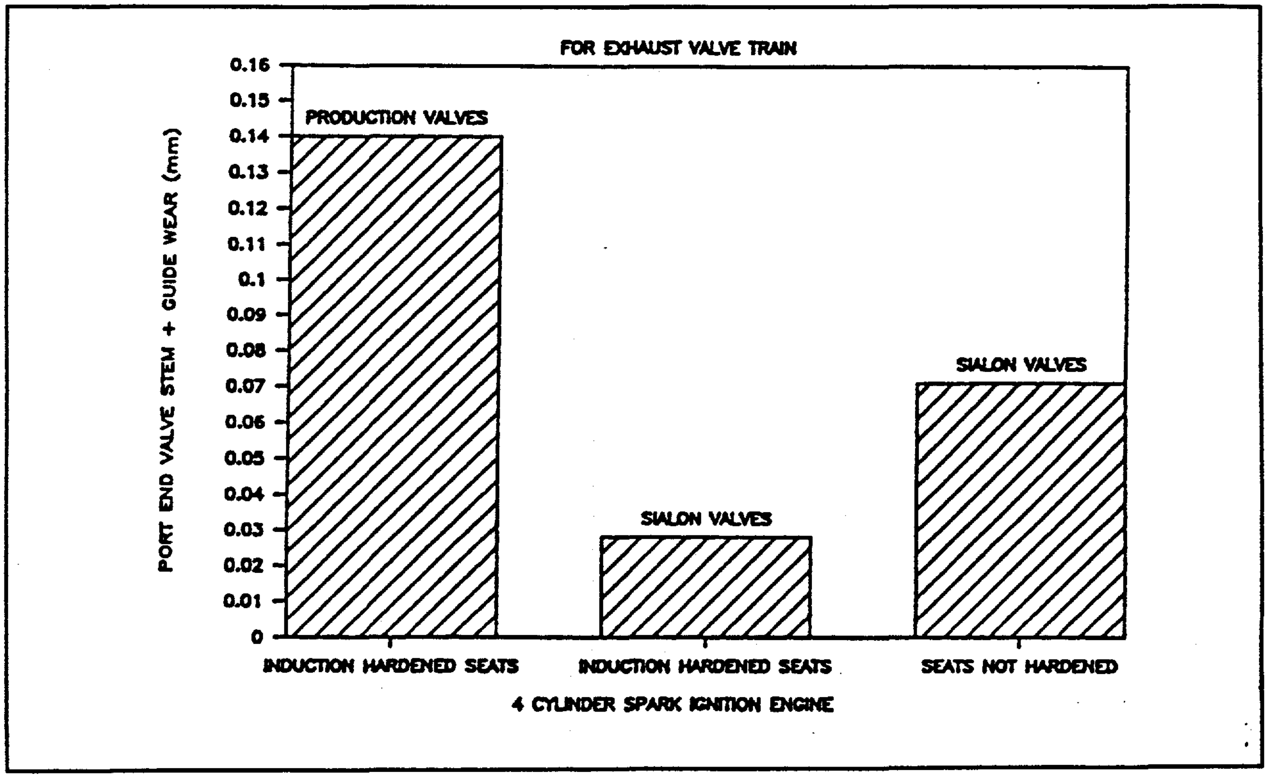


Figure 4 - Average 100 Hour Valve Stem and Guide Wear Rates



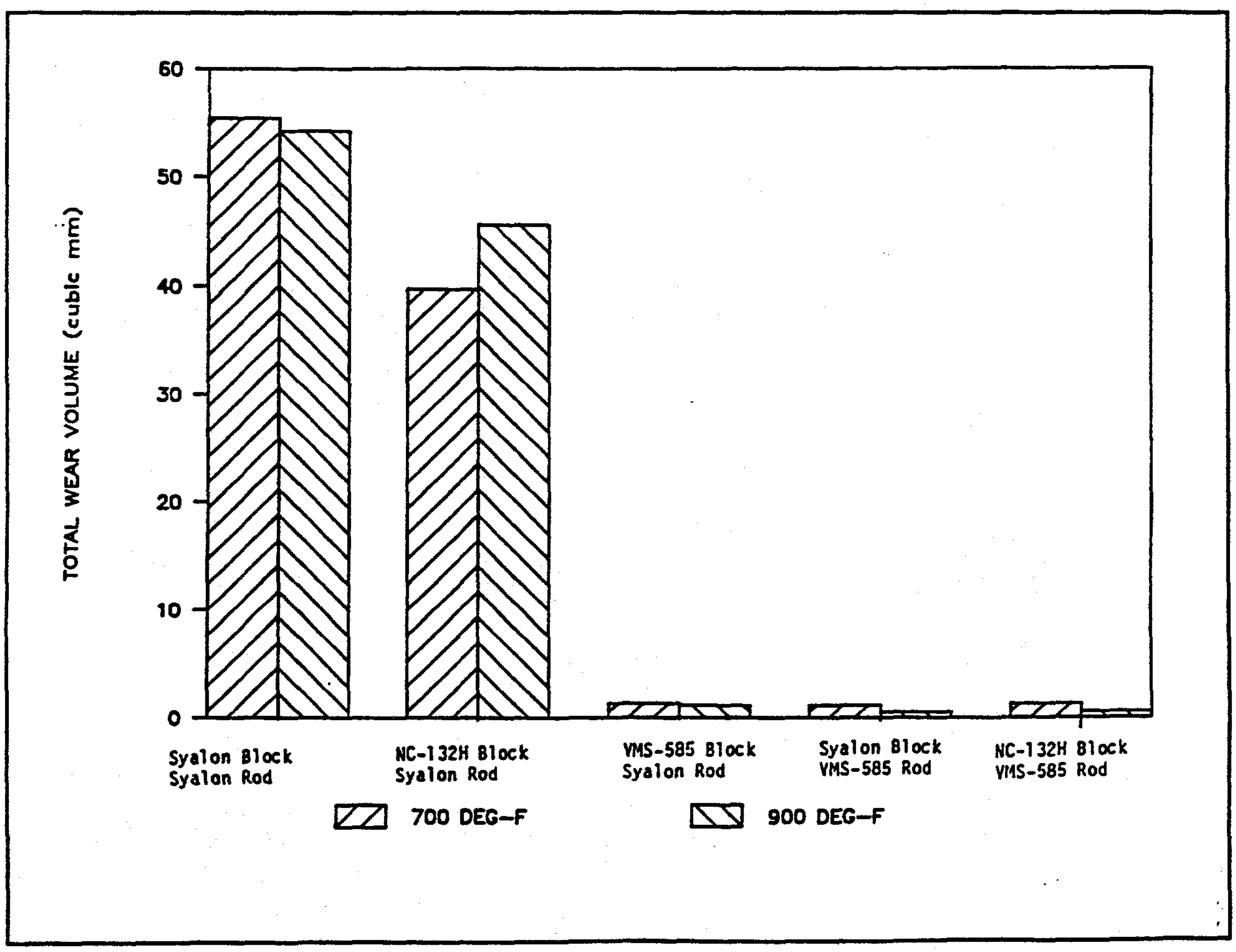
changes the chemical composition of the surface and increases its roughness, both of which lead to increased wear.

Subsequent laboratory rig tests were performed to compare the effects of material selection, temperature and lubrication conditions on the wear performance of ceramic hardware. In the first of these tests, ceramic-ceramic or ceramic-metal wear couples were examined at two temperatures. These tests consisted of placing two test materials in contact with each other under an applied load. One of the materials consisted of a rotating rod. The second material was a flat pad. The conditions of these tests were as follows:

Load	55 Kgs Normal Force
Speed	Speed 150 RPM (6 meters/sec)
Duration	78 minutes
Atmosphere	Air
Temperature	700°F and 900°F
Lubrication	None

Comparative materials included SiAlON, Si_3N_4 (NC132H) and a standard stainless steel composition typically used for valves (VMS585). The results are shown in Figure 5. Two important features

Figure 5 - Ceramic-Ceramic and Ceramic-Metal Wear Pair Results



are noted from these tests. First, use of ceramic-ceramic wear couples is ill advised, particularly under these moderate temperature and unlubricated conditions. Therefore, utilization of ceramic valves and ceramic seats may increase overall wear instead of reducing it, particularly for natural gas engines. Second, when ceramics are coupled to metals, the overall wear conditions are improved and preferable to metallic hardware only. The wear rates are approximately one order of magnitude lower when utilizing a ceramic-metal wear pair. Consequently, in selected material combinations for valve trains, a ceramic valve on a metal seat or a metal valve on a ceramic seat appears ideal, whereas a ceramic valve and seat combination is ill-advised.

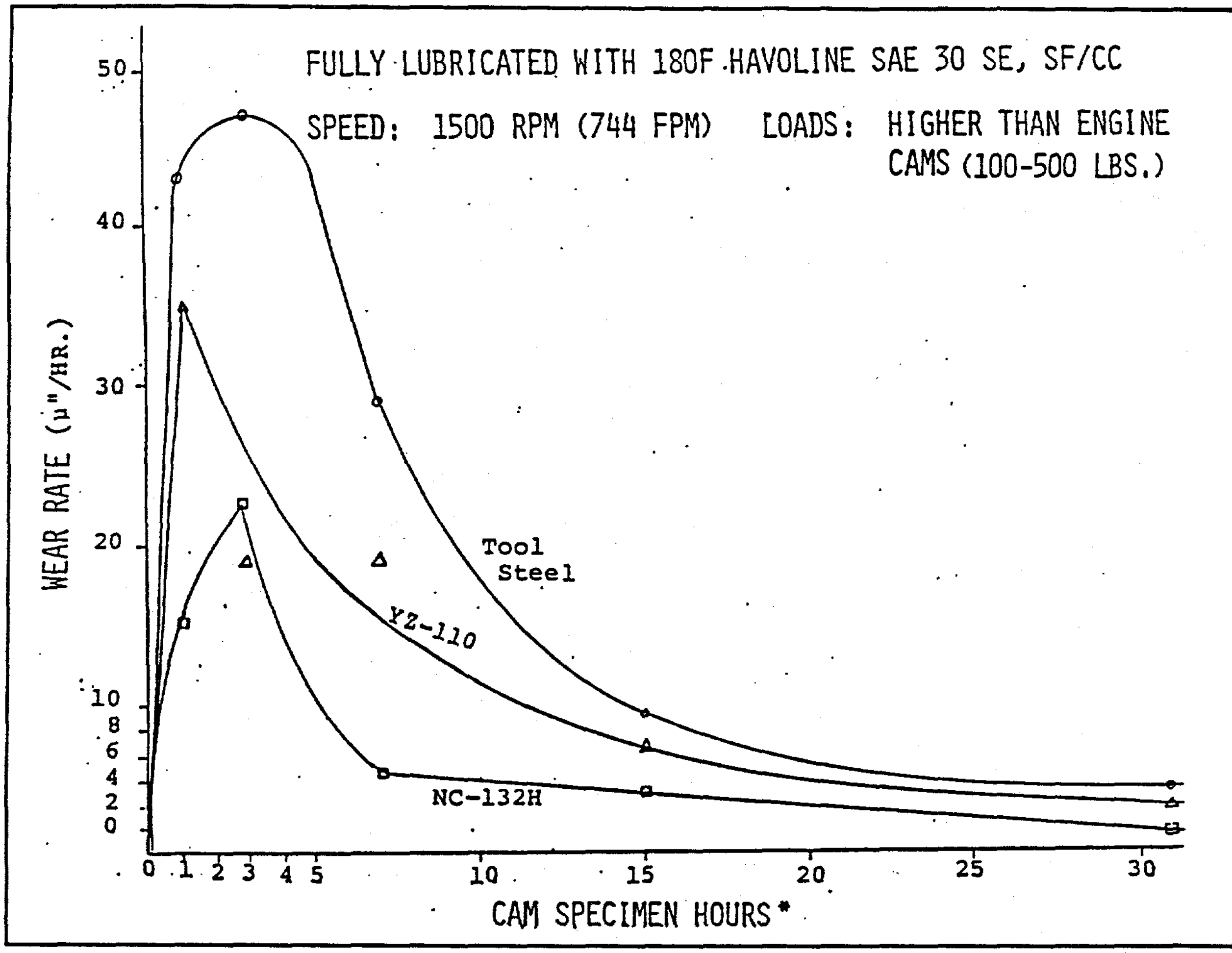
In a second laboratory wear test, a cam roller follower wear machine was designed and constructed. The equipment was built to mimic actual engine conditions, and allowed the alternative use of ceramic or metallic components for both the roller and wear pad. An actual automotive valve spring was used to apply normal loads to the roller and pad. Tests were conducted under adequate and low lubrication conditions at RPM levels experienced in actual engines. In the lubricated condition test, a silicon nitride (NC132H), a zirconia (YZ110), and D-2 tool steel were run under comparative conditions at loads higher than typically observed in standard piston engines. The wear rates of these three materials were then compared. Results are shown in Figure 6. The data demonstrate high initial wear rates for all three materials. However, both of the ceramic materials performed better than the D-2 tool steel. Of the two ceramics, the Si_3N_4 composition was the best material. At extended test times, the wear rates for the Si_3N_4 and ZrO_2 materials are lower, with the Si_3N_4 composition being less than half that of the tool steel. The second wear test duplicated these conditions, except with light mist-oil lubrication. In this test, it was found that Si_3N_4 materials were again preferable. Overall, they showed the greatest resistance to galling, and had better wear and lower to equivalent friction coefficients than metallic components. However, in the same test, the ZrO_2 material exhibited a greater tendency to gall, or show surface pitting, than did the metal hardware.

- Temperature Control - SiAlON ceramics have higher thermal conductivities than the preferred metallic valve seat material (TP-15). A higher thermal conductivity in the valve seat is advantageous from the viewpoint that it reduces valve temperatures and thereby decreases pre-combustion, knock, and emissions within the engine. To assess whether significant changes in valve temperature could be realized, ceramic seats were inserted in cylinder tests and compared to metallic seats under identical conditions. The temperature profiles of the valves were determined by testing the hardness of the material (i.e., hardness relaxation method), and also by direct thermocouple placement. The results of this analysis are given in Figure 7. The curves show the temperature distribution along the length of the valve and across its head as a function of the seat insert material. As expected, the ceramic seat inserts resulted in valve face, head, and under-head temperatures approximately 100°F lower in most areas.

- Vehicle Testing - To date, ceramic hardware has been installed and road tested in a wide variety of conventional test vehicles. Included in these tests have been valves, roller followers, piston pins, and other wear parts. Mileage on individual vehicles has ranged from a low of ≈50,000 miles [1] to a high of over 85,000 miles. Extended fleet tests have been on-going for over five years with cumulative vehicle experience of over 300,000 miles.[5] The limited data suggest that these materials have the adequate durability and performance behavior for conventional engines.

- Diesel Engines - The benefits of ceramic hardware for diesel engines are basically identical to those outlined above for gasoline engines. Improvements in fuel economy, performance, wear, corrosion, and temperature control are expected. However, contrary to the extensive amount of testing that has been conducted on conventional spark-ignition engines, relatively little testing has been performed in diesel engines. This is due partly to the extensive cost of the tests. A major program

Figure 6 - Pad Wear Rates As A Function of Cam Operating Hours
Fully Lubricated Sliding Conditions

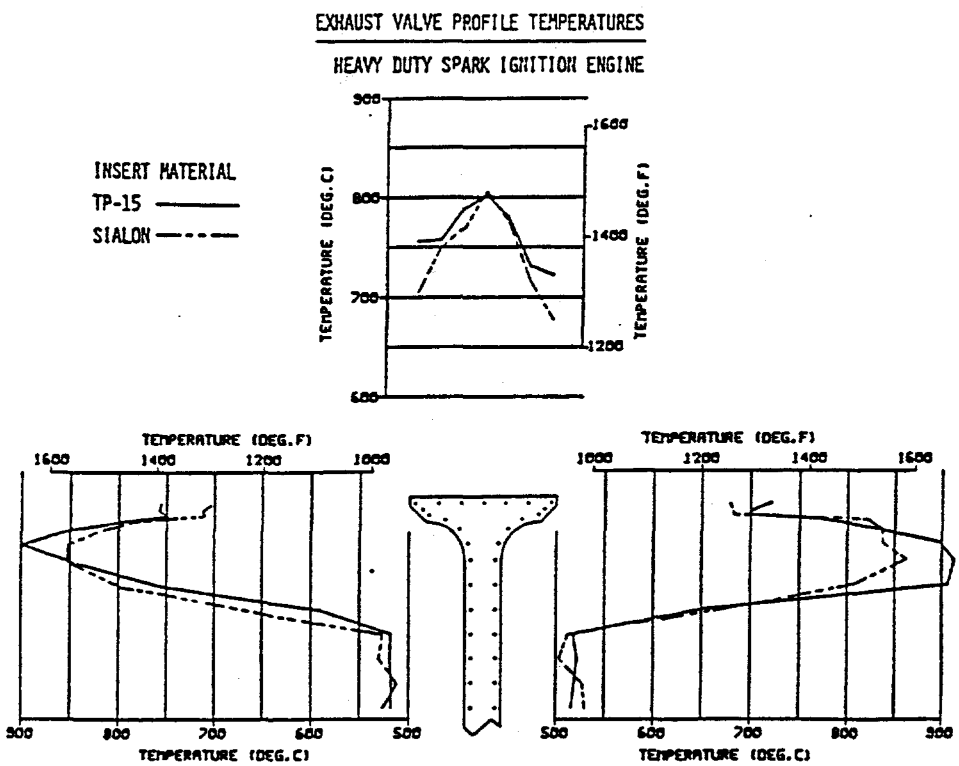


at Detroit Diesel Corporation has been a notable exception.[6] One other test has been conducted to demonstrate the corrosion-resistance advantage of ceramic hardware. This test is described below.

- Corrosion - In cooperation with Dow Chemical Company, a Caterpillar 3304 six cylinder diesel engine was tested as a method to safely dispose of methylene chloride. In the test, methylene chloride was mixed with diesel fuel, then burned within the engine. However, the corrosive nature of this compound was expected to limit the life of the valve train hardware. Consequently, comparative tests were conducted using SiAlON ceramic and Inconel metal valves. Both types of valves were installed in the engine and run for up to 700 hours. The metallic hardware began failing at ~50 hours run-time due to severe corrosion on the seating area of the valve and in the head region. The ceramic components showed no corrosive attack or wear during the entire test. The metal valve showed severe necking in the under-head region and seat resulting from sulfidation and oxidation attack. The ceramic remained pristine on seat, but had non-harmful soot deposits on the under-head region.

- Racing Engines - There is, perhaps, no other area where more testing of ceramic valve-train hardware has been conducted. However, because of the highly competitive nature of racing, very

Figure 7 - Exhaust Valve Temperature Profiles For Metal and Ceramic Seats



little is known and essentially no published data are available. What is known, is that ceramic hardware has been evaluated in a number of race engines ranging from conventional and modified stock cars (NASCAR) to high-performance Formula 1 vehicles. In fact, track trials and races have been run with this hardware at RPM levels in excess of 14,000 RPM, and total elapsed distances of over 250 kilometers. The light-weight nature of ceramic hardware makes it particularly attractive for racing enthusiasts. Higher engine speeds and better combustion efficiencies are realized when using ceramics. However, few quantitative data are known or available. Controlled testing in rigs has not been the norm for the racing industry. To better understand the potential benefits of ceramic valves in race engines, Norton and TRW evaluated the performance behavior of ceramic valves in a stock NASCAR engine as part of this DOE supported program. The test results are described below.

- NASCAR 5.7 Liter Motorized Rig Test - Dynamic evaluation tests were run on three valve material types to determine seating velocity, seating stress, and bounce. They were: (1) SiAlON ceramic, (2) titanium, and (3) conventional steel. A standard Chevrolet NASCAR 5.7-liter engine was procured for the testing of these components. The engine head was separated from the block for the dynamic studies. Full engine sets of the three valve material types were installed in this motorized test head. An Optron Camera was used to track the valve motion throughout the lift events for each component type, while a Bentley Nevada proximity sensor recorded the near seating motion of the metal valves. Because of the inability of the ceramic material to disrupt the magnetic field, only the Optron Camera was used for the ceramic valve lift. In all three cases a cut-off limit of 0.25 mm bounce was the stop point for dynamic evaluation. For the dynamic analysis runs, the data were acquired simultaneously at 10 second intervals. The individual component masses are given in Table III, while the complete system masses are shown in Table IV. In addition to motion dynamics, the power consumption of these three valve trains was recorded, up to each of their respective rated speeds, directly from the dynamometer. Strain gages were mounted on the stainless steel valve and the ceramic valve to verify stress magnitudes as a function of density, velocity, and modulus. The titanium valve stresses were back-calculated from the dynamic loading and material properties. During the first ceramic valve power consumption run, several intake valves failed in the under-head radius. Consequently, a finite element analysis (FEA) was completed on the design of these components. Excessive stress was found in the failure region. The valves were redesigned to reduce this stress concentration. The redesigned ceramic valves had a slight weight increase. Valve motion and power consumption tests were run a second time for these redesigned valves. The results represent valve motion and stresses for the second design.

Table III - Valve Component Masses (grams)

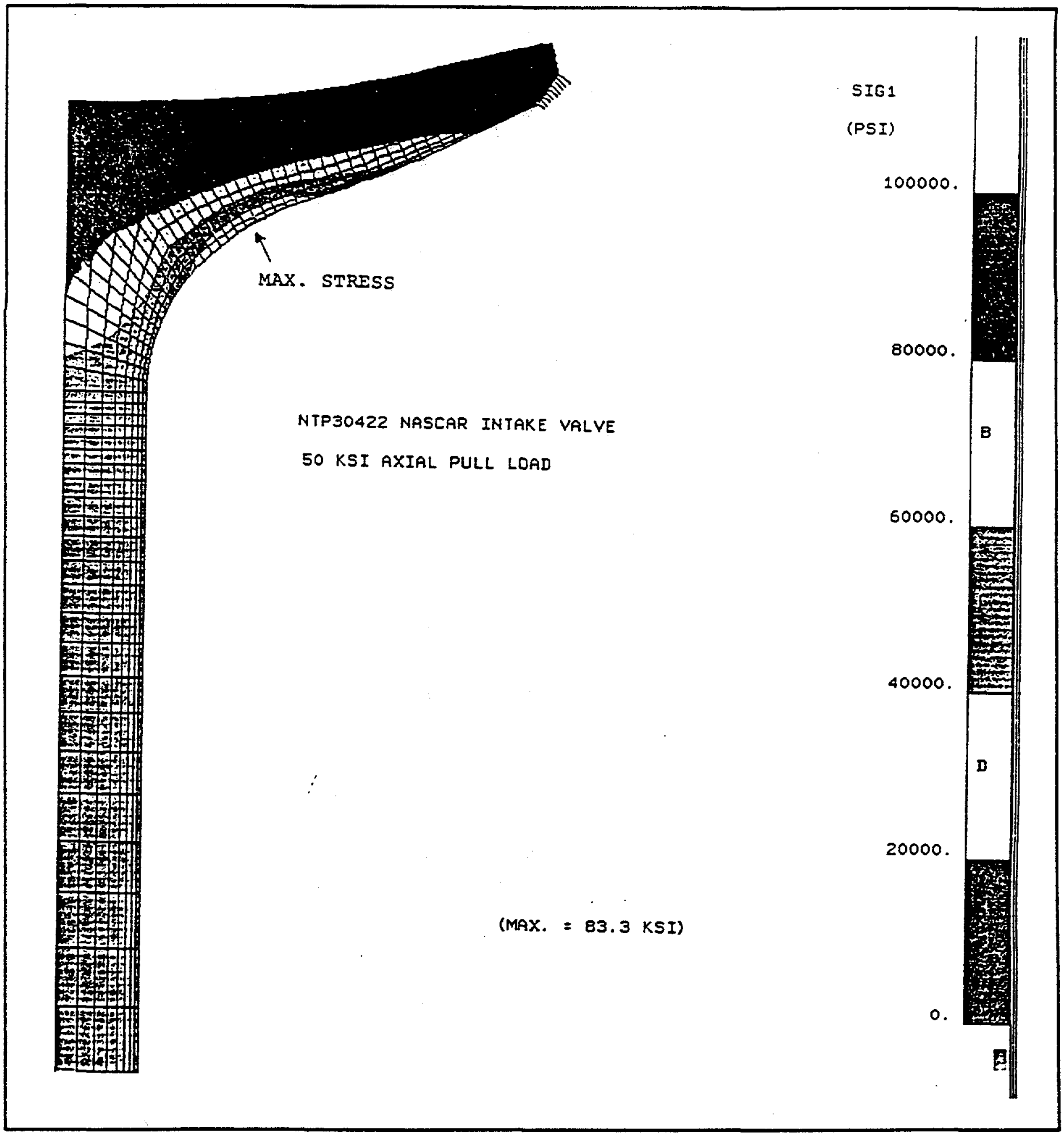
Material	Intake	Exhaust
Stainless Steel	136	119
Titanium	83	70
1st Design Ceramic	56	51
2nd Design Ceramic	70	55

Motorized Test No. 1 - Only ceramic hardware was evaluated during the first motorized test. The engine was run from 5400 RPM to 9000 RPM in 200 RPM increments that lasted approximately 5 minutes. During the test, five ceramic valves failed, including four intake and one exhaust. Failures of all four intake valves occurred at speeds approaching 9000 RPM. With the exception of one component, all of the intake failures occurred in the blended radius area between the stem and head. One of the parts failed within the stem at approximately two-thirds of its length away from the head. The exhaust valve failed by chipping on the seat area, (i.e., non-catastrophic). Each of the valves was evaluated for microstructural imperfections which might have contributed to failure. In general, it was found that the flaw origins within these components were small and within predicted levels. Prior to engine testing, components were subjected to a 241 MPa bending proof-test and a 345 ksi axial pull proof-test. Fractography on the failed components indicated that failure stresses were in excess of these proof-test levels. Consequently, an estimate was made of the stresses present in the head of the valves at the time of failure. This was accomplished by combining the results of a finite-element analysis of the head geometry and the results of runs using strain-gauged steel valves. The FEA results are presented in Figure 8. The data indicate that average stresses in the components ranged from 130 MPa to ~276 MPa. However, due to head flexing, bending stresses as high as ~572 MPa (83 ksi) could be observed. The highest stresses were exactly where most of the failures were observed. Because of this problem, it was decided to redesign the valves. To reduce both average and maximum

Table IV - Valve Train Mass (grams)

Material	Intake	Exhaust
Stainless Steel	335	322
Titanium	282	273
1st Design Ceramic	255	254
2nd Design Ceramic	269	258

Figure 8 - Finite Element Analysis Of NASCAR 5.7 Liter Ceramic Valve



principal stress levels, the redesigned valves had material added to the head portion of the valve by increasing the under-head angle and radius. A FEA was performed on the redesigned components, showing a reduction in maximum stress of ≈276 MPa, and average stresses of only ≈100 MPa. This redesign added approximately 14 grams of weight to the intake valve and 4 grams to the exhaust valve.

Motorized Test No. 2 - Following completion of the redesign, ceramic components were then refabricated for the second motorized test. This second test was run successfully at speeds up to 8000 RPM. Higher speeds were not investigated because of valve-train instability. At speeds above 9000 RPM, seating velocities of ≈4 meters/second were expected, which increased the risk of hardware failure. Notwithstanding this limitation, the ceramic valves showed improved performance over both the titanium and steel hardware. Figures 9 and 10 illustrate the impact of valve material and weight on seating velocity. The 19% system weight reduction of the ceramic intake versus the stainless steel is obvious at high RPM ranges, where inertia becomes dominant. Figures 11 and 12 show stem stresses of the three valve materials as a function of their respective speed ranges. An interesting point to note is the overall higher stress amplitude of the ceramic exhaust valve over the metal counterparts. This principally results from the material's higher elastic modulus. The exhaust position has a greater valve-to-guide clearance to compensate for the thermal expansion of the components. Figures 13 and 14 show the valve-train frictional torque and power consumption. Note the improvement of the ceramic valves at speeds above 7200 RPM.

In summary, valve dynamics were evaluated for three valve types to determine seating velocities, stress, and bounce conditions. From this study, it was found that:

(1) The operating speed range of ceramic valves was approximately equal to that of titanium valves. The inertial forces for these two materials were similar. However, motoring torque and power consumption were lower by 3-5% at high engine speeds (above 6,000 rpm) for the ceramic as compared to titanium. In all cases, these two materials were significantly better than conventional steel components.

(2) The dynamic stress levels for the ceramic valves were substantially higher than either the titanium or steel valves, primarily due to the ceramic's higher elastic modulus. The higher stresses resulted in failure of ceramic hardware during the first test. A redesign of the ceramic valves enabled a second test to be completed successfully. However, this engine represents substantial risk for use of ceramics due to transient thermal stresses and uncontrolled flexing of the head. The engine could be optimized for ceramic valves, but engine speeds and temperatures must be controlled carefully to ensure against breakage. Recommended changes to the engine design are as follows:

- A reduction in spring loads to ≈40% of those required for metal valves;
- Tighter guide clearances to minimize flexing of the ceramic;
- A reduction in guide lengths to minimize bending moment constraints on the ceramic.

(3) Overall, ceramic valves have significant potential benefit for NASCAR engines. They allow higher operating speeds before valve-train instability is observed. In turn, this increases horsepower and reduces fuel consumption. These advantages must be moderated against the risk of ceramic failure if engine speeds become excessive, or if temperature gradients within the head result in uncontrolled flexing.

IV. Summary.

Considerable testing and evaluation of ceramic hardware has been conducted over the past 5-7 years. Ceramic components have been installed in a number of engine types ranging from conventional to advanced designs. For gasoline engines, the major benefit of ceramic valves is reduced mass. Light-weight components allow for: (1) improved combustion performance, (2) higher operating speeds, and (3) better fuel economy. By using ceramic valves, mass reductions between 20% and 70% have been demonstrated. In comparison with standard production engines, ceramic valves have provided ≈20% improvement in maximum engine RPM, along with ≈30% reduction in spring force. Increases of up to 7% in fuel economy have also been demonstrated. Ceramic valve-train hardware has performed

Figure 9 - Intake Valve Seating Velocities

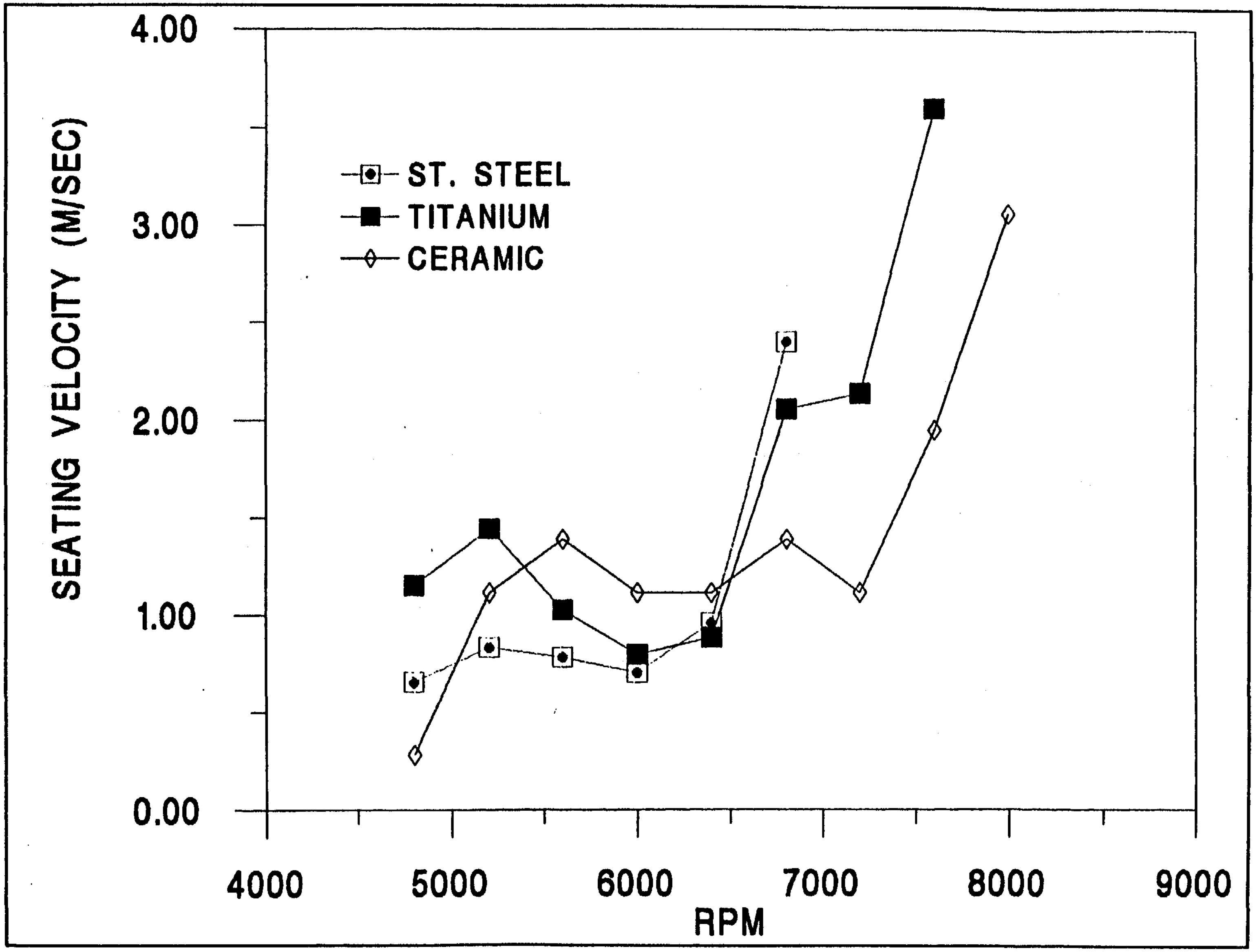


Figure 10 - Exhaust Valve Seating Velocities

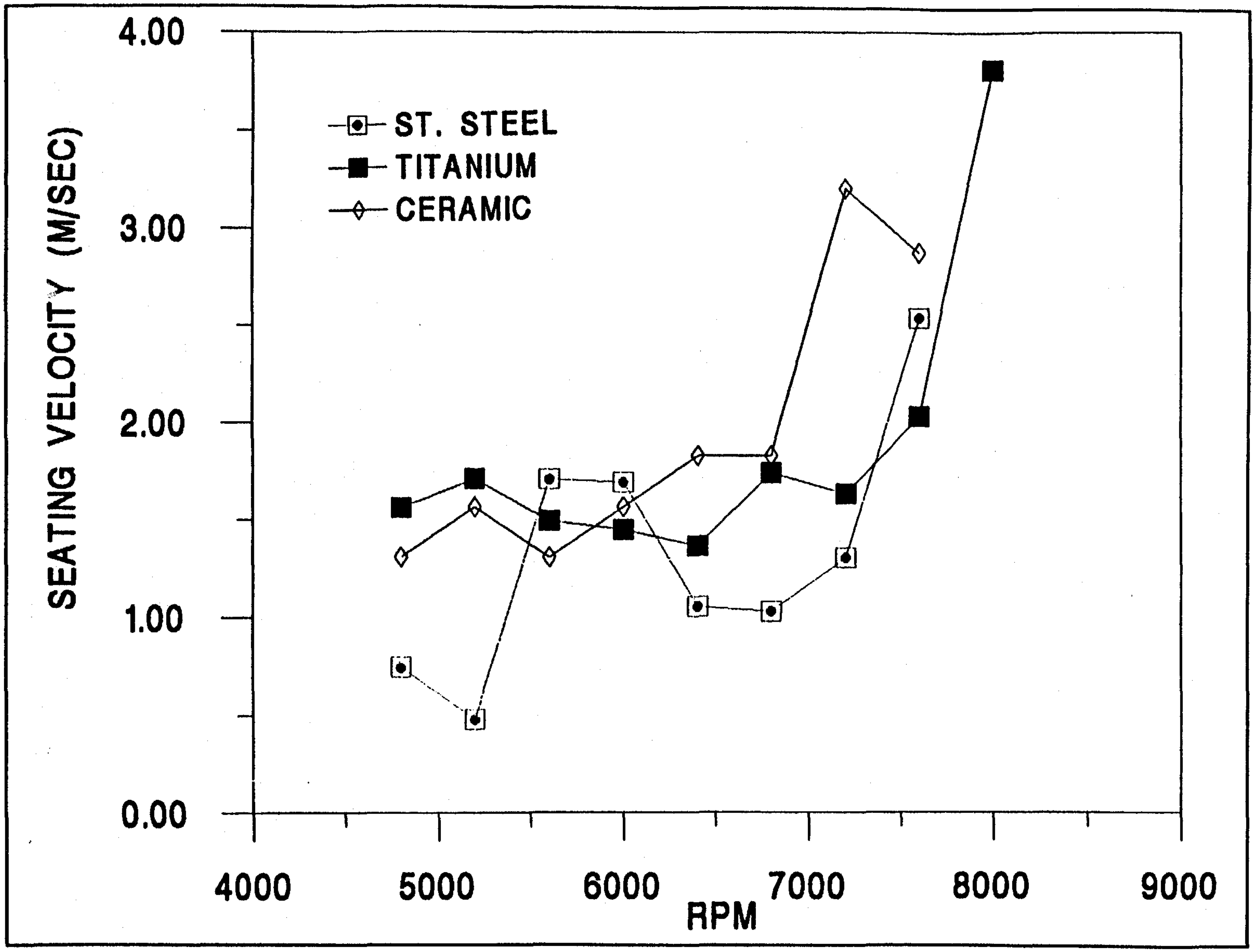


Figure 11 - Intake Valve Seating Stress

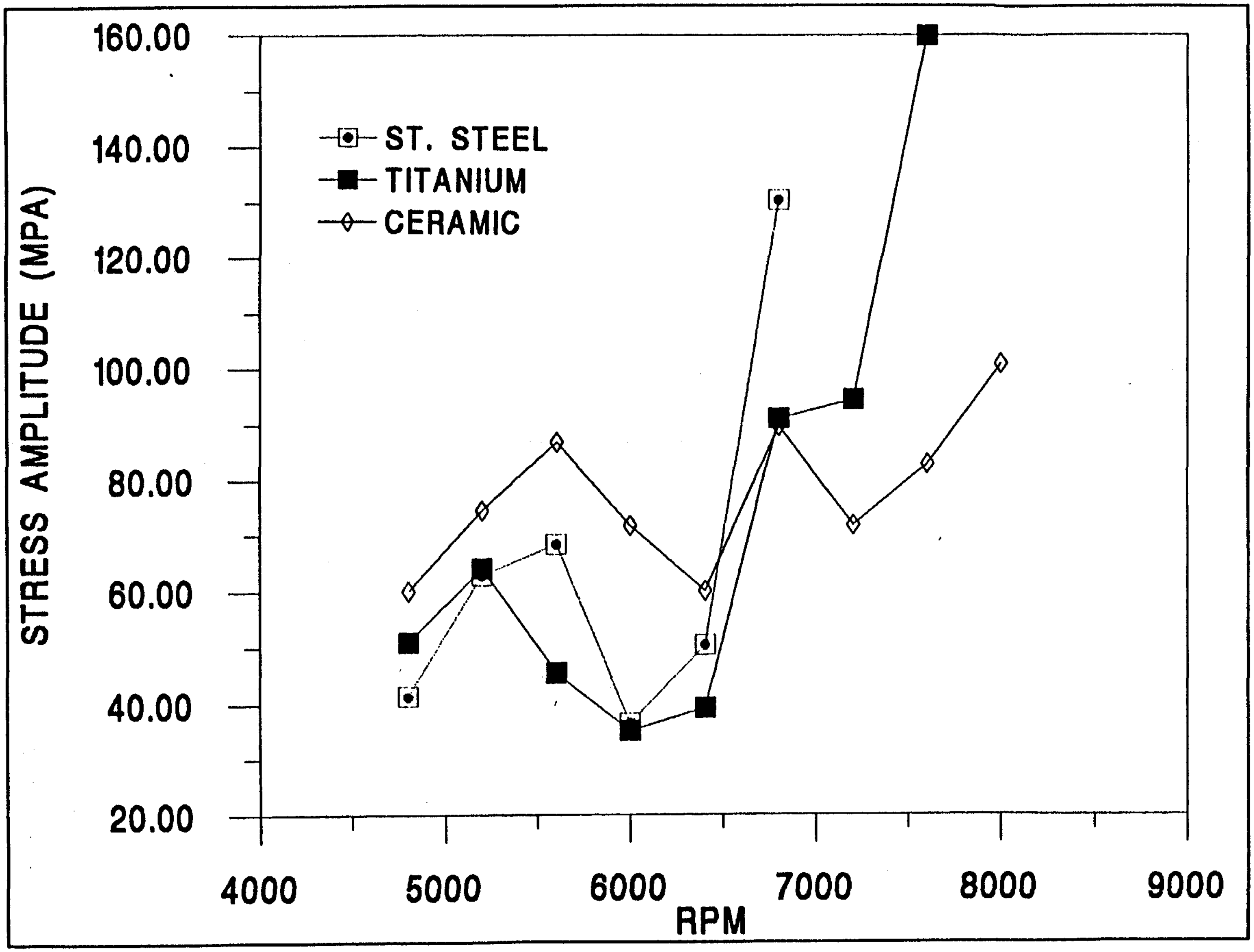


Figure 12 - Exhaust Valve Seating Stress

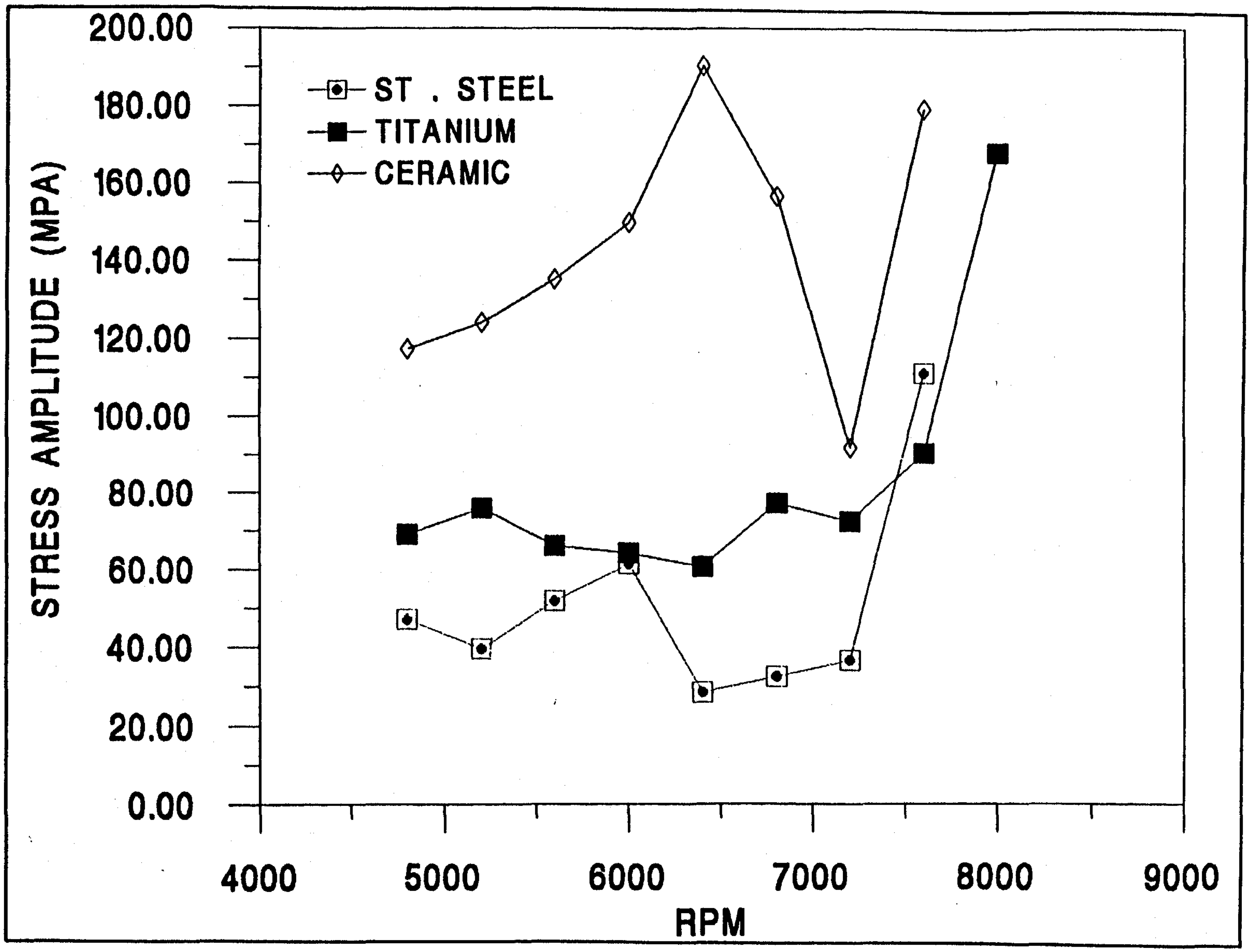


Figure 13 - Camshaft Frictional Torque For Intake Valves

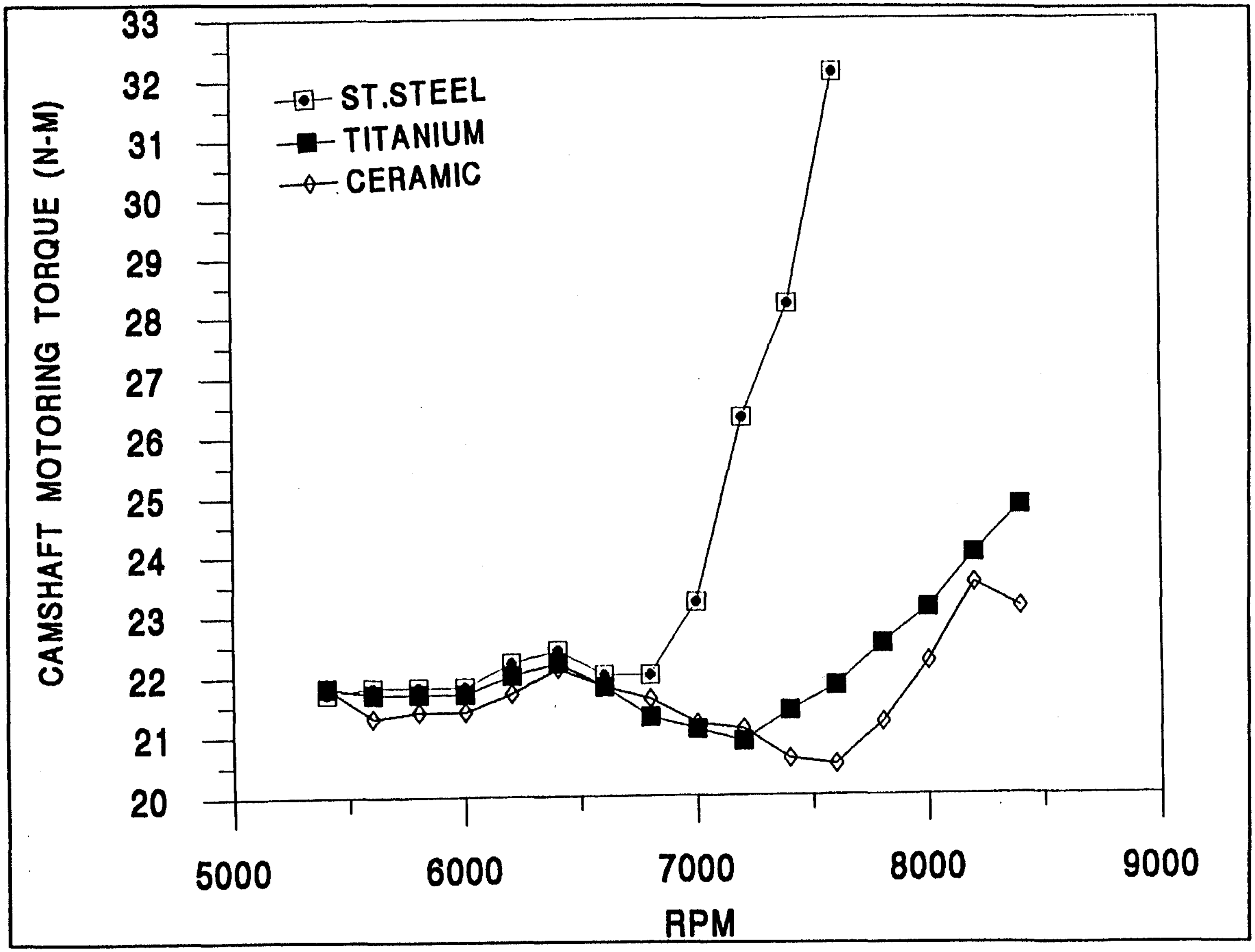
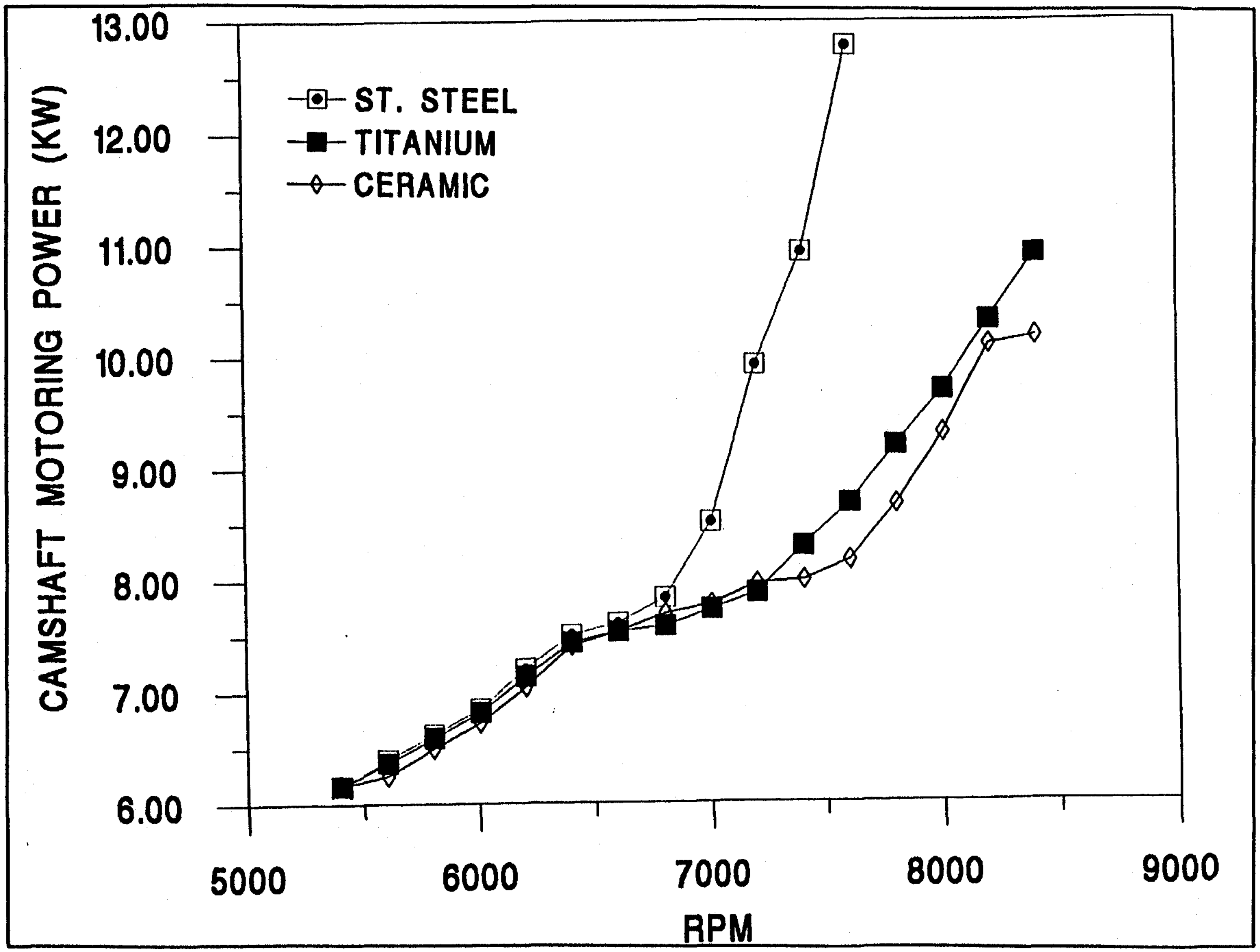


Figure 14 - Camshaft Power Requirements For Exhaust Valves



admirably, surviving extended rig and road trials ranging between 50,000 miles and 300,000 miles. Ceramic valves have also been installed in state-of-the-art Formula 1 race cars, and have endured track-trials under race conditions for in excess of 250 kilometers at engine speeds up to 14,000 RPM. Ceramics also provide major advantages in wear and corrosion resistance. Corrosion and erosion of exhaust valves are significant problems in diesel engines when using unrefined crude, natural gas, or coal fuels. For heavy-duty gasoline and diesel engine tests using ceramic valves, reductions in valve-train wear of up to 80% have been observed. Valves and related components have endured extended tests (up to 750 hours) in highly corrosive environments, and have outlasted comparable metal parts by factors of 4 to 5 in life. Ultimately, design of the ceramic hardware and redesigns to the engine are required to take full advantage of the ceramics' capabilities. Simple substitution often results in failure. However, with appropriate designs, ceramic components can provide many system benefits.

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