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Evaluation of Thermal Barrier and PS–200 Self-Lubricating Coatings in an Air-Cooled Rotary Engine

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SUMMARY

This Small Business Innovation Research Phase II Project explores the materials and methods for applying a thermal barrier coating overlaid with a wear coating on the internal surfaces of the combustion area of rotary engines and evaluates the feasibility and desirability of operating rotary engines with such coatings.

Application of a thermal barrier coating on the interior of a rotary engine was expected to reduce the transfer of combustion heat into the metal engine parts, reducing the engine housing cooling requirements and increasing the surface temperatures of the internal engine components. The internal temperatures were expected to exceed the thermal breakdown temperatures of known oil-based lubricants, requiring application of a solid lubricant which is able to withstand the high temperatures. Zirconia was applied as the thermal barrier coating (TBC) and PS-200 as the wear coating.

Several rotary engines were used in the tests with coatings applied by two different vendors. It was determined that a computer-controlled plasma spraying process was needed to achieve even moderate success in application of the coatings at the specified thickness and uniformity over the interior surfaces. Various methods of grinding and honing were used in attempts to achieve uniformly smooth finished surfaces.

Engine tests were run on a fully instrumented dynamometer with temperature sensors attached at key points throughout the engine. Base-line tests were run first to obtain all pertinent readings from an uncoated engine. Early attempts to obtain temperatures along the length of the rotor using slip-rings had limited success and temperature pins (tempins) were substituted. They proved to be a reliable method of obtaining maximum temperatures at selected points on the rotor. The base line tests were followed by test runs of the coated engines and the results compared. Additional tests were conducted using a titanium rotor to determine the effects of its lower thermal conductivity. Thermally insulating the titanium rotor was also tested.

The tests demonstrated the benefits of the thermal barrier coatings in that significantly lower specific fuel consumption was consistently achieved. The PS-200 wear coating proved to be very durable, even under some severe test conditions.

INTRODUCTION

This Phase II Small Business Innovation Research Project followed a successful Phase I effort in which the feasibility and benefits of coating the side housings of a rotary engine were explored. The purpose of this contractual effort was to evaluate the results of the application of a thermal barrier coating (TBC) overlaid with a permanent coating of a self-lubricating material for wear resistance on all internal surfaces in the combustion area of an internal combustion (rotary) engine. Zirconia was specified as the thermal insulating material and PS-200 as the self-lubricating wear coating. Both coatings were applied by plasma spraying. It was anticipated that the thermal barrier coating would reduce the heat rejection of the engine, thus requiring less cooling and increasing thermal efficiency. It would also raise the temperature of the internal engine surfaces above the thermal breakdown temperature of known oil-based lubricants, requiring the use of a high temperature, dry film lubricant coating to control friction and wear.

To be assured that adequate data was gathered for evaluation, it was planned that temperature readings would be obtained from all key points throughout the rotor housing and, through the use of a multiple slip ring assembly developed as part of the work, temperatures would also be obtained at six points along the length of the rotor. The fuel flow and fuel/air ratio were to be accurately controlled and recorded and exhaust gases monitored. A complete set of baseline tests was planned to measure all pertinent operating parameters and temperatures on a standard uncoated engine. Then the identical tests and measurements were to be repeated with the insulated engine and the results compared.

Additional tests of the insulated rotary engine were planned to evaluate the use of a titanium rotor to replace the standard cast iron rotor, and to determine the feasibility of air cooling the rotor and employing direct fuel/air induction rather than routing the air/fuel mixture through the rotor for cooling and then to the intake port.

Development of the slip ring assembly was considerably more challenging than anticipated and was supplanted by temperature pins (tempins) which gave adequate readings of the temperatures reached at various points along the rotor.

Application of TBC on the flat surfaces of sidewalls was quite successful. Coating and finishing the trochoid surface proved to be very challenging. A vendor was found who has a computer-controlled plasma spraying process. After several attempts, some improvement was noted but additional work with the supplier is needed to achieve the ability to consistently apply uniform coatings of the intended thickness over the trochoid and finish it to the tolerences desired. Despite these difficulties, significant results were achieved.

The test results indicate that the thermal barrier coating is very effective in improving specific fuel consumption (SFC) and the PS-200 wear coating held up well under quite severe conditions.

PS200 was invented by Harold E. Sliney of the Surface Science Branch, Materials Division at NASA's Lewis Research Center, Cleveland, Ohio. The concept of carbide/fluoride/silver self-lubricating materials, including PS200, is described in:
U.S. Patent 4,728,488: *Carbide/Fluoride/Silver Self-Lubricating Composites*
Issued: March 1, 1988
Assignee: U.S. Government, NASA

AIR-COOLED ROTOR SELECTION FOR TESTS

The highest potential power output of the rotary engine is realized by air-cooling the rotor rather than charge-cooling it. The charge-cooled rotor generates a lower volumetric efficiency due to both the pressure drop across the rotor and the heated induction charge. The first two engine tests were base-line runs to determine the differences faced by addressing these engine alternatives. A major concern with either an air-cooled or charge-cooled rotary engine is the operating temperature of the bearings because higher temperatures have limited the bearing life. The charge-cooled rotor is cooled by both the incoming induction air and the fuel. The base-line charge-cooled engine showed a moderately high 338°F at the drive end crank and 349°F at the accessory end crank. These temperatures would be expected to be considerably less than the average bearing temperature. Since the engine was running at a very modest output of 14.4 HP, it was not difficult to see why a charge-cooled engine would operate at high rotor bearing temperatures. Our slip-ring temperature data suggested that the rotor bearing has operated at temperatures around 500°F. It was decided therefore to lower the base-line crankshaft temperatures during our series of tests. The goal was to maintain a specific crankshaft temperature of as close to 275°F as possible at 14.4 HP. That way we could determine the benefits of using a titanium rotor by measuring the air flow required to maintain the crankshaft at this temperature. The ability to control the air flow through the rotor and hence control the bearing temperature supported using the air-cooled rotor engine for all subsequent tests.

The documented test data from all of the tests are shown in Appendix 1. The tabulated summary of these tests is shown in Figure 1. The locations of the various thermo-couples tabulated in Figure 1 are shown in Figure 2.

SPECIFIC FUEL CONSUMPTION

One of the hoped-for advantages of the thermal barrier coating was that it might reduce the fuel quenching action of the rotary engine's large combustion surface area. Historically this has been one of the main arguments against the rotary engine's ability to compete with the piston engine on specific fuel consumption. The tests were run with a fairly rich mixture, i.e., CO at 6+%, so that only relative SFC changes with different engine configurations should be considered significant. As anticipated, the charge-cooled rotor engine gave a better SFC than the air-cooled rotor since the charge-cooled rotor mixing and rotor heating of the incoming air/fuel mixture generates a better atomized and more uniformly distributed mixture. Thermal efficiency might be expected to go up slightly as well with the heated incoming air. The tabulated results (Figure 1) shows a 13% decrease in SFC for the charge-cooled rotor over the air-cooled rotor.

Thermally coating the side-walls and continuing the use of a stock OMC air-cooled rotor showed a 8.6% reduction in SFC (Test 3 compared with Test 2, Figure 1). Test 4 used a rotor-face and wear-surface-coated titanium rotor in a non-TBC side-wall engine. This titanium rotor reduced the SFC by 4.3% (Test 4 vs. Test 2, Figure 1). Finally, using TBC sidewalls together with a fully coated titanium rotor reduced the SFC by a total of 16.1% (Test 5 compared with Test 2, Figure 1). The final test (Test 6), in which the TBC was also used on the rotor housing (trochoid), did not allow a meaningful comparison of SFC because the poorly-finished trochoid surface led to a number of local hot spots due to high pressure and temperature gas leakage paths. It is anticipated that if the rotor housing had been properly coated that an additional reduction in SFC might be possible (i.e., the rotor housing surface is substantially larger than the sidewalls during the period of maximum combustion pressures and heat flux). The result is better than expected and, if proved to be true at other power settings, would make the TBC rotary engine highly competitive with a comparable piston engine.

SLIP-RING ASSEMBLY FOR MEASURING ROTOR INTERNAL TEMPERATURES

The first 6 months of this study were primarily occupied with the development of a multi-channel slip-ring assembly that could be used in the hostile environment of the rotary engine's rotor. The development of a slip-ring temperature measuring assembly was considered a valuable tool because it would provide real-time temperature information within the rotor which is unquestionably the key dynamic component of the rotary engine. Data on the temperature environment of the rotor of the rotary engine is particularly important when the rotor is air or charge-cooled. In this case, maintaining an acceptable temperature at the rotor bearing determines much of the engine's design and performance. For example, a charge-cooled rotor has a specific quantity of air and fuel available to cool it. In the past this has limited power output of the engine in order to avoid causing the rotor bearing temperature to exceed its allowable limit.

Figure (3) shows the placement within the rotor of the various resistance temperature devices (RTD). All RTD's were glued to their positions using a ceramic epoxy. An example of the recorded raw data is also shown in this figure. The noise is seen as spikes while the base temperature is reasonably determinable. The results show the highest recorded temperature at each position during this run. It would appear that the temperatures had reached a steady state and it was surprising to note the high temperatures that were reached near the bearing. The engine tested (OMC) would typically be used in snowmobiles where the ambient temperature entering rotor is probably 100°F cooler. Even with a lower temperature cooling air which would lower the rotor temperature, one would still expect to see a temperature of ~500°F at the rotor bearing outer race. The engine in this limited test was operating at only one-half power (15 HP at 3,000 RPM) The results suggest that a charge-cooled rotary engine will be hard pressed to keep the typical iron rotor bearing at reasonable temperatures (<400°F) even at modest ambient temperatures. The alternative of an insulated rotor would seem to provide the only viable approach to creating a charge-cooled rotary engine capable of operating at attractive BMEP's. An alternative is to air-cool the rotor through the use of forced external cooling. In this case the volume of cooling air can be substantially increased to lower the bearing temperatures. The need to provide an external source of cooling air will generally add to the engine cost and weight. Using an insulated rotor in this case would reduce the volume of external air needed and could make it possible, in the case of ducted fans, to use the available pressure head to provide the cooling air.

Figure (4) provides a lay-out of the slip-ring assembly. While the slip-ring development did not succeed in developing a reliable long-run recorder, it did provide some data that was very useful. One suggested improvement that should be made to extend the life of the present slip-ring design is the replacement of the teflon with a machinable ceramic.

WEAR CHARACTERISTICS OF THERMAL BARRIER COMPOSITE COATING

Test 3 introduced TBC side-walls and a 2.5 hour run was completed. The engine was then disassembled to remove the temp-pins used to record the rotor operating temperatures. A small cracked area in the TBC appeared on the drive side end housing. It did not appear to be the result of heating since it was in a cool area of the engine. The appearance as shown in Figure 5 suggests a defect in the plasma spraying since another small piece chipped out in the dowel area. This was the first and last time this has happened. We decided to scrap this end housing rather than have a catastrophic failure in one of the following tests. The PS-200 showed no measureable wear and only improved in its finish during the tests (beginning RMS = 21 micro-inches, ending RMS = 7 micro-inches). Figure 6 shows a micro-photograph (220x) of the PS-200 surface as sprayed and then finish-ground. Figure 7 shows a micro-photograph (130x) before running a 2 hour test and after the test. Aside from a slight color change, the surface appears to be identical. The next documented test (Test 4) used the titanium rotor with its sides coated with chrome-oxide for wear resistance and the rotor flanks coated with alumina micro-spheres for insulation. This rotor was run against a stock OMC side-wall on the drive side and a PS-200 coated side-wall on the accessory side. Again no measurable wear was recorded. This flank TBC worked well in reducing the heat transfer to the rotor as indicated by the considerable reduction in cooling air required to cool the rotor. Surface temperatures on the rotor flank must have been considerably increased as noted from the lack of carbon deposits on the surface. Test 5 included the addition of a thermal barrier to the sidewalls which considerably reduced the temperature of these components. The final test (Test 6) included a thermal barrier coating on the rotor housing (trochoid). After many attempts by outside vendors, we were still unable to get a supplier who could lay down the zirconia and PS-200 coating as specified. The first coating combination produced by APS Materials was determined to be too uneven to allow finishing (build-up at the minor axis was too thick for both the zirconia and the PS-200) We then switched vendors to Plasma Technologies where we funded the computerization of a cam follower to coat the material more evenly. Their first housing to us was more even but, because they sprayed a thinner layer of PS-200 than we had specified, there was not sufficient PS-200 to allow a clean-up and, in fact, we broke through to the zirconia in a number of places without reaching a cleaned-up surface. The next housing from Plasma Technologies was way over the specified dimensions on both the zirconia and the PS-200. We attempted to grind back to within .005" of the specified dimension, but we again broke through into the zirconia . We then began a third rotor by Plasma Technologies but were not able to finish it because time was running out. Concurrently, we had decided to try grinding the original AP Materials rotor housing to shape with mixed results. Before we were able to clean up the rotor housing shape we broke through the PS-200 near the spark plug. Some areas had not cleaned up yet which meant that there would be small leakage paths for the high temperature pressurized gas. We were uncertain of the consequences of the less-than-flat surface. It was felt, however, that the final test was to determine the durability of the TBC on the rotor housing since we had already determined the effectiveness of the TBC coating as an insulator on the side-walls. Certainly this final test would be a severe test of the TBC coating under these less-than-ideally-prepared conditions. Historically, chattering of the apex seals just past the minor axis has been a continuous rotary engine concern. The right amount of apex seal weight and trochoid surface friction can prevent chatter but this is difficult to achieve. Alternatively one can use a very hard surface like OMC's tungsten carbide and thereby ensure that the surface is not damaged even if chatter occurs. The survivability of a TBC on the trochoid was probably the biggest question mark in this study. The operating friction coefficients and seal dynamics could not be easily predicted. A short run would determine whether chattering was a problem. The test was a success inasmuch as no seal chatter or surface break-down was observed. As it turned out, the poorly finished trochoid put the seals and surface to an unusually severe test. Temperature data show very high temperature at certain points in the engine. Areas where leakage occurred are highly discolored (Figure 8) and there is some minor wear in the center of the apex seal where it came in contact with the zirconia in a housing area where chatter was most likely to occur. Generally, however, the housing surface remained intact and smooth and the test was considered very successful in establishing the wear surface durability. The wear surface improved during the run (RMS in micro-inches improved from 24 to 17).

Because of the geometric relationship between the camera and the trochoid surface it was not possible to get a well-defined picture of its surface.

A longer run (20 hours) was anticipated but in view of the extreme temperatures reached even the 2 hour run was foreshortened to 1.5 hours.

THERMAL GRADIENTS WITHIN ROTOR STRUCTURE

Historically, the failure mode of the charge-cooled rotary engine has been bearing failure or rotor stress cracking. Both of these failure modes are more likely to occur if thermal gradients cause distortions of the rotor, which generally appears to be the case. One of the elements in our titanium rotor design that should have reduced these stresses was the separation of the rotor flank (titanium) from the hub, gear, and bearing (steel). These were pinned together using dowel pins between the two sections. Tempins were used to record the rotor temperatures. The lay-out of these selected positions and recorded temperatures is shown on Figures 9 and 10.

Three positions on the rotor were chosen to represent significant temperature differences and absolute values. For example, Test 1 (charge-cooled rotor) on the Rotor Temperature Distribution Schematic, (Figures 9 & 10), shows a maximum temperature difference within the rotor of 251°F and a maximum side-to-side differential of 62°F. The air-cooled rotor has a maximum temperature differential of 303°F and a side-to-side differential of 53°F. The average temperature within the air-cooled rotor is significantly less than the charge-cooled rotor due to the higher cooling air-flow. It would appear that the fuel-air mixture provides a more even cooling than air alone where one expects greater temperature differentials with the more aggressive cooling. Using TBC coated side-walls has only a small effect on raising the rotor temperatures; i.e., average temperature on the accessory side increased by only 4.7°F.

Using a titanium rotor modified the temperature distribution throughout the rotor. One would expect higher temperatures at the apex seal region because of the reduced thermal conductivity of titanium and conversely, the temperature away from the flank (#2 on Test 4), was lower than this same position on the iron rotor (#2 on Test 2). Test 5, where the titanium rotor has a thermal barrier coating, is also consistent with expectations. The apex seal region is 62°F hotter with the titanium rotor than with the OMC iron rotor due to the reduced air-flow used with the titanium rotor. Position #3 under the pocket is nearly the same temperature while position #2 nearer the bearing is 36°F cooler than the standard OMC iron rotor. The air-cooled rotor is seen to create higher thermal gradients in the rotor, however the two-piece rotor design is expected to help off-set the stress-producing effects of these gradients. A finite element analysis would be needed to confirm this expectation.

THERMAL BARRIER COATING EFFECT ON ROTOR HOUSING COOLING LOAD

Air-cooling a rotary engine is more challenging than air-cooling a piston engine. The combustion chamber of a rotary engine never sees a cooling cycle and the resulting continuous heat flux is very high. It is probably impossible to provide sufficient cooling fin area to cool an existing rotary engine housing with air for BMEP's greater than 100 psi. The TBC offers a method to reduce this cooling load. The test results, as tabulated in Figure (1), demonstrate the effectiveness of the thermal barrier coating when applied only to the side-walls. The heat flux as measured by a thermo-couple indicates the following:

	Drive side temperature reduction T3 position	Accessory side temperature reduction T8 position	Accessory side heat flux as measured by cooling air in vs.out (T15 minus T13, Fig. 1)
Stock rotor with TBC coated sidewalls (Test 3 vs. Test 2)	32°F	34°F	22.3% reduction
Titanium rotor coated sidewalls (Test 5 vs. Test 2)	36 F	52°F	19.4% reduction

Since less heat was transferred to the side-walls due to the TBC, they ran cooler. The rotor housing at the spark plug also ran cooler with TBC sidewalls which suggests that more heat must be transferred from the rotor housing to the cooler side-walls. This is surprising since the TBC existed between the rotor housing and the side-walls as well (manufacturing convenience). Test 6 would have established the specific benefits on the rotor housing cooling load when using a TBC over an entire rotary engine Unfortunately, the poor surface on the trochoid seems to have created more heat than the TBC was able to insulate against. The TBC side-wall results, however, support the benefits of using a TBC wherever possible.

ROTOR COOLING AIR REQUIREMENTS TO CONTROL CRANKSHAFT TEMPERATURE AT BEARING INNER RACE

The volume of cooling air required to maintain the bearing at or near a specific temperature is very important. Since volume flow squared is proportional to the differential pressure required to supply the flow, this can become an important accessory power consideration. For example, many ducted fan applications would like to use the differential pressure across that fan to provide for rotor cooling. This pressure differential is probably quite modest, generally not exceeding 0.5 psi.

The tests performed on the air-cooled rotor engine provided an interesting set of results depending on the design priorities. For example, using TBC side-walls increased the required rotor flow since the rotor was not able to transfer as much heat out through the side-walls (Test 3 vs. Test 2). The required flow increase was 10.3%. An initial test with the titanium rotor without flank or rotor side wear coating and without TBC side-walls increased the flow required even further. In this test the titanium rotor sides were uncoated and the resulting wear on the side-walls and rotor was very large (rotor .003" narrower in 2 hours with both SX 331 and PS-200 sidewalls well worn). The added friction from these incompatible wear surfaces probably accounts for the increased rotor temperature. It would appear that this conclusion is borne out in the next test where the volume flow required is reduced by nearly 6% (Test 4 vs. Test 2) when the titanium rotor sides are coated with chrome-oxide wear surfaces. Finally, coating the titanium rotor faces with a thermal layer (alumina-spheres) reduced the total cooling air volume flow required by 16.2% (Test 5 vs. Test 3) and thereby reduced the power required to provide the cooling air by over 42%. Test 6 was inconclusive because of the excess heating of the rotor housing (trochoid).

For comparison it is interesting to note that the charge-cooled engine had only half as much volume flow through the rotor at this power and RPM. Despite the extra cooling provided by the fuel, the rotor temperatures ran 63°F to 65°F hotter. (See Figures 9 & 10)

CONCLUSIONS

The benefits of applying a thermal barrier coating (TBC) to various combustion area surfaces of an air-cooled rotor rotary engine was demonstrated. A solid lubricant (PS-200) was successfully used over an insulator (zirconia) on all wear surfaces while an alumina sphere matrix was applied as an insulator on the rotor flank or face. The following conclusions were drawn:

1.) The use of a TBC on the side-walls with an iron rotor reduced specific fuel consumption (SFC) by 8.6%. Using TBC on both the side-walls and the rotor face of a titanium rotor reduced the SFC by 16.1%.

2.) Using a TBC coated titanium rotor reduced the required rotor cooling air-flow by 16.2% over the original OMC iron rotor. This represents more than a 42% reduction in power required to provide the cooling air.

3.) TBC on the side-walls reduced the heat flux out of the side-walls (end housings) by over 22% while lowering the temperature at one point on the side-wall by 52°F.

4.) The use of a titanium rotor increased the thermal gradients within the rotor. Applying a TBC to the rotor face substantially reduced these gradients but they remained higher than those within the iron rotor. The maximum temperature difference was 62°F for the titanium rotor at the apex seals.

5.) The TBC coating remained intact and in good condition on the side-walls, rotor face and trochoid (rotor housing). In particular, the poorly finished trochoid surface was severely tested due to its elevated temperatures and a small region that was not coated by PS-200. Despite this, the PS-200 surface appeared to be chatter-free or at worst, free from damage due to apex seal chatter.

6.) The slip-ring assembly which was developed to provide real-time temperature data on the rotor, was not fully successful. While only a limited amount of data was generated, this data did prove valuable in determining transient rotor temperature rise during engine start-up as well as steady-state maximum temperatures and temperature distribution. At the more modest temperatures that exist with an air-cooled rotor, the slip-ring assembly might have achieved an extended life. To expand this limited data-base, temperature measuring pins (tempins) were successfully used to measure rotor temperatures.

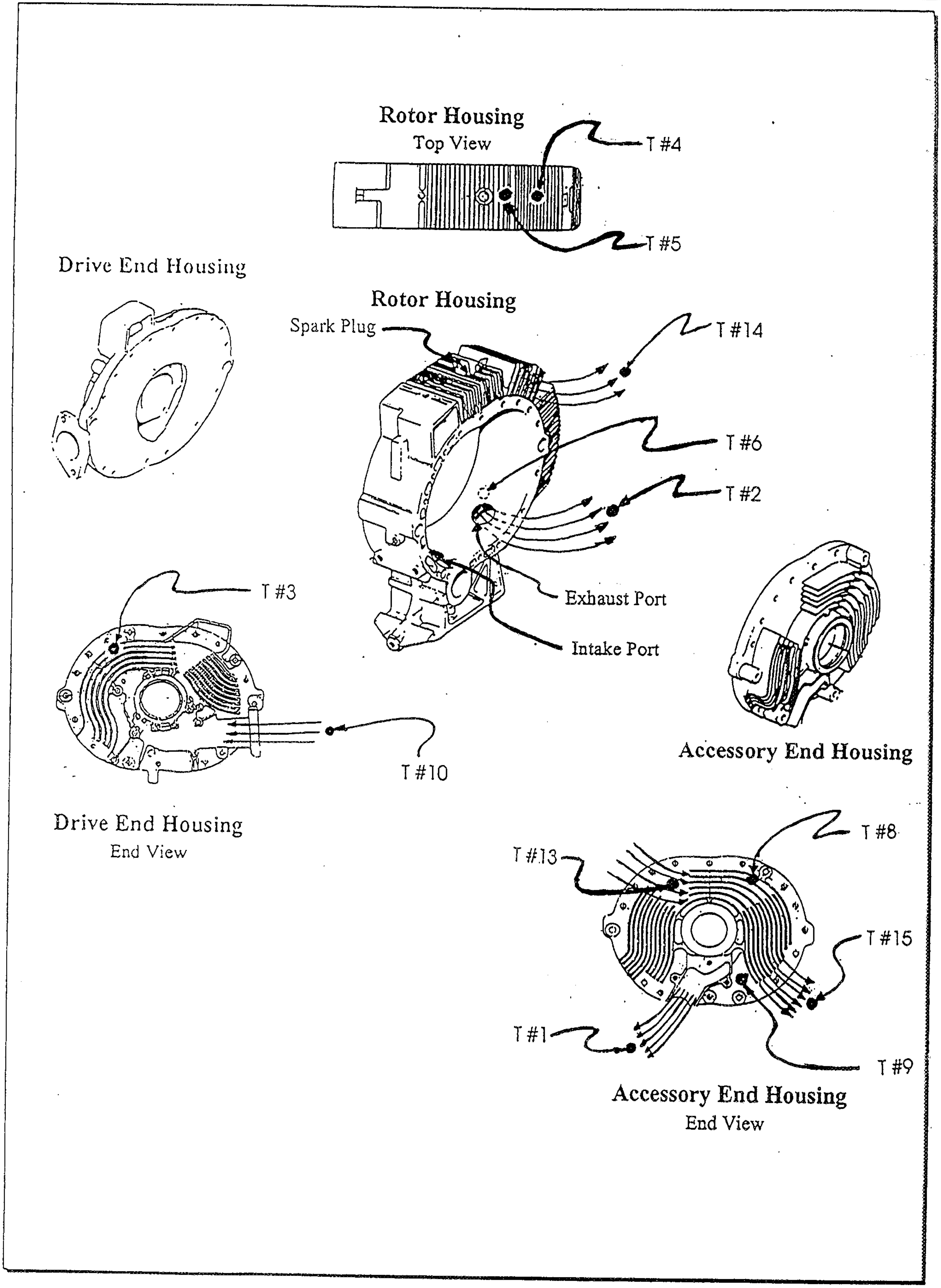
FIGURES

Compilation of Average Values for All Tests

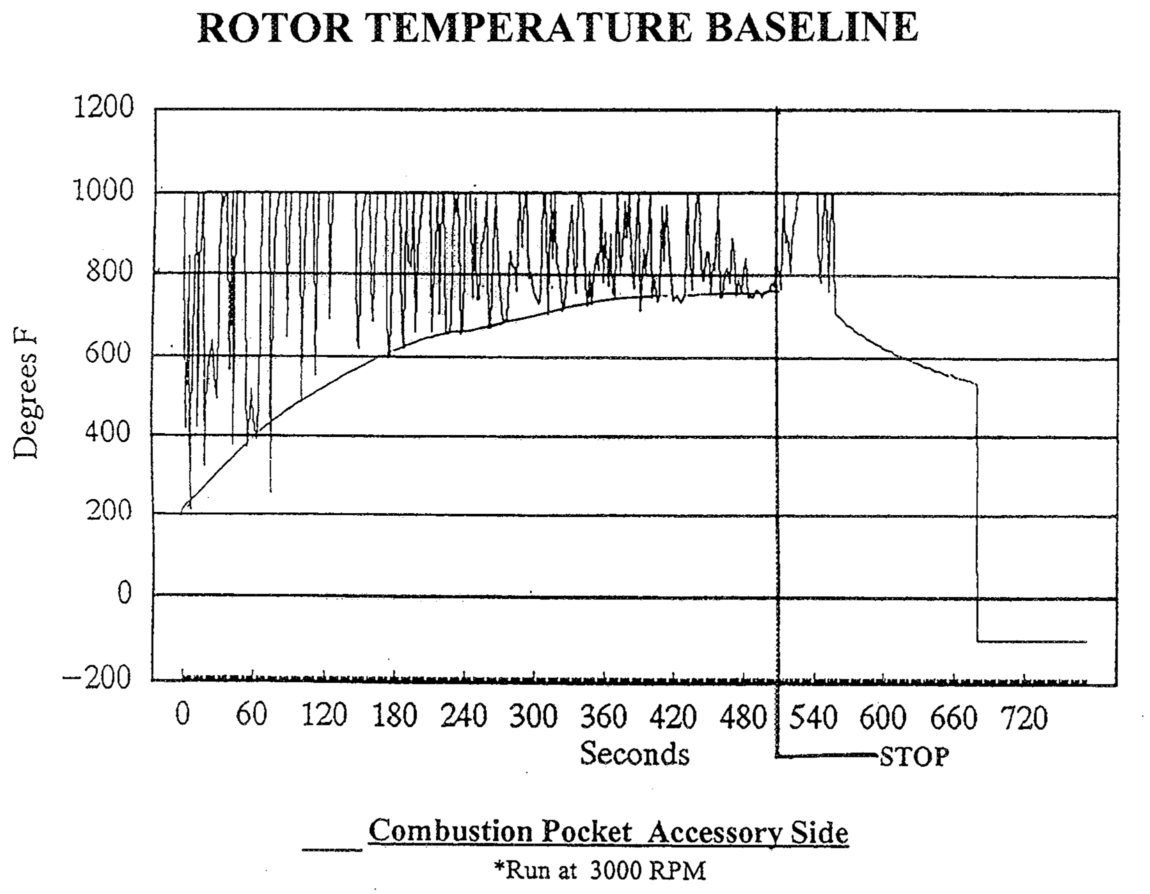
TEST #	Rotor:	Rotor Housing	Acc. end housing	Drive end housing	RUN TIME	FUEL FLOW	%CO	%CO2	%O2	HC	T 1	T 2	T 3	T 4	T 5	T 6	T 8	T 9	T 10	T 11	T 12	T 13	T 14	T 15	RCA FLOW
Charge cooled baseline test.																									
1	Stock OMC (iron)	Stock OMC (Tungsten Carbide)	Stock OMC (Al)	OMC (Al)	2:19	0.81	6.294	10.41	0.590	111	225	1545	393	382	386	427	365	353	N/A	338	349	148	122	187	Calc. to be 33
Air cooled baseline.																									
2	Stock OMC (iron)	Stock OMC (Tungsten Carbide)	Molybdenum coated	Molybdenum coated	2:03	0.93	6.123	10.47	1.003	244	254	1503	394	385	384	436	364	391	112	275	284	123	127	190	65.66
Air cooled, TBC sidewalls only.																									
3	Stock OMC (iron)	Stock OMC (Tungsten Carbide)	TBC	TBC	2:30	0.85	6.040	10.64	1.108	296	260	1459	362	380	379	433	330	370	117	263	272	125	132	177	72.43
Air cooled, OMC Style coated titanium rotor.*																									
4	Coated Titanium	Stock OMC (Tungsten Carbide)	PS-200 coated	OMC (Al)	2:09	0.89	6.104	10.57	1.230	244	254	1447	N/A	393	380	435	359	389	118	270	276	121	130	189	61.88
Air cooled, OMC style coated titanium rotor*, TBC sidewalls.																									
5	Coated Titanium	Stock OMC (Tungsten Carbide)	TBC	TBC	2:04	0.78	6.198	10.86	1.030	196	232	1488	358	364	358	459	312	355	118	N/A	277	120	125	174	55.00
Air cooled, OMC style coated titanium rotor*, TBC sidewalls, TBC trochoid.																									
6	Coated Titanium	TBC	TBC	TBC	1:29	0.89	6.461	10.05	1.377	282	229	1406	386	400	379	476	340	359	120	276	281	122	134	183	61.67
						FUEL FLOW [lb/HP*hour]	CARBON MONOXIDE [%]	CARBON DIOXIDE [%]	OXYGEN [%]	HYDRO-CARBONS [ppm]	RCA OUT [*F]	EXAUST [*F]	DRIVE SIDE FLUX AREA[*F]	TROCHOID FLUX AREA[*F]	TROCHOID SPARK [*F]	EXAUST PORT [*F]	ACC. SIDE FLUX AREA[*F]	ACC. "HOT SPOT" [*F]	RCA IN [*F]	DRIVE END CRANK [*F]	ACC. END CRANK [*F]	ACC. FIN AIR IN [*F]	TROCHOID FIN AIR OUT [*F]	ACC. FIN AIR OUT [*F]	RCA AIR FLOW [FT^3/MIN]
	*Coated titanium rotor has alumina microspheres on face and Cr2O3 on sides																								
ALL TESTS RUN AT 4100 RPM AND 14.4 H.P.																									

FIGURE 1

Temperature Datapoint Locations **FIGURE 2**

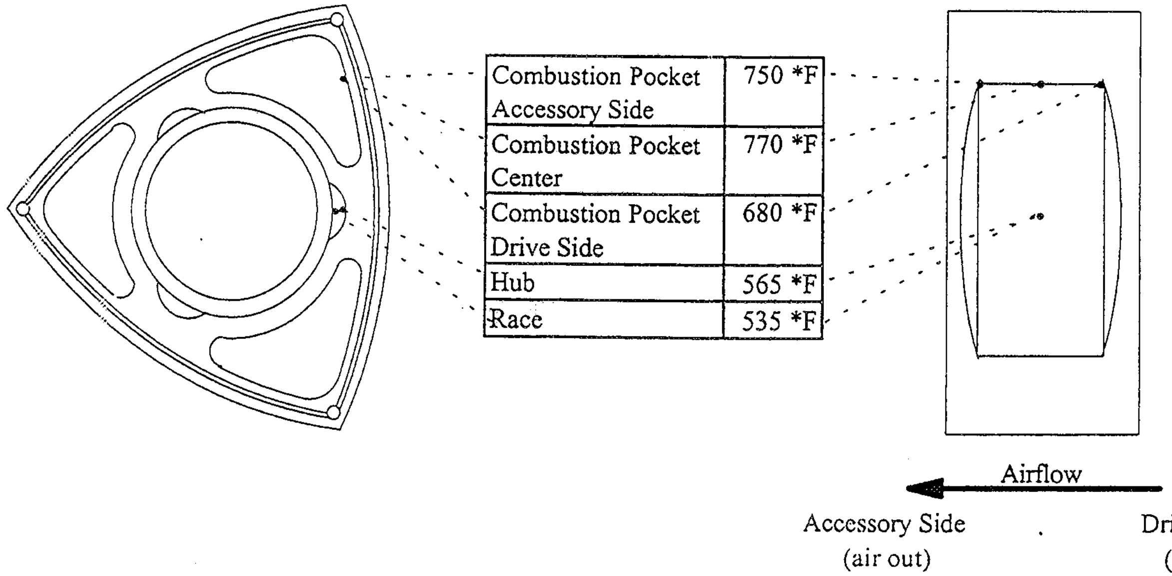


Slip Ring Assembly Rotor Steady State Temperatures FIGURE 3



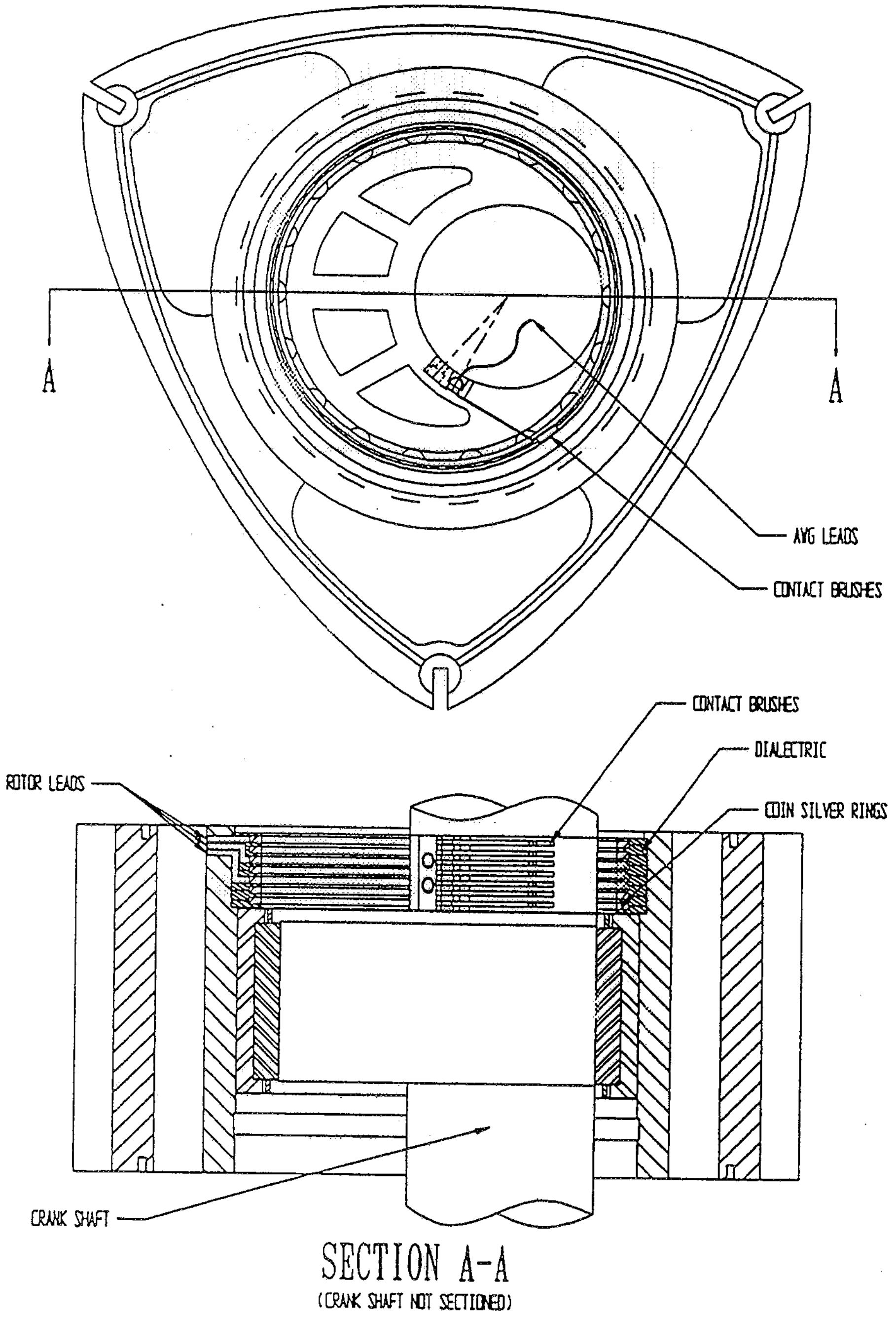
Typical graph of rotor temperatures.

Rotor Steady State Temperatures and Locations



Combustion Pocket Accessory Side	750 *F
Combustion Pocket Center	770 *F
Combustion Pocket Drive Side	680 *F
Hub	565 *F
Race	535 *F

Diagram of Slip Ring Assembly Prototype FIGURE 4



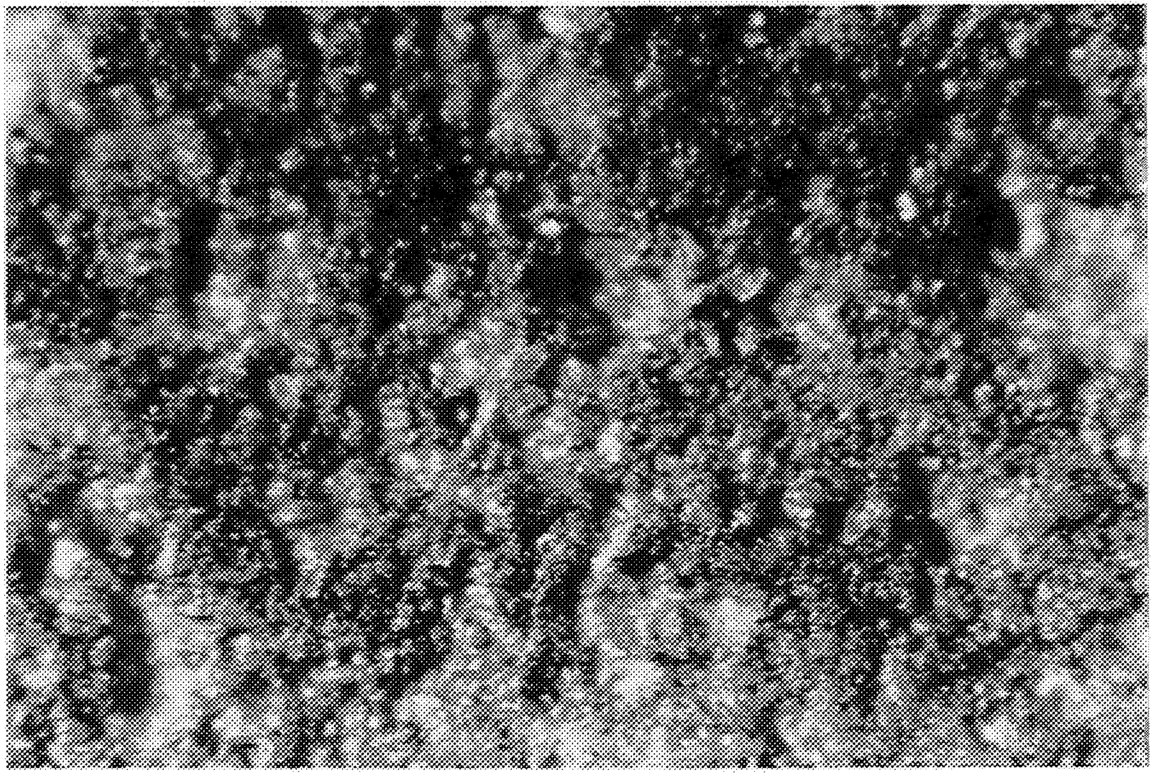
Failure Crack In PS-200 of T.B.C on Drive End Housing ~130X FIGURE 5

Accessory End Housing PS-200 Plasma Spray Before Grind ~ 220X FIGURE 6

(a)

Accessory End Housing PS-200 Plasma Spray After Grind ~ 220X FIGURE 6

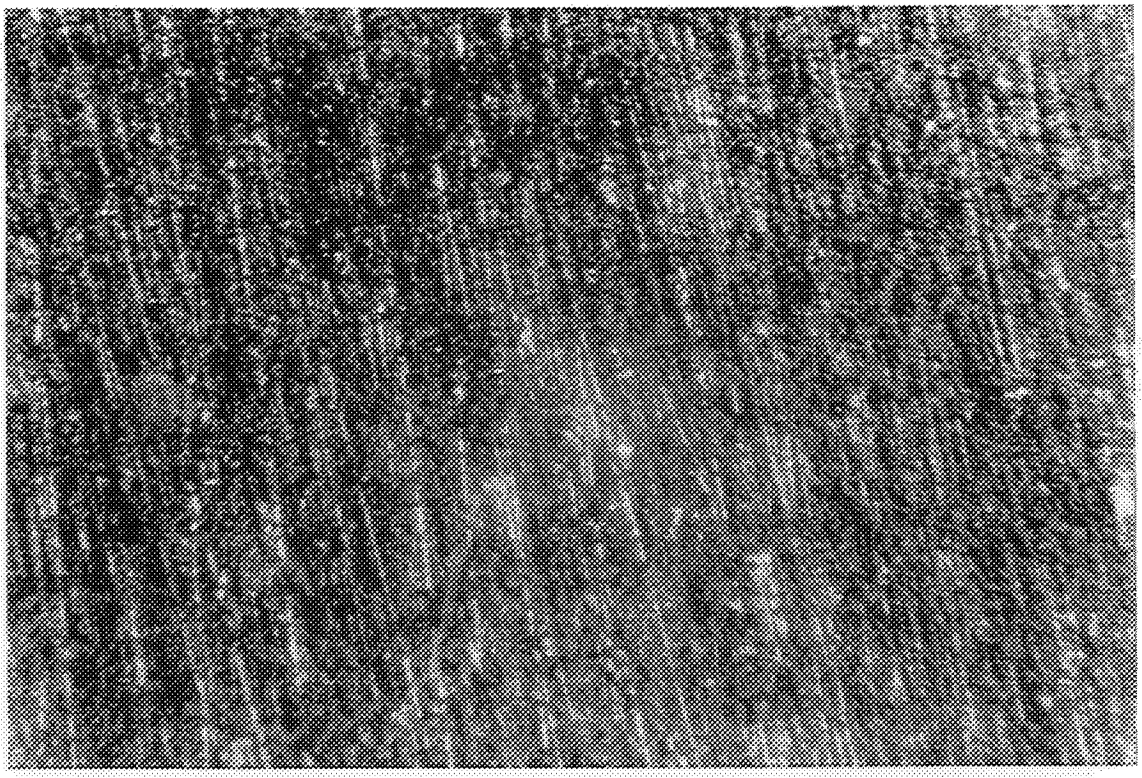
(b)



Drive End Housing PS-200 Plasma Spray After Final Grind and Finish Lap Prior to Run ~ 130X Surface root mean squared = 21 micro-inches.

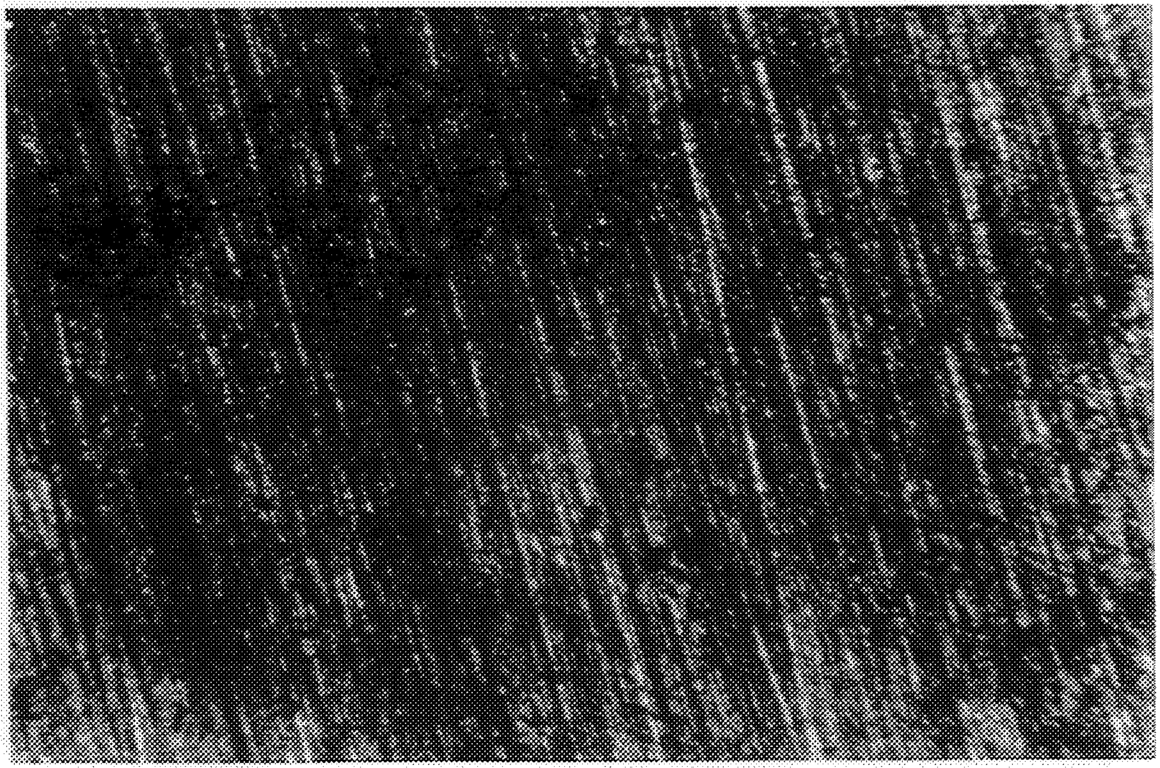
FIGURE 7

(a)



Accessory End Housing PS-200 Plasma Spray After Run ~ 130X
Surface root mean squared = 7 micro-inches

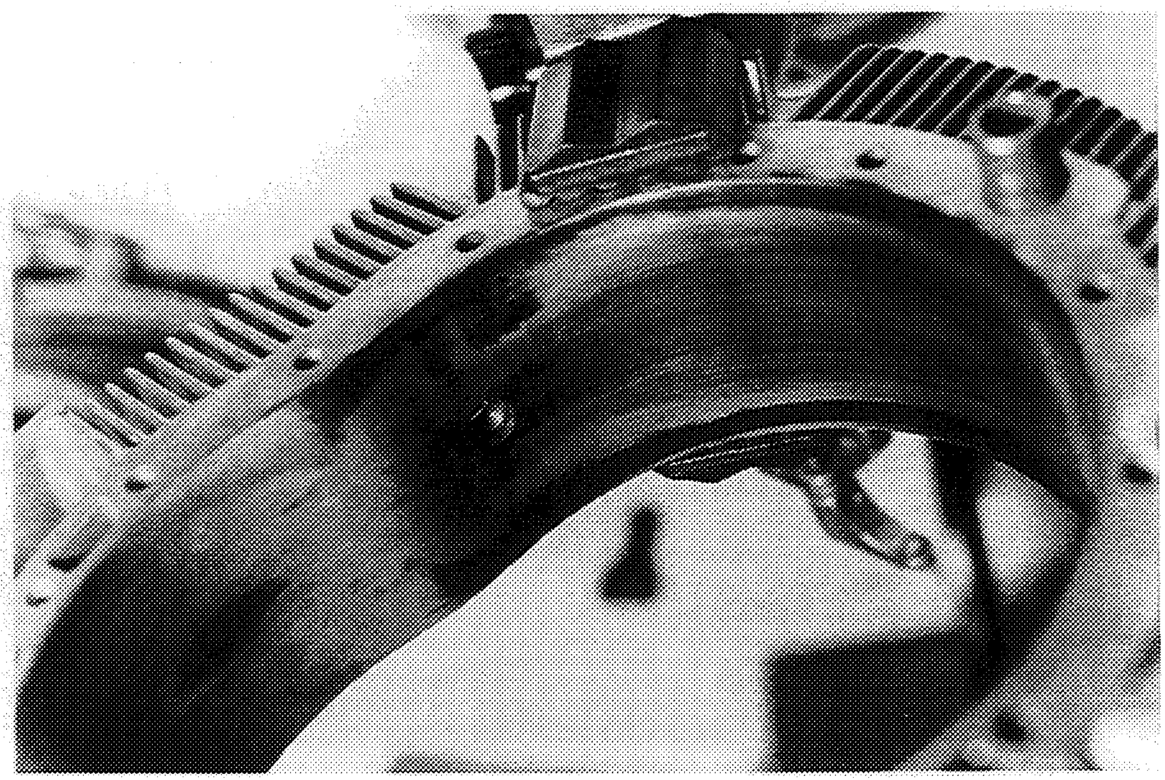
(b)



Spark Area of TBC Trochoid After Run

*Dark areas caused by high temperatures due to gas leakage.

(a)



Exhaust Area of TBC Trochoid After Run

*Dark areas caused by high temperatures due to gas leakage.

(b)

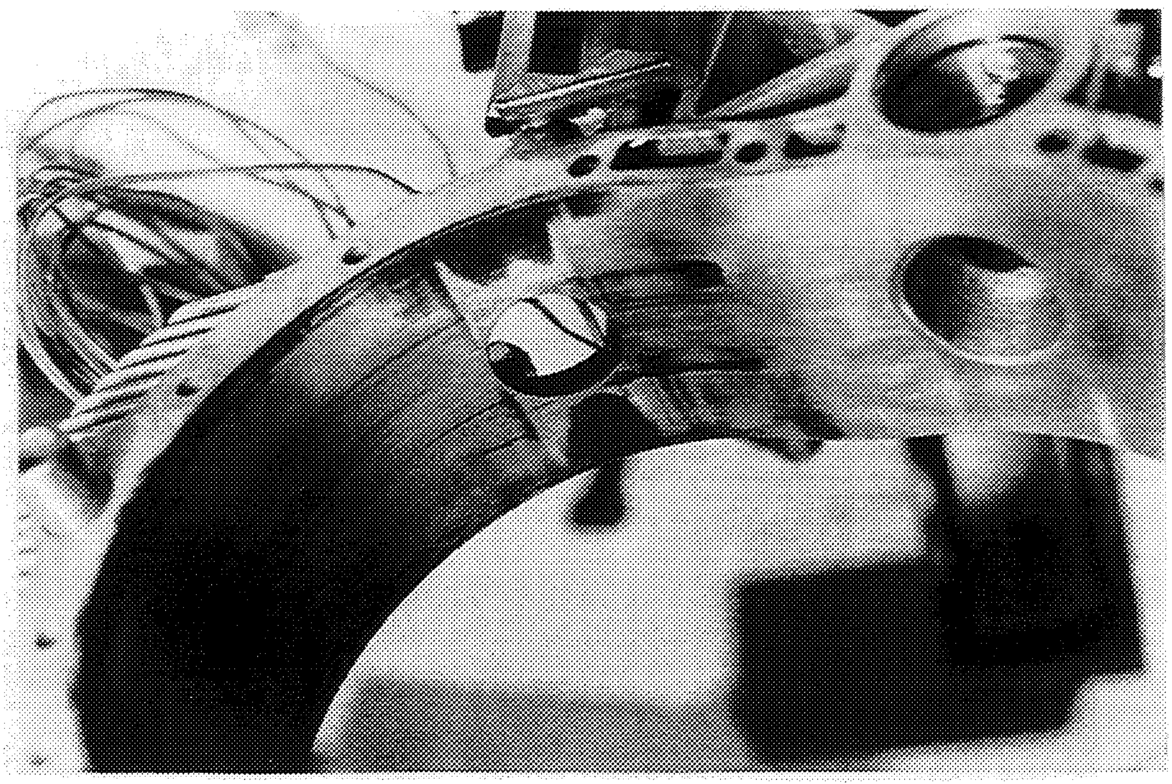
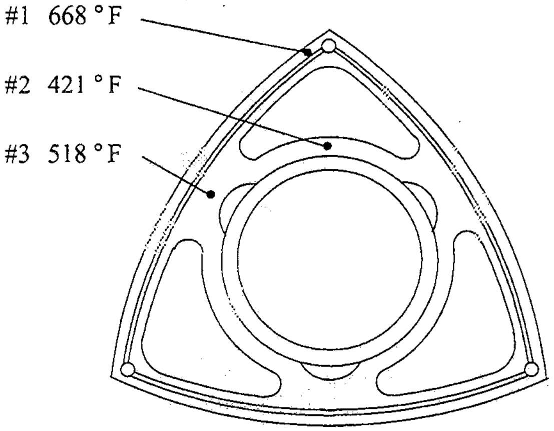


FIGURE 9

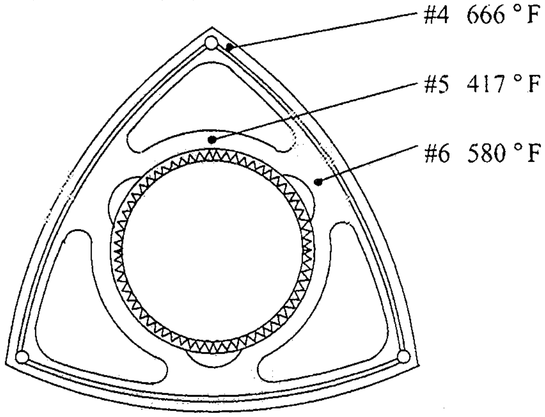
Rotor Temperature Distribution Schematic

Charge cooled baseline test.

TEST #	Rotor:	Rotor Housing:	Acc. end housing:	Drive end housing:	RUN TIME
1	Stock OMC (iron)	Stock OMC (Tungsten Carbide)	Stock OMC (Al)	Stock OMC (Al)	2:19



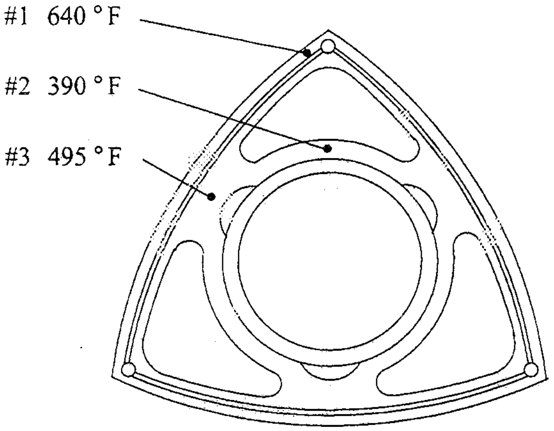
ACCESSORY SIDE (air out)



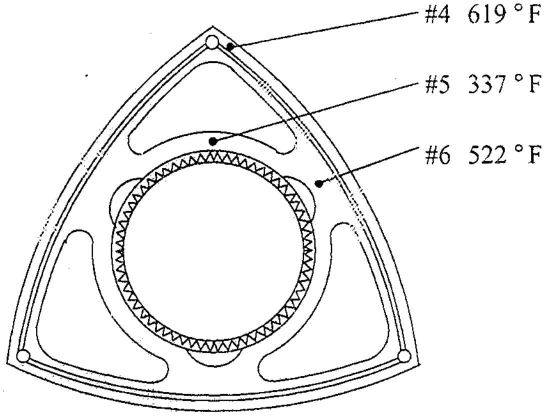
DRIVE SIDE (air in)

Air cooled baseline.

TEST #	Rotor:	Rotor Housing:	Acc. end housing:	Drive end housing:	RUN TIME
2	Stock OMC (iron)	Stock OMC (Tungsten Carbide)	Molybdnum coated	Molybdnum coated	2:03



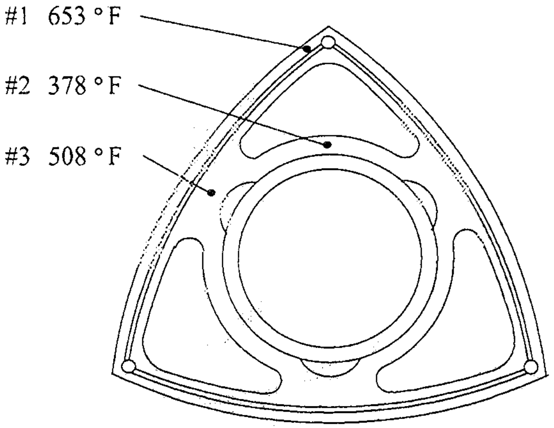
ACCESSORY SIDE (air out)



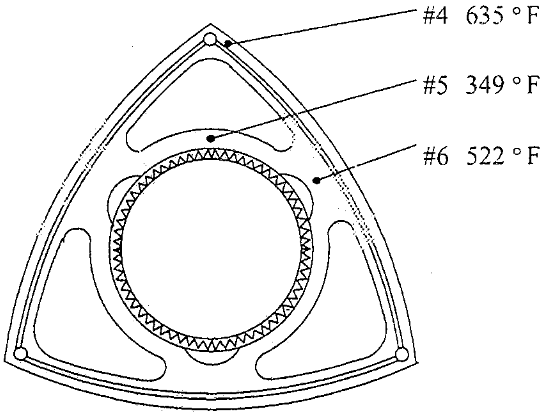
DRIVE SIDE (air in)

Air cooled, TBC sidewalls only.

TEST #	Rotor:	Rotor Housing:	Acc. end housing:	Drive end housing:	RUN TIME
3	Stock OMC (iron)	Stock OMC (Tungsten Carbide)	TBC	TBC	2:30



ACCESSORY SIDE (air out)



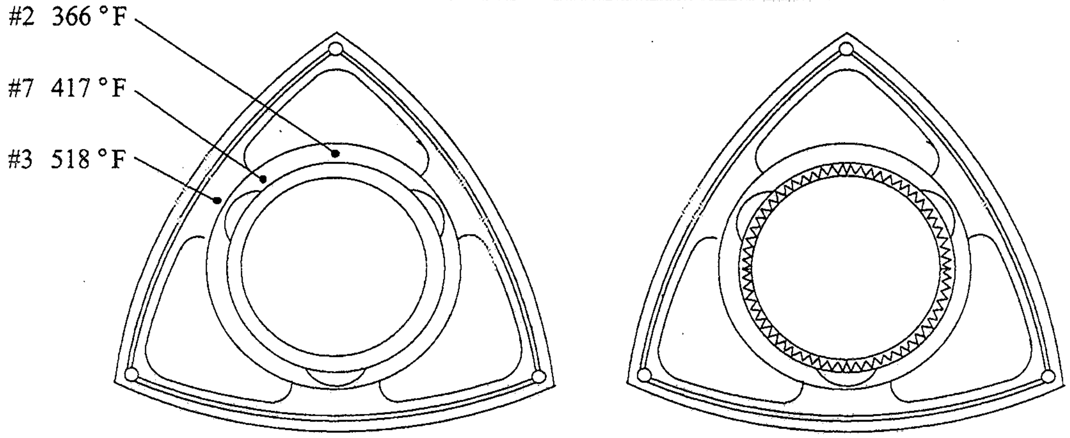
DRIVE SIDE (air in)

FIGURE 10

Rotor Temperature Distribution Schematic

Air cooled, OMC Style coated titanium rotor.

TEST #	Rotor:	Rotor Housing:	Acc. end housing:	Drive end housing:	RUN TIME
4	Coated Titanium	Stock OMC (Tungsten Carbide)	PS-200 coated	Stock OMC (Al)	2:09

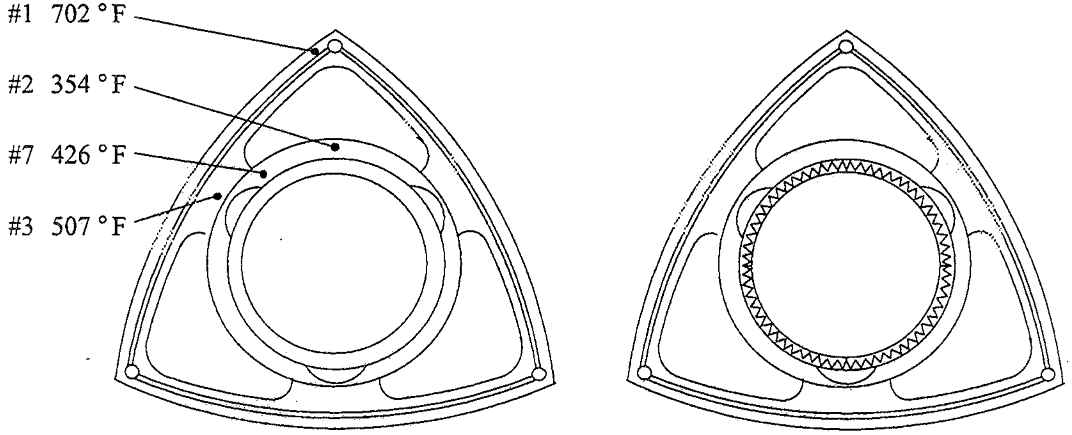


ACCESSORY SIDE (air out)

DRIVE SIDE (air in)

Air cooled, OMC style coated titanium rotor, TBC sidewalls.

TEST #	Rotor:	Rotor Housing:	Acc. end housing:	Drive end housing:	RUN TIME
5	Coated Titanium	Stock OMC (Tungsten Carbide)	TBC	TBC	2:04

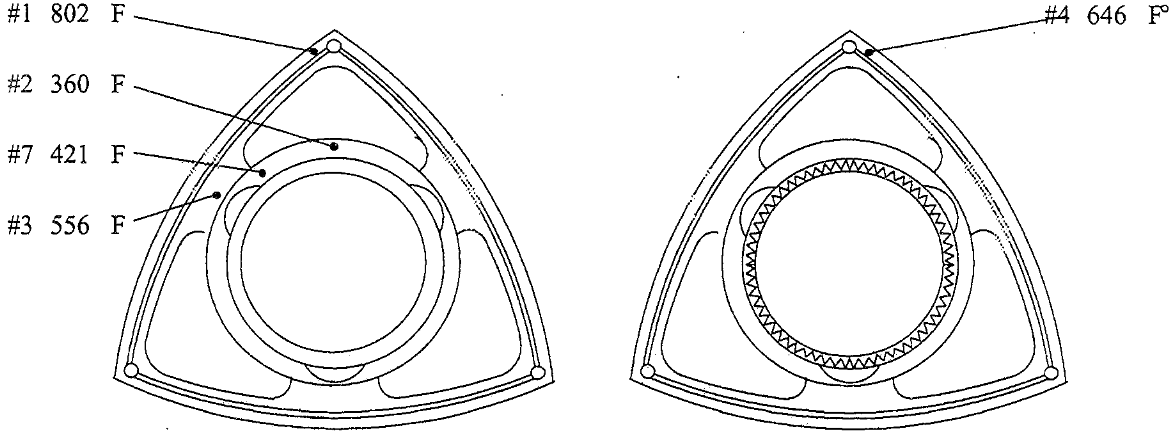


ACCESSORY SIDE (air out)

DRIVE SIDE (air in)

Air cooled, OMC style coated titanium rotor, TBC sidewalls and trochoid.

TEST #	Rotor:	Rotor Housing:	Acc. end housing:	Drive end housing:	RUN TIME
6	Coated Titanium	TBC	TBC	TBC	1:29



ACCESSORY SIDE (air out)

DRIVE SIDE (air in)

APPENDIX A

TEST RUN DATA

Test #1 Charge Cooled Baseline Test

APPENDIX A-1a

date:	3/3/93				**Engine:**					Charge cooled baseline test														
test stand:		waterbrake			**Rotor:**					Stock OMC (iron)														
end pitot:		0.86			**Rotor Housing:**					Stock OMC (Tungsten Carbide)														
ambient temp:		68 *F			**Accessory end housing:**					Stock OMC (Al)														
notes:	RPM more like .412				**Drive end housing:**					Stock OMC (Al)														
TIME	**RPM**	**LOAD**	**FUEL FLOW**	**FUEL FLOW**	**% CO**	**% CO2**	**% O2**	**HC**	**T-1**	**T-2**	**T-3**	**T-4**	**T-5**	**T-6**	**T-8**	**T-9**	**T-10**	**T-11**	**T-12**	**T-13**	**T-14**	**T-15**	**Δ P**	**RCA FLOW**
2:43	4000	0.70			7.17	9.82		236	198	1518	360	355	356	410	345	325		288	297	144	118	181	N/A	N/A
2:50	4100	0.71	46.5	0.83	6.34	10.39		148	230	1552	389	377	380	437	361	350		324	336	156	129	194		
2:58	4100	0.70			6.34	10.39		112	234	1550	395	382	387	444	366	357		327	325	151	122	189		
3:03	4110	0.70	49.9	0.77	6.23	10.38		106	235	1545	389	376	381	437	361	353		325	333	149	120	187		
3:13	**STOP throttle varying #after**								304	332	324	320	320	296	318	317		403	397	171	145	77		
3:30	4080	0.70			5.62	10.92		96	222	1551	400	389	393	437	369	358		316	327	151	124	190		
3:45	4100	0.70	45.5	0.84	5.64	10.94	0.59	92	230	1542	401	389	394	436	367	358		320	329	151	124	189		
3:53	4100	0.70			6.45	10.26	0.59	107	227	1538	397	385	390	434	366	358		325	333	151	122	189		
4:01	4100	0.71			6.56	10.14	0.59	115	226	1535	392	379	384	429	362	353		325	334	147	118	183		
	STOP- tape coming off crankshaft																							
	START day two				**date:**	3/8/93		**ambient:**		80,4		**end pitot:**			0.8									
10:14	4100	0.70			6.40	10.74	0.59	187	184	1524	362	359	360	388	342	323		284	288	140	115	176		
10:17					6.21	10.79	0.47	150	222	1540	391	382												
10:23		0.71	47.0	0.82	5.91	10.98	0.47	141	223	1539	392	381	384	415	339	348		482	421	144	118	183		
10:30	4120	0.71	48.0	0.80	5.65	11.05	0.47	115	225	1544	396	386	390	422	364	355		397	396	147	120	187		
10:40	4120	0.70			5.73	11.09	0.47	110	227	1546	399	387	391	424	365	357		388	376	147	120	185		
10:46	4100	0.70			5.90	10.9	0.47	98	224	1545	397	387	391	423	367	355		396	383	147	126	185		
10:52	4120	0.70	47.0	0.82	6.17	10.63	0.47	104	224	1540	396	385	390	421	365	354		403	396	145	118	185		
11:00	4120	0.70			5.95	10.81	0.47	102	228	1565	395	383	387	420	362	353		376	370	147	122	187		
11:10	4120	0.70			5.95	10.81	0.47	102	225	1567	395	383	387	418	362	353				145	120	185		
11:15	4140	0.70	48.0	0.80	5.95				223	1535	392	382	385	419	360	351				147	120	185		
	STOP end of test																							
Average Values:																		RCA flow not measured in this test.						
2:19	4086	0.70	47.30	0.81	6.29	10.41	0.59	111	225	1545	393	382	386	427	365	353	N/A	338	349	148	122	187	N/A	N/A
				FUEL FLOW [sec's/250ml]	CARBON MONOXIDE [%]	CARBON DIOXIDE [%]	OXYGEN [%]	HYDRO-CARBONS [ppm]	RCA OUT [*F]	EXAUST [*F]	DRIVE SIDE FLUX [*F	TROCHOID FLUX [*F]	TROCHOID SPARK [*F]	TROCHOID EXAUST [*F]	ACC. SIDE FLUX [*F]	ACC. "HOT SPOT" [*F]	RCA IN [*F]	DRIVE END CRANK [*F]	ACC. END CRANK [*F]	ACC. FIN AIR IN [*F]	TROCHOID FIN AIR OUT [*F]	ACC. FIN AIR OUT [*F]	RCA DRIVE PRESSURE [in. H2O	RCA AIR FLOW [FT^3/MIN]

▨ = Deviant not used in average.

☐ =Values Shown in the compilation of average values (Figure 1).

APPENDIX A-1b

Test #1: Charge Cooled Baseline

Rotor: Stock OMC (iron)
Rotor Housing: Stock OMC (tungsten carbide)
Accessory End Housing: Stock OMC (aluminum)
Drive End Housing: Stock OMC (aluminum)

Results After Test

- Engine very clean overall.
- No damage noticed except previously slightly damaged trochoid.
- Very little wear measured on all seals.
- Springs showed no signs of thermal fatigue.
- Very little carbon buildup under button seals or on back of apex seals.
- Photographs were taken to get visual record and qualitative set of results.
- Main and rotor bearings were very clean and well oiled.
- Thrust bearing was slightly dirty.
- Ground wire to the RTD was found to be broken in the crank at the connector.
  Probably the cause of the erratic ohm readings in the second day of testing
  First day readings are adequate for a baseline of data points.

Test #2 Air Cooled Baseline Test, Day One

Date:	4/5/93				Engine:						Air cooled baseline														
Test Stand:		waterbrake			Rotor:						Stock OMC (iron)														
End pitot:		0.89			Rotor Housing:						Stock OMC (Tungsten Carbide)														
AmbientTemp		62 *F			Accessory end housing:						Molybdenum coated														
					Drive end housing:						Molybdenum coated														
																								55.00	
TIME	RPM	LOAD	FUEL FLOW	FUEL FLOW	% CO	% CO2	% O2	HC	T-1	T-2	T-3	T-4	T-5	T-6	T-8	T-9	T-10	T-11	T-12	T-13	T-14	T-15	Δ P	RCA FLOW	oil volts
11:30	3900	0.5			8	-Engine break in T-1 not over 230								Leakdown		50	54	54	-good						
13:50	START																								
13:53	4100	0.7			9.1	8.57		568																	
13:58	4150	0.7	41	0.94	6.9	10	1.2	371	258	1471	388	379	379	429	359	392	109	270	279	117	122	187	1.16	63.80	16
14:04	4100	0.7			5.9	10.62	1.2	264	255	1485	392	383	383	435	362	393	108	270	279	117	124	189	1.24	68.20	16
14:08	4100	0.7	41	0.94	5.9	10.54	1.1	263	252	1486	393	384	383	434	363	394	109	270	279	120	126	190	1.20	66.00	16
14:15	4100	0.7			6	10.52	1.1	255	257	1492	397	386	386	437	366	398	112	273	284	120	126	190	1.20	66.00	16
14:20	4100	0.7			5.9	10.46	1.1	244	257	1495	396	387	387	488	365	397	112	273	282	122	127	190	1.22	67.10	16
14:25	4100	0.7	41	0.94	5.9	10.47	1.1	238	256	1492	396	387	387	436	365	396	113	271	282	124	127	192	1.23	67.65	16
14:32	4110	0.7			5.8	10.52	1.1	225	256	1506	403	395	392	443	373	400	113	273	282	131	133	196	1.23	67.65	16
14:40	4100	0.7			6.1	10.36	1.1	235	256	1502	398	390	387	438	369	396	113	273	282	129	133	194	1.22	67.10	16
14:46	4100	0.71			6	10.48	0.9	226	253	1498	399	391	390	437	370	394	113	286	291	127	131	192	1.27	69.85	17
14:53	-STOP bearing warming up 1600 at end but not overheating.																								
	TEST CONTINUED NEXT PAGE																								

Test #2 Air Cooled Baseline Test, Day Two

CONTINUED TEST NEXT DAY			
Date:	4/6/93	**Engine:**	Air cooled basclinc
Test Stand:	waterbrake	**Rotor:**	Stock OMC (iron)
End pitot:	0.87	**Rotor Housing:**	Stock OMC (Tungsten Carbide)
AmbientTemp	81 *F	**Accessory end housing:**	Molybdcnum coated
Notes:	Max T-11 is 1720 (375 *F)	**Drive end housing:**	Molybdcnum coated

TIME	RPM	LOAD	FUEL FLOW	FUEL FLOW	% CO	% CO2	% O2	HC	T-1	T-2	T-3	T-4	T-5	T-6	T-8	T-9	T-10	T-11	T-12	T-13	T-14	T-15	Δ P	RCA FLOW	oil volts
	-START next day																								
15:42	4100	0.7			6.7	10.15	0.9	408	251	1488	383	376	373	419	354	380	111	288	300	122	126	187	0.98	53.90	16
15:48	4100	0.7			6.5	10.24	0.9	280	254	1499	388	379	379	426	357	383	111	324	324	122	127	189	1.15	63.25	16
15:53	4100	0.7			6.5	10.29	note cleaned slip rings witout stopping																		
15:53	4100	0.7			6.5	10.44	0.9	244	252	1506	390	381	378	429	359	386	112	273	288	120	124	189	1.19	65.45	16
15:58	4100	0.7	42	0.91	6.2	10.44	0.9	237	256	1509	392	382	380	430	361	389	112	270	279	127	129	190	1.14	62.70	16
16:05	4100	0.7			5.8	10.69	0.9	207	253	1518	392	384	381	434	362	389	113	268	277	124	127	190	1.22	67.10	16
16:12	4100	0.7			5.9	10.69	0.9	204	253	1520	393	383	381	432	361	387	112	268	277	122	126	189	1.21	66.55	16
16:20	4100	0.7	42	0.91	5.9	10.72	0.9	181	256	1520	395	386	383	434	365	391	114	271	282	122	127	190	1.18	64.90	16
16:25	4100	0.7			6	10.52	0.9	195	256	1516	398	388	385	436	367	392	114	271	282	127	127	192	1.17	64.35	16
16:30	4100	0.7			6.1	10.56	0.9	203	255	1516	398	389	386	437	367	392	114	270	279	122	122	190	1.22	67.10	16
16:40	4100	0.7	42	0.91	6	10.67	0.9	192	252	1519	398	389	386	437	367	391	113	268	277	129	129	192	1.21	66.55	16
16:45	4100	0.7			6.1	10.58	0.9	202	251	1514	396	387	384	433	364	388	114	266	277	122	122	190	1.22	67.10	16
	STOP end of test				**NOTE:**		**A slight breeze came up at end of testing**								**Probably accounted for cooling down right at end.**										
Average Values:																									
2:03	4102.9	0.7	41.5	0.93	6.1	10.47	1.00	244	254	1503	394	385	384	436	364	391	112	275	284	123	127	190	1.19	65.66	16
				FUEL FLOW [sec's/250ml]	CARBON MONOXIDE [%]	CARBON DIOXIDE [%]	OXYGEN [%]	HYDRO-CARBONS [ppm]	RCA OUT [*F]	EXAUST [*F]	DRIVE SIDE FLUX [*F	TROCHOID FLUX [*F]	TROCHOID SPARK [*F]	TROCHOID EXAUST [*F]	ACC. SIDE FLUX [*F]	ACC. "HOT SPOT" [*F]	RCA IN [*F]	DRIVE END CRANK [*F]	ACC. END CRANK [*F]	ACC. FIN AIR IN [*F]	TROCHOID FIN AIR OUT [*F]	ACC. FIN AIR OUT [*F]	RCA DRIVE PRESSURE [in. H20]	RCA AIR FLOW [FT^3/MIN]	

▨ = Deviant not used in average.

☐ =Values Shown in the compilation of average values (Figure 1).

Test #2: Air Cooled Baseline

Rotor: Stock OMC (iron)
Rotor Housing: Stock OMC (tungsten carbide)
Accessory End Housing: Molybdenum coated
Drive End Housing: Molybdenum coated

Results After Test

- Engine ran and performed well.
- Was easy to tune to 6% CO and 4100 RPM.
- Slip ring assembly continued to get dirty causing resistance values to increase. Cured this problem by cleaning the slip ring with a towel & acetone during the tests, especially prior to taking readings.
- Small amounts of sludge found in rotor cooling air T.P. passage Most likely due to H.P. grease used in assembly.
- Engine very clean but the rotor had more buildup than the previous test. Either due to the Silkolene oil or the different cooling method.
- Moly side housings looked excellent, very little deposits left. Not going to clean them before next test.

Test #3 Air Cooled TBC Sidewalls Only

APPENDIX A-3a

Date:	6/24/93				Engine:						Air cooled														
Test Stand:		waterbrake			Rotor:						Stock OMC (iron)														
End Pitot:		0.89			Rotor Housing:						Stock OMC (Tungsten Carbide)														
Ambient Temp		80 *F			Accessory end housing:						T.B.C. (PS-200 over zirconia)														
					Drive end housing:						T.B.C. (PS-200 over zirconia)														
TIME	**RPM**	**LOAD**	**FUEL FLOW**	**FUEL FLOW**	**% CO**	**% CO2**	**% O2**	**HC**	**T-1**	**T-2**	**T-3**	**T-4**	**T-5**	**T-6**	**T-8**	**T-9**	**T-10**	**T-11**	**T-12**	**T-13**	**T-14**	**T-15**	**Δ P**	**RCA FLOW**	**oil volts**
8:55	4100	0.7			6.63	10.47	1.08	542	251	1433	347	371	366	415	320	360	113	250	259	120	126	172	1.36	74.80	16
9:01	4100	0.7			6.11	10.6	1.08	353	259	1440	362	382	378	434	331	372	113	257	266	124	138	178	1.41	77.55	16
9:06	4100	0.7	46	0.84	5.88	10.69	1.08	293	261	1449	366	384	381	435	333	375	112	259	270	127	133	181	1.43	78.65	16
9:15	4100	0.7	46	0.84	5.9	10.6	1.2	264	263	1447	363	380	379	433	330	373	114	262	271	124	129	178	1.33	73.15	16
9:21	4100	0.7			6.01	10.66	1.08	242	264	1453	362	378	375	435	330	373	115	264	273	124	129	178	1.33	73.15	16
9:30	**STOP**	**0.46**			**check load cell**				**Load cell OK**																
10:01	**START**																								
10:02	4100	0.7			5.93	10.87	1.08	446	260	1457	352	375	371	422	329	361	118	259	266	120	129	172	1.28	70.40	16
10:08	4100	0.7			5.82	10.85	1.08	272	260	1462	366	375	384	435	329	371	116	264	277	124	131	178	1.30	71.50	16
10:18	4100	0.7	45	0.85	5.93	10.62	1.2	245	260	1451	363	382	381	434	329	370	117	266	275	124	135	178	1.32	72.60	16
10:28	4100	0.7	44	0.87	6.07	10.6	1.2	240	261	1452	365	383	382	436	330	371	118	268	277	124	133	178	1.28	70.40	16
10:46	4100	0.7	45	0.85	6.04	10.58	1.08	240	262	1457	365	383	383	438	331	373	119	268	277	127	133	180	1.27	69.85	16
10:55	4100	0.7			6.08	10.54	1.08	238	263	1456	366	385	382	439	334	374	121	270	277	127	135	172	1.28	70.40	16
11:10	4100	0.7	44	0.87	6.02	10.65	1.08	240	260	1456	365	382	379	438	330	372	120	266	275	131	135	180	1.28	70.40	16
11:25	4100	0.7	45	0.85	6.1	10.62	1.08	237	260	1558	364	382	382	438	330	371	120	266	275	127	135	180	1.25	68.75	16
	-STOP END OF TEST					**leak down**		**58**	**58**	**58**															
Average Values:																									
2:30	4100	0.7	45	0.85	6.04	10.64	1.11	296	260	1459	362	380	379	433	330	370	117	263.0	272.1	124.9	132.2	177.2	1.32	72.43	16
				FUEL FLOW [sec's/250ml]	CARBON MONOXIDE [%]	CARBON DIOXIDE [%]	OXYGEN [%]	HYDRO-CARBONS [ppm]	RCA OUT [*F]	EXAUST [*F]	DRIVE SIDE FLUX [*F	TROCHOID FLUX [*F]	TROCHOID SPARK [*F]	TROCHOID EXAUST [*F]	ACC. SIDE FLUX [*F]	ACC. "HOT SPOT" [*F]	RCA IN [*F]	DRIVE END CRANK [*F]	ACC. END CRANK [*F]	ACC. FIN AIR IN [*F]	TROCHOID FIN AIR OUT [*F]	ACC. FIN AIR OUT [*F]	RCA DRIVE PRESSURE [in. H2O]	RCA AIR FLOW [FT^3/MIN]	

▨ = Deviant not used in average.

=Values Shown in the compilation of average values (Figure 1).

Test #3: Air Cooled, TBC Sidewalls only

Rotor: Stock OMC (iron)
Rotor Housing: Stock OMC (tungsten carbide)
Accessory End Housing: TBC
Drive End Housing: TBC

Results After Test

- Lower temps on the sidewall thermocouples. In some cases 30 °F difference.
- Engine ran and performed well.
- Trochoid temps only slightly cooler.
- Trochoid temps at exhaust areas almost identical.
- All seals showed very little wear.
- Small crack in drive end housing thermal barrier.
- Appeared to be some defect in spray application since a small piece chipped out near the dowel pin which was in the general vicinity.
- PS 200 seems to be a durable coating but putting it over zirconia may be a problem.

Test #4 Air Cooled, OMC style Coated Titanium Rotor

Date:	9/10/93				**Engine:**						Air Cooled														
Test Stand:	waterbrake				**Rotor:**						OMC style titanium with alumina microspheres on face and Cr2O3 on sides.														
End Pitot:		0.71			**Rotor Housing:**						Stock OMC (Tungsten Carbide)														
Ambient Temp		80 *F			**Accessory end housing:**						PS-200														
					Drive end housing:						Stock OMC (Al)														
TIME	**RPM**	**LOAD**	**FUEL FLOW**	**FUEL FLOW**	**% CO**	**% CO2**	**% O2**	**HC**	**T-1**	**T-2**	**T-3**	**T-4**	**T-5**	**T-6**	**T-8**	**T-9**	**T-10**	**T-11**	**T-12**	**T-13**	**T-14**	**T-15**	**Δ P**	**RCA FLOW**	**oil volts**
8:03	4100	0.7			6.33	10.63	1.29	696	256	[illegible]		389	375	423	358	386	115	270	275	118	129	185	[illegible]	[illegible]	16
8:12	4100	0.7	41	0.94	6.13	10.75	1.29	4.9	257	1441		396	383	435	365	395	113	270	277	122	129	190	1.22	67.10	16
8:21	4100	0.7			6.00	10.76	1.29	314	256	1440		399	387	438	367	396	115	270	277	120	131	192	1.15	63.25	16
8:28	4100	0.7	43	0.89	6.31	10.61	1.29	312	254	1436		395	386	436	363	392	116	270	275	120	129	190	1.16	63.80	16
8:40	4100	0.7	43	0.89	6.19	10.70	1.29	274	253	1446		392	380	433	358	388	116	268	273	117	129	189	1.13	62.15	16
8:50	4100	0.7			6.30	10.64	1.29	256	256	1452		393	381	433	358	390	118	271	277	122	129	189	1.11	61.05	16
9:00	4100	0.7	43	0.89	5.97	10.72	1.16	247	255	1451		394	382	436	359	389	118	271	277	122	129	189	1.11	61.05	16
9:10	4100	0.7			6.08	10.56	1.29	259	254	1445		393	381	436	358	389	118	271	275	124	133	190	1.13	62.15	16
9:20	4100	0.7			6.05	10.59	1.16	249	252	1447		389	377	434	354	386	118	270	273	120	129	189	1.13	62.15	16
9:25	**STOP out of gas**																								
9:28	**START**																								
9:30	4100	0.7	44	0.87	5.82	10.40	1.29	273	256	1452		394	381	437	359	390	119	273	277	118	129	189	1.09	59.95	16
9:40	4100	0.7			5.85	10.41	1.16	249	254	1449		391	378	434	355	387	119	271	277	122	129	189	1.12	61.60	16
9:50	4100	0.7	44	0.87	6.15	10.19	1.16	246	253	1449		389	376	433	355	386	120	270	275	118	129	187	1.12	61.60	
10:00	4100	0.7			6.3	10.5	1.16	253	253	1451		391	377	433	357	386	120	270	275	122	131	189	1.12	61.60	
10:10	4100	0.7	43	0.89	6.2	10.63	1.16	234	253	1454		389	375	431	354	384	119	271	277	120	129	187	1.11	61.05	
10:12	**-STOP END OF TEST**					Leakdown		43	44	43															
Average Values:											#3 not used														
2:09	4100	0.7	43	0.89	6.1	10.57	1.23	244	254	1447	N/A	393	380	435	359	389	118	270	276	121	130	189	1.13	61.88	16
				FUEL FLOW [sec's/250ml]	CARBON MONOXIDE [%]	CARBON DIOXIDE [%]	OXYGEN [%]	HYDRO-CARBONS [ppm]	RCA OUT [*F]	EXAUST [*F]	DRIVE SIDE FLUX [*F	TROCHOID FLUX [*F]	TROCHOID SPARK [*F]	TROCHOID EXAUST [*F]	ACC. SIDE FLUX [*F]	ACC. "HOT SPOT" [*F]	RCA IN [*F]	DRIVE END CRANK [*F]	ACC. END CRANK [*F]	ACC. FIN AIR IN [*F]	TROCHOID FIN AIR OUT [*F]	ACC. FIN AIR OUT [*F]	RCA DRIVE PRESSURE [in. H2O]	RCA AIR FLOW [FT^3/MIN]	

▨ = Deviant not used in average.

☐ =Values Shown in the compilation of average values (Figure 1).

APPENDIX A-4b

Test #4B: First Preparation Test for Test #4 Air Cooled OMC style coated titanium rotor.

Rotor: titanium
Rotor Housing: Stock OMC (tungsten carbide)
Accessory End Housing: PS-200
Drive End Housing: SX-331

Results After Test

- Upon boroscopic examination after break in some small scratches were noticed on the drive side (SX-331)
- The decision was made to tear down and investigate.
- Small piece of SX-331 seemed to have come out and welded itself to the titanium causing a groove in the end housing
- After bearing measurements were taken it was found that the ID was on the tighter end of the spectrum.

  We decided to grind .001" off the OD and re-press into the rotor.
- Re-lapped the SX-331 and the PS-200
- Dynamically re balanced the entire engine assembly (rotor, flywheel and counterweight)

APPENDIX A-4c

Test #4B: Second Preparation Test for Test #4 Air Cooled OMC style coated titanium rotor.

Rotor: titanium
Rotor Housing: Stock OMC (tungsten carbide)
Accessory End Housing: PS-200
Drive End Housing: SX-331

Results After Test

- After brief break in boroscopic examination was inconclusive
  Entire 2 hour test was run.
- Severe scratching on the SX-331 side
- Severe side seal wear on both sides, especially the accessory side (PS-200)
- PS-200 looked able to withstand this destructive environment
- Small Piece of SX-331 seemed to have welded to titanium.
- Appeared that severe SX-331 scratching pushed the rotor over to the PS-200 side (which stayed flat) and ,with SX-331 grit, caused severe wear (in some cases .030")
- Rotor itself showed signs of wear (.002 at hub and up to .006 at apex).
- Impressive that PS-200 withstood this punishment.
- Temp plugs are the same as last test because 2 hour test was not done last time.

APPENDIX A-4d

Test #4: Air Cooled, OMC style coated titanium rotor.

Rotor: titanium coated with Alumina micro spheres on face and Cr_2O_3 on sides
Rotor Housing: Stock OMC (tungsten carbide)
Accessory End Housing: PS-200
Drive End Housing: Stock OMC (aluminum)

Results After Test

- Titanium rotor flank coated with AlO or Alumina micro spheres.
- New seals and new elgiloy springs were used.
- In the coating process the rotor was heated to 950 *F which distorted the center hub.
- To fix this we had to have the bearing race built up with hard chrome and reground to a .002 press.
- The sides (wear surfaces) of the titanium rotor have been coated with Cr_2O_3 a very hard wear surface.
- We have found out verbally from other sources that titanium galls with almost anything it comes in contact with including PS-200.
- We will be using the PS-200 again. it looked OK under the microscope from previous tests. but two sections that had started peeling up were ground back.
- New stock gear side end housing will be used as the SX-331 side housing was ruined in our last test.
- High leak down readings at the end of the 2 hour test was encouraging as was the initial disassembly inspection
- Sidewalls not damaged in anyway.
- Stock hi-sil side housing showed signs of high polishing where the rotor had made contact.
- PS-200 sidewall also looked good

  maybe slightly more polished than when assembled.
- Side and apex seals showed very little signs of wear.
- Seals showed less wear on the PS-200 side
- Engine started easily even after stopping to refuel
- Carbon only built up on the iron parts of the rotor

  Titanium surface must have been too hot for buildup.

Test #5 Air Cooled, OMC style Coated Titanium Rotor, TBC Sidewalls

Date:	9/17/93				**Engine:**						Air cooled with TBC sidewall														
Test Stand:		waterbrake			**Rotor:**						OMC style titanium with alumina microspheres on face and Cr2O3 on sides.														
End Pitot:		0.74			**Rotor Housing:**						Stock OMC (Tungsten Carbide)														
Ambient Temp		80 *F			**Accessory end housing:**						TBC (PS-200 over SX-331)														
					Drive end housing:						TBC (PS-200 over SX-331)														
TIME	**RPM**	**LOAD**	**FUEL FLOW**	**FUEL FLOW**	**% CO**	**% CO2**	**% O2**	**HC**	**T-1**	**T-2**	**T-3**	**T-4**	**T-5**	**T-6**	**T-8**	**T-9**	**T-10**	**T-11**	**T-12**	**T-13**	**T-14**	**T-15**	**Δ P**	**RCA FLOW**	**oil volts**
9:27		**WARM UP**																							
9:32	4100	0.7			3.43	9.52	1.16	481	237	1426	351	356	349	439	305	349	114		280	118	[illegible]	169	0.93	[illegible]	
9:43	4100	0.7	48	0.80	7.50	10.00	1.03	304	232	1450	354	358	353	448	307	328	113		277	118	122	172	1.03	56.65	16
9:52	4100	0.7			6.47	10.71	1.03	227	233	1477	358	362	359	456	310	358	115		279	118	122	172	1.03	56.65	16
10:00	4100	0.7	49	0.78	6.21	10.85	1.03	201	231	1484	359	363	357	459	311	359	116		277	120	124	172	0.98	53.90	16
10:10	4100	0.7			6.08	10.97	1.03	185	232	1491	359	364	359	459	312	359	117		279	120	124	174	0.99	54.45	16
10:20	4100	0.7	49	0.78	6.08	10.93	1.03	179	232	1491	359	364	357	459	312	341	118		279	120	124	172	0.99	54.45	16
10:30	4100	0.7			6.12	10.99	1.03	188	233	1490	359	365	357	460	312	359	118		279	120	124	174	0.99	54.45	16
10:40	4100	0.7	50	0.77	5.98	10.99	1.03	186	233	1490	361	367	360	462	313	361	118		279	120	126	174	0.99	54.45	16
10:50	4100	0.7			6.10	10.94	1.03	179	232	1498	355	364	356	459	312	358	119		275	120	126	174	1.00	55.00	16
11:00	4100	0.7	50	0.77	5.89	11.02	1.03	176	233	1497	358	365	358	461	313	359	120		277	120	126	174	1.00	55.00	16
11:10	4100	0.7			5.95	10.97	1.03	175	232	1496	359	366	359	460	313	360	120		277	122	126	174	1.00	55.00	16
11:20	4100	0.7	50	0.77	5.95	10.96	1.03	174	233	1499	358	367	360	461	313	361	121		277	122	127	176	1.00	55.00	16
11:30	4100	0.7	50	0.77	6.05	10.98	1.03	177	233	1498	358	366	359	461	314	361	122		277	122	129	176	1.00	55.00	16
11:31	**-STOP END OF TEST**				**Leakdown**			**45**	**48**	**46**															
Average Values:																		RTD wire broke inside of engine							
2:04	4100	0.7	49.43	0.78	6.2	10.86	1.03	196	232	1488	358	364	358	459	312	355	118	N/A	277	120	125	174	1.00	55.00	16
				FUEL FLOW [sec's/250ml]	CARBON MONOXIDE [%]	CARBON DIOXIDE [%]	OXYGEN [%]	HYDRO-CARBONS [ppm]	RCA OUT [*F]	EXAUST [*F]	DRIVE SIDE FLUX [*F	TROCHOID FLUX [*F]	TROCHOID SPARK [*F]	TROCHOID EXAUST [*F]	ACC. SIDE FLUX [*F]	ACC. "HOT SPOT" [*F]	RCA IN [*F]	DRIVE END CRANK [*F]	ACC. END CRANK [*F]	ACC. FIN AIR IN [*F]	TROCHOID FIN AIR OUT [*F]	ACC. FIN AIR OUT [*F]	RCA DRIVE PRESSURE [in. H20]	RCA AIR FLOW [FT^3/MIN]	
▨ = Deviant not used in average.						☐ =Values Shown in the compilation of average values (Figure 1).																			

Test #5: Air Cooled OMC style coated titanium rotor, TBC sidewalls.

Rotor: titanium coated with Alumina micro spheres on face and Cr_2O_3 on sides
Rotor Housing: Stock OMC (tungsten carbide)
Accessory End Housing: TBC
Drive End Housing: TBC

Results After Test

- Engine ran and performed well everything held together
- Lost one of the crankshaft thermocouples in the beginning of the test. Continued because the other one was functioning well.
- Able to hold crankshaft journal temps to the same as previous numbers which took even less air to do.
- T.P. temp (rotor air out) was also quite a bit lower even at reduced flow rate.
- Looks like the rotor insulation is working well.
- It would be useful to compare the coated rotor to the uncoated titanium rotor under identical conditions.
- No wear on the side seals and buttons on the PS-200 side.
- The small cracking region in the drive end housing TBC coating did not seem to propagate. (Came from previous severe tests prior to beginning this program).
- We will continue to use these TBC components.

APPENDIX A-6a

Test #6 Air Cooled, OMC style Coated Titanium Rotor, TBC Sidewalls, TBC Trochoid

Date:	9/28/93				**Engine:**					Complete TBC engine with coated titanium rotor															
Test Stand:		waterbrake			**Rotor:**					OMC style titanium with alumina microspheres on face and Cr2O3 on sides.															
End Pitot:		0.74			**Rotor Housing:**					TBC (PS-200 over SX-331)															
Ambient Temp:		93 *F			**Accessory end housing:**					TBC (PS-200 over SX-331)															
					Drive end housing:					TBC (PS-200 over SX-331)															
TIME	**RPM**	**LOAD**	**FUEL FLOW**	**FUEL FLOW**	**% CO**	**% CO2**	**% O2**	**HC**	**T-1**	**T-2**	**T-3**	**T-4**	**T-5**	**T-6**	**T-8**	**T-9**	**T-10**	**T-11**	**T-12**	**T-13**	**T-14**	**T-15**	**Δ P**	**RCA FLOW**	**oil volts**
11:25	4100	0.7			4.72	10.96	1.7	305	232	1414	400	420	391	511	349	372	117	280	284	126	134.6	189	0.12	6.33	16
11:30	**STOP**																								
11:34	**START**				7.20																				
11:36	4100	0.7			7.14	9.72	1.4	343	237	1392	392	392	371	480	334	345	120	282	286	120	131	180	1.01	55.55	16
11:39	4100	0.7	43	0.89	6.82	9.86	1.4	307	227	1397	384	398	375	487	338	360	117	275	282	118	131	181	1.20	66.00	16
11:48	4100	0.7			6.61	9.95	1.4	311	232	1390	387	402	378	466	340	360	117	279	284	118	131	181	1.14	62.70	16
11:55	4100	0.7	42	0.91	6.48	10.00	1.4	290	227	1394	388	403	396	465	342	361	118	273	280	120	131	183	1.00	55.00	16
11:57	SHUT DOWN to inspect leakdown						43	43	42																
1:29	**START**																								
1:21	4100	0.7			6.98	9.91	1.4	316	236	1399	374	391	369	466	332	355	123	280	282	120	132.8	180	0.90	49.50	16
1:26	4100	0.7			6.26	10.20	1.4	267	233	1408	387	402	379	481	344	366	120	280	288	126	136.4	187	1.13	62.15	16
1:35	4100	0.7	43	0.89	6.20	10.23	1.3	240	225	1417	385	401	378	476	341	359	120	271	279	124	134.6	185	1.10	60.50	16
1:45	4100	0.7	43	0.89	6.06	10.31	1.3	234	227	1421	387	402	379	478	341	359	121	273	279	126	136.4	185	1.11	61.05	16
1:55	4100	0.7			6.10	10.3	1.3	230	221	1417	385	400	379	477	339	358	121	270	277	122	134.6	183	1.16	63.80	16
2:10	4100	0.7	45	0.85	6				227	1420	390	408	384	485	344	363	122	271	279	126	138.2	187	1.12	61.60	16
2:20	**STOP END OF TEST**				leakdown		48		49	50				505			125								
Average Values:																									
1:29	4100	0.7	43.2	0.89	6.46	10.05	1.4	282	229	1406	386	400	379	476	340	359	120	276	281	122	133.7	183	1.09	61.67	16
				FUEL FLOW [sec's/250ml]	CARBON MONOXIDE [%]	CARBON DIOXIDE [%]	OXYGEN [%]	HYDRO-CARBONS [ppm]	RCA OUT [*F]	EXAUST [*F]	DRIVE SIDE FLUX [*F	TROCHOID FLUX [*F]	TROCHOID SPARK *F	TROCHOID EXAUST [*F]	ACC. SIDE FLUX [*F]	ACC. "HOT SPOT" [*F]	RCA IN [*F]	DRIVE END CRANK [*F]	ACC. END CRANK [*F]	ACC. FIN AIR IN [*F]	TROCHOID FIN AIR OUT [*F]	ACC. FIN AIR OUT [*F]	RCA DRIVE PRESSURE [in. H2O]	RCA AIR FLOW [FT^3/MIN]	

▓ = Deviant not used in average.

☐ =Values Shown in the compilation of average values (Figure 1).

APPENDIX A-6b

Test #6: Air Cooled OMC style coated titanium rotor, TBC sidewalls, TBC trochoid.

Rotor: titanium coated with Alumina micro spheres on face and Cr_2O_3 on sides
Rotor Housing: TBC
Accessory End Housing: TBC
Drive End Housing: TBC

Results After Test

- Engine ran well and leak down #'s continually improved when measured.
- Trochoid temperatures went up and exhaust gas temperatures went down.
- Trochoid probably hotter because there was leakage of the combustion gases by the rotor. This was apparent from visible carbon deposits on the outer portions of the trochoid and the section near the exhaust port.
- Trochoid surface finish was adequate but the uneven spraying and honing process left a less than perfectly flat surface especially near the exhaust port (where the excessively high temperatures were measured).
- The leakage was also apparent on the rotor where carbon was built up near the edges.
- The test was run for only 1.5 hours as the temperature at the exhaust port went over 500*F Close to the tolerable limit of aluminum alloy.
- The PS-200 held up with no signs of cracking and the seals showed no signs of significant wear except the apex seals showed some roughness in the center.

  This is where we broke through the PS-200 during honing.
  This didn't seem to pose a problem though.

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This project provides an evaluation of the feasibility and desirability of applying a thermal barrier coating overlaid with a wear coating on the internal surfaces of the combustion area of rotary engines. Many experiments were conducted with different combinations of coatings applied to engine components of aluminum, iron and titanium, and the engines were run on a well-instrumented test stand. Significant improvements in specific fuel consumption were achieved and the wear coating, PS–200, which was invented at NASA's Lewis Research Center, held up well under severe test conditions.

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