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Thermal Barrier Coatings for Jet Engines

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ABSTRACT

Thermal barrier coatings (TBC) have been used in jet engine combustors for over 15 years. However, it is only recently that they have been actively used in the harsh turbine environment on nozzle guide vane platforms. It is intended to use TBCs on vane airfoils, and on rotating turbine blades where the maximum payoff will be realized. Much work has been done in the last five years towards this goal. Problem areas that need to be addressed are as follows:

1. Prevent coating failure due to:
    a. thermal cycling of the ceramic layer.
    b. oxidation of the bond coat.
    c. erosion due to gas stream solid particles.
    d. deposition of gas stream molten debris.
    e. acid leaching of coating phase stabilizers.
2. Minimize performance losses due to rough coatings.
3. Insure consistent high quality coatings.

This report will review some of the work done by Rolls-Royce that would hopefully allow an increased use of TBCs on turbine components in the future.

NOMENCLATURE

APS	air plasma spray
α	coefficient of thermal expansion
CST	chromia silica titania
CYZ	ceria yttria stabilized zirconia
dW	coupon weight change
Er	erosion rate
FSE	flight service evaluation
IPT	intermediate pressure turbine
k	roughness element height
M	(CrAlY) metal ie. Ni, Co, Fe
MSZ	magnesia stabilized zirconia
η	cascade primary efficiency
PVD	physical vapor deposition
Qp	Weight of particles hitting target
Re_k	roughness Reynolds number
SPS	shrouded plasma spray
STC	standard test conditions
ss	steady state conditions
T'	non-transformable tetragonal phase
U	velocity
VPS	vacuum plasma spray
ν	kinematic viscosity
YSZ	yttria stabilized
ZTY	zirconia titania yttria

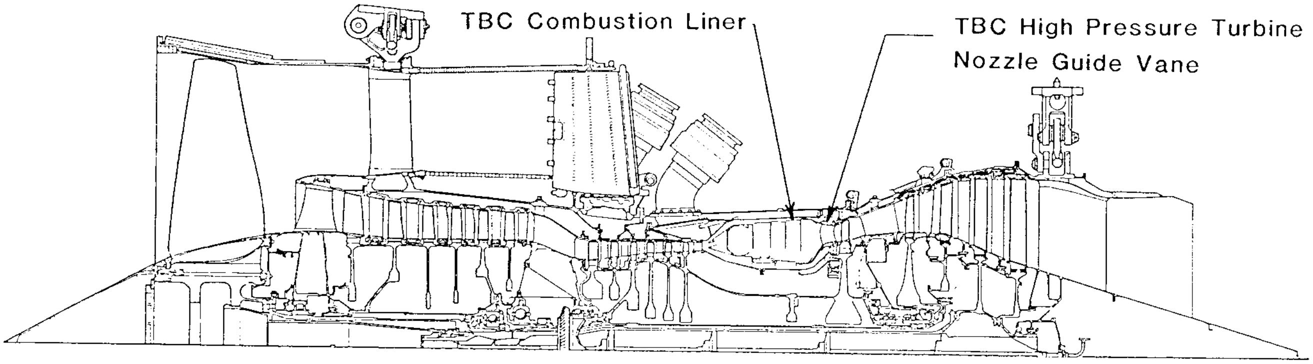

Figure 1 Use of TBCs on the Rolls-Royce 535-E4 Jet Engine.

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INTRODUCTION

Rolls-Royce has used ceramic thermal barrier coatings in jet engine combustors for many years. They are used in most of our engines today. They are being used on high pressure turbine (HPT) nozzle guide vane (NGV) platforms in several engines, including the RB211 535-E4 (32,000 pound thrust class engine) that powers the Boeing 757, and is shown in figure 1. There have been limited applications on NGV airfoils to date. They are bill of material on the lower temperature RB162 and are being service trialed on the RB211-22B. Much testing of TBCs has been done on turbine rotor blades, and we look forward to using them in regular service in the future.

TBCs are of prime interest because of their ability to improve gas turbine performance, at a time when potential improvements from alloy modifications and cooling efficiencies are all but exhausted. Thin ceramic coatings can reduce the metal temperature several hundreds of degrees resulting in significant life improvement. The improved life can be traded off for a) higher inlet temperatures and thus increased thrust, or b) for reduced cooling air usage and thus reduced fuel consumption. Figure 2a shows a typical HPT rotor blade with a highly efficient cooling scheme. This scheme can be simplified with the use of TBCs, as shown in figure 2b. This blade only has a pressure side patch of TBC, but this gives a significant improvement in performance. The use of a .025cm (.01") of ceramic coating can reduce the mass average temperature at a typical cruise condition by over 125°C (200°F). If however the temperature and life are unchanged, the cooling can be reduced, improving the specific fuel consumption by 0.6%.

	MSZ	YSZ
ΔT_{MEAN}	140°F	230°F
Δ SFC	.3%	.6%

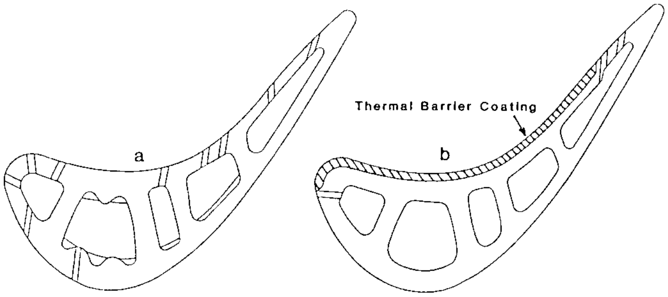


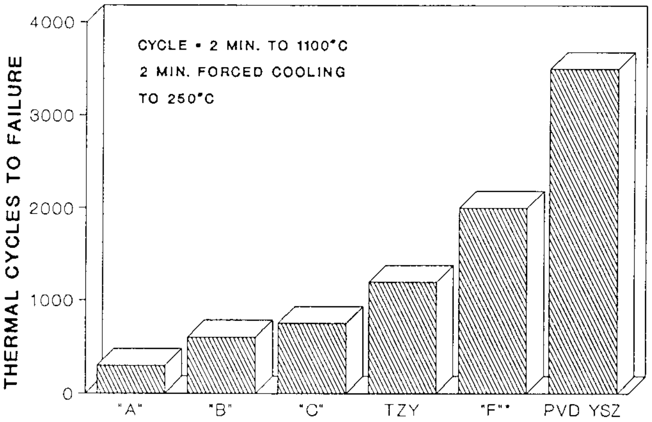
Figure 2 Benefits of TBCs on HPT Blades.

DISCUSSION of WORK TO DATE

The Effect of Thermal Cycles

Thermal Cycle Test Program.

One of the major failure modes of TBC systems is the spallation of ceramic topcoat due to thermal cycling. The failures are believed to be caused by stresses induced by coefficient of expansion (α) mismatches and oxidation of the bond coat. The cycle used, heats the ceramic surface to 1100°C (2010°F) for 2 minutes, then force cools it to 250°C (480°F) for 2 minumtes. This was the case with earlier TBC systems such as 3 layer magnesia stabilized zirconia (MSZ). Removal of the cermet, thought to ameliorate the α differential between the bond coat and the ceramic, resulted in a significant improvement in cycle life, as can be seen in figure 3. The cyclic life was still low however, due to crystalline phase changes which occurred above 950°C (1740°F). At the same time conductivity of the MSZ increases, thus accelerating the failure in hot spot regions. It was thought that changing to a more stable (in phase change and conductivity) material such as yttria stabilized zirconia (YSZ) would help. The fully stabilized (20%) zirconia was cubic in phase and had a very short cycle life [1]. But, a partially stabilized system resulted in a non-transformable tetragonal (T') phase which was very stable. Further improvements were seen by going to high density, oxidation resistant MCrAlY bond coats. Three methods are available to obtain the superior bond coats: 1) shrouded plasma spraying (SPS), 2) vacuum plasma spraying (VPS),and 3) physical vapor deposition (PVD). This change gave the most dramatic improvement in cycle life, as seen in figure 3. Previous work showed the SPS system equal in cycle life to VPS [1]. Applying the ceramic by PVD creates a very strain tolerant columnar structure, resulting in the best thermal cycle life to date. TZY, an erosion resistant coating lasted 1200 cycles.



• IN PREVIOUS TESTING "E" WAS THE SAME AS "F" [1]

SEE TABLE I

Figure 3. TBC Thermal Cycle Test Results

The Effect of Oxidation Due to Time at Temperature

Flight Service Evaluation Program.

As mentioned earlier, oxidation of the bond coat is a major mode of failure to TBC systems. The amount of oxidation that occurs is dependent on the amount of time spent at different temperatures. Determining this effect of time at temperature is not as easy as with thermal cycles, especially when trying to simulate the engine environment and the interaction with thermal cycles. The easiest and cheapest way is to actually do the testing in real engines. Therefore a flight service evaluation (FSE) was initiated [1 and 3].

The criteria for an FSE component are mutually incompatible in that, it must have a reasonably high surface temperature and heat flux, but have a fairly long life in service. After considerable review, the RB211-22B intermediate pressure turbine (IPT) NGV was chosen (see figure 4). Prior work on a bench engine had shown that the NGV platform application was considerably more demanding than the combustion chamber environment.

The coating was initially applied only to the inner diameter pressure side platform area, to minimize the reduction of flow area through the throat of the vane set. More recently however, the pressure side of the airfoil of some vanes have been coated as shown by the crosshatching in figure 4. The vane is nominally 20 cm long, 7.6 cm wide and 10 cm tall (8 x 3 x 4 inches). It is made of an uncoated nickel base superalloy.

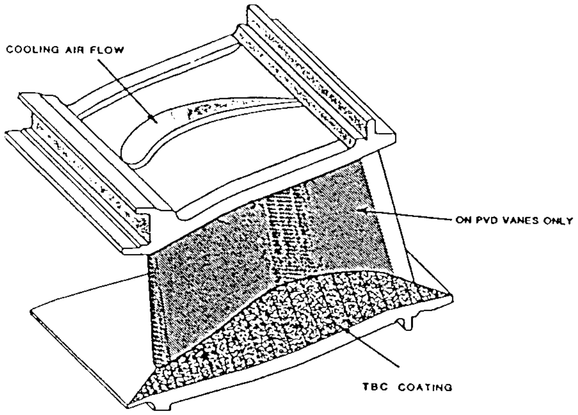


Figure 4 Intermediate Pressure Turbine Vane with TBCs.

A TBC system is comprised of a metallic bond coat and a ceramic top coat. Eight systems were evaluated, and are listed in Table I. Five different bond coat materials were evaluated, which were applied by 4 different techniques. Three different ceramic materials were included, applied by 2 different processes. The coatings were given designations for identification; for example "A" was 3 layer MSZ, the standard combustor coating. Coating "B" was 2 layer MSZ, which is similar to "A", but leaves out the cermet (a NiCrAl + MSZ mixture). Coating "C" used the same NiCrAl bond coat (as A and B) but with a 6-8% yttria partially stabilized zirconia (YSZ) top coat. Coating "D" had a CoNiCrAlY bond coat + YSZ, however, the wrong powder had been used, and it had failed by the first overhaul inspection. "D" was removed from the program and redesignated "G" for future engine builds. Coatings A through D were applied by air plasma spray (APS). Coating "E" had the same CoNiCrAlY bond coat as "D", but it was applied by SPS. Coating "F" also has a CoNiCrAlY bond coat applied by VPS plus a YSZ top coat.

Coatings "G", "H", and "I" were not included in the initial engine builds. They were added later, and therefore have less time on them. Coating "G" is an APS version of "F". It was hoped that coatings "E","F", and "G" would give a direct comparison of the bond coat performance as applied by 3 significantly different techniques. It had accumulated 2200 hours as of December 1988. Coating "H" is a APS NiCrAlY + $CaO.TiO_2$. We became interested in this coating, as it was claimed to be resistant to acid leaching from low grade fuels [2]. It did very well in thermal cycle testing (figure 3) and was therefore added to this FSE program. It had 3300 hours as of December. Coating "I" had a NiCoCrAlY bond coat plus 8% YSZ, both applied by PVD. The coating has a unique columnar structure that makes it very strain tolerant and gives a good surface finish. As of December this coating had 2600 hours on it. None of the engines have been into the shop for overhaul since these 3 coatings were installed, and therefore, have not been inspected to date.

Current Status of FSE Program. The flight status for the 4 engines as of December, 1987 is given in Table II. Engine build 2 had over 12,000 hours, and still had 15 of its original 25 coated vanes. This engine was removed in August 1986, with 9838 hours /5013 cycles. A report for this engine at 2539 hours was given earlier [1]. To get the approximate number of cycles for any engine, divide the hours by 2.

Table II TBC Service Evaluation Status December, 1987

ENGINE BUILD	FLIGHT HOURS	TIME OF INSPECTIONS HOURS	TIME ON NEWER COATINGS	ORIGINAL VANES
1	10130	4100, 7500	"H,I"(2600)	9
2	12900	2500, 9800		15
3	9100	6900	"G"(2200)	15
4	8700	5500	"H"(3300)	19

Results of Inspection at 9800 Hours/5000 Cycles. Coating "A" suffered the highest amount of coating loss (spalling). One of the vanes, shown in the photograph in figure 5 lost 37% ceramic by area. At the 2500 hour (1350 cycles) inspection it had only lost 3% of the coating. The average loss for the 5 vanes was 32% compared to 5% at 2500 hours. Bond coat was also missing in the fillet radius of one vane.

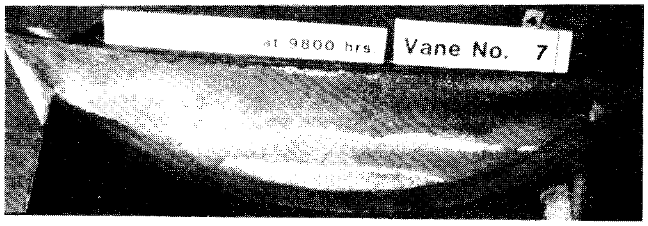


Figure 5 "A" APS NiCrAl + Cermet + MSZ on IPT NGV.

Table I Coatings Used on RB211 IPT NGV Flight Service Evaluation

ID. LETTER	BOND COAT	CERAMIC (APS)	BOND COAT METHOD	ON ENGINES	TOTAL COATED VANES
A	NiCrAl+C*	MSZ	APS	1,2,3,4	24
B	NiCrAl	MSZ	APS	1,2,3a	12
C	NiCrAl	YSZ	APS	1,2,3,4	23
E	CoNiCrAlY	YSZ	SPS	1,2,3,4	23
F	CoNiCrAlY	YSZ	VPS	1b,2,4a	15
G	CoNiCrAlY	YSZ	APS	3a	16
H	NiCrAlY	$CaO.TiO_2$	APS	1b,4a	10
I	NiCoCrAlY	YSZ (PVD)	PVD	1b	5
	Uncoated Vanes				11
*Cermet = NiCrAl + MSZ				TOTALS	139

Figure 6 "B" APS NiCrAl + MSZ on IPT NGV Platform.

Coating "B" was significantly better than the "A", but was still not acceptable. One vane had 7.5% coating loss by area compared to no coating loss at 2500 hours. Two vanes had bond coat missing in the fillet radius as seen in figure 6.

Coating "C" had very little coating loss, less than 5% by area. The NiCrAl bond coat ran cooler than on "A" or "B" because of the lower conductivity of the YSZ ceramic, and bond coat loss was minimal. Three vanes had ceramic loss near the fillet radius. There was bond coat loss in the fillet radius at midchord where it's temperature was higher because it was not covered by the ceramic. Reference 3 has more photographs.

Coating "E", had minimal ceramic loss, less than 1% by area, and those losses were associated with edge effects in the fillet radius as seen in figure 7. The bond coat on these vanes was in excellent condition. To date, this coating has consistently performed the best.

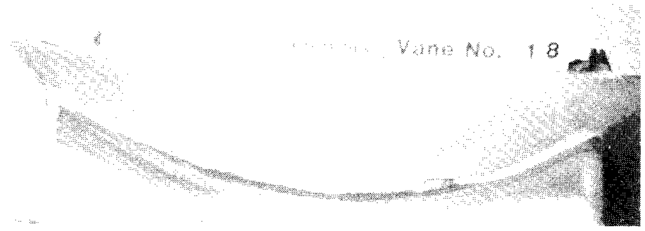


Figure 7 "E" SPS CoNiCrAlY + YSZ on IPT NGV.

Coating "F" had more coating losses than coating "C". The maximum loss on a vane was 10%, the average loss (5 vanes) was however, only 3%. The bond coat itself was in excellent condition. Because the losses seem to be confined to 1 or 2 vanes in each set, and in light of the good results other operators [5 and 6] have had, we believe the coating losses are due to application problems.

By measuring the area of coating loss on each platform, and dividing it by the original area for each inspection period, we get the percent coating loss for each coating versus time. Figure 8 shows the average area loss for coatings A through E. The smooth curves were obtained from a regression analysis of the data. It shows the improvement achieved by using high density bond coats such as those obtained by VPS and SPS.

The order of ranking of the TBCs tested in the harsh turbine environment does not necessarily follow the order of figure 8. Coating "C" lost bond coat on several vanes where not covered by ceramic. Toriz et al [1] has shown the bond coat loss as early as 4100 hours. This indicates that the bond on "C" is at or near its oxidation temperature limit, depending if it is on a hot or cool vane. It also indicates that "C" will not be very useful at higher temperatures.

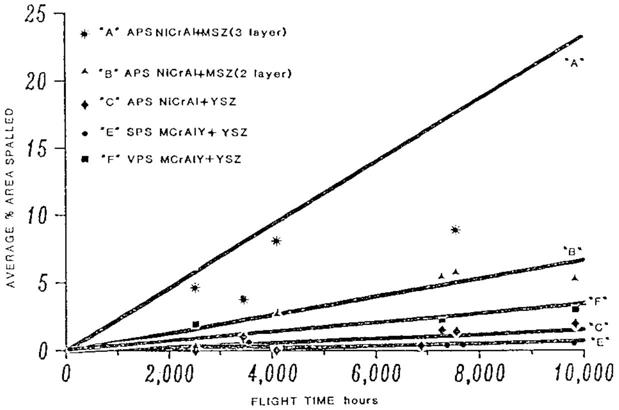


Figure 8 IPT NGV Coating Loss (% area) with Time.

Therefore, the ranking to date from this FSE program is as follows:

1. Coating "E" SPS CoNiCrAlY + YSZ
2. Coating "F" VPS CoNiCrAlY + YSZ
3. Coating "C" APS NiCrAl + YSZ
4. Coating "B" APS NiCrAl + MSZ
5. Coating "A" APS NiCrAl + Cermet +MSZ

Many of the vanes had indications of ceramic erosion near the fillet radius at midchord. We initially believed that erosion would be life limiting to TBCs on airfoils, but would not be a factor on platforms parallel to the gas stream flow. Most of the erosion on the NGV's shows up in the midchord region first, because geometry constraints cause it to have the thinnest coating. Several vanes polished early in the program polished through the ceramic at this point, exposing the dark grey bond coat. This observation emphasized the need to understand the erosion behavior of ceramic TBCs.

The Effect of Particulate Erosion

TBC Erosion Program Another concern with the use of TBCs is that of erosion. Based on combustor experience we know that erosion is not a problem when a low velocity gas stream with entrapped particles flows parallel to the surface. However, the ceramic is removed quite easily by grit blasting at moderate to high (90°) angles of incidence. As mentioned earlier, the IPT vanes in the service evaluation program showed signs of erosion on the platform near the airfoil fillet radius. Due to secondary flows, impingment angles of up to about 20° are possible. If erosion occurs at these low angles, erosion on the airfoil could be much worse since impingment angles are higher.

A study was undertaken to measure the particulate erosion rate of TBCs under similar but accelerated conditions as found in the high pressure turbine. The program aimed to rank the erosion rate of several TBC systems as compared to the RB211-535-E4 bill of material 8% YSZ, and determine the influence of several variables on erosion rates. The testing was done at the University of Cincinnati by graduate students under the supervision of Dr. W. Tabakoff and F.C. Toriz. Their high temperature erosion rig was used [6]. It is a vertical tunnel, with an in-line combustor fed with compressed air to obtain the high temperatures needed. A long acceleration tunnel allows the injected particles to obtain a uniform velocity and distribution by the time they hit the 2.5cm sq. (1"x1") target in the 10.2cm sq. (4sq.") test section.

The variables evaluated and the ranges tested were:

1. Temperature (T) 260-815°C (500-1500°F)
2. Velocity (V) 122-305m/s (400-1000fps)
3. Impingment angle (A) 20-90°
4. Particle size (S) 8-130μ (.0003-.005")
5. Surface finish (R) 1-7.7μ (40-300+μin)

Nine TBC systems were evaluated, as well as a laser glazed system and an uncoated nickel base sample. Systems evaluated included several variations of YSZ, MSZ, ceria stabilized zirconia (CYZ), Alumina (Al_2O_3), calcium titanate ($CaO.TiO_2$) and chromia silica titania (CST).

Because of the accelerated nature of the testing, the absolute erosion rates (Er) measured are not very meaningful, so they were normalized by dividing by the Er of APS YSZ . This testing is to be correlated with TBC vanes flying on the FSE program described earlier.

The materials tested are listed in table III. Most of the coupons were air plasma sprayed (APS) in the UK, such as the standard 6-8% YSZ, and the MSZ. Some, however, were obtained in the USA, such as the Al_2O_3 which was obtained from the Carboride Corp. (Cleveland, OH). The calcium titanate was obtained from Solar Gas Turbines (San Diego, CA). The Cr_2O_3.SiTi (CST), and the titania yttria zirconia (TYZ) are denser ceramics to be used as thin erosion resistant top coats. The 8% YSZ coupons obtained from Chromalloy (Orangeburg, NY), were applied by physical vapor deposition (PVD). The densities of the systems vary significantly, from about 84% for the low conductivity coatings to 97% for the erosion resistant top coats. Each system has its benefits, so they were applied as they would be in an engine application to determine the corresponding erosion rates, irrespective of density.

Table III Erosion of TBCs - Test Matrix

COATING	NO. OF DATA POINTS PER VARIABLE				
	T	V	A	S	R
1. APS YSZ	4	3	5	3	3
2. PVD YSZ	4	3	4	3	1
3. Al_2O_3	1	1	4	1	1
4. ZTY	1	1	3	1	1
5. CST	1	1	1	1	1
6. $CaO.TiO_2$	1	1	1	1	1
7. CYZ	1	1	1	1	1
8. CYZ glazed	1	1	2	1	1
9. 20% YSZ	1	1	1	1	1
10. APS MSZ	1	1	1	1	1
11. Mar-M002	1	1	2	1	1

The variables were set to cover the ranges that might be experienced by the high pressure turbine NGV and blade. Table III shows the number of levels tested for each variable, for each material. A detailed study of the variables was only done for two TBC systems; the standard APS YSZ and the PVD YSZ, which was expected to be one of the most erosion resistant. A standard test condition (STC) was defined and one variable at a time was varied to determine its effect on erosion rate. STC is defined as: T=1000°F (540°C), V=122m/s (400fps), A=90°, P=40μ, R=1μ (40μin.)

Temperature - Er was not expected to vary much with temperature below 2000°F (1100°C). This was in fact the agreed consensus of the authors of ceramic erosion papers in references 7, 8, 9 and 10. In fact the erosion work done in references 4, 8 and 11 were done at room temperature. Tests were run at T=260, 540, 705 and 815°C (500, 1000, 1300 and 1500°F).

Velocity - Velocities through the HPT vary significantly, to cover the range, tests were run at V= 122, 213, 305m/s (400, 700 and 1000fps).

Impingment Angle - Particles tend to hit the platforms, and airfoil suction side surfaces at low angles of incidence, while the leading edge of the airfoils are hit at higher angles of incidence up to 90°. Angles tested were A=20, 30, 40, 60 and 90°.

Particle Type - Al_2O_3 particles were used for accelerated testing. If carbon were used testing would have taken much longer. Commercially sized powders were used to evaluate the effect of particle size on Er. Sand was not used as it can become soft or sticky at turbine temperatures. Materials similar to those used in other erosion testing were used so a comparison might be possible. Other researchers [7, 9 and 10] tested at higher temperatures and used Al_2O_3 oxide particles. The particles were purchased from the Norton Co. [12].

Particle Size - Erosive particles flowing through the HPT vary quite a bit, typically from 2μ-150μ. Newer designs are reducing this range to below 50μ. However, to better test the effect of size three powder sizes were used:

	Average	3%[<]	50%	6%[>]
1.	8μ	16μ	8.3μ	4μ
2.	40μ	73μ	40-44μ	25μ
3.	130μ	149μ	130μ	105μ

Powders 1 and 2 were used as received, but 3 was sieved using a 100 mesh sieve to eliminate particles larger than 149μ, and a 140 mesh sieve to reduced the smallest particle to 105μ. This then meets the specifications used by NASA [9].

Surface Finish - Most of the TBC coupons were polished to 1-1.5μ (40-60μ in.) before testing. The PVD YSZ coupons were not polished, but were 1-1.5μ (40-60μ-in.) as received. The as sprayed YSZ was over 7.7μ (300μ-in.); one was polished to 5μ (200μ-in.).

Each test piece was weighed (± .01mg) before and after testing. The coupon average thickness, and the surface finish was measured. The weights were rounded off to the nearest 0.1mg. The erosion rate is the sample weight loss (dW) divided by the total weight of the particles (Qp) hitting the target; Er=dW/Qp (mg/g). Each point was run to a steady state erosion rate. was

Erosion Test Results. The steady state erosion rate at STC (90°) was compared for each of the systems listed in table III. The ranking is given in the bar chart of figure 9. The ranking was consistent for all the ceramic systems tested at other impingment angles as we will see later in figure 10. The standard YSZ was not very erosion resistant, it was used to normalize the erosion rates of all the systems tested, therefore it's Er=1.0. It ranked 9th out of the 10 different systems tested, only ahead of CYZ. The best, most erosion resistant TBC was the PVD YSZ. This held true regardless of variables tested. It did however, have a higher Er than the bare nickel alloy. The 2 dense coatings also did well. The TYZ was 2nd in the ranking with CST close behind. The Al_2O_3 was 4th with an Er equal to about 3 times that of PVD YSZ. The laser glazed CYZ had a low initial erosion rate. The Calcium titanate rated 6th, just ahead of the MSZ (24% MgO), and the fully stabilized 20% YSZ ranked 8th.

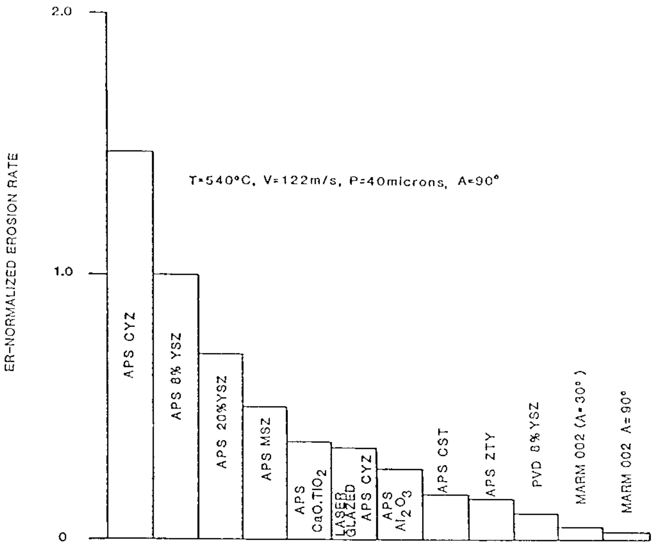


Figure 9 Normalized TBC Erosion Rates.

It was found that Er increases with increasing angles (A) of particle impingment. This was particularly true with the standard YSZ system where Er at 90° was 5 times higher than at 20° as can be seen in figure 10. This is consistent with the traditional response of "brittle materials". The bare metal Er is lower at 90° than it is at 30°, which is the traditional response for "ductile materials".

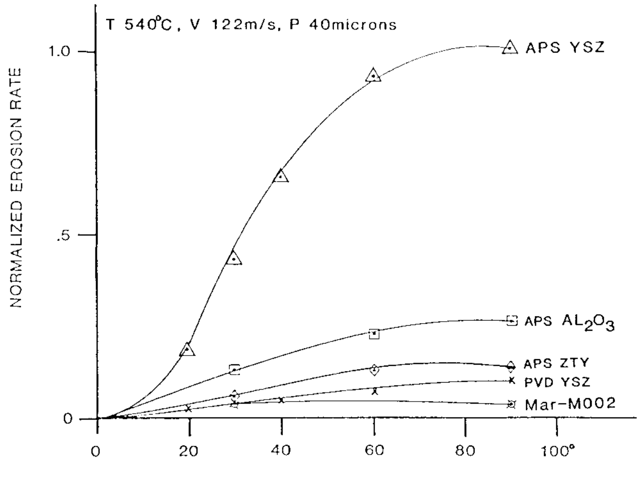


Figure 10 The Effect of Impingment Angle on Erosion.

Er also increases with increasing particle velocity. For the standard YSZ Er at 305m/s (1000fps) is 2.3 times greater than at 122m/s (400fps). Contrary to expectation and the available literature, Er increases with temperature in the range tested. For the standard YSZ Er at 815°C (1500°F) is about twice that at 590°C (1000°F) Er increases with increasing particle size, but the increase levels off at about 100μ for both the standard and PVD systems.

Typically, the initial Er's of the ceramics were high, but leveled off to a steady state (ss) condition with time (or sum of particle weight hitting the target). However, when the CYZ coupons were laser glazed, the initial Er was very low, and eventually increased so that the final steady state Er was the same as that for the unglazed samples eroded at A=90°. The glazed surface is erosion resistant, but mud flat cracking occurred in the glazing as can be seen in the 100X photograph in figure 11. These cracks exposed the less erosion resistant substructure which was selectively eroded. Even at shallow angles of attack (30°), it resulted in isolated islands of minimal erosion, with heavy material loss elsewhere. This can be seen in the 50X photograph of figure 12. Similar results occurred where laser passes failed to overlap, and a plowing effect was seen. The low initial Er can be probably be maintained with process improvements.

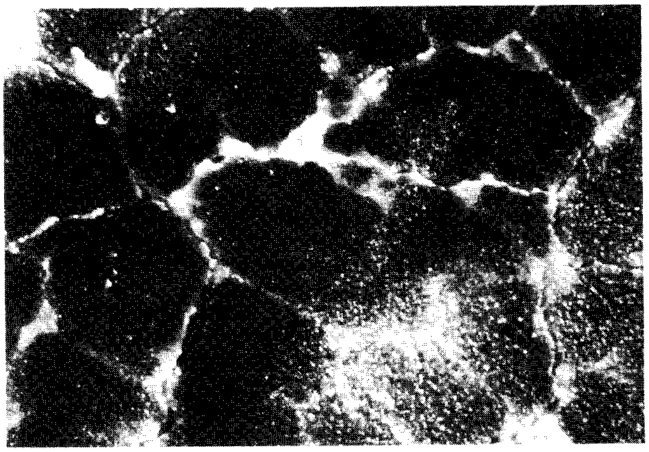


Figure 11 Laser Glazed CYZ with Mud Flat Crazing: 100X

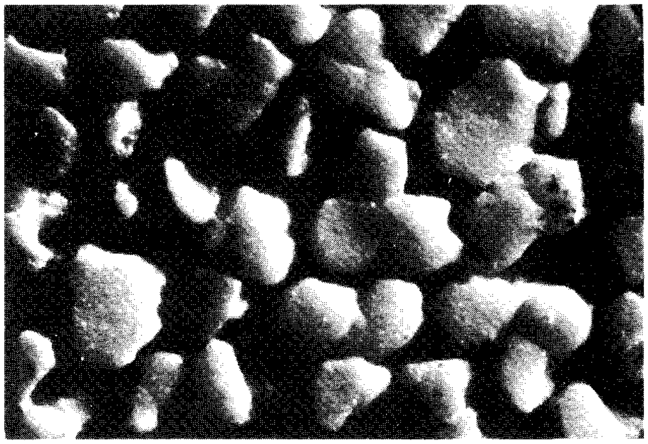


Figure 12 Laser Glazed CYZ Eroded At A=30°: at 50X.

The Effect of Surface Finish on Performance

Roughness Experience on FSE NGVs Another concern with the use of TBCs is the loss of aerodynamic performance due to rough surfaces, which can cause earlier onset of laminar-turbulent transition and, for a fully turbulent boundary layer, increased skin friction. These effects are apparent in numerous cascade, turbine and compressor rig tests involving a range of roughness types [13]. We were reluctant to add TBCs to the airfoils in the FSE program mentioned earlier , since the APS coatings are very rough (7.7μ) as sprayed. Even with polishing they were still rougher than desired 3.2μ (125μ-in.). The PVD ceramic surface finish however, was only 1.3μ (50μ-in.), so it was added to the pressure side airfoil, avoiding the throat at the trailing edge, and wrapping around the leading edge to the suction side. A photograph of a PVD coated vane is shown in figure 13.

Coatings A, B, C, and F (Table I) were polished for engine builds 1 and 2. Their roughness increased with flight time. Table IV summarizes the results. None of coating "E" were polished; and they stayed at about 7.7μ for up to 9800 hours.

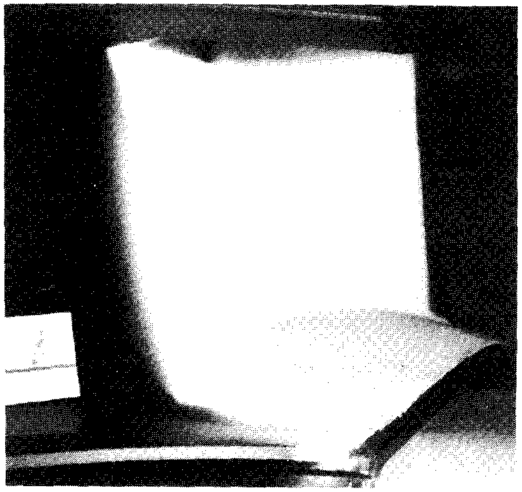


Figure 13 PVD YSZ on IPT NGV Airfoil and Platform.

Table IV FSE NGV Surface Roughness with Time

COATING	INITIAL ROUGHNESS μ	μ-in.	FINAL ROUGHNESS μ	μ-in.	TIME HOURS
A	2.8	110	3.5	135	9800
B	2.8	110	5.1	200	9800
C	2.8	110	5.1	200	9800
E	7.7	300	7.7	300	9800
F	2.8	110	3.8	150	9800

Roughness Experience from Erosion Program. In our erosion program we found that the TBC surface finish deteriorated with time (or as more particles hit the target). In figure 14 the standard YSZ (polished to 1μ) decayed to over 7.7μ. when eroded at A=90°. At A=20° the deterioration is much slower, and probably comparable to that of the FSE NGVs. Table IV indicates that it took 9800 hours to deteriorate from 2.8μ to 5.1μ surface finish at low angles of attack. In figure 14 this takes approximately 25g. (28-3), which roughly represents 10,000 hours. So by 8000 hours (20g) the leading edge of an airfoil (A=90°) would have a surface finish of about 7.7μ. Its surface finish would be 5.1μ in only 1000 hours. The PVD YSZ however, will still have a good surface finish 1-1.5μ (40-60μ-in) at 13,000 hours (32.5g). Note the difference in eroded surface structures in the 500X SEM photographs of the APS YSZ (figure 15) and the PVD YSZ (figure 16).

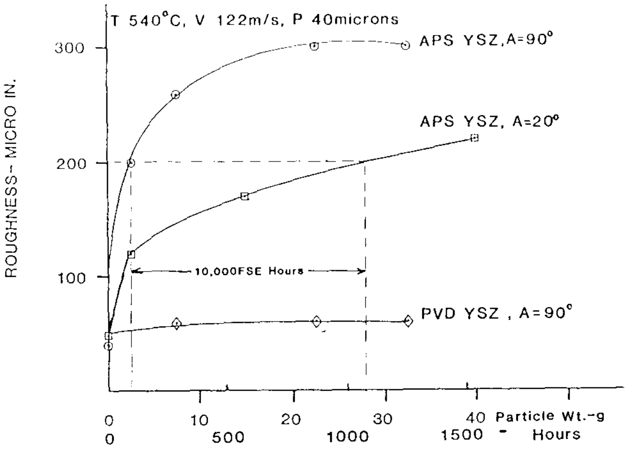


Figure 14 Roughness Variations with Erosion and Time.

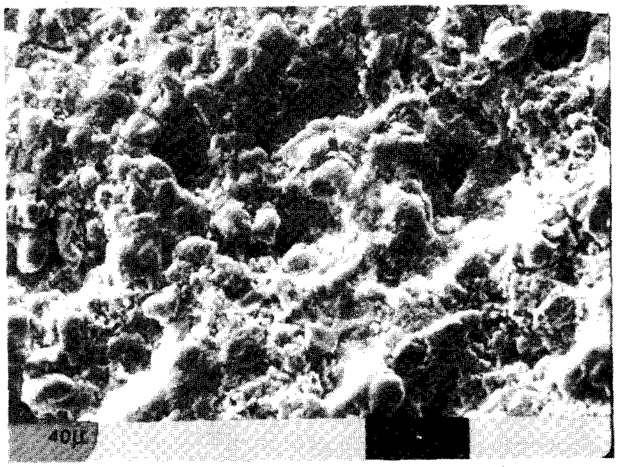


Figure 15 Eroded APS YSZ: V= 305m/s, A= 90°, at 500X.

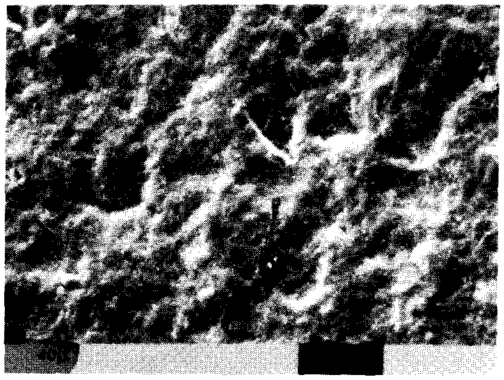


Figure 16 Eroded PVD YSZ: V= 122m/s, A= 90°, at 500X.

Surface Finish vs. Performance. The important question is however, how does the surface finish of a TBC actually effect the aerodynamic performance of gas turbine airfoils. We have investigated and documented this [13] for a profile typical of current designs. Cascade tests indicate a potential for significant extra loss, depending on Reynolds number (Re), due to a TBC in its "as-sprayed" state. In this situation, polishing of the coated vanes is very effective in restoring their performance. The measurements also suggest a critical low Re below which the range of roughness tested has no effect on cascade efficiency.

The work was done at room temperature, using a two-dimensional cascade rig, in the Oxford University Short Duration Transonic Blowdown Tunnel. In this facility the Mach and Re numbers can be varied continuously, independently, and over realistic ranges for present day turbines. The parameter of prime importance is the roughness Reynolds Number Re_k, where the characteristic length is the average height of the roughness elements. Transition studies have shown that, for the case of incompressible flow past a flat-plate with sand-grain roughness, $Re_k = 120$ represents a critical value below which the onset of transition is unaffected. At higher Re's, the point of onset of transition moves progressively nearer to the plate leading-edge with increasing Re_k.

The magnitude of Re_k also determines the degree of influence, of roughness on fully developed turbulent boundary layers, as can be seen from figure 17. Generally speaking, at high Re ($Re_k > 1000$), the rougher the surface, the greater the skin friction coefficient. On the other hand, for Re_k lower than 100, turbulent boundary layer skin friction is effectively independent of roughness and varies only with Re. The following three flow regimes are conventionally identified,

$Re_k < 100$ ($C_f = f(Re)$) : Hydraulically smooth
$100 < Re_k < 1000$ ($C_f = f(Re, k)$): Transitionally-rough
$Re_k > 1000$ ($C_f = f(k)$) : Fully-rough

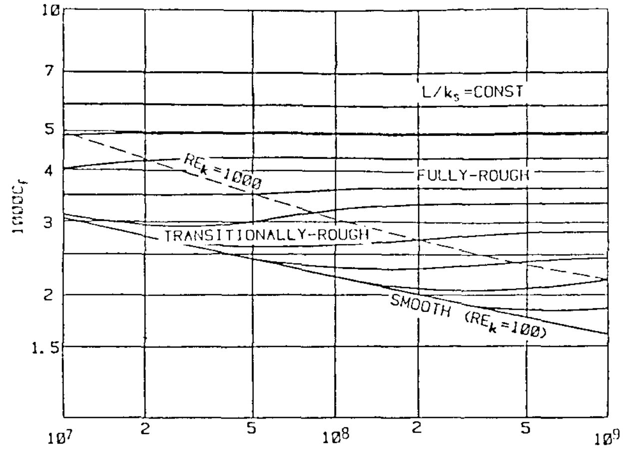


Figure 17 Skin Friction Coefficient for Turbulent Boundary Layers on Rough Flat Plates.

The effects of roughness are therefore dependent on properties of the fluid, which is particularly relevant since operating pressures vary throughout the turbine. As a result, high pressure airfoils are most sensitive to the effects of surface roughness and require more stringent effort to avoid exceeding the "admissible" roughness level. As a general rule, it is given by $k_{adm} = 100\upsilon/U$, where υ is the kinetic viscosity, and U is the fluid velocity.

Pressure variations were measured through a wake of each variant at the design condition. The processed data is shown as a plot of "primary loss coefficient" ($1-\mu$) versus Re in figure 18. The majority of data in this figure correspond to nominally 4% inlet turbulence intensity. The influence of free stream turbulence on primary efficiency is simply tested at a few selected conditions.

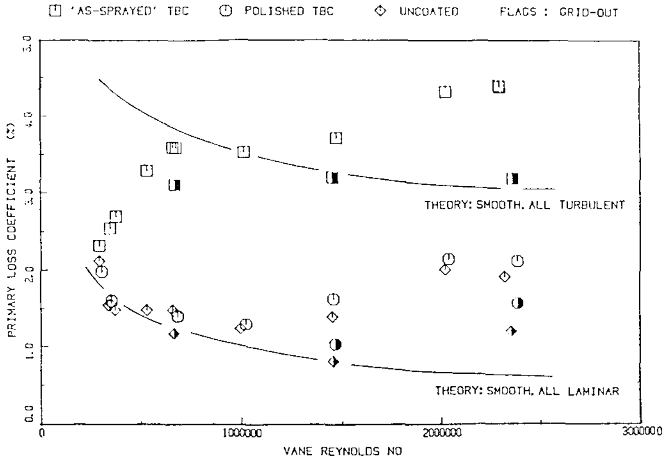


Figure 18 Profile Loss Measurements.

The suction side surfaces only are considered since roughness on these is expected to be most influential. The critical area was found to be from the throat to the trailing edge along the convex surface.

OTHER CURRENT AND FUTURE PROGRAMS

The Effect of Flow Stream Laden Molten Debris

Another potential failure mechanism is the deposition of molten debris such as salt and sand flowing through the engine. Sand is very erosive in the compressor, and can be in the turbine also if the particle temperature is below 1100°C (2000°F). Above 1200°C (2100°F) sand become molten and adheres to components it strikes. Figure 19 shows a blade from an engine operated in a sandy mid-eastern country. The molten debris can work its way into the porous TBC structure and corrosively attack the bond coat, or simply increase the stresses due to the thermal mismatch and thus reduce the thermal cycle life of the coating.

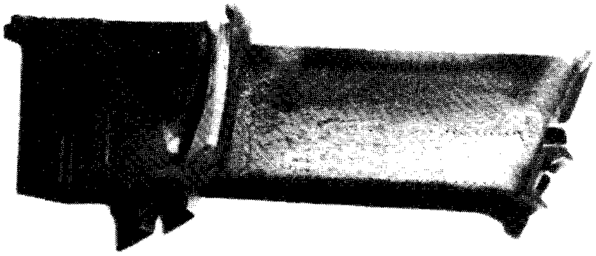


Figure 19 HPT Blade with Molten Debris.

We are currently involved in a 3 year joint venture program to evaluate the effects of molten debris deposition. The study will include salt, sand, fly ash and other corrosive debris.

The Effect of Acid Leaching

With the use of low grade fuels, or operations in salt environments, there is the potential problem involving the acid leaching of the phase stabilizers (ie. yttria, MgO) from TBCs. At 10,000 hours, in our FSE program discussed earlier, we detected no signs of acid leaching. But, these were operating with good fuel in the relatively clean USA atmosphere. Testing with fuels contaminated with sulfur, phosphorus, and alkali metals have caused zirconia coatings to become unstable (reference 2). In that study $CaO.TiO_2$ coating was found to be stable in the presence of vanadium, sulfur, and other contaminants found in low grade fuels, while the YSZ coating became unstable in the presence of vanadium. The $CaO.TiO_2$ coating also performed well in our thermal cycle testing as described earlier. Another coating with the potential to be resistant to high temperature acid leaching is CYZ [14].

Producing Consistent High Quality Coatings

It has been found that results in TBC testing can vary significantly as powder sources, spray parameters, substrate material, temperature and geometry vary. Up until now it has been more of an art than a science. It is important to reproduce high quality coatings consistently. Much work has been done, and continues, on process development and process control, to optimize application parameters. Robotic spray booths appear to be a necessary ingredient. In writing specifications, an effort has been made to combine the 3 major specification routes, namely:

1. Specify the properties desired, with little regard for how one gets there.
2. Specify stringent procedures, which, if followed faithfully should give the desired properties.
3. Specify the end metallographic structure required, regardless of path.

Computer modeling, to include the coatings in the initial design, and life analysis are a must.

CONCLUSIONS

Turbine components should be designed to make full use of TBC systems which have now demonstrated 10,000 + hours in the harsh turbine environment. We believe that advanced TBC systems, as as described in this paper, will be required for future turbine airfoil applications. This is especially true on rotating airfoils. Work should, however, continue to increase the temperature capabilities of TBC systems. To design these components, a life prediction model will be required which takes into account all possible stresses and material strengths, based on well-defined material specifications, process parameters.

High density bond coats such as those produced by shrouded plasma spray, vacuum plasma spray and physical vapor deposition, resulted in significant improvements in thermal cycle life, and time at temperature oxidation life. Thermal cycle rig testing has shown that 6-8% yttria stabilized zirconia with a high percentage of the non-transformable tetragonal phase (T') and about 15% porosity results in good cycle lives. Physical vapor deposition of similar compositions also looks promising. An in-flight service evaluation program has shown that high density bond coats plus YSZ can last up to 10,000 hours/5000 cycles in the harsh turbine environment.

Erosion is a potential problem that will have to be dealt with on airfoils, or where high angles of impingment occur. Here PVD YSZ, or APS erosion resistant top coats in conjunction with low conductivity ceramic underneath, can be used. Laser glazing also shows potential, if the plowing and mud flat cracking problems can be overcome.

Most commercial operators are free of molten debris and corrosive attack (acid leaching) of the TBC, however work should continue for solutions for industrial, military, and mid eastern operations. $CaO.TiO_2$ has done well in thermal cycling and is resistant to acid leaching of its phase stabilizer. Laser glazing may also offer protect against molten debris. Cascade testing has confirmed that there is a potential for significant aerodynamic performance loss due to rough TBC surfaces depending on the Reynolds number. Therefore, on high pressure turbine flow path components, smooth PVD coatings should be used. APS ceramic coatings may be used if polished, but bear in mind that they can roughen significantly with time.

Process development and control through automation will be necessary to assure consistent TBC results. Specifications must not only define the properties required of the end product, but spell out the steps required to get there, and what metallographic structures should result.

ACKNOWLEDGEMENTS

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