A PHILOSOPHY FOR THERMAL BARRIER COATING DESIGN AND ITS CORROBORATION BY 10 000 h SERVICE EXPERIENCE ON RB211 NOZZLE GUIDE VANES*

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Summary

Rolls–Royce has used ceramic thermal barrier coatings (TBCs) in jet engine combustors for well over a decade and on turbine nozzle guide vane platforms (RB211-535E4) and aerofoils (RB162) for several years. Much work has been done to characterize and improve TBC systems for use in more aggressive engine applications. The philosophy and some of the studies performed are reviewed in this paper to understand better the failure mechanisms which govern coating life in service. Findings are correlated with relatively simple laboratory rig test evaluations and with a rainbow service trial involving over ten thermal barrier systems. Some of these systems have been inspected after close to 10 000 flying hours (5000 cycles) and found to be in near-perfect condition.

1. Introduction

In considering the use of thermal barrier coatings (TBCs) in aero gas turbine engines, several potential design philosophies can be considered. One of these is to design the component so that it has an adequate service life without a coating and then to extend the life by up to three times, say, by using a TBC. This is a relatively safe way to use the coating, as it assumes that the coating can fail and fall off without any significant detriment to engine durability. A more efficient philosophy assumes that the coating will survive and designs a component which has an adequate life if coated but a severely restricted life without the coating. Even to consider the latter philosophy requires a very high degree of confidence in and understanding of the behavior of the TBC. This in turn demands well-developed

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models of the coating process and coating behavior, extensive quality assurance procedures, a validated life prediction technique and preferably some form of in-service monitoring and feedback loop. Current designs are exclusively based on the former, safe and conservative philosophy. However, efforts are continuing to develop the technology required to enable a coating-dependent type of design.

2. Thermal barrier coating lifing

2.1. Stresses

For a coating behavior model, perhaps the first things required are an understanding of the strength of the material and the stresses it must withstand. Once these are understood, processing and design can be manipulated to ensure the greatest possible ratio of strength to stress to ensure the highest probability of coating survival. Measuring strengths and stresses in very thin and fragile coatings can be an extremely complex and difficult task.

The assessment of which particular strengths and stresses are important, and whether stress or strain is the quantity to be measured, can be an equally daunting problem. (For simplicity, stress and strength will be used for the rest of this work, but the reader should be aware that imposed strain and strain to failure are probably more important and accurate terms in the context of TBC behavior.)

If we concentrate first on stresses which arise solely from operational origins, thermal expansion stresses between coating and substrate and thermal gradient stresses in the coating itself can be identified. In an aero engine turbine, thermal gradients in an insulating material are caused by heat from the flame, and force cooling when the flame is removed. The gradient will be highest in the outer half of the coating. In practice coating failures generally occur very close to the substrate interface, away from the highest thermal gradient and the highest gradient-induced stresses, indicating that these are not the primary cause of failure. Expansion mismatch stresses will be highest at the interface. For typical substrate and ceramic materials, strains over 0.05% can be calculated for a coated sample heated from ambient to 1000 °C (1830 °F) [1].

The stresses induced by these expansion mismatch strains appear more consistent with the failure location, but the stresses will be tensile in the coating and compressive in the substrate. Extensive work on tensile testing, bend testing and fatigue testing of the ceramic coatings shows that it is extremely difficult to cause coating spallation by tensile stresses, provided that the coating is genuinely thin [2]. By contrast, compressive stresses in the plane of the coating can cause spallation quite readily.

If the properties of the materials involved in TBC systems are considered, it can be seen that both the substrate and the ceramic have relatively good creep resistance. However, bond coats used to provide a mechanical

bond between the substrate and ceramic have extremely poor creep resistance. Creep rates well above 0.1% s^{-1} have been measured on representative materials by Rolls–Royce at 850 °C (1560 °F) and under very low loads. Such a material would be expected to deform readily at operating temperatures, and this would effectively strain isolate the coating. On cooldown, however, the creep strength of the bond coat will increase, and at some temperature, dependent on several factors, the bond coat will begin to transmit appreciable stresses. Because it has a lower rate of contraction, the ceramic will be driven into compression by the substrate and develop a normal tensile force across the interfacial layers. This force, if large enough, can act on pre-existing laminar defects, causing coating delamination failure.

The expansion mismatch stress is considered to be the primary failure motivator, and the thermal gradient stress a modifier, of the overall situation. Many other stresses are also at work and must be taken into account. Loading on turbine blades will include rotation forces and bending forces from the gas flow. The stress fields will be modified by geometrical factors, both macro (such as component curvature) and micro (such as bond coat to ceramic interface roughness). Similarly there can be very significant stresses in the coating resulting from the process history involved in its manufacture. Such stresses are well known [3] and their effects can alter coating performance by at least two orders of magnitude [4].

A full understanding of the behavior of the coating must take all these possible stresses into account, in any attempt to design reliability into coated components. Clearly, sympathetic design of component geometry and operating schedules using stressing mechanisms that are well understood at the design stage will play a major part in the success or failure of the coating in use.

2.2. Strength

It is possible, by varying the composition of the powder material used in the plasma spray process, to cause a variation in the material behavior by two orders of magnitude as a result of changes of coating structure [5]. The strength of a material can be said to be dependent on its phase structure and its microstructure. With the plasma spray process, there is only a matter of 1 or 2 μs between the powder's being in the injection nozzle before entering the plasma and its being incorporated in the coating. For the optimum phase structure, the so-called non-transformable tetragonal (T′) phase [6] is required.

For this, total chemical homogeneity in the coating is needed. This means there can only be extremely short-range chemical inhomogeneity in the feed stock. Deviations from this cause phase instabilities in the coating, which on cycling produce new origins of stress and can cause premature failure.

Process variations, as well as affecting residual stress, can heavily influence microstructures. The behavior of TBCs as a function of microstructural features such as density and crack systems has been the subject

of much work. In some cases this can be extremely detailed but very system specific [7]. Some researchers have used a pull-off test to measure strength [8]. This type of test has been suggested as a good method for coating quality assessment and production control [9]. It should be remembered, however, that the tensile stresses here arise as a result of biaxial compressive strains. Pure strength may not be the ideal goal, but a low Poisson's ratio and Young's modulus, with a high strain to failure, are the probable requirements. As the density decreases from 100% the modulus decreases and so does the strength. The net effect, because strain can be accommodated by crack opening and flexing, is an improved coating performance. This performance level peaks at around 15% porosity [7]. Further density reductions decrease strength more rapidly than they decrease the stresses imposed. Results of pull-off tests should thus be approached with some caution, although the test can be very useful if correctly analyzed.

2.3. Degradation mechanisms

When some understanding of strength and stress has been developed, a component can be designed for the proposed environment. On its entry into service several mechanisms will begin to operate which will either degrade its strength or increase its stresses, or will effect some combination of these, until failure ensues. A knowledge of these mechanisms is a prerequisite for an accurate prediction of coating life and for coating technology development to produce more durable coatings.

There is a large body of evidence in the literature on thermal barrier coating which relates to engine testing [10 - 12] and which relates to laboratory work on zirconia coatings [13 - 15]. Considerable work has also been done within Rolls–Royce. Some of our rig experience is summarized in Fig. 1 from our previous work [5]. The significant improvement in cycle life for the dense bond coats should be noted.

The role of the bond coat as a strain isolator has already been described. It is proposed that the thermomechanical behavior of the bond coat is progressively modified by oxidation such that its creep resistance increases. The exact mechanism is unknown, and both the experimental data to support the hypothesis and the mechanism to support the data are being actively pursued. However, it is further proposed that the ceramic will still be effectively strain isolated at peak temperatures but that the bond coat will begin to transmit stress at higher and higher temperatures as oxidation progresses and its creep behavior is modified. Thus the stress per cycle will steadily increase as the exposure to oxidation continues. Evidence of dramatically extended lives in flame-heated cyclic tests where the oxidation potential is kept low by using rich fuel-to-air mixtures supports the belief that little or no damage is done to the ceramic until the stresses imposed exceed some critical level. When this level is passed, relatively rapid coating failure will ensue as the inherent crack network is extended and coalescence of cracks leads to a large-scale delamination. When the delaminated area is heated, its temperature will rise very quickly and it may become
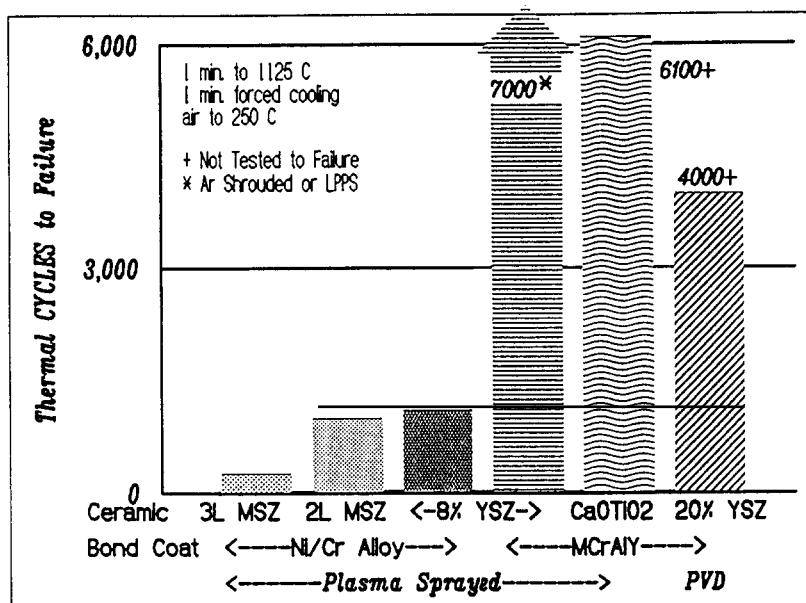
Fig. 1. Rig data on the effects of material and process variants on thermal cycle life.

incandescent. High compressive stresses from the restraint of relatively cool surrounding material can now cause local coating failure on the heat-up part of the cycle, sometimes with explosive force.

Figure 2 is a simple diagram that illustrates the basic hypothesis. Clearly, as described it refers to a well-designed component in a clean environment. Poor design, leading to gross overstressing on the first cycle, requires no oxidation to produce failure. Corrosive [16] and erosive [17] conditions depending on the situations can be considered in terms of an additional stress burden on the outer surface of the coating, leading to surface loss or further promoting large-scale loss of the whole coating.

The diagram can be used to help develop novel coating systems and programs for extending coating life, and experiments can be devised to test the hypothesis. In its current form it gives an adequate qualitative understanding of the factors which affect coating life. To produce a quantitative predictive method, the exact mechanisms and reaction kinetics
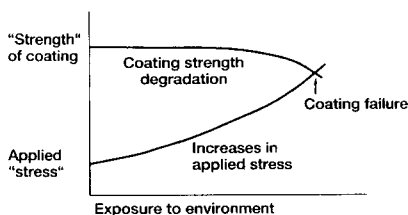

Fig. 2. Factors affecting thermal cycle fatigue life of TBCs.

and a sound process model are required, which will involve a massive amount of data. This is currently being addressed by most major TBC users. However, in parallel to this effort, some form of engine test work is a vital requirement, as it provides both cost and time efficiency in terms of quantitative data. It also eliminates doubt about the accuracy or otherwise of laboratory simulation work.

3. Service experience

3.1. Objectives

As a part of the ongoing program to develop TBC systems suitable for future use on turbine components, an in-service flight trial is being undertaken. One of the primary objectives is to cross-correlate simple laboratory rig tests with genuine turbine exposure, particularly to evaluate bond coat oxidation behavior. Consequently a long-haul operator has been selected. The baseline coating for the trial is the three-layer magnesium zirconate (3LMSZ) coating used on combustors since 1975 and used extensively in both laboratory and bench engine tests since then. Further objectives are (1) to identify any new degradation mechanisms and failure modes not already known from previous work and (2) to generate increased confidence in the capabilities of new coating systems which have performed excellently in the laboratory, but have had little exposure to real engine conditions.

This flight trial will thus provide a severe test for the behavioral hypothesis and generate considerable data towards making a quantitative model.

3.2. Test vehicle

For a flight service evaluation, the chosen component must not be dependent on the coating nor must its performance be prejudiced by the coating. It must have a reasonably high surface temperature and heat flux but have a fairly long life in service. These criteria are mutually incompatible, so any test vehicle component will be a compromise. After considerable debate, the RB211-22B intermediate pressure turbine nozzle guide vane (IPTNGV) platform was chosen as shown in Fig. 3. The uncoated platform runs at temperatures in excess of 925 °C (1700 °F). Prior work on a bench engine had shown that the nozzle guide vane platform application was considerably more demanding than the combustion chamber environment, but the vanes have a normal service life of around 12 000 h.

The coating was originally applied only to the inner diameter pressure side platform area to minimize the reduction in flow area through the throat of the vane set. More recently, however, the pressure side of the aerofoil of some vanes has been coated to within 1.25 cm (0.5 in) of the trailing edge, and 1.25 cm (0.5 in) has been wrapped around the leading edge towards the suction side of the aerofoil as shown by the shading in Fig. 3. The vane is nominally 20 cm long, 7.6 cm wide and 10 cm tall (8 in ×
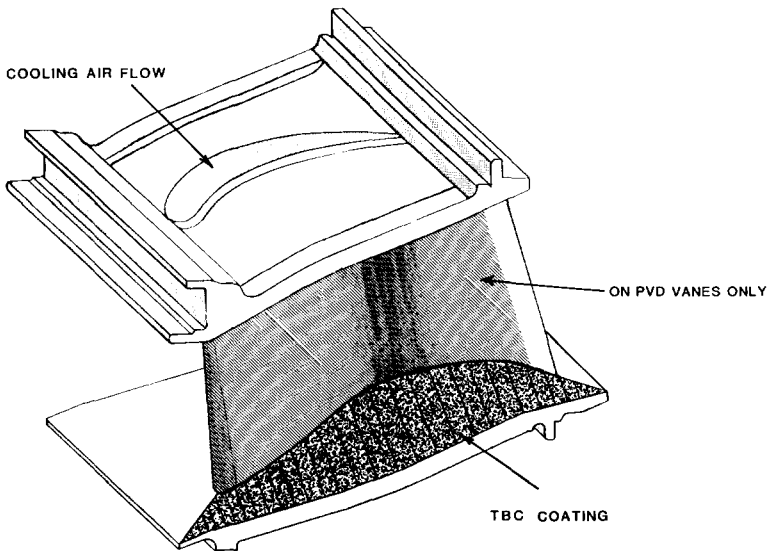
Fig. 3. RB211 IPTNGV with TBC.

3 in × 4 in). It is made of the nickel-base alloy C1023 and does not normally have any form of coating applied to it.

3.3. Coating systems evaluated

A metallic bond coat and a ceramic top coat constitute a TBC system. Variations in application technique, powder source, coating thicknesses and post-spray treatments make up the ten systems evaluated. These systems are listed in Table 1. Five different bond coat materials, which were applied by

TABLE 1

Coatings used on RB211 intermediate pressure turbine nozzle guide vane service evaluation

Identi- fication	Bond coat	APS ceramic	Bond coat method	Engines	Total number of vanes
A	Metco 443 + 441	MSZ	APS	1, 2, 3, 4	24
B	Metco 443	MSZ	APS	1, 2, 3a	12
C	Metco 443	YSZ	APS	1, 2, 3, 4	23
'D	CoNiCrAlY	YSZ	VPS	1a, 2b	5
E	CoNiCrAlY	YSZ	SPS	1, 2, 3, 4	23
F	CoNiCrAlY	YSZ	VPS	1b, 2, 4a	10
G	CoNiCrAlY	YSZ	APS	3, 4	11
H	NiCrAlY	$CaO \cdot TiO_2$	APS	1b, 2, 4a	10
I	NiCoCrAlY	YSZ (PVD)	PVD	1b	5
J	CoNiCrAlY	YSZ	APS	3a	5
Uncoated vanes					11
Total					139

four different techniques, have been evaluated. Three different ceramic materials applied by two different processes are included. The coatings were given designations for identification, *e.g.* coating B is two-layer magnesium zirconate (2LMSZ). The coatings were tested in rainbow fashion, typically five coatings per engine, five vanes per coating on four engines. The vanes were clocked to different locations in each engine as shown in Fig. 4. Coating A was installed in all four engines for a total of 24 vanes. Coating B was installed in engines 1 and 3 for a total of 12 vanes. Coating C used the same Metco 443 (NiCrAl) bond coat as coatings A and B but with a 6% - 8% yttria partially stabilized zirconia (YSZ) top coat. Coating C was installed in all four engines. Coatings A, B and C were applied by air plasma spraying (APS). Coating D has a CoNiCrAlY bond coat applied by vacuum plasma spraying (VPS) plus a 7% YSZ top coat. This coating was not used in the initial engine builds because the bond coat was applied too thickly (0.012 in instead of 0.005 in); it was, however, installed later at teardowns for builds designated 1a and 2b. Coating E has the same CoNiCrAlY bond coat as coating D, but it was applied by argon shrouding (shrouded plasma spraying (SPS)). The ceramic is 7% YSZ. Coating F is the same as coating D, but with the correct bond coat thickness.

Coating G is an APS variation of coatings D and E using the same (CoNiCrAlY) bond coat composition. This will now give us a direct comparison of the performances of bond coats applied by three significantly different techniques. The coating loss for coating G was 11% by area at 5400 h and 18% at 7000 h. This poor showing may be due to the use of a powder size that was too fine. New vanes have been sprayed with the correct powder and spray parameters and designated coating J. Coating H is $CaO \cdot TiO_2$ on an NiCrAlY bond coat. We originally became interested in this coating because of its claimed resistance to the acid leaching associated with the use of low grade fuels [18]. It did very well in thermal cycle rig tests
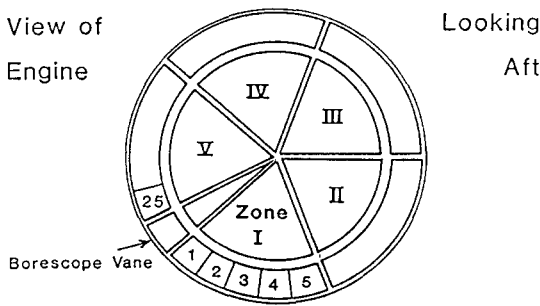
ENGINE ZONE	I	II	III	IV	V
NUMBER	COATINGS				
1	A	B	C		E
2	E	A	B	C	D
3	D	E	A	G	C
4	C	D	E	A	G

Fig. 4. Location of coatings used in service evaluation.

(Fig. 1) and was therefore added to this program on engine builds 1b and 4a. This coating has over 3300 h on it but has not been inspected yet.

Coating I has an NiCoCrAlY bond coat plus 6% YSZ, both applied by physical vapor deposition (PVD). The unique feature of this coating is its columnar structure which makes it very strain tolerant and gives it a very smooth finish. This coating has run for over 1400 h but has not been inspected yet.

After having demonstrated that some coating systems could last in excess of 5000 hours (roughly one overhaul period) on the vane platforms, we desired to move onto the airfoil with TBCs. We were, however, reluctant to do so since the APS coatings are very rough (more than 300 μin) as sprayed and even with polishing are still rougher than we desired (125 μin). The PVD ceramic surface finish proved to be only 50 μin, so we added it to the pressure side airfoil, avoiding the throat at the trailing edge and wrapping it around the leading edge suction side. A photograph of a PVD-coated vane is shown in Fig. 5.

Eleven vanes were uncoated, typically one per engine build; that brings the total to 139 vanes in the program as summarized in Table 1.
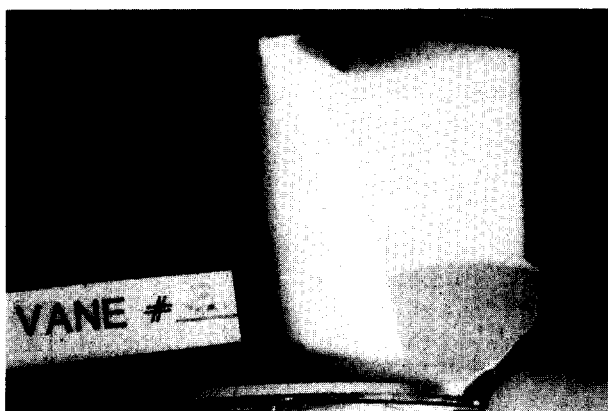

Fig. 5. Vane airfoil coated with PVD-applied MCrAlY + YSZ.

3.4. Variables

In addition to the variables mentioned such as varying coating thickness, some ceramics were polished and some were not. Most vanes were new, but 48 (12 of coating A, 11 of coating C, 11 of coating G and 14 of coating D) were cleaned-up used vanes which probably had been run for between 2000 and 4000 h.

3.5. Flight status

The flight status for the four engines as of March 1987 is given in Table 2. The time shown is for the longest exposed time TBC system on a given engine. Engine build 2 is close to 11 000 h now with 15 of its original

TABLE 2

Thermal barrier coating service evaluation status (February 1987)

Engine build	Flight hours	Inspection times (h)	Time (h) on new coatings	Number of original vanes
1	8886	4100, 7500	PVD YSZ (1400)	9
2	10887	2500, 9800		20
3	6887	6900		15
4	8765	5500	$CaO \cdot TiO_2$ (3300)	19

25 coated vanes. To obtain the approximate number of cycles, the time in hours should be divided by 2. At 9838 h, engine build 2 had 5013 cycles.

3.6. Results

Engine build 2 was removed on August 23, 1986, for exceeding the turbine gas temperature (TGT) limit on climb, so the vanes were perhaps running a little hotter than was typical at the end. The time on most vanes was 9838 h (5013 cycles). The engine report for this same set of vanes at 2539 h is given in ref. 5 and additional photographs are given in ref. 19. This engine had five different coatings systems, five vanes each, plus one uncoated vane (the borescope vane). The vanes were grouped together starting at the borescope vane going counterclockwise when looking aft (Fig. 4). The borescope vane is roughly at the 7:30 position so that the first group F is centered at approximately the 6:00 position.

At the 2500 h inspection one of each vane was removed for laboratory evaluation and replaced in kind. Unfortunately, they were not placed back in the engine in the desired positions as can be seen in the composite photograph in Fig. 6. This photograph shows the vanes *in situ* looking aft. The discoloration on the airfoils gives an indication of the thermal distress and circumferential temperature variations. The vanes are numbered counterclockwise with the uncoated borescope vane as number 26. The coating loss on vanes 5 - 8 and 13 should be noted.

3.6.1. Vane condition

Coating A suffered the highest amount of coating loss (spalling). One of the worst vanes (position 7) had lost 37% ceramic by area (Fig. 7) compared with only 3% at 2500 h. The average loss was 32% compared with 5% at 2500 h. 7.6 cm (3 in) of bond coat was also missing in the fillet radius of one vane. Photographs of the vanes at 2500 h can be found in refs. 5 and 19.

Coating B (2LMSZ) is significantly better than the 3LMSZ coating but still not acceptable. Vane 13 had 7.5% coating loss by area compared with no loss at 2500 h. Vanes 12 and 15 each had about 8 cm of bond coat missing in the fillet radius as seen in Fig. 8.

RB211-22B
IPT NGV at 9838 hrs/5013 cyc.
THERMAL BARRIER COATING SERVICE EVALUATION

Key: A · 3 layer MSZ
B · 2 layer MSZ
C · M443+YSZ
E · LCO22 (SPS)+YSZ
F · LCO22 (VPS)+YSZ

Fig. 6. Overall view of the TBC-coated vanes after 9800 h.

Coating C had very little coating loss, less than 5% by area. The Metco 443 bond coat was running cooler because of the lower conductivity of the YSZ ceramic than that of coatings A or B, and bond coat loss was minimal. Three vanes had ceramic loss in the fillet radius up to 2.5 cm (1 in). Vane 20 is shown in the photograph in Fig. 9. It shows bond coat loss in the fillet radius at midchord where not covered by the ceramic.

Coating F with the VPS bond coat does not look as good as coating C. The loss on vane 4 (Fig. 10) was 10%; the average loss was, however, only 3%. The bond coat itself was in excellent condition.
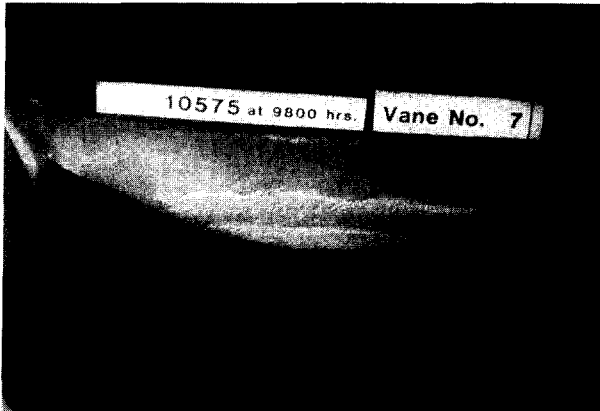
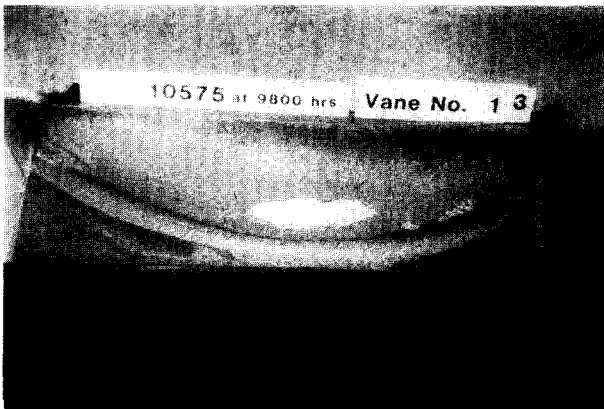Fig. 7. Coating A (3LMSZ) after 9800 h (5013 cycles).

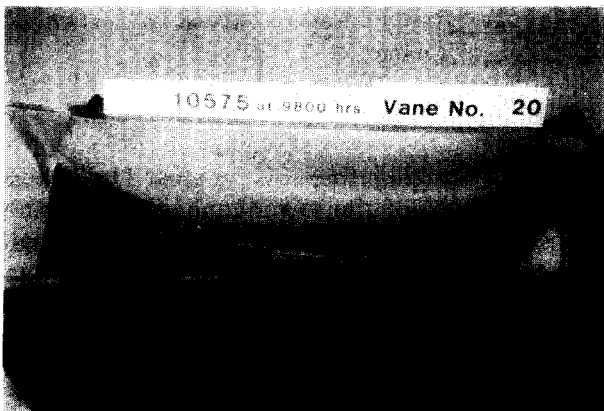Fig. 8. Coating B (2LMSZ) after 9800 h (5013 cycles).

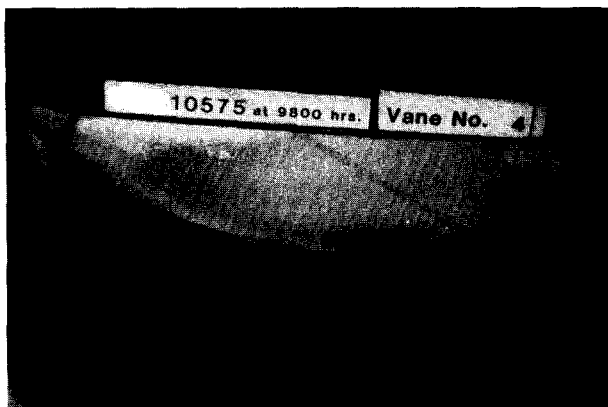Fig. 9. Coating C (Metco 443 + YSZ) after 9800 h (5013 cycles).

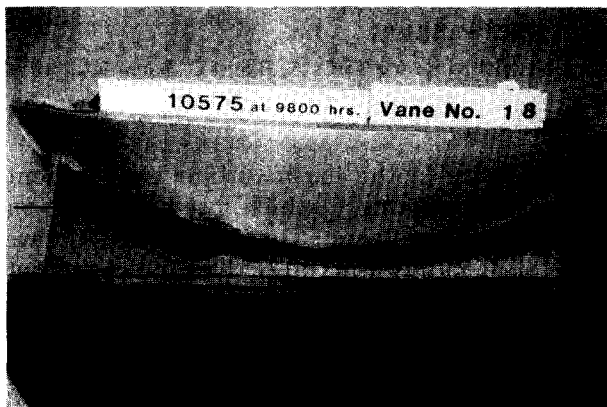Fig. 10. Coating F (VPS MCrAlY + YSZ) after 9800 h (5013 cycles).

Fig. 11. Coating E (SPS MCrAlY + YSZ) after 9800 h (5013 cycles).

Coating E, the argon SPS bond coat, had minimal ceramic loss, less than 1% by area, and those losses were associated with edge effects in the fillet radius as seen on vane 18 (Fig. 11). The bond coat on these vanes was in excellent condition. To date, this coating has consistently looked the best.

3.6.2. Coating loss with time

By measuring the area of coating loss and dividing it by the original area for each inspection period, we can obtain the percentage coating loss for each vane. Figure 12 shows the average loss for coatings A, B and C. The smooth curves were obtained from a regression analysis of the data. Figure 13 shows the improvement when high density bond coats such as those obtained by VPS and SPS are used. Area losses to both were small and the former is possibly applicator related.
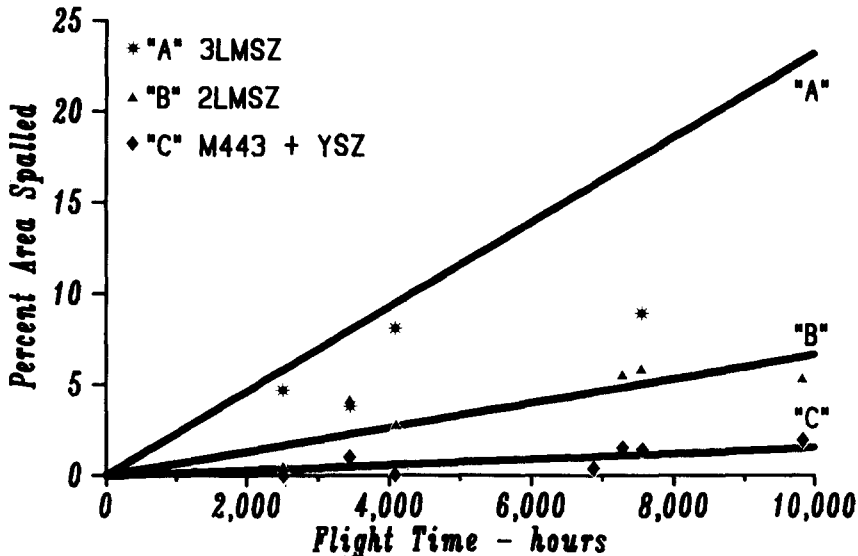
Fig. 12. Average percentage area spalled with time for TBCs A, B and C. Each data point is the average of four or five vanes.

The order of ranking for longevity in the harsh turbine environment is obvious from these plots except for coating C which lost bond coat on several vanes where it was not covered by ceramic. Toriz *et al.* [5, 19] have shown the bond coat loss in the fillet radius at 4100 h. This indicates that coating C is at (hot vanes) or near (cold vanes) its oxidation limit and will not be very useful at higher temperatures. The ranking therefore from this in-service program is as follows: (1) coating E, SPS CoNiCrAlY + YSZ; (2) coating D, VPS CoNiCrAlY + YSZ; (3) coating C, Metco 443 + YSZ; (4) coating B, 2LMSZ; (5) coating A, 3LMSZ.

3.6.3. Polishing

Coatings A - D and F were polished for engine builds 1 and 2. They seemed to roughen with flight time. The results are summarized in Table 3.

None of coating E or the coatings in builds 3 and 4 was polished, and those that were measured stayed at about 300 μin for up to 9800 h.

3.6.4. Erosion

Many of the vanes showed 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 flow path. This program indicates it will be an important factor even on parallel surfaces. This is probably due to secondary flows in the airfoil–platform intersection at midchord where the flow turns sharply. Most of the erosion on our NGVs shows up in the midchord region first because geometry constraints cause it to have the thinnest coating. Several
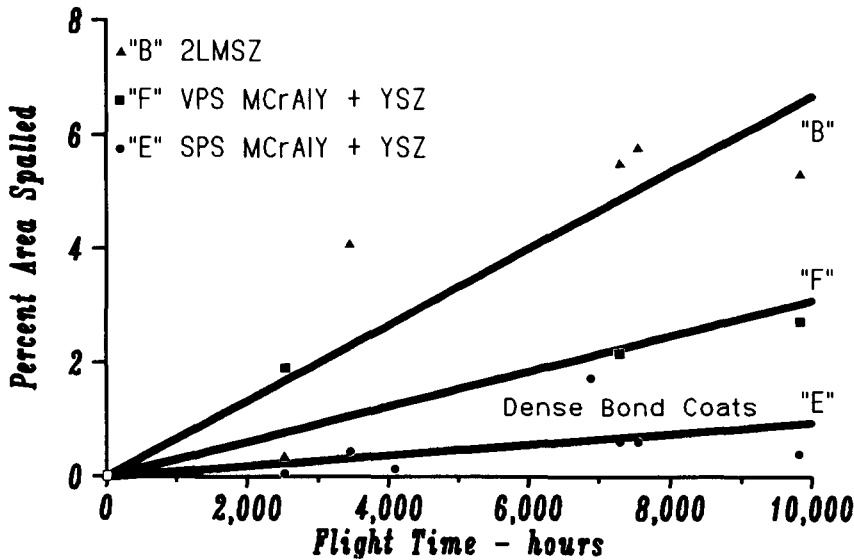
Fig. 13. Average percentage area spalled with time for TBCs B, E and F. Each data point is the average of four or five vanes.

TABLE 3

Change in surface roughness with time

Coating	Initial roughness (μin)	Final roughness (μin)	Time (h)
A	110	135	9800
B	110	200	9800
C	110	200	9800
D	130	185	3500
E	300	300	9800
F	110	150	9800

vanes polished early in the program were polished through the ceramic at this point, exposing the dark grey bond coat.

The change in length of this eroded area with time is an indication of the erosion severity. For example a vane with coating A at the 4100 h inspection was thin but had no bond coat exposed in the area of interest [5, 19]. The same vane at the 7500 h inspection had 1.8 cm (0.7 in) of bond coat (grey) exposed. Similarly, a vane with coating C had only 1.3 cm (0.5 in) of grey at 2500 h and 2.8 cm (1.1 in) at 9800 h. The vane in Fig. 8 has spalling, but no grey showing, in contrast with the vanes in Figs. 9 and 10 which have several centimeters of erosion (grey) showing.

Ceramics behave as brittle materials in erosion: they erode more severely with normal impact angles (90°) than with glancing blows (20°). A

recent Rolls–Royce erosion program agrees with the Garrett Turbine Engine Co. [20] data that indicate that normal erosion rates for APS YSZ will be of the order of four to five times as great as for 20° impingement.

One way to reduce the erosion rate significantly is with the use of PVD ceramics. Here again our recent erosion study confirms the Garrett [20] data, indicating that PVD YSZ is three to four times more erosion resistant than the standard APS YSZ.

4. Conclusions

Turbine components should be designed to make full use of TBCs which have now been demonstrated for 10 000 h in the harsh turbine environment using high density bond coats. We believe that these bond coats will be required for future turbine applications such as those on airfoils and especially on rotating airfoils.

To design these components, a life prediction model will be required which takes into account all possible stresses and material strengths on the basis of well-defined material specifications, process parameters and required metallographic structures.

The resultant model should be verified by comparing predicted lives with actual in-service data such as those presented in this report. The model could also be used to help develop coating systems and programs for extending coating life.

Erosion which is significant at 10 000 h on surfaces parallel to the flow stream may be significant at only 3000 h on vane leading edges or wherever normal impingement may occur. For airfoil applications that require smooth finishes and good erosion resistance, PVD ceramics may be the answer.

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