Editorial

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Thermal Barrier Coatings of the Future

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Thermal Barrier Coatings (TBCs) in current gas turbine engines routinely deliver metal temperature reductions of 50 to 80°C under normal conditions and as much as 140°C temperature reductions in hot spots (Ref 1). This temperature reduction can be used to lower metal component temperatures under constant operating conditions to achieve longer life, or to increase the performance of the engine through higher operating temperatures while maintaining constant life of the component, as indicated by the horizontal arrows in Fig. 1. A middle road of longer life and increased engine performance/efficiency is also possible. The choice of how to use the thermal benefits derived from TBCs is critical, especially if the intent is to follow the high economic payoff path of increasing the operating temperatures to increase engine efficiency. In this case, large increases in operating temperature and engine efficiency are possible with the insulating capability of TBCs. The problem is that if the temperatures are increased to take full advantage of the TBC insulating ability, and a large fraction of the coating spalls, the remaining bare metallic component would be subjected to high temperatures and unacceptably rapid degradation (Fig. 1). Obviously, the risk of coating failure must be balanced against the benefit of coating use.

It is worthwhile to examine the three general options for balancing TBC benefits against the risk of TBC failure. Of course, these three options can be implemented in myriad ways.

1. The first option is to use a fraction of the TBC capability to achieve some efficiency gains, but to limit the operating temperature increase to ensure that the component would not degrade severely if the coating spalled. In fact, this option is used in current engines by controlling engine conditions so that if a coating falls off, the component will survive to at least the next inspection cycle. At the time of the next inspection, coating failure would be discovered and the component health evaluated. In this case, the thermal benefit that can be taken is dictated by the component capabilities, not the coating capabilities. Therefore, any improvements in coating capabilities cannot contribute to increases in efficiency (Fig. 1).

   Whereas an improvement in the coating capability does not lead to an increase in efficiency, increases in coating durability will lead to less down time incurred by coating loss. Reducing the cost of down time and replacement of components at less than their full life makes the pursuit of increased TBC durability attractive. It should also be noted that current coatings typically survive the entire life of the component with little or no coating damage, let alone complete spallation.
2. A second possibility is to develop coatings that are "immune" to failure under engine operating conditions. Design of coatings that are "immune" to failure requires consideration of the statistical distribution of the capabilities of any given coating system (see Fig. 2). The coating capabilities plotted in Fig. 2 could be, for instance, coating life for a given thermal condition or coating temperature capability for a given lifetime. Development of failure "immune" coatings might be accomplished by developing coatings with greater capabilities, higher temperature capability (from Curve A to Curve B in Fig. 2), for instance, and then using the coatings well below the lower limits of the coating capability distribution (design point 1 as compared to design point 2 in Fig. 2). In this case, the thermal benefit to a component would be limited not by the component temperature capabilities but by the capabilities of the coating. As improvements are made in the coating, the thermal benefits would increase. In practice, the statistical distribution of coating capabilities often contains a number of "short time" failures. Although the statistical likelihood of "short time" failures is small, it is larger than is desirable for a coating that must be immune to failure. The oc-

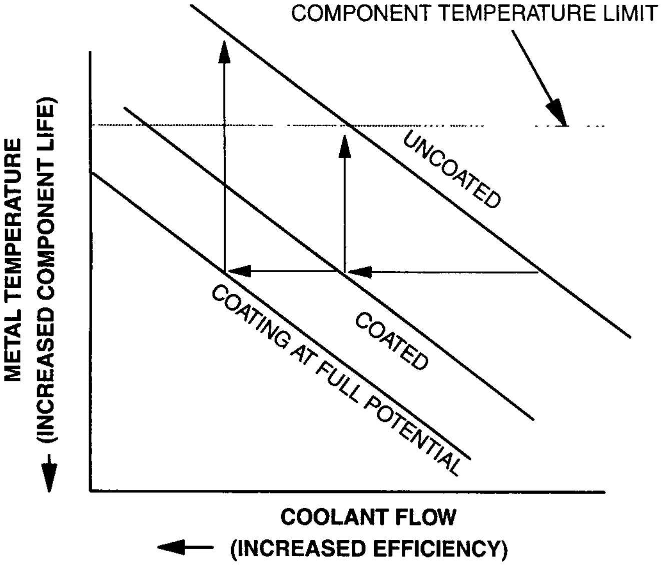

Fig. 1 The horizontal arrows indicate the increase in efficiency for a constant metal temperature made possible by addition of a TBC to an uncoated component. The vertical arrows indicate the jump in metal temperature that would occur if a large fraction of the coating spalled. The metal temperature jump for a coating used at its full potential exceeds the component temperature capability for a given component lifetime.

currence of short time failures is due to variable coating quality and a lack of suitable NDE methods to eliminate poor quality coatings.

Also, it is not clear if it will ever be philosophically acceptable to use a coating that must be 100% reliable. A compromise combining dramatically improved coating capability tempered by limits imposed by the metallic component in option 1 is possible. Specifically, it may be possible to set slightly more aggressive goals for engine operation than in option 1 if there is sufficient confidence in the durability of improved coatings (compromise design point in Fig. 2) and if the inspection cycles can be made shorter.

An encouraging point with regard to durability, reliability, and temperature capability is that there have been vast improvements over the last several years. These improvements have come in the form of increased control of coating processing, improved coating design, more robust coating compositions and structures, improved life prediction models and other areas. These durability improvements have resulted in the confident use of TBCs on critical components, such as turbine blades, albeit at a level where coating failure does not jeopardize the component, as described for option 1. Development of effective NDE methods for TBCs could provide a further jump in durability and reliability, and an attendant jump in user confidence.

3. The last means of increasing the benefits of TBCs is a step beyond the traditional coating development approaches noted in 1 and 2 above. This "non-traditional" approach would combine traditional coating development with "in-situ" TBC health monitoring systems. In the most ambitious form, a coating health system would monitor the coating during operation and be able to predict the remaining life of the coating. The sensors to monitor coating health could be internal sensors in "smart coatings" or sensors external to the coating. In either case, the sensory data would be analyzed in real time through the use of a fundamentals-based life prediction model covering all possible operating conditions. The system would enable an operator to make quick decisions regarding coating health and the impact of the coating health on the engine. In this way, the engine could be operated to use the coating capabilities more aggressively than in options 1 or 2 (see Fig. 3) and yet allow control of engine operation to avoid component damage if a coating was to fail. Such a system could also allow scheduling of maintenance on an as-needed basis system rather than setting schedules based on time of operation. This would save money by avoiding unnecessary downtime.

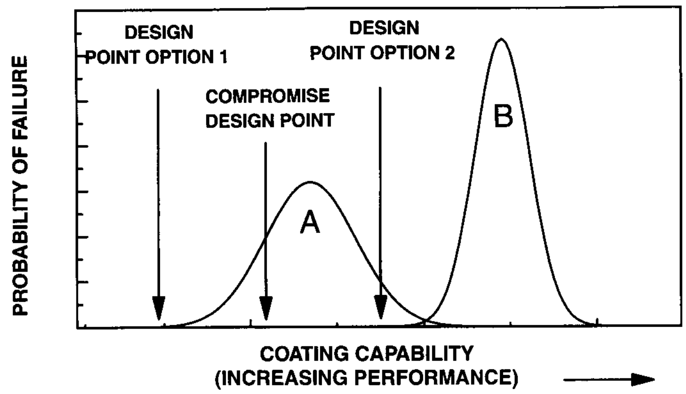

Fig. 2 The probability of a coating system having a certain capability is reflected by a statistical distribution. Curve B coating capability has a higher average capability and a small range, indicative of a coating with higher durability and higher reliability. Design point 1 schematically shows design with component temperature capabilities as a criterion, design point 2 shows design with a coating durability criterion and the compromise design point shows a possible design criterion for highly durable coatings and/or more frequent inspection cycles than option 1.

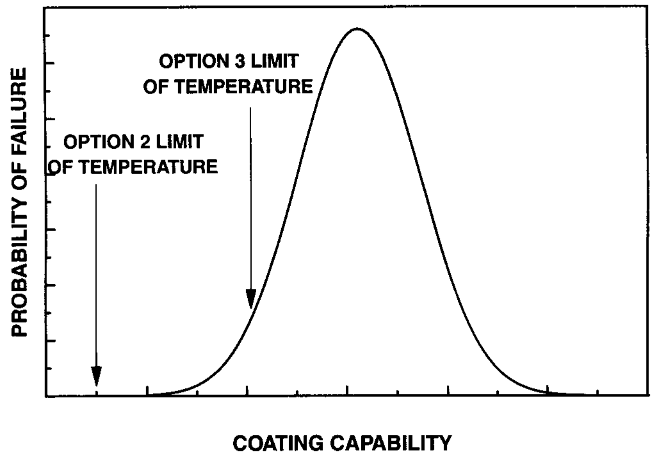

Fig. 3. Incorporation of a TBC health monitoring system could enable an increase in the temperatures at which a coating is used from that in option 2 for a highly durable coating. The system would monitor coating health and predict the remaining life of the coating.

The monitoring system is clearly a system of the future that first requires the successful completion of tasks that are being pursued currently. The challenges for current TBC development are significant: development of even more durable and reliable TBCs; development of NDE to establish tighter quality control of coatings as well as to inspect coatings in-service; and development of accurate, fundamentals-based life prediction models. Life prediction models further require not only methods appropriate to the task but also rigorous characterization of failure mechanisms and coating properties under a wide variety of conditions. The results of some of the current work pursuing these goals were presented at the 1995 TBC Workshop and are included in this and the next issue of this journal. The goal of the Workshop, sponsored by NASA, DOE, and NIST, was to provide a look at TBC history and current TBC development in order to define the significant challenges for future TBC development. It is hoped that these papers will provide a basis from which to pursue continued traditional advances in TBC technology that enable the non-traditional advances required for future engines.

References

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