Westinghouse Thermal Barrier Coatings Development

John G. Goedjen (407-281-5372)
Stephen Sabol (407-281-5136)
Westinghouse Power Generation
A Division of CBS
4400 Alafaya Trail, MC 303
Orlando, FL 32826-2399

Shyam Dighe (412-256-2235)
Westinghouse Power Generation
A Division of CBS
Science & Technology Center
Madison, PA 15633

Abstract

Westinghouse, under the Department of Energy - Oak Ridge National Laboratory Thermal Barrier Coatings (TBC's) Program, has focused on advancing the capabilities of TBC's to achieve the full benefits of this technology on the Westinghouse Advanced Turbine Systems (ATS) industrial gas turbine. Bond coat chemistries and processing are being optimized to extend the operational limits of TBC systems. Chemistries which promote the formation of a slow-growing, adherent oxide scale, and reduce interdiffusion offer potential performance improvements. New ceramic chemistries, alternatives to the current 8%YSZ thermal barrier coating, have been selected and evaluated to establish the long-term thermal stability required for reliable service on industrial gas turbines. The most promising of these materials systems have been tested under accelerated thermal conditions and will now be advanced to the recently completed Westinghouse High Heat Flux Test Facility. This plasma-fired test facility is capable of testing TBC systems under ATS thermal conditions. The use of a plasma thermal source has enabled Westinghouse to construct a highly controlled, highly automated, cost effective test facility. This advanced facility allows Westinghouse to define the operational capabilities of these advanced material systems in a controlled, low risk environment; insuring successful implementation on the Westinghouse ATS engine.

Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under contract DE-AC05-95OR22242 with Westinghouse Electric Corporation, 4400 Alafaya Trail, Orlando, FL 32826

Introduction

Westinghouse, in conjunction with the Department of Energy and Oak Ridge National Laboratory, has embarked upon a program for the development of advanced thermal barrier coatings for industrial gas turbines. Development of thermal barrier coatings (TBC's) for industrial gas turbines has relied heavily on the transfer of technology from the aerospace industry. Significant differences in the time/temperature/stress duty cycles exist between these two coating applications. Coating systems which perform well in aerospace applications may not been optimized to meet power generation performance requirements. This program is focused on development of TBC's to meet the specific needs of power generation applications.

The program is directed at developing a state-of-the-art coating system with a minimum coating life of 25,000 hours at service temperatures required to meet increasing operating efficiency goals. Westinghouse has assembled a team of industry leaders to accomplish this goal. Chromalloy Turbine Technologies, Inc. and Sermatech International, Inc. have provided bond coat and TBC deposition technology. Praxair Specialty Powders, Inc. has fabricated all bond coat and ceramic powders for the program. Southwest Research Institute is responsible for TBC life prediction modeling effort.

Westinghouse and its partners have deposited and put into test a number of new bond coat and TBC ceramic compositions to meet the goals of this program. Bond coat development is focused on optimizing and evaluating alternate deposition processes, and developing new bond coat chemistries which provide improved oxidation and interdiffusion performance. New TBC ceramics effort continues to test alternative ceramic chemistries, for both APS and EB-PVD applications, which will allow for increased operational temperatures over the current 8% yttria stabilized zirconia.

Bond Coat Development

Low Pressure Plasma Spraying (LPPS) remains the primary deposition technique for critical life components. LPPS results in high density, low oxide content bond coats. The High Velocity Oxygen-Fuel (HVOF) process offers a cost effective alternative to the LPPS process. The HVOF process does not require use of expensive vacuum systems; while providing high powder velocities which minimize the dwell time of the powder in the gas stream, thus minimizing oxidation. The high particle impact velocity produces a high density coating with high bond strength. In general, Air Plasma sprayed coatings have greater oxide content and greater connected porosity than HVOF coatings. The process, nonetheless, remains appealing for is cost benefit.

Bond coat testing under accelerated temperature conditions indicates that High Velocity Oxygen Fuel (HVOF) coatings, can provide, on average, comparable performance to an LPPS bond coat. These same tests indicate that Air Plasma Sprayed (APS) bond coats had superior performance as a bond coat, over LPPS bond coats, **Figure 1.**

Microstructural comparison of the furnace tested bond coats illustrates that the LPPS bond coat, **Figure 2,** had maintained a dense alumina scale at failure, with a significant amount of beta phase in reserve at the time of failure. In contrast, the APS bond coat contained a significant amount of internal oxidation, **Figure 3.** The internal oxides were formed as layers along the interconnected splat boundaries of the coating. Upon failure of the TBC, there was little beta phase in reserve. While

APS bond coat provides an improvement in TBC spallation life under accelerated furnace testing the, the significant internal oxidation and low beta phase content suggest that it will have a lower oxidation life, relative to LPPS, during engine operation.

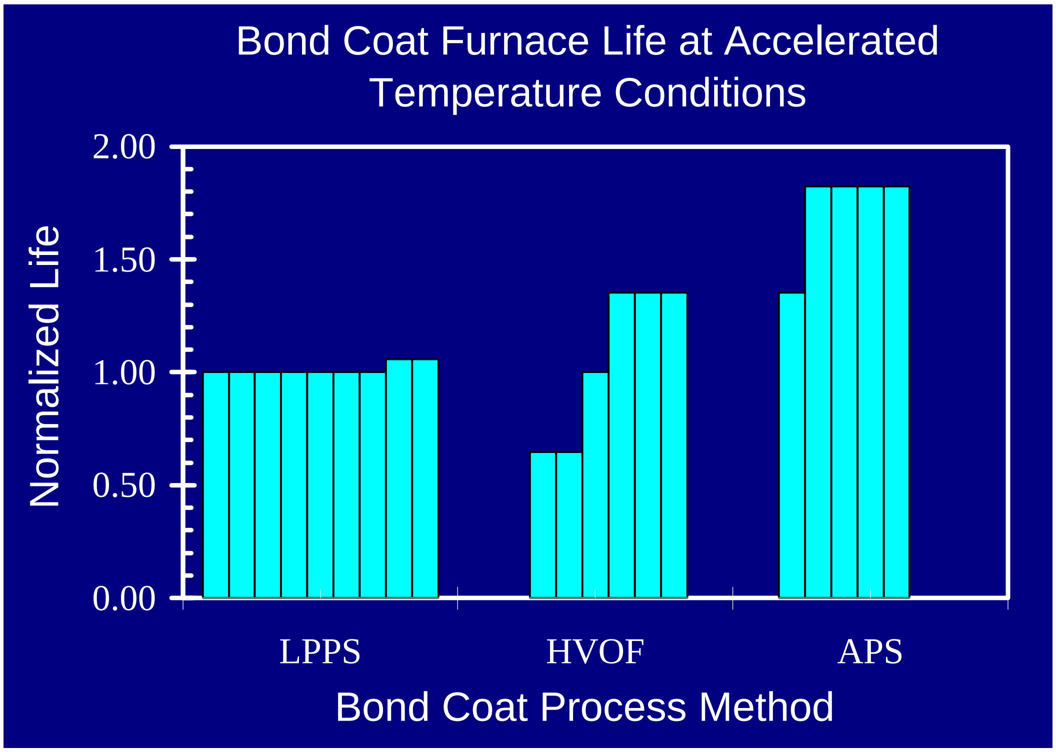

Figure 1. Normalized time to spallation under cyclic oxidation furnace test conditions.

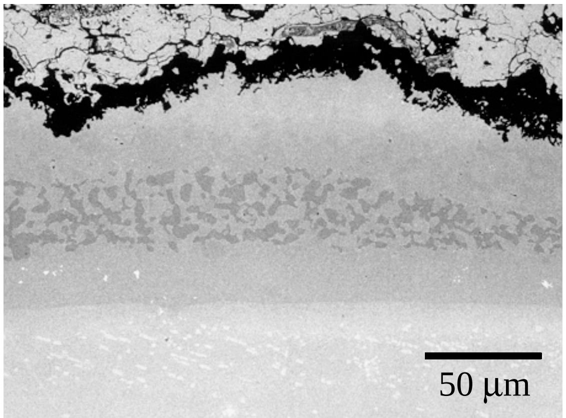

Figure 2. LPPS bond coat at failure.

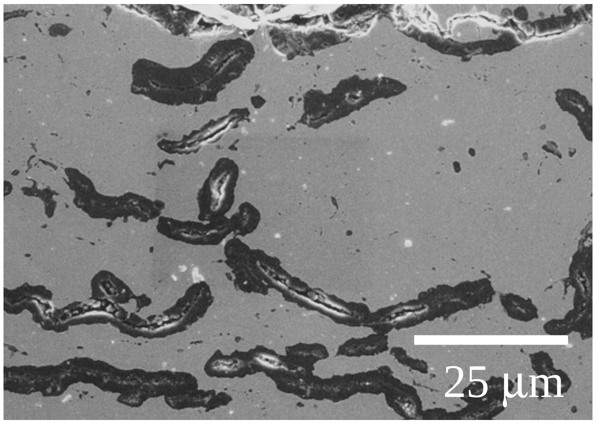

Figure 3. Internal oxidation along connected internal porosity boundaries within the APS bond coat.

Alternate bond coat chemistries are also being evaluated with the objective of reducing deleterious diffusion processes. Diffusion of aluminum from the bond coat to the substrate decreases the life of the coating system by reducing critical aluminum reservoirs needed to maintain a slow-growing alumina scale. Deleterious elements such as hafnium and sulfur can also diffuse from the substrate to the protective oxide layer; disrupting the protective capacity of the oxide.

Bond coat chemistries were formulated to establish a third phase within the bond coat to act as a physical and/or chemical diffusion barrier, **Figure 4**. These third phase additions have provided a performance improvement over conventional NiCoCrAlY bond coats under accelerated furnace test conditions. Furnace testing is continuing at nominal conditions more representative of engine operating temperatures to verify the long-term performance improvement.

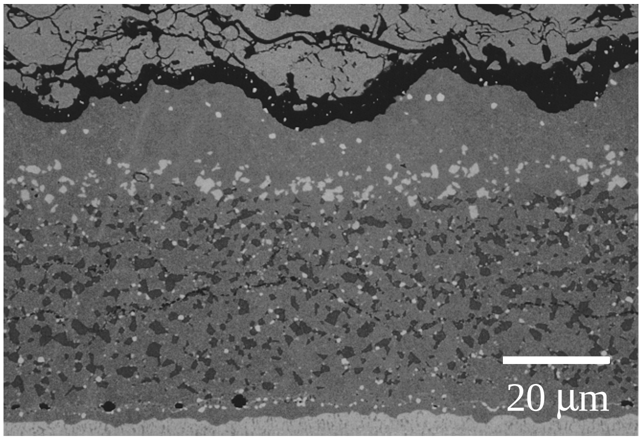

Figure 4. Third phase addition bond coat chemistry designed to reduce interdiffusion between the substrate and oxide.

TBC Ceramics

A systems approach to improving coating performance must also consider the ceramic thermal barrier. The use of 8% yttria stabilized zirconia has demonstrated performance in the aerospace industry. It has many desirable properties, thermal stability at high temperature, high thermal expansion and low thermal conductivity. While the life-limiting failure mechanism remains oxidation of the bond coat; it can be argued that improvements in the ceramic TBC performance under these circumstances is of secondary importance. As bond coat developments provide increased oxidation resistance, the influence of ceramic TBC properties on coating durability will increase. While the development of new ceramics is a challenging task; there are tremendous commercial benefits in extending the operating temperature range of thermal barrier coatings. It is not enough to simply increase the operating temperature limits, the 24,000 hour life must also be maintained.

Ceramic material candidates must exhibit long-term stability at high temperatures. Phase constituents, thermal conductivity and strain compliance must be maintained over the life of the coating system. Selection of ceramic alternatives to conventional 8% yttria stabilized zirconia (8YSZ) is a challenging task. The paucity of data, such as thermal conductivity and phase diagrams requires extensive laboratory screening before committing to development scale deposition trials.

Westinghouse has deposited a number of alternate ceramic materials by both APS and EB-PVD techniques. These ceramics are being evaluated as free-standing coatings at high temperatures to establish their long-term phase stability. The materials are aged at temperatures of greater than 1200ºC. The stability of the materials is then evaluated using x-ray and thermal conductivity measurements.

The new ceramics are also deposited onto bond coated substrates. While this limits the temperatures to which the ceramics can be tested, it provides insights as to the performance of the ceramic as part of the complete coating system. For example, the potential for reaction of the TBC ceramic with the protective alumina scale must also be evaluated. The TBC may react with the protective alumina scale, forming a non-protective oxide, **Figure 5**, decreasing coating life. If the reaction is kinetically slow, the reaction zone between the TBC ceramic and alumina scale has the potential to increase adhesive strength of the TBC, potentially improving thermal fatigue life without compromising oxidation performance.

The coating deposition process can result in chemical and phase composition changes from that of the precursor powders. The rapid solidification of molten particles during deposition, or the evaporation of volatile components can result in compositional and phase changes between the precursor ceramic and the final coating. A single phase material may be deposited as a two phase as a direct result of processing. **Figure 6**. Evaporation and condensation of ceramics in the EB-PVD process can pose similar processing results. While the presence of multiple or non-equilibrium phases does not always pose a decrease in TBC system life, the long-term stability of all phases must be carefully assessed.

In developing new ceramics, it is important to realize that conditions which provided optimal performance for conventional 8YSZ materials, may not be optimal for new chemistries. In developing new ceramics for APS, extensive Design Of Experiment deposition studies are performed to optimize performance. Each chemistry is deposited over a range of conditions, providing a range of deposition and coating characteristics, such as density and porosity distribution. Each of these samples is tested to develop optimal coating properties representative of the new chemistry.

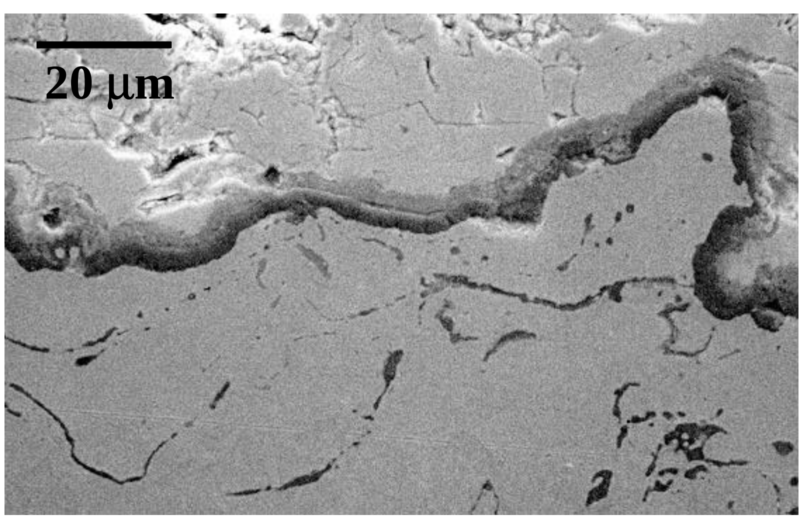

Figure 5. Deleterious reaction between the ceramic TBC and the protective alumina scale.

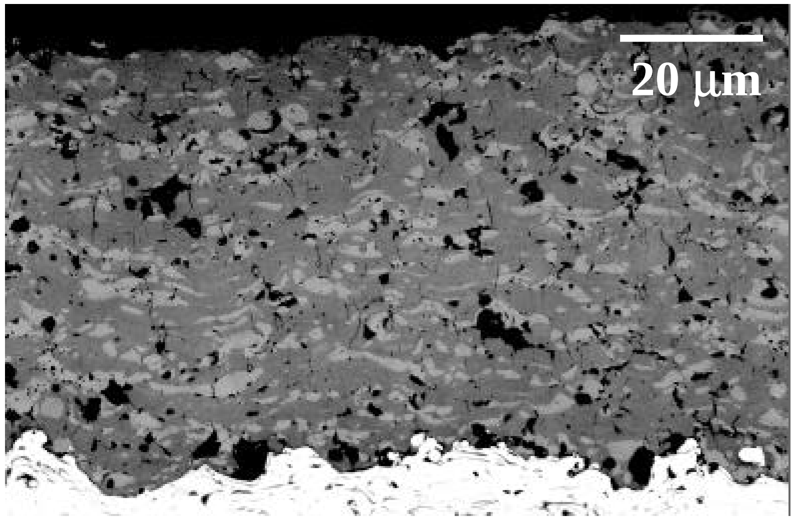

Figure 6. A multiphase coating resulting from plasma sprayed deposition of a single phase ceramic powder.

High Heat Flux test Facility

Furnace testing is an efficient means of evaluating the performance of TBC systems. Such testing enables a determination of oxidation resistance, thermal shock resistance and TBC adherence. The temperatures at which new ceramics/bond coat systems can be evaluated under isothermal condition s is limited by the temperature limits of the bond coat. The bond coat and substrate alloys have limited life at the temperatures required to evaluate the long-term stability of alternative ceramics. In testing TBC systems under iso-thermal conditions, the effect of the temperature gradient on TBC system life is also lost. For example, the effect of sintering at the TBC surface on TBC life can not be easily demonstrated in an isothermal test.

The TBC surface temperature, the bond coat temperature and the associated ΔT across the TBC have a synergistic effect on coating life which cannot be captured in an isothermal test. To evaluate these effects in a controlled manner, for existing and advanced TBC systems Westinghouse has constructed a state-of-the-art High Heat Flux Test Facility.

In developing the test facility a number of key criteria were used to establish the appropriate thermal source. Of key importance was the ability to obtain ATS thermal conditions across the sample. It was clear that conventional radiant or inductive sources lacked the necessary power and heat transfer capability required to achieve the required temperatures. This was also true for ambient pressure, liquid or gas fueled burner rigs in common use. While these systems are quite capable of achieving high temperatures under isothermal conditions, they could not provide the high heat flux required for a thermal gradient test. Pressurized burner rigs, combustion rigs and E-beam systems were also evaluated. To make the test facility affordable, the rig needed to be capable of running 24 hours a day with minimal personnel oversight. These systems posed safety concerns which made unattended operation difficult and cost prohibitive.

The two prime candidates for the thermal source were a plasma torch or laser. Lasers have been in use for TBC testing for some time. They offer a highly controlled, stable thermal source for thermal gradient testing. Zirconia is transparent to wavelengths of less than 8 microns. The use of a short wavelength laser, less than 8microns, requires that a coating, typically an oxide, be applied to the surface of the TBC to ensure that the laser energy is absorbed, rather than transmitted through the zirconia. These couplant coatings, if not chosen carefully can degrade the performance of the TBC. Such couplants can accelerate sintering of the TBC, or alter the composition and phase constituents of the TBC at the required exposure times and temperatures. The use of a long wavelength CO_2 laser is attractive because it does not require use of couplants for most oxide ceramics. While the use of a CO_2 laser source was attractive, restrictions on sample geometry and beam uniformity over the spot sizes required for TBC testing remained a concern.

Plasma torches have also been effectively used for testing TBC's under high thermal gradient conditions. The plasma provides a high temperature thermal source capable of meeting the temperature requirements of the test. While the plasma has a high radiant energy component, a significant amount of convection heat transfer can be achieved. The torches can be operated at ambient pressure, they are amenable to automation and provide a highly controlled, reproducible thermal source. The development risk in using a plasma was also significantly less for the plasma system than for the laser system because of established Westinghouse experience base in plasma torch design and construction.

The plasma torch was selected as the thermal source for the High Heat Flux Test facility. The plasma is focused onto a rotating hollow cylinder sample. The sample can be either water or air cooled, **Figure 7.** The bond coat temperature is measured using an embedded thermocouple. The surface temperature is measured using an optical pyrometer. The system is integrated with both computer control and computer data acquisition systems.

The plasma torch High Heat Flux Test facility is currently being used to define the design envelope for advanced TBC systems. Initial tests on an APS TBC were successful in demonstrating the effect of ceramic sintering. Sintering of the ceramic caused densification and loss of strain compliance in the coating as evidenced in **Figure 8**. The sintering resulted in a layered spallation of the TBC. As each layer spalled, the total thermal resistance of the coating decreased resulting in a decrease in surface temperature, **Figure 9.**

Continued testing of both APS and EB-PVD TBCs will provide critical insights and data for understanding the operational limits of these TBC systems. Such testing will be used to support lifing model effort.. As advance bond coats and ceramics are advanced within the program, they will be evaluated at the High Heat Flux Test Facility.

Acknowledgments

Research sponsored by the U.S. Department of Energy's Morgantown Energy Technology Center, under contract DE-AC05-95OR22242 with Westinghouse Electric Corporation, 4400 Alafaya Trail, Orlando, FL 32826

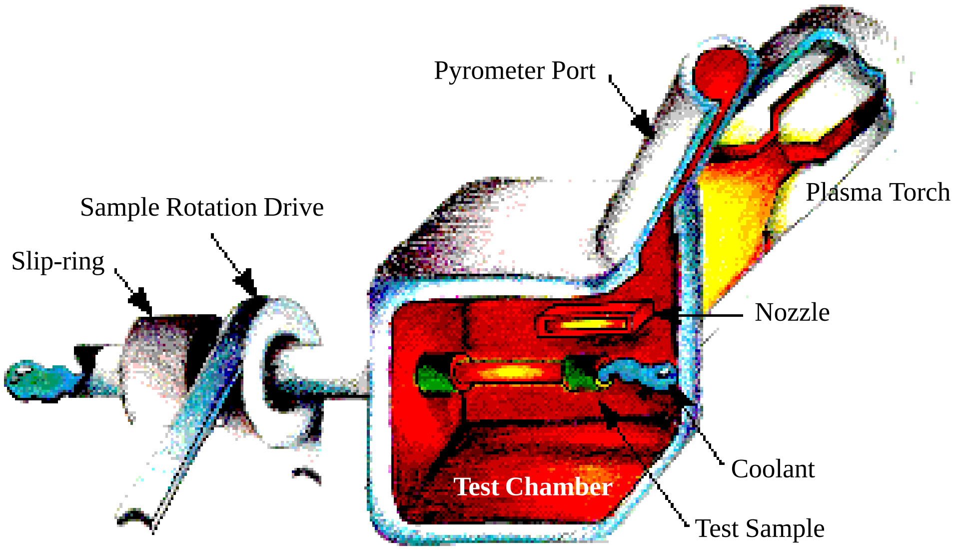

Figure 7. Schematic illustration of High Heat Flux Test Facility.

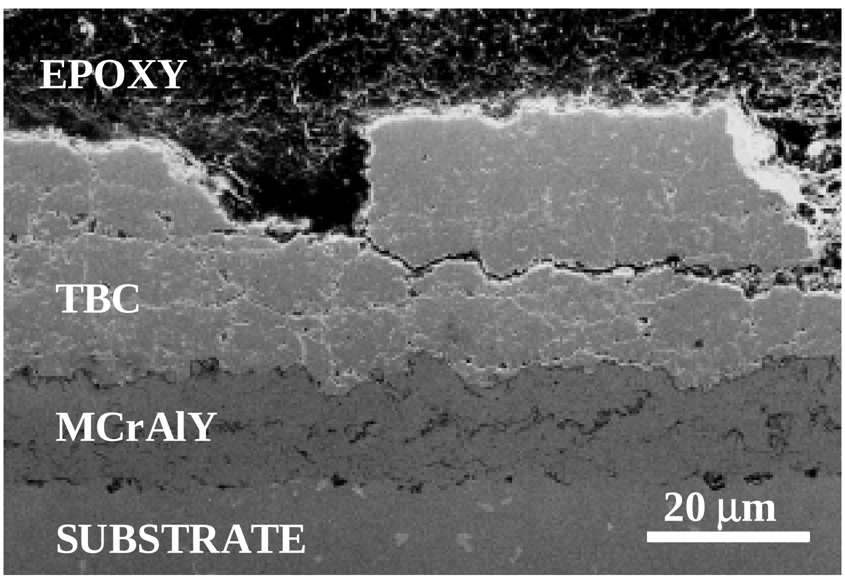

Figure 8. Spalled surface of an APS TBC.

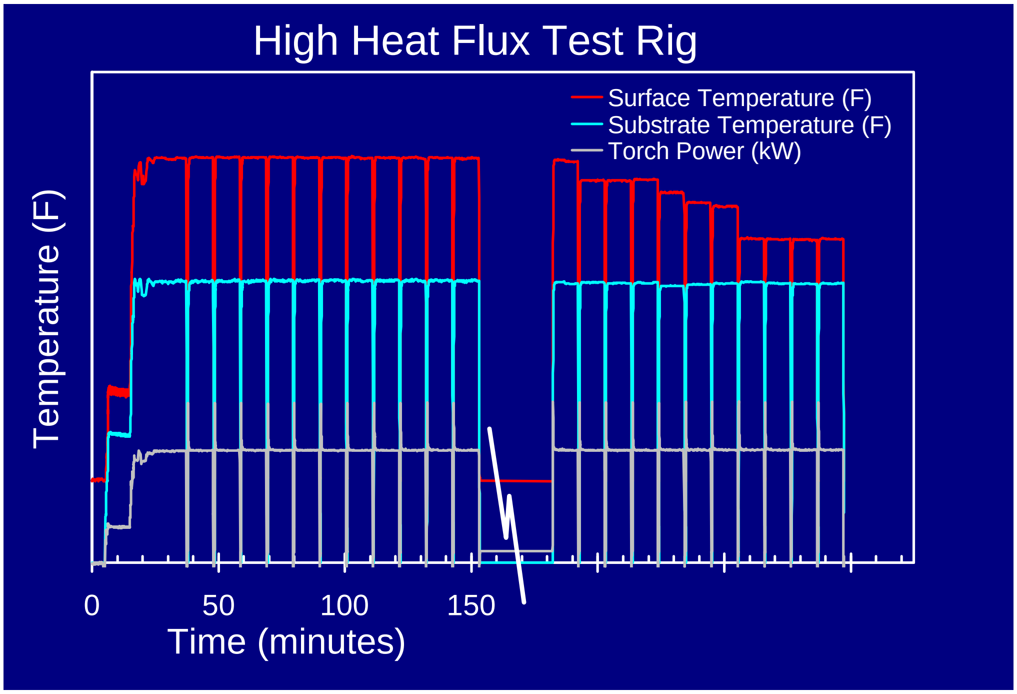

Figure 9. Characteristic time/temperature plot illustrating the stability and reproducibility of the plasma torch test. The decrease in surface temperature occurred as a result of layer spallation of the TBC.