ADVANCED THERMAL BARRIER COATINGS FOR OPERATION IN HIGH HYDROGEN CONTENT FUELED GAS TURBINES

FINAL PROGRESS REPORT

Reporting Period Start Date: 10/1/2010
Reporting Period End Date: 12/31/2014

Reporting Date: April 2, 2015

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DOE Award: DE-FE0004771

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OUTLINE

EXECUTIVE SUMMARY

The Center for Thermal Spray Research (CTSR) at Stony Brook University in partnership with its industrial *Consortium for Thermal Spray Technology* is investigating science and technology related to advanced metallic alloy bond coats and ceramic thermal barrier coatings for applications in the hot section of gasified coal-based high hydrogen turbine power systems. In conjunction with our OEM partners (*GE* and *Siemens*) and through strategic partnership with Oak Ridge National Laboratory (ORNL) (materials degradation group and high temperature materials laboratory), a systems approach, considering all components of the TBC (multilayer ceramic top coat, metallic bond coat & superalloy substrate) is being taken during multi-layered coating design, process development and subsequent environmental testing. Recent advances in process science and advanced *in situ* thermal spray coating property measurement enabled within CTSR has been incorporated for full-field enhancement of coating and process reliability.

The development of bond coat processing during this program explored various aspects of processing and microstructure and linked them to performance. The determination of the bond coat material was carried out during the initial stages of the program. Based on tests conducted both at Stony Brook University as well as those carried out at ORNL it was determined that the NiCoCrAlYHfSi (Amdry) bond coats had considerable benefits over NiCoCrAlY bond coats. Since the studies were also conducted at different cycling frequencies, thereby addressing an associated need for performance under different loading conditions, the Amdry bond coat was selected as the material of choice going forward in the program. With initial investigations focused on the fabrication of HVOF bond coats and the performance of TBC under furnace cycle tests , several processing strategies were developed. Two-layered HVOF bond coats were developed to render optimal balance of density and surface roughness and resulted in improved TBC lifetimes. Processing based approaches of identifying optimal processing regimes deploying advanced in-situ coating property measurements and in-flight diagnostic tools were used to develop process maps for bond coats. Having established a framework for the bond coat processing using the HVOF process, effort were channeled towards fabrication of APS and VPS bond coats with the same material composition. Comparative evaluation of the three deposition processes with regard to their microstrcuture , surface profiles and TBC performance were carried out and provided valuable insights into factors that require concurrent consideration for the development of bond coats for advanced TBC systems.

Over the course of this program several advancements were made on the development of durable thermal barrier coatings. Process optimization techniques were utilized to identify processing regimes for both conventional YSZ as well as other TBC compositions such as Gadolinium Zirconate and other Co-doped materials. Measurement of critical properties for these formed the initial stages of the program to identify potential challenges in their implementation as part of a TBC system. High temperature thermal conductivity measurements as well as sintering behavior of both YSZ and GDZ coatings were evaluated as part of initial efforts to undersand the influence of processing on coating properties. By effectively linking fundamental coating properties of fracture toughness and elastic modulus to the cyclic performance of coatings, a durability strategy for APS YSZ coatings was developed. In order to meet the goals of fabricating a multimaterial TBC system further research was carried out on the development of a gradient thermal conductivity model and the evaluation of sintering behavior of multimaterial coatings. Layer optimization for desired properties in the multimaterial TBC was achieved by an iterative feedback approach utilizing process maps and in-situ and ex-situ coating property sensors. Addressing the challenges pertaining to the integration of the two materials YSZ and GDZ led to one of most the critical outcomes of this program, the development of durable multimaterial, multifunctional TBC systems.

APPROACH AND ACTIVITIES

Task 2: Bond Coat Processing and Evaluation

Task 2.1: Bond Coat processing and Microstructural Evaluation/TGO stress measurements

One of the key elements of a TBC system is the bond coat, its composition and microstructure. Due to the highly processing sensitive nature of these metallic alloys detailed investigations were carried out on the identification of processing regimes which render optimal coating performance. Exploring deposition techniques such as APS, VPS and HVOF in the context of bond coat development and TBC durability provided key insights during this program.

Task 2.2: Determination of bond coat oxidation behavior in high temperature water vapor/Evaluation of VPS bond coats

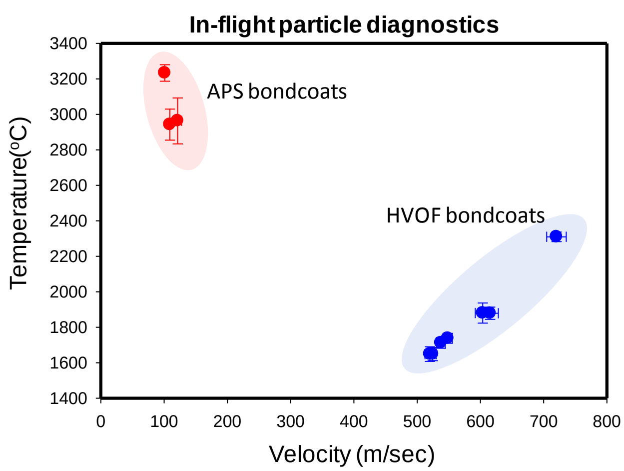
Investigations were carried out to study the influence of water vapor at high temperatures during the cycling of TBCs. While no significant microstructural changes were observed in the TBC a thicker TGO was observed for the bond coats cycled in the presence of water vapor. The evaluation of VPS bond coats and their effect on TBC performance was carried out to further understand bond coat oxidation behavior. Engineered/layered bond coat strategies were also implemented with the VPS coatings to further advance the benefits of processing science on bond coat development.

Task 2.3: Final selection of bond coat material for system level coating

The selection of bond coat material was based on their performance under oxidation tests carried out to evaluate TBC durability. The presence of rare earth elements seemed to strongly influence the bond coat performance. The final down selection was carried out in collaboration with ORNL where similar trends in bond coat material performances were observed.

RESULTS AND DISCUSSION

The utilization of in-flight particle diagnostics enables the assessment of processing regimes to meet specific coating requirements. Extensive diagnostic measurements coupled with in-situ curvature based stress measurements were carried out to arrive at optimized coating architectures. A representative plot of the particle diagnostic measurement as wells as coating's stress measurements has been shown in Figure 1. While HVOF bond coats were used for majority of the TBC developmental activities APS bond coats were also investigated for their oxidation behavior and performance. A layered bond coat architecture was adopted to render the optimal combination of density and surface roughness to HVOF coatings. Similar schemes were investigated with a combination of HVOF and APS coatings as well. One of the highlights of this program with regard to bond coat processing has been the identification of processing regimes and development of process maps which can provide a means to design similar MCrAlY bond coats for TBC applications.



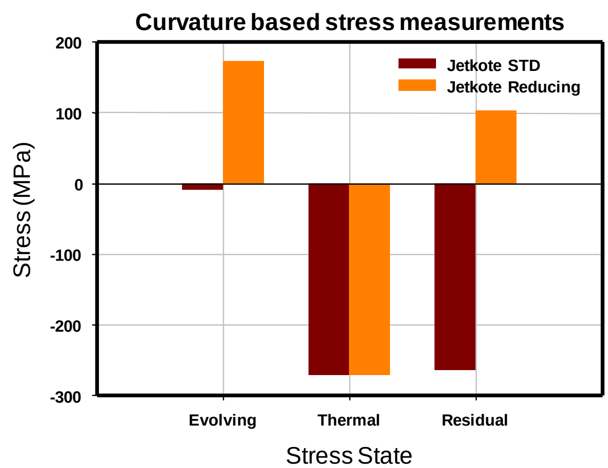


Figure 1: Development of process maps for bond coats deposited with different processes. In situ curvature based stress measurements help tailor processing condition to optimize residual stresses in coatings

To address the concerns of water vapor at high temperatures and its detrimental effect on bond coats, some preliminary investigations were conducted on HVOF bond coats. The microstructures comparing bond coats cycled for similar time periods (72 hours) under ambient nad moist conditions is shown in Figure 2. While it does appear that the coatings under water vapor environments form a thicker TGO, further quantification and analysis would be required to outline possible mechanisms at play in such scenarios.

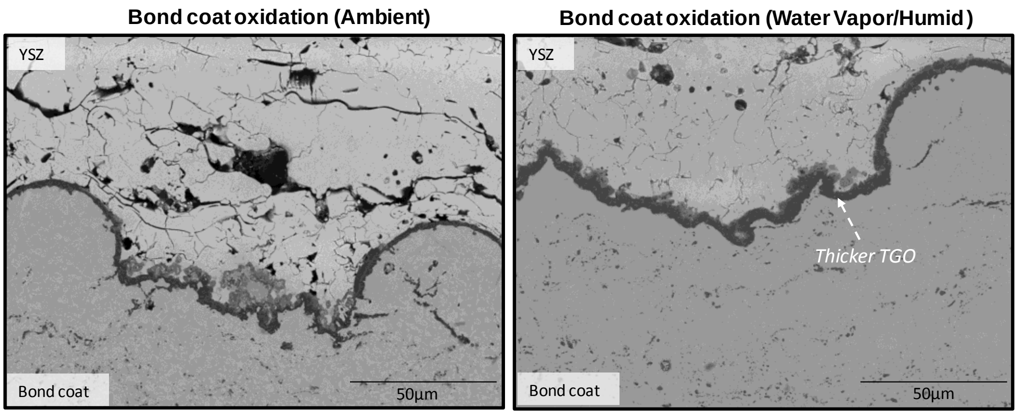


Figure 2: Oxidation behavior of bond coats under high temperature water vapor environments.

Vacuum Plasma Sprayed (VPS) deposition presents immense potential in fabrication of bond coats for TBCs and hence was one of the aspects that were investigated during this program. VPS coatings were evaluated in collaboration with CTSR's consortium member Mitsubishi Hitachi Power Systems. The feedstock composition was kept the same (NiCoCrAlYHfSi) as the HVOF and APS bond coats to facilitate direct comparison of processes. Having established the two layered bond coat strategy for the HVOF process a similar approached was extended to VPS coatings as well. The microstructures of the VPS coatings have been shown in Figure 3.

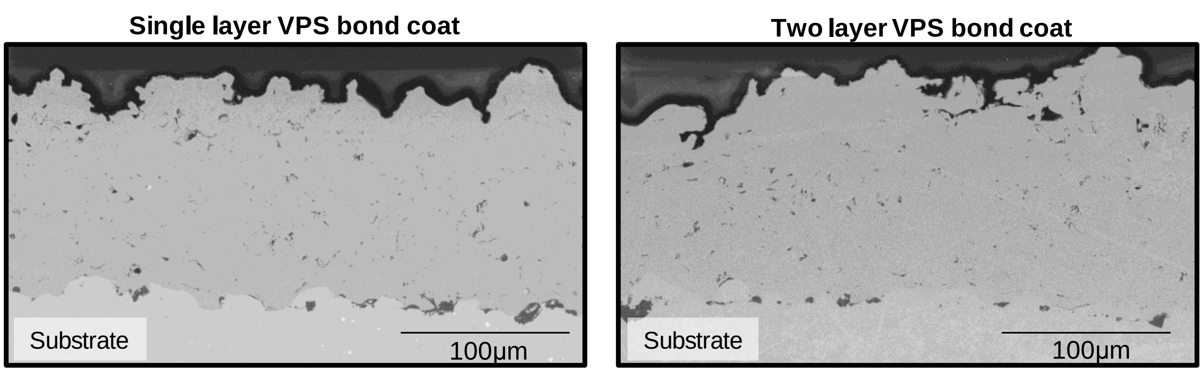


Figure 3: Evaluation of VPS bond coats. Processing strategies of depositing two layered coatings were extended to these processes

Figure 4 illustrates the key milestones that were accomplished with regard to the bond coat development during the program. A synthesis of the critical elements with regard to bond coat composition, oxidation behavior and process selection can be summarized as follows:

- MCrAlY based bond coat material was investigated in detail for their processing, property and performance assessment. The presence of rare earth elements Hf and Si increased the TBC cyclic life and hence the NiCoCrAlYHfSi material was chosen for all the developmental activities during this program

- The development of process maps has greatly enabled the identification of optimal processing regimes specific to each deposition technique (HVOF, APS). The measurement of coating stresses during deposition ,combined with microstructural assessment provides a robust platform to transition fundamental knowledge to address system level issues
- The oxidation behavior of bond coats is sensitive to the processing conditions as well as deposition technique. Greater inter-lamellar oxidation is a common feature of APS coatings while HVOF coatings exhibit lower internal oxidation.
- Collective assessment of the various deposition processes of bond coats suggests that surface roughness clearly plays a part in governing TBC life as evidenced by the single layer and two layer bond coats. VPS bond coats by far offer the maximum cyclic durability for TBCs

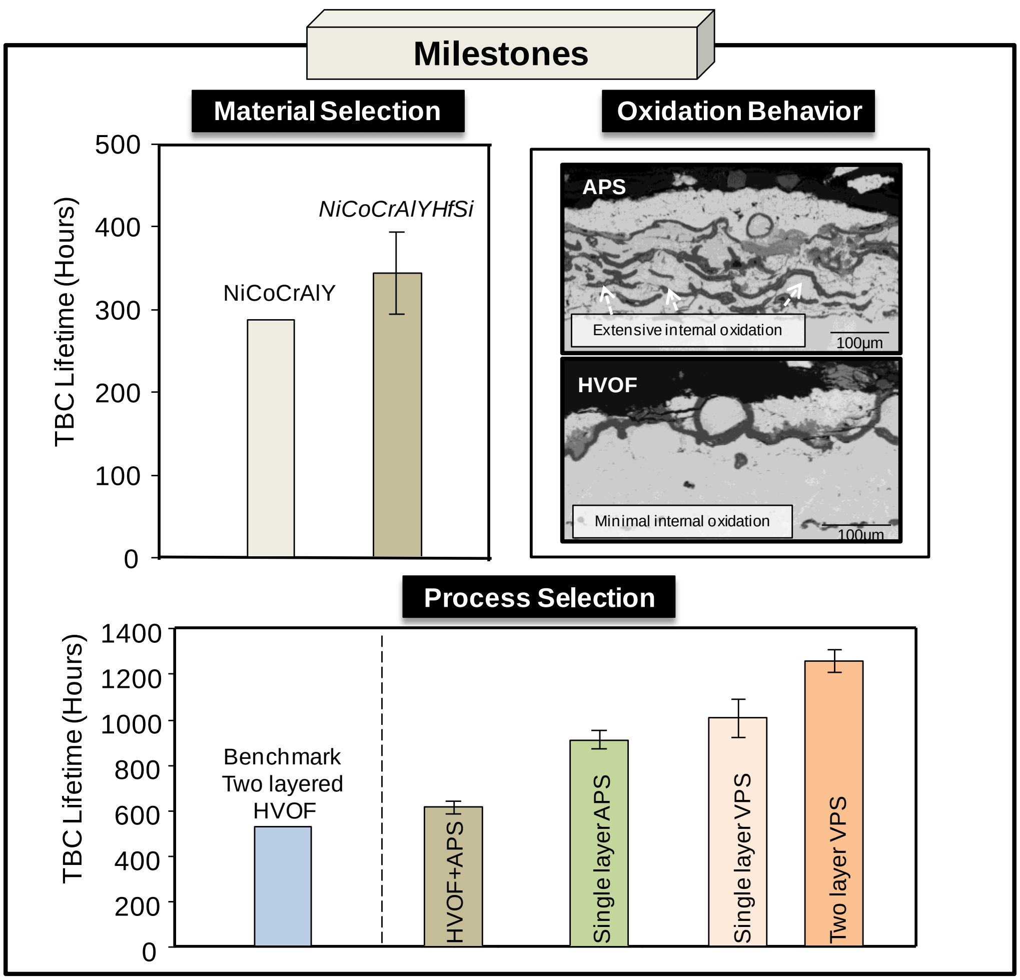


Figure 4: Compilation of key milestones accomplished on bond coat processing and microstructural evaluation. Rare earth containing bond coat compositions chosen for improved TBC life. Oxidation and TGO growth investigated for different bond coats. Overall assessment of various bond coat processes and strategies carried out in the context of TBC life.

Task 3: Thermal Barrier Coating Processing and Evaluation

Task 3.1: Process optimization of zirconates using diagnostics and in-situ property sensing

The introduction of gadolinium zirconate coatings as part of a multilayered TBC was initiated by carrying out extensive process optimization and in-situ coating property measurements. By developing first order and second order process maps of zirconates robust correlations were established between processing conditions and properties of TBCs.

Task 3.2: Evaluate sintering behavior of bi layer TBCs/Evaluating design strategies

To address oxidation driven failure mechanisms of TBCs a bi layered TBC strategy was conceptualized and tested extensively. The design strategies formulated based on the assessment of fundamental properties and rigorous testing provided vital insights into the behavior of such bi layered TBCs. Sintering behavior was evaluated for select specimens under gradient conditions as well.

Task 3.3: Determine thermal conductivity changes under thermal gradient exposure/Quantitative non-destructive evaluation

Gradient thermal conductivity model was developed and analyzed for both GDZ and YSZ systems. The results obtained from calculations showed the excellent sintering resistant properties of GDZ coating. The advantages of using GDZ as a top layer in a multilayered TBC were quite evident from the results.

Task 3.4: Determine co-efficient of expansion of Gadolinum Zirconate coating

The thermal expansion co-efficient of Gadolinium zirconate was extracted from dilatometer measurements prior to integrating it as part of a multilayer TBC.

RESULTS AND DISCUSSION

As part of the efforts aimed at the development of advanced thermal barrier coatings for this program, systematic incorporation of new TBC composition to the existing YSZ platform was carried out. Gadolinium zirconate was the material of choice due to its demonstrated capabilities in mitigating CMAS/ash attack as well as high temperature stability. Process map development for zirconates with YSZ as the baseline was initiated. Simultaneously the assessment of deposition related stresses in TBCs using the in-situ coating property sensor provided critical inputs for coating design. The significantly different properties of different TBC compositions present challenges in integrating them into a single system. Figure 5 presents a representative plot of particle diagnostics and in-situ measurement of stress for gadolinium zirconate coatings

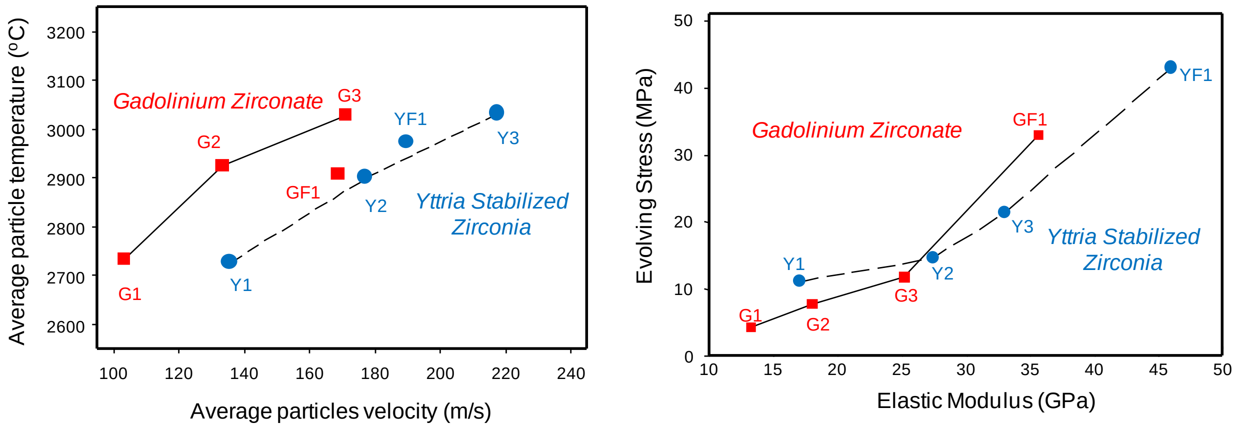


Figure 5: Representative schematics illustrating the development of process map of zirconates using diagnostics. The utilization of curvature based measurements for in-situ property assessment of GDZ coatings.

The sintering behavior of bi layered TBCs comprising of both YSZ and GDZ coatings were studied. Initial observations suggested that improved sintering resistance of GDZ coatings could result in thermal stresses at the interfaces of a multimaterial coating. Studies carried out on free standing forms of such coatings showed significant residual curvature thereby suggesting mismatch stresses. However on coatings deposited on superalloy substrates the high stiffness of the substrates would dominate and thus stresses due to such sintering mismatch might be minimal.

Based on the assessment of critical factors governing TBC failure, design strategies were formulated for durable YSZ TBCs. Figure 6 represents the plot which captures the durability strategy for bi layered YSZ coatings developed during this program.

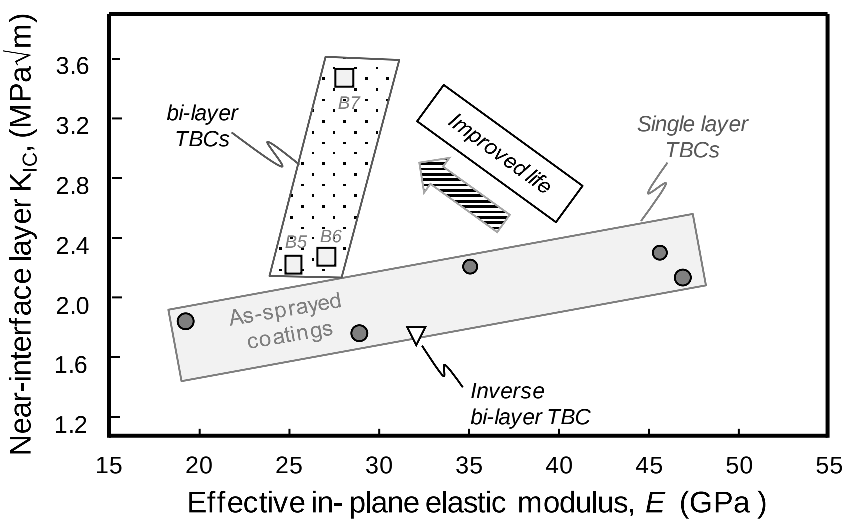


Figure 6: Formulation of design strategies for durable YSZ coatings based on the evaluation of bi-layered coatings. The key coating properties of fracture toughness and elastic modulus were utilized to engineer the two layered TBCs.

By engineering the high fracture toughness interfacial layers of YSZ along with reduced elastic modulus via processing strategies a framework for the fabrication of durable bi layered TBCs was synthesized during this program.

To estimate the role of sintering driven changes in thermal conductivity of multilayered coatings. a gradient thermal conductivity model was built to compute changes in YSZ and GDZ coatings. The details of the input parameters utilized for this model have been furnished in previous quarterly reports of this program. The temperature profiles are plotted with respect to the normalized thickness (x*) of the coating as shown in Figure 8. It was observed that the reduction in temperature gradient across the coating thickness was larger in the case of YSZ as compared to GDZ. After 10 hours of exposure, the changes in temperature profile was negligible for GDZ, however YSZ continued to show significant drop in temperature gradient with higher sintering time. Such estimates further enabled the engineering of multilayered YSZ GDZ coatings during the later stages of this program.

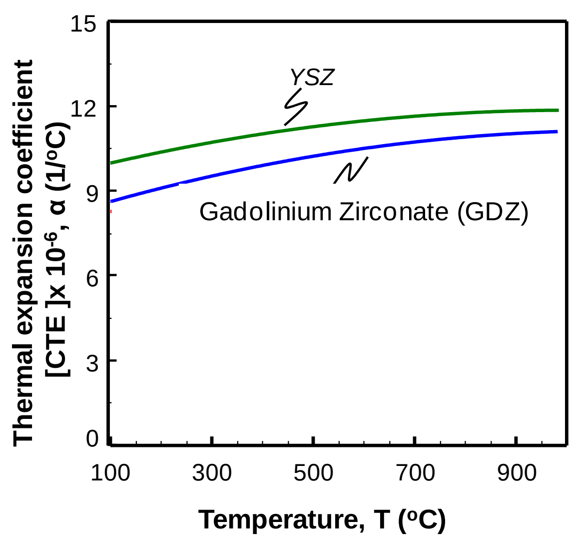


Figure 7: Thermal expansion measurements of gadolinium zirconate (GDZ) coatings. Measured values for YSZ coatings have been included for reference.

In order to extend the fabrication to multimaterial TBCs the thermal expansion co-efficient of GDZ coatings was measured and found to be slightly less than that of regular 7 YSZ as shown in Figure 7

Figure 8 illustrates the key milestones that were accomplished with regard to thermal barrier coating processing and evaluation. The most valuable insights obtained from these investigations can be summarized as follows:

- Development of process maps for new TBC compositions(eg Gadolinium Zirconate) offers significant insights and enables identification of regimes of interest for specific microstructure and properties
- The low fracture toughness of GDZ coatings presents significant implementation challenges. The computation of coating stresses using the in-situ coating property sensor and the nonlinear elastic behavior of these TBCs using the ex-situ coating property sensor offered vital insights into both formation dynamics as well as elastic response of coatings.
- Durability strategies were formulated for YSZ coatings by engineering the layered architectures to incorporate appropriate fracture toughness and elastic modulus for these systems.
- The gradient thermal conductivity model developed for YSZ and GDZ coatings demonstrated the improved thermal performance of GDZ. Based on the model lower interface temperature were obtained with the GDZ even upon thermal aging thereby necessitating that to be the topmost layer in advanced multilayered TBCs.
- In order to address the lower fracture toughness and the associated issue of poor erosion resistance of GDZ coatings, further processing advancements were made. Utilizing process maps and property correlations dense vertically cracked (DVC) coatings of GDZ were fabricated and improved erosion resistance over the porous variants of GDZ coatings were observed. Such erosion resistant architectures would comprise the topmost layer in multilayered YSZ-GDZ coatings.

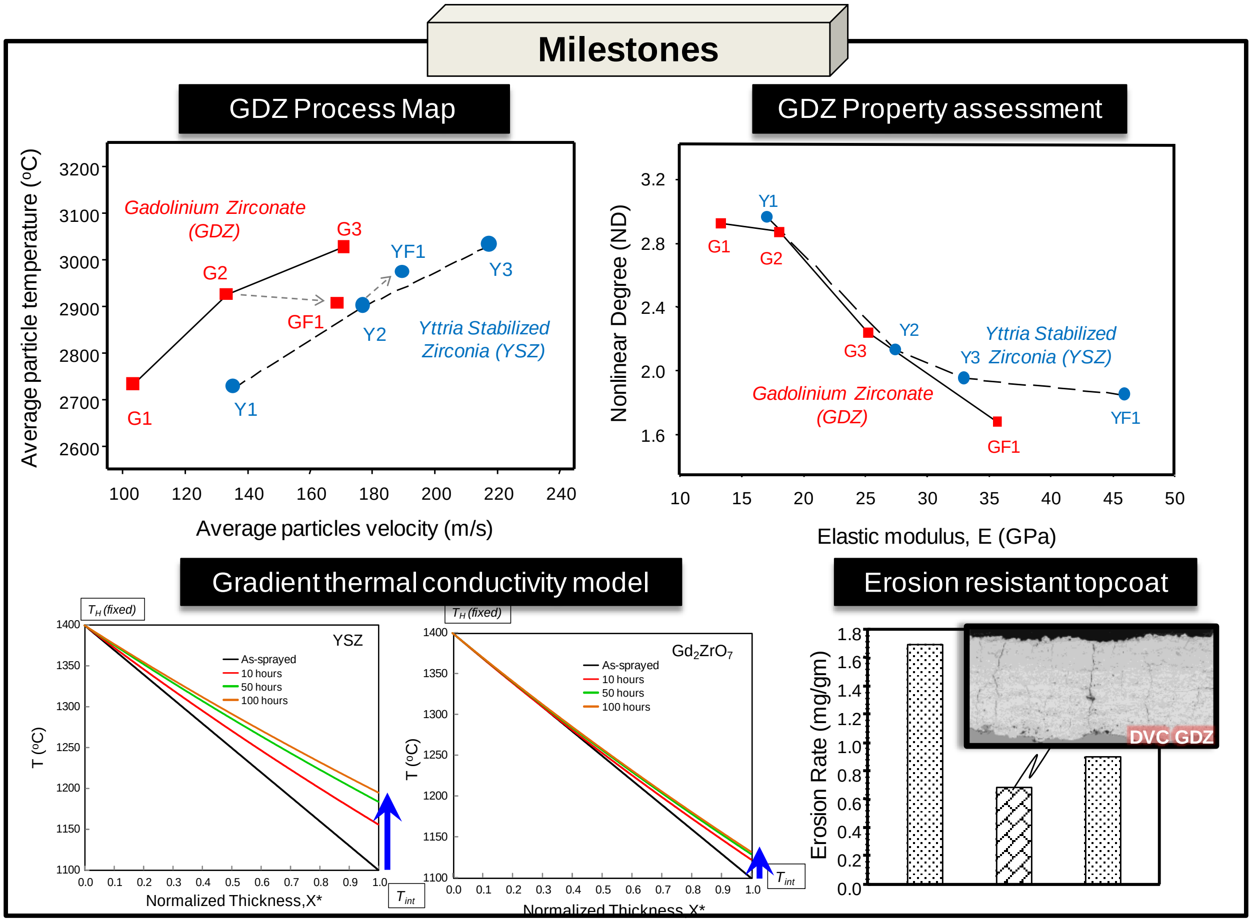


Figure 8: Compilation of key milestones accomplished with regard to thermal barrier coating processing and evaluation. Development of process maps and property evaluation of GDZ coatings were carried out using in-flight particle diagnostics and curvature based measurements respectively. Thermal gradient model was developed for GDZ coatings to estimate functional benefits during high temperature cycling. Erosion resistant DVC GDZ coatings developed to comprise the topmost layer in multilayered TBC architecture

Task 4: System Level Evaluation of Multifunctional Coatings

Task 4.1: Production of multilayer TBC

In order to address the needs of advanced TBCs multilayered architectures comprising of YSZ and GDZ coating were engineered. Necessary properties were imparted via process control and optimization of both TBC compositions.

Task 4.2: Rig testing / Evaluating performance of bi layered coatings

The bi layered YSZ TBCs exhibited significant improvement in in their performance under isothermal oxidation tests. The durability strategy were formulated based on FCT results which indicated similar failure mechanisms for both single layered and bi layered YSZ coatings. Gradient testing was carried out on bi layered TBCs to understand their failure mechanisms under such conditions.

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Task 4.3: System level oxidation and hot corrosion testing / High temperature ex-citu curvature measurement to monitor changes in coating compliance due to ash attack

System level oxidation tests were carried out with YSZ coating. In order to evaluate compliance changes in TBC during thermal aging the ex-situ curvature measurement sensor was utilized. A Hastelloy substrate with a bond coat and TBC was carefully studied to observe changes in its curvature-temperature response.

Task 4.5: Additional ex-situ characterization of multilayer coatings

Single layered TBCs have been characterized extensively for their mechanical properties to determine elastic modulus during this program. Similar measurement of mechanical and thermal properties of multilayered YSZ-GDZ coatings was carried out to assess their microstructural sensitivity.

RESULTS AND DISCUSSION

Following the insights obtained in the development of bi layered TBCs multilayered coatings of YSZ and GDZ were fabricated as shown in Figure 9. Utilizing CTSR’s knowledge base on the processing of TBCs several variants were developed incorporating various elements of fracture toughness , elastic modulus and thermal conductivity.

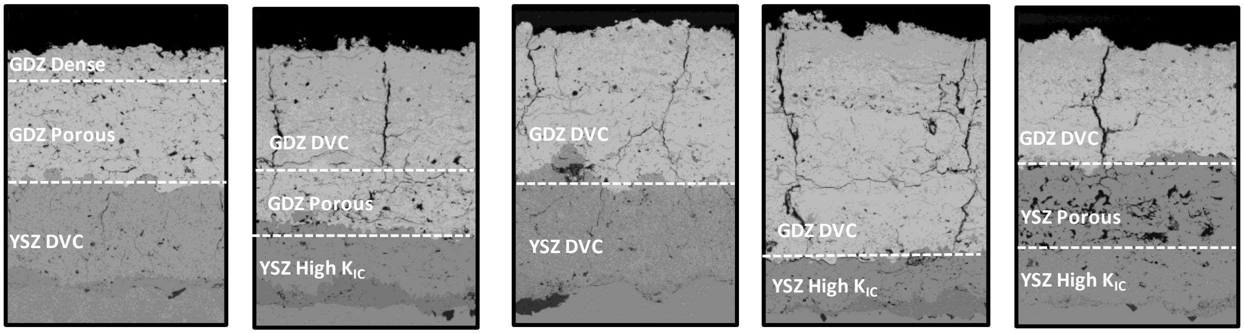

Figure 9: Engineered architecture of multilayered YSZ-GDZ TBCs. Each architecture incorporates different microstructural variants of both the materials

The performance assessments of these coatings combined with the computation of elastic energy in the TBC system lead to the durability strategies for multimaterial TBCs during this program. With durable variants of such mutlimaterial YSZ-GDZ coatings significant operational benefits and CMAS/ashattack mitigation in service can be expected.

While the identification of failure mechanisms and the development of bi layered TBCs were carried out using isothermal furnace cycle tests, investigations were also done under gradient thermal cycling conditions. The bi layered TBCs were evaluated under gradient thermal cycling conditions using the burner rig facility at CTSR. The objective was to compare failure modes for conventional single layered and bi layered YSZ coatings.

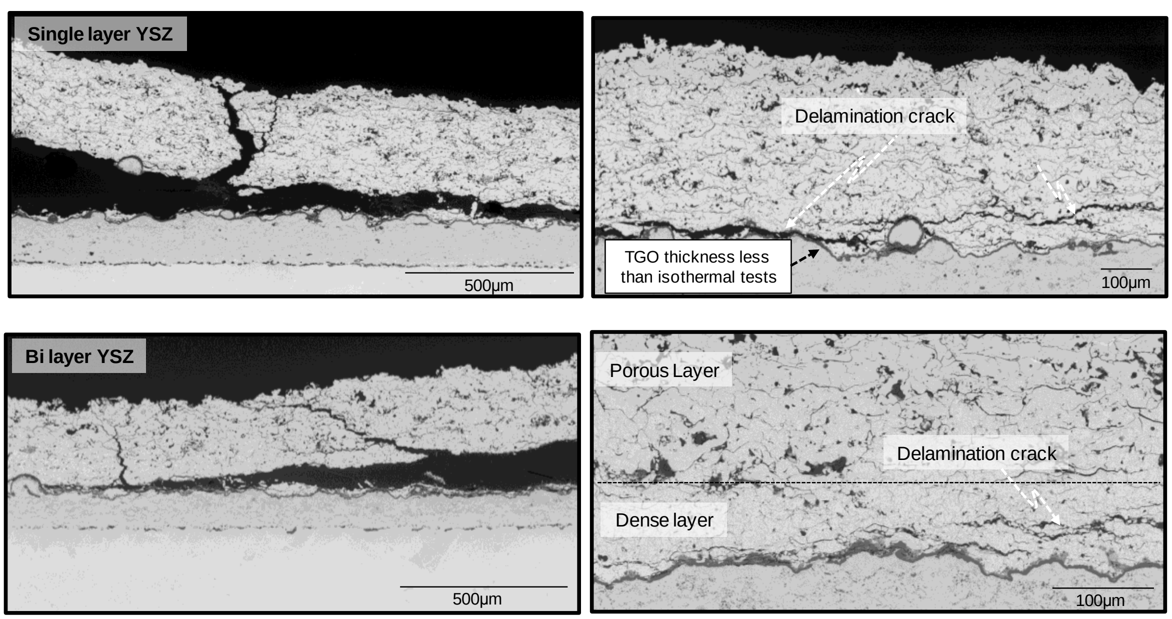

Figure 10: Evaluating bi layered YSZ coatings under gradient rig testing. Similar mechanisms appear to be operative in both single layered and the durable bi layered YSZ coatings under sintering driven failure.

Results did not indicate any cohesive failure between the two layers of YSZ which were in accordance with the observations from all the isothermal tests. Microstructural observations as shown in Figure 10 indicate sintering driven failure under gradient conditions. Further testing of these coatings to determine cycles to failure are currently being carried out in collaboration with CTSR's consortium member Praxair and would provide more insights in the future.

In order to examine system level changes in TBCs a novel approach of utilizing curvature based measurements to capture aging was explored. The ex-citu coating property sensor was utilized to measure changes in coating compliance after high temperature thermal aging. As seen in Figure 11 specimen after heat treatment demonstrated significant difference in their curvature-temperature response . This could be attributed to the stiffening of the TBC during heat treatment. Concurrent microstructural observations of the specimen indicated signs of bond coat oxidation for the tested period. Thus although high temperature curvature based measurements provide a methodology of investigating TBC stiffening there is a need to decouple the effects of substrate and bond coats to provide quantitative assessments .

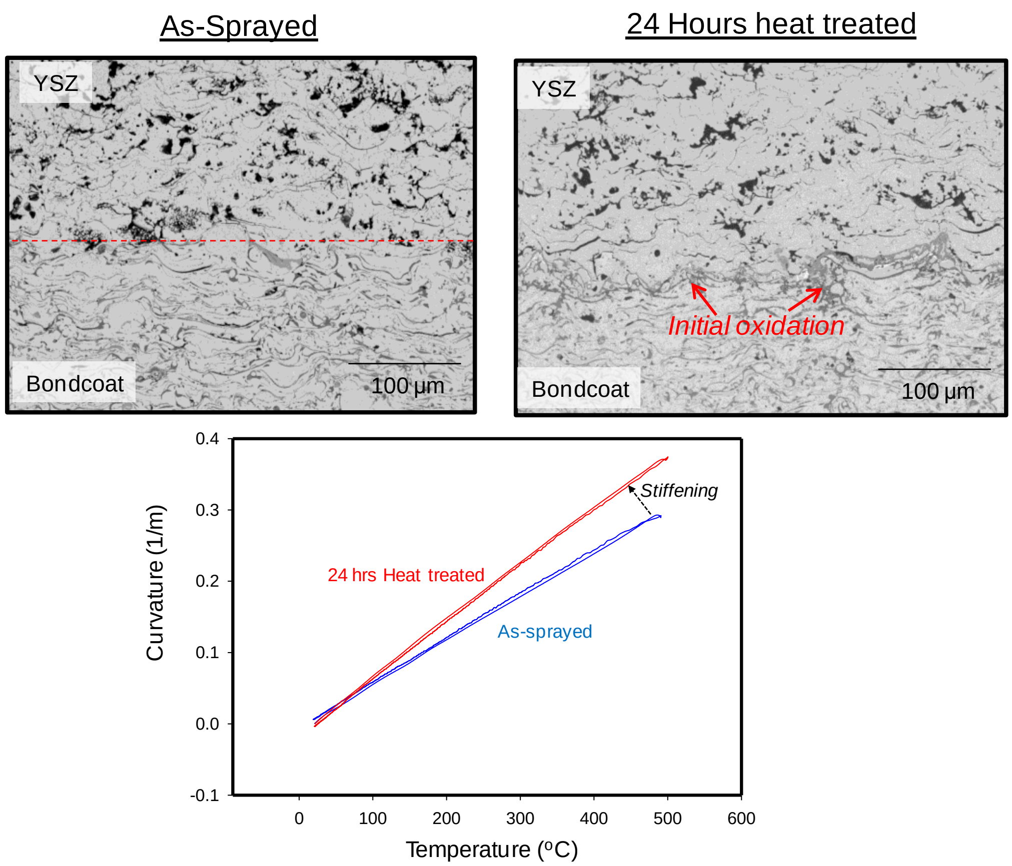

Figure 11: System level oxidation study using high temperature ex-citu curvature measurement technique. Increased stiffening of the overall TBC system is captured in the curvature response along with microstructural evidences of bond coat oxidation.

The multilayered YSZ-GDZ coatings that were fabricated and tested for their durability were also assessed for their sensitivity to microstructural changes. As in the case of single layered TBCs multilayered coatings exhibited significant difference in both thermal conductivity as well as elastic modulus of the coatings. While lower overall conductivity is observed for multimaterial coatings, DVC type architectures of even GDZ results in increase in conductivities. A synopsis of this has been shown in Figure 12. The measured elastic modulus suggested microstructural sensitivities in multilayered YSZ-GDZ coatings. Multilayered variants incorporating porous architectures exhibited lower overall elastic modulus than those with dense layers.

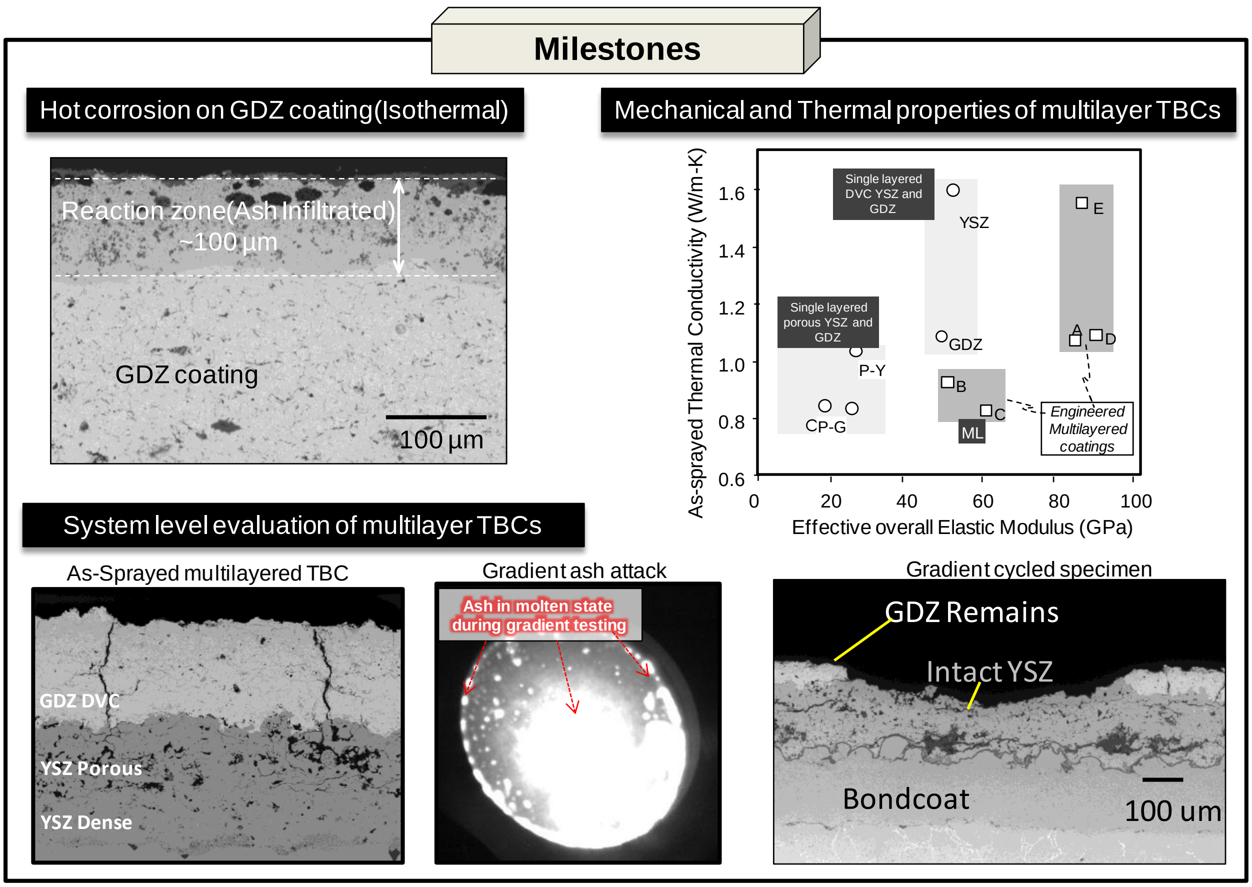

Figure 12: Compilation of key milestones accomplished with regard to system level evaluation of multifunctional coatings. Corrosive lignite ash studies were carried out on the candidate top coat material GDZ. The conductivity-modulus relationships were established for multilayered multimaterial TBCs. System level testing of multimateail coatings carried out under CMAS like attack under gradient conditions.

Figure 12 illustrates the key milestones that were accomplished with regard to the system level evaluation of multifunctional coatings. The most valuable insights obtained from these investigations can be summarized as follows:

- In order to further evaluate the bi layered YSZ coatings gradient testing was conducted to observed their failure modes. Results suggested that failure mechanisms for both single layered coatings and bi layered YSZ coatings under gradient condition were similar. Microstructural evidences suggest that cracks originating from within the TBC resulted in the delamination of both classes of coatings.
- The utilization of high temperature ex-situ curvature measurement sensor to evaluate changes in TBC stiffness with aging opens up new opportunities for further exploration and understanding of failure mechanisms.
- The development of bi layered YSZ TBCs provided the groundwork for the fabrication and assessment of multilayered YSZ –GDZ coatings. Utilizing first order and second order process maps developed in the early stage of the program for both YSZ and GDZ coatings, several microstructural variants of multimaterial coatings were deposited and evaluated
- Apart from the performance assessment of multilayered coatings critical properties such as elastic modulus and thermal conductivity were measured. These provide vital information on the microstructural sensitivity in such advanced TBC systems.
- Studies conducted to simulate high temperature ash attack suggested that the multilayered TBCs designed during the program hold promise in addressing CMAS/ash attack. Tests conducted under gradient conditions with lignite ash provided qualitative evidence on the improved cyclic durability of these YSZ-GDZ coatings.

SUMMARY

Over the course of this program various facets of TBC development were investigated ranging from bond coat processing, to fabrication and performance assessment of multilayered multimaterial coatings. The linkages established between the fundamental concepts and industrially relevant approaches towards addressing scientific challenges proved to be extremely vital.

Research on bond coats focused on developing processing strategies for improving TBC durability. Due to the processing sensitivity of coating microstructures extensive efforts on the optimization of process conditions was carried out using particle diagnostics. Apart from addressing bond coat requirements from a single process (HVOF) concurrent research on other processing techniques such as APS and VPS were also pursued. Performance evaluations of these bond coats were based on TBC cyclic life. Collective assessment of the different bond coat processes as well as deposition strategies provided a broad perspective on the techniques suitable for advanced TBC structures.

One among the several accomplishments during this program has been the formulation of design strategies for durable TBCs. Having ascertained the critical drivers governing oxidation driven failure, a fracture toughness and elastic modulus based approach for designing TBCs was adopted. The efficacy of the durable bi layered YSZ TBC strategy was tested extensively for processing and material variances such as bond coat and substrate chemistry. These efforts lead to the development of multimaterial YSZ-GDZ TBCs. Identification of failure mechanisms in such coating systems spawned efforts on the evaluation of elastic energies in multimaterial coatings and formulation of durability strategies for the same. Implementation of these strategies was brought about by advanced process control and robust coating property measurements.

Qualitative evaluations of the performance of the multimaterial TBCs were carried out under CMAS like attack in gradient conditions. While results do suggest improved performance of these coatings, extensive gradient testing of these coating continues to remain a bottleneck due to the arduous nature of the test. However such tests are currently underway in collaboration with CTSR's consortium members and hence would eventually provide vital information on such issues as well.

Task Discription	Start	End	% Progress	Status	Comment
1. Project Management and Planning	**Fri 10/1/10**	**Mon 9/30/14**			
1.1 Revise and Maintain Project Management Plan	Fri 10/1/10	Fri 8/30/14	100	**Completed**	
1.2 Quarterly Assessment and Reporting	Fri 10/1/10	Mon 9/30/14	100	**Completed**	
1.3 Annual Meetings	Fri 10/1/10	Mon 9/30/14	100	**Completed**	
1.4 Final Report	Mon 9/2/13	Tue 03/31/15	0	On schedule	
2. Bond Coat Processing and Evaluation	**Fri 10/1/10**	**Fri 9/30/13**			
2.1 Bond Coat Processing and Microstructural Evaluation	Fri 10/1/10	Mon 2/28/13	100	**Completed**	
2.2 Determination of Bond Coat Oxidation Behavior in High Temperature Water Vapor	Mon 5/2/11	Wed 8/31/13	100	**Completed**	
2.3 Final Selection of Bond Coat Material for System-Level Coating	Thu 9/1/11	Thu 9/29/13	100	**Completed**	
controlled atmospheres	Wed 8/31/11	Wed 8/31/11	100	**Completed**	
MILESTONE: Down-selection of optimum bond coat material and processing for multilayer coating	Fri 9/30/11	Fri 9/30/11	100	**Completed**	
3. Thermal Barrier Processing and Evaluation	**Tue 3/1/11**	**Mon 4/30/14**			
3.1 Process Optimization of Zirconates Using Diagnostics and In Situ Property Sensing	Tue 3/1/11	Fri 7/29/11	100	**Completed**	
3.2 Evaluate Sintering Behavior of Bilayer TBC	Mon 8/1/11	Fri 12/30/13	100	**Completed**	
3.3 Determine Thermal Conductivity Changes Due to Thermal Gradient Exposure	Mon 8/1/11	Fri 6/30/14	100	**Completed**	Preliminary thermal data on the gradient tested specimen was not conclusive. We are attempting a gradient mechanical property analysis to determine the through thickness properties.
3.4 Determine Coefficient of Thermal Expansion for Gd2Zr2O7	Mon 10/3/11	Fri 12/30/11	100	**Completed**	
3.5 Erosion Testing of Dense Top Coat	Mon 1/2/12	Mon 4/30/12	100	**Completed**	
MILESTONE: Process maps will be completed relating processing conditions to properties for plasma sprayed Gd2Zr2O7	Wed 8/31/11	Wed 8/31/11	100	**Completed**	
MILESTONE: Development of gradient thermal conductivity model for plasma sprayed Gd2Zr2O7	Tue 1/31/12	Tue 1/31/12	100	**Completed**	
MILESTONE: Development of erosion-resistant Gd2Zr2O7 top layer for TBC	Mon 4/30/12	Mon 4/30/12	100	**Completed**	
4. System-Level Evaluation of Multifunctional Coating	**Tue 5/1/12**	**Fri 8/30/14**			
4.1 Production of Multilayer TBC	Tue 5/1/12	Fri 6/29/12	100	**Completed**	
4.2 Rig Testing	Mon 7/2/12	Mon 12/31/14	100	**Completed**	
4.3 System-Level Oxidation and Hot Corrosion Testing	Mon 7/2/12	Thu 2/28/13	100	**Completed**	
4.4 Residual Stress and Composition Evolution in Multilayer Coatings	Fri 3/1/13	Fri 8/30/14	100	**Completed**	
4.5 Additional Ex Situ Characterization of Multilayer Coatings	Fri 3/1/13	Fri 8/30/14	100	**Completed**	
MILESTONE: System-level determination of oxidation and hot corrosion behavior of multilayer TBC	Thu 2/28/13	Thu 2/28/14	100	**Completed**	
MILESTONE: Determination of residual stress state and compositional evolution in multilayer coatings exposed to high temperature water vapor atmospheres	Fri 8/30/13	Fri 8/30/14	NA	NA	
MILESTONE: Determination of thermal and mechanical properties in multilayer TBCs after high temperature, controlled atmosphere exposures	Fri 8/30/13	Fri 8/30/14	100	**Completed**	