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Phase I Final Report

Low-Cost Protective Layer Coatings on Thermal Barrier Coatings via CCVD

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Summary

This Phase I program investigated the use of the combustion chemical vapor deposition (CCVD) process to deposit oxygen or sintering barrier coatings for thermal barrier coating (TBC) applications. Oxidation barrier materials have potential to act as a protective layer within a TBC or as a protective or sintering inhibitor layer on top of a TBC. Vacuum-based technologies such as chemical vapor deposition and sputtering are capable of applying these coatings but are expensive, capital intensive and have a low throughput. MicroCoating Technologies' (MCT) CCVD process was proposed as an alternative to these techniques to produce oxide coatings. Scanning electron microscopy, x-ray diffraction and oxidation testing were performed to assess coating performance.

Alumina and yttria CCVD coatings were investigated, and preparatory research was performed using quartz and sapphire substrates. Studies on deposition rate and reaction to heat treatment were done. Heating of the coated substrates to 1100 °C for up to 500 hours did not result in any coating loss, however, changes in coating morphology were observed. Coatings deposited onto bond-coated superalloy and TBC-coated superalloy coupons were thermally cycled by the industrial collaborator for this project. All coatings tested failed prematurely compared to the standard number of cycles for the uncoated substrates. The determination was made that such thin film coatings were not well-suited as barrier layers on the rough bond coat or TBC.

Subsequently, investigations were made on nanopowder-based coatings for smoothing the TBC, an application suggested by the collaborator. Smoothing of rough surfaces has been shown by others to have application in reducing drag on rotating parts or improving erosion or chemical resistance. Current smoothing techniques are usually mechanical, such as grinding and/or polishing, which may take away necessary material or may not be possible due to part configuration. The coatings investigated in this project were based on MCT's yttria stabilized zirconia (YSZ) and alumina nanopowders. Sintering of the powder was observed at 1100 °C, a temperature relatively low for these materials. In addition, smoothing of substrate surfaces by 50% was observed by profilometry.

Phase I Purpose and Background.

From the Phase I proposal: "The goal of this Phase I program is to demonstrate the capability of the CCVD process to deposit low cost, oxidation resistant alumina and yttria coatings as an effective oxygen/sintering barrier for TBC applications."

Thermal Barrier Coatings (TBC) are well-established systems for providing thermal protection to an underlying substrate used in elevated temperature environments. However, these systems have inherent faults that have produced on-going issues with their use. Although the basic thermal barrier coating systems used in land-based gas turbine engines has not changed significantly for many years, there has been extensive research to improve their performance. One of the driving forces for this research is higher turbine efficiency through the use of higher operating temperatures, thus requiring the coating systems to perform in conditions harsher than those they currently experience. The other factor less worked on is increased efficiency provided by smoother, more aerodynamic surface finishes. The smoother surfaces create less turbulence which also reduces erosion.

The basic thermal barrier coating system consists of a substrate, onto which is deposited a bond coat, usually of MCrAlY (M=Ni, Co, etc.) or platinum aluminide, followed by the thermal barrier coating, usually of yttria stabilized zirconia (YSZ). Most of the technology associated with thermal barrier coating systems is based upon micron-scale morphologies. The air plasma spray (APS) technique is often used to deposit the bond coat and the TBC. Tens to hundreds of microns-sized powder is used in this technique, and coating thickness is built up by "splats" of material impacting the substrate and causing significant surface roughness. Also popular for the TBC is electron beam physical vapor deposition (EB-PVD), which results in a controlled, columnar microstructure, where column width is measured in microns.

Research.

The combustion chemical vapor deposition (CCVD) process, depicted in Figure 1, was used in this project to form oxide coatings. In the process, precursors are dissolved in a solvent, which also acts as the combustible fuel. This solution is atomized to form submicron droplets (NanoSpraySM process) by means of the Nanomiser[®] technology. These nano-droplets are then convected by an oxygen stream to the flame where they combust similar to a gas fuel. The substrate is coated by drawing it over the flame plasma. The flame provides the energy required for the precursors to react and to vapor deposit on the substrates.

Figure 1. Schematic Representation of the NanoSpraySM CCVD System.

The list of objectives below for this project is taken verbatim from the Phase I proposal, written by the original PI who is no longer at MCT (a formal change of PI was completed in February, 2003). A brief summary of the results, listed by task from the Phase I proposal, to fulfill the objectives follows this list.

1. Selection of prototype substrates and coating materials, and determination of the performance of initial material depositions.
2. Development and demonstration of coating apparatus.
3. Study and optimization of key process parameters of solution concentrations, depositions on candidate substrate materials.
4. Perform characterization and analysis of the coated components for performance.
5. Conduct cyclic oxidation testing of coated substrates and evaluate their performance over uncoated samples.
6. Plan for process scaling and automation for economical production.
7. Development of a working relationship with collaboration and co-sponsorship of Phases II and III of this SBIR project.
8. Reports on Phase I research findings.

Task 1 Results. Select and Acquire Material Supplies.

Alumina (Al_2O_3) and yttria (Y_2O_3) coatings were deposited by the CCVD technique. The coatings were deposited onto substrates of sapphire, fused silica, CMSX-4 superalloy, bond-coated superalloy (from Solar Turbines) and thermal barrier-coated, bond-coated superalloy (from Solar Turbines). Al_2O_3 and yttria stabilized zirconia nanopowder-based coatings were also formed from powders produced at MCT.

Task 2 Results. Design and Construct Experimental CCVD Apparatus.

An existing Nanomiser[®] device was used in an existing deposition exhaust hood. A substrate holding apparatus was built as part of this project. This apparatus allowed coating of the substrate without any obstruction of the face to be coated. In addition, it could be moved into or out of the flame path automatically and quickly. The apparatus was equipped with thermocouples to estimate the substrate temperature from the back.

Task 3 Results. Deposit Coatings and Optimize CCVD Process Parameters.

Over 200 samples were coated during Phase I. Results of the coating investigations led MCT to modify its emphasis from thin films to somewhat thicker, nanopowder-based films, where the nanopowder was created from NanospraySM droplets using the Nanomiser[®] device.

There were essentially three main aspects to the bulk of the thin film investigations performed:

- A. Assessment of coating reaction when heated to elevated temperatures.
- B. Optimization of coating thickness and deposition rate.
- C. Testing of superalloy coupons by industrial collaborator.

Deposition solution chemistry, concentration and flow rate as well as deposition temperature were investigated, as detailed under the next Task.

Task 4 Results. Characterize Specimens for Quality and Performance.

The following results summarize work performed under the Phase I contract.

Results of Thin Film Investigations

Over 200 samples were made; only representative coatings are shown or listed in the following figures and tables.

A Investigations: Heat Treatment

The A aspect of the investigations, from Task 3, included the coating of approximately 1 cm² sapphire substrates with alumina or yttria and then heat treating these samples for varying amounts of time. The deposition of the coatings was done at 1000 °C and 1200 °C (flame temperature next to the substrate, defined as *deposition temperature* throughout this report) for 20 and 60 minutes. The heat treatments were carried out at 1100 °C for 100, 200, 300, 400 and 500 hours for each combination of deposition conditions. For all coatings heat treated, the samples were weighed to within 0.000002 g before and after heat treatment. Insignificant weight change was recorded for all of the samples.

Figure 2 through Figure 5 illustrate yttria coatings in cross-section before and after heat treatment at shorter times (100 or 200 hours) and longer treatment time (500 hours). Only these time extremes are shown to illustrate the effects of heat treatment. Each of these samples was also analyzed through x-ray diffraction (XRD) to assess changes in the coating with heat treatment. The deposition and XRD results are summarized in Table 1 for the samples shown in Figure 2 through Figure 5. All coatings were deposited at the same solution flow rate, y , and were made from solutions with the same Y precursor concentration, x_Y .

Figure 2. SEM micrographs of yttria deposited onto sapphire at 1000 °C for 20 min., (a) as-deposited, (b) heat-treated at 1100 °C for 100 hr, and (c) heat-treated at 1100 °C for 500 hr.

Figure 3. SEM micrograph of yttria deposited onto sapphire at 1000 °C for 60 min, (a) as-deposited, (b) heat-treated at 1100 °C for 200 h, and (c) heat-treated at 1100 °C for 500 hr.

Figure 4. SEM micrograph of yttria deposited onto sapphire at 1200 °C for 20 min., (b) as-deposited, (b) heat-treated at 1100 °C for 100 hr, and (c) heat-treated at 1100 °C for 500 hr.

Figure 5. SEM micrograph of yttria deposited onto sapphire at 1200 °C for 60 min., (a) as-deposited, (b) heat-treated at 1100 °C for 100 hr, and (c) heat-treated at 1100 °C for 500 hr.

Table 1. Yttria coating summary from heat treatment. (Sapphire substrate, y solution flow rate, x_Y solution concentration)

Coating: Yttria	Deposition Temp. (°C)	Approx. Sub. Temp. (°C)	Deposition Time (Min.)	Heat Treat Time (Hours)	Approx. Coating Thick. (μm)	Extra XRD Peaks*
Figure 2a	1000	608	20	-	0.2	
Figure 2b	1000	540	20	100	0.2	$\text{Al}_2\text{Y}_4\text{O}_9$
Figure 2c	1000	560	20	500	0.2	AlYO_3
Figure 3a	1000	662	60	-	0.9	
Figure 3b	1000	554	60	200	0.4	$\text{Al}_2\text{Y}_4\text{O}_9$
Figure 3c	1000	580	60	500	0.6	$\text{Al}_2\text{Y}_4\text{O}_9$
Figure 4a	1200	700	20	-	0.4	$\text{Al}_2\text{Y}_4\text{O}_9$
Figure 4b	1200	680	20	100	0.4	$\text{Al}_2\text{Y}_4\text{O}_9$
Figure 4c	1200	680	20	500	0.4	$\text{Al}_2\text{Y}_4\text{O}_9$
Figure 5a	1200	640	60	-	0.7	
Figure 5b	1200	680	60	100	0.9	$\text{Al}_2\text{Y}_4\text{O}_9$
Figure 5c	1200	636	60	500	0.7	$\text{Al}_2\text{Y}_4\text{O}_9$

*After heat treatment on heat treated samples.

The following observations were made from this investigation:

- A deposition temperature of 1200 °C generally produced thicker coatings than a deposition temperature of 1000 °C. There is one exception in the list, though, which is the coating deposited at 1000 °C for 60 minutes. This coating is thicker than the coating deposited at 1200 °C for 60 minutes. The approximate substrate temperature as measured at the back of the substrate was higher for the 1000 °C deposition than for the 1200 °C in this case. A higher substrate temperature allowing a higher growth is reasonable, although the reason for the higher substrate temperature at the lower deposition temperature in this case is unknown; insulation of the substrate from the back may have been more efficient for that deposition. Coating deposition rate was not consistent for each sample set, so absolute statements based on the coating thickness cannot be made.
- Longer deposition time generally results in thicker coatings for a given set of conditions.
- Yttria coating morphology changes during heat treatment. The figures illustrate that the as-deposited coatings tended to appear more faceted, but after heat treatment, they appear much less faceted and possibly more dense.
- Some interaction of the coating and sapphire substrate occurred during heat treatment. All XRD patterns from the pictured coatings revealed peaks that matched the sapphire (corundum PDF 42-1468) and yttrium oxide (PDF 41-1105) 2-theta values. However, all of the heat treated samples also displayed an additional Al-Y-O compound. In addition, the as-deposited coating from Figure 4a also showed an Al-Y-O compound. This may have resulted from the slightly higher substrate temperature recorded.

The alumina coatings deposited onto sapphire and heat treated did not produce any useful results. Figure 6 illustrates one set of alumina samples deposited at 1000 °C for 60 minutes. The coating thicknesses are negligible and the respective XRD patterns do not show any polycrystallinity to the coatings; only the single crystal pattern of the sapphire substrate is evident. These coatings are probably amorphous.

Figure 6. SEM micrographs of (left) alumina deposited onto sapphire at 1000 °C for 60 min, (center) alumina deposited onto sapphire at 1000 °C for 60 min then heat-treated at 1100 °C for 100 hr, and (right) alumina deposited onto sapphire at 1000 °C for 60 min. and heat treated for 500 hours; respective XRD diffraction patterns are below figures.

Conclusions for the A aspect of the investigations:

- Ytria is not a reasonable candidate as a coating on the bond coat since it may react with the aluminum in the bond coat during elevated temperature cycling.
- Ytria may not be reasonable as a sintering inhibitor since its own morphology appeared to have densified (sintered?) during heat treatment.
- Alumina deposition rate is relatively slow.

B Investigations: Deposition Rate

The B aspect of the investigations, from Task 3, included experiments to increase the deposition rate of the coating materials. The limited investigations into yttria deposition rate revealed that its rate could be increased, but that its growth morphology changed significantly as well. Depositions were done onto sapphire to allow easy cross-section analysis of the deposited coating. Figure 7 through Figure 9 show the result of doubled solution concentration of yttrium as deposited at two different temperatures and two different solution flow rates (note that coatings shown in Figure 8a and b were deposited for 0.6 the time of those shown in Figure 7a and b). The microstructures show a distinct columnar growth pattern. Coatings deposited at even higher concentrations (5x_y) showed columnar growth, but in a much less dense manner (Figure 9a and b). Table 2 summarizes the growth rate studies of yttria.

Figure 7. SEM micrographs of yttria coating on sapphire, (a) as deposited at 1200 °C, 5 ml/min. solution and (b) as deposited at 1300 °C, y flow rate of solution.

Figure 8. SEM micrographs of yttria coating on sapphire, (a) as deposited at 1200 °C, 1.6*y flow rate of solution (0.6 deposition time of Figure 7a) and (b) as deposited at 1300 °C, 1.6*y flow rate of solution (0.6 deposition time of Figure 7b).

Figure 9. SEM micrographs of yttria coating on sapphire, (a) as deposited at 1200 °C, y flow rate of solution (0.8 deposition time of Figure 7a) and (b) as deposited at 1200 °C, 1.6*y flow rate of solution (0.4 deposition time of Figure 7b).

Table 2. Summary of yttria. (Sapphire substrate.)

Coating: Yttria	Deposition Temperature (°C)	Deposition Time (min)	Solution Flow Rate (ml/min)	Relative Solution Concentration	Approximate Coating Thickness (μm)
Figure 7a	1200	50	y	2x _y	1.9
Figure 7b	1300	50	y	2x _y	2.3
Figure 8a	1200	30	1.6*y	2x _y	0.7
Figure 8b	1300	30	1.6*y	2x _y	0.8
Figure 9a	1200	40	y	5x _y	1.7, negligible
Figure 9b	1200	20	1.6*y	5x _y	1.4, negligible

Optimization of CCVD alumina coating deposition was performed to try to increase the deposition rate of the coating. To aid in this study, sapphire or fused silica substrates were used so they could be cracked easily and the resulting cross-sections viewed in the SEM to assess coating thickness. However, the coatings did not adhere well to the more economical fused silica and tended to crack since the deposition temperatures were generally at least 1000 °C; the thermal expansion mismatch between the two materials (silica $\sim 0.5 \text{ }^{\circ}\text{C}^{-1} \times 10^6$, alumina $\sim 8 \text{ }^{\circ}\text{C}^{-1} \times 10^6$) is large and is a prominent factor in coating adhesion at these elevated temperatures. The coatings on fused silica tended to exhibit thin film interference colors, a good indication of a dense coating, but could be wiped off the substrate. Since the interference colors were present and the cross-sections appeared fairly dense, the adhesion on the less than optimum substrate was ignored, and the coatings were considered reasonable.

The main parameters investigated for deposition rate optimization were solution concentration and deposition temperature. To help increase solution concentration, the solution used above to deposit the coatings used in the furnace studies was changed; a different solvent was used that allowed a higher concentration without becoming inhomogeneous (referred to hereafter as Solution B, x_{Al} nominal concentration). The new solvent is a proprietary solvent used in the CCVD process for excellent atomization. Figure 10 shows a cross-section of a coating on fused silica made with Solution B at a deposition temperature of 1000 °C, a time of 60 minutes, and a flow rate of y . The coating is greater than 0.5 μm thick. This coating can be compared to that shown in Figure 11, a coating deposited under the same conditions (on sapphire), but with a $2x_{\text{Al}}$ concentration solution. Its thickness is greater than 0.9 μm , almost twice as thick as that deposited with the $1x_{\text{Al}}$ concentration solution.

Figure 12 shows a coating that is greater than 0.9 μm thick, as deposited at 1200 °C (on fused silica), all other parameters being the same as the coating in Figure 10. This coating is again almost twice as thick as that deposited at the lower temperature. Figure 13 shows a coating produced under the same conditions (on sapphire) as that shown in Figure 11, but with a $2x_{\text{Al}}$ concentration solution. This coating is more than 1 μm thick. For a further comparison, Figure 14 and Figure 15 show coatings produced (on fused silica) under the same conditions as those shown in Figure 12 and Figure 13, but with a $5x_{\text{Al}}$ and $10x_{\text{Al}}$ concentration solution, respectively, with the shorter deposition time used for the sample in Figure 15. These coatings are almost 3 μm and 4.3 μm thick, respectively, although the rough surface means the thickness varies somewhat in the sections observed. The coatings shown in Figure 10 through Figure 15 are summarized in Table 3.

Figure 10. SEM micrographs of CCVD alumina coating on fused silica in cross-section (left) and planar (right). 1000 °C deposition temperature, x_{Al} concentration.

Figure 11. SEM micrograph of CCVD alumina coating on sapphire in cross-section (left) and planar (right). 1000 °C deposition temperature, $2x_{Al}$ concentration.

Figure 12. SEM micrograph of CCVD alumina coating on fused silica in cross-section (left) and planar (right). 1200 °C deposition temperature, x_{Al} concentration.

Figure 13. SEM micrograph of CCVD alumina coating on sapphire in cross-section (left) and planar (right). 1200 °C deposition temperature, $2x_{Al}$ concentration.

Figure 14. SEM micrograph of CCVD alumina coating on fused silica in cross-section (left) and planar (right). 1200 °C deposition temperature, $5x_{Al}$ concentration.

Figure 15. SEM micrograph of CCVD alumina on fused silica in cross-section (left) and planar (right). 1200 °C deposition temperature, 10x_{Al} concentration.

Table 3. Alumina coating summary (y solution flow rate, 60 minutes—except Figure 15 coating).

Coating: Alumina	Relative Solution Concentration	Deposition Temperature (°C)	Substrate	Approximate Coating Thickness (μm)
Figure 10	1x _{Al}	1000	Fused Silica	0.6
Figure 11	2x _{Al}	1000	Sapphire	0.9
Figure 12	1x _{Al}	1200	Fused Silica	0.9
Figure 13	2x _{Al}	1200	Sapphire	1.2
Figure 14	5x _{Al}	1200	Fused Silica	3.0
Figure 15*	10x _{Al}	1200	Fused Silica	4.3

*30 minute deposition time

Higher solution concentrations tended to produce more powdery (less dense) coatings. In general, though, two conclusions can be made:

- Coating deposition rate generally increased with solution concentration.
- Coating deposition rate was generally higher at 1200 °C compared to 1000 °C.

The repeatability of deposition rate was somewhat inconsistent, though, so absolute correlations between solution concentration or deposition temperature and deposition rate cannot be made at this time.

C Investigations: Testing by Collaborator

The C aspect of the investigations, from Task 3, included testing of coated superalloy specimens by our industrial collaborator, Solar Turbines. Substrates used for testing included bond-coated superalloy specimens and TBC-coated bond coat specimens. The following samples were tested:

- CCVD yttria / bond coat / superalloy
- CCVD alumina / bond coat / superalloy
- CCVD alumina / TBC / bond coat / superalloy

The coatings deposited were similar to those created in the A investigations above. Table 4 summarizes the testing and results. Essentially, the CCVD coatings were not beneficial since the samples with these coatings failed prematurely. A cross-section done by Solar Turbines of a

CCVD alumina coating on the bond coat with a subsequent TBC layer did not show any visible alumina layer. This layer was probably too thin to provide any oxidation protection and/or was abraded away during TBC application.

Table 4. Solar Turbines test results.

Coating	Test Conditions	Standard # Cycles	CCVD Results
CCVD coating on bond coat with subsequent TBC	1149 °C (2100 °F) in 10 hour cycles	120 cycles	80 cycles
CCVD coating on TBC	1093 °C (2000 °F) in 10 hour cycles	400 cycles	<400 cycles

Results of Thicker Nanopowder-based Coatings

YSZ and Al₂O₃ nanopowders were applied to thermal barrier-coated substrates, bond-coated substrates and pieces of alumina ceramic to assess the ability to sinter these powders to form coatings on the substrates. Roughness values were taken to evaluate the smoothing property of such a coating, with roughness decreased by >50% in most cases.

The powders were pressed onto the substrates by hand and then wetted with a solution of Zr organometallic + Y organometallic or a solution of Al organometallic, or a solvent, depending on the powder used. The resultant paste was pressed onto the substrates and skimmed off even with the highest points on the rough surface to produce a uniform coating. All samples were dried and then heat-treated to 1100 °C for 10 hours.

The results of these experiments are summarized below. Table 5 lists the roughness values, R_a, obtained from profilometry of specimens before and after coating. In all cases, the roughness was decreased. Some extent of drying and sintering cracking was evident in all of these un-optimized coatings after heating and may have affected the R_a measurements. Figure 16 through Figure 21 show the surfaces of the resultant coatings compared to the plain substrates. The coatings shown in Figure 16 and Figure 17 were formed on recycled TBC-coated superalloy coupons from a past project. The coatings shown in Figure 18 were formed on recycled bond-coated superalloy. Figure 19 shows the Figure 18 coatings in high magnification, illustrating the particle sintering but also showing the porosity still evident. The coatings shown in Figure 20 and Figure 21 were formed on two different high alumina ceramics that were chosen only because of their rougher surface textures and ability to act as high temperature substrates.

The top-coat concept was identified in the final month of the Phase I. More work needs to be done to identify the proper conditions to form a crack-free coating. The cracking does illustrate coating formation; however, no additional tests could be performed in the time frame available to verify hardness or density of the coating.

Table 5. Roughness values from uncoated and coated substrates (specific R_a values could not be obtained from Al_2O_3 ceramic C since it was so rough).

Substrate	Uncoated Morphology	R_a of Substrate (μm)	Coating on Substrate	Coated Morphology	R_a after Coating and Sintering (μm)
Thermal barrier-coated superalloy A	Figure 16a	1.9-4.5	YSZ	Figure 16b	1.6-1.7
Thermal barrier-coated superalloy B	Figure 17a	4.1	YSZ	Figure 17b	1.0-3.3
Bond-coated superalloy	Figure 18a	8.7	YSZ	Figure 18b	2.7
Bond-coated superalloy	Figure 18a	8.7	Al_2O_3	Figure 18c	2.2
Al_2O_3 ceramic B	Figure 20a	3.0	YSZ + Al_2O_3^*	Figure 20b	1.3
Al_2O_3 ceramic C	Figure 21a	>9	YSZ + Al_2O_3^*	Figure 21b	3.4
Al_2O_3 ceramic C	Figure 21a	>9	$\text{Al}_2\text{O}_3^{**}$	Figure 21c	3.1

* Al_2O_3 additions were $0.3 \mu\text{m}$ powder from Leco, ~2:1 by weight YSZ: Al_2O_3 .

**Also contained a pre- Al_2O_3 precursor formed, plus $0.05 \mu\text{m}$ alumina colloid.

Figure 16. SEM micrographs of (a, left) uncoated TBC-coated superalloy A and (b, right) YSZ-coated TBC-coated superalloy. Note that there is charging evident in the figures.

Figure 17. SEM micrographs of (a, left) uncoated TBC-coated superalloy B and (b, right) densified nano-YSZ-coated TBC-coated superalloy.

Figure 18. SEM micrographs of (a, left) “uncoated” bond-coated superalloy, (b, center) YSZ-coated bond-coated superalloy, and (c, right) alumina-coated bond-coated superalloy. Note that the substrate shown in ‘a’ does have a “coluform” type coating present on the peaks and somewhat in the valleys of the bond coat that was deposited for another project; this substrate was used here for illustrative purposes only.

Figure 19. SEM micrographs of sub-micron formed top coatings shown in Figure 18 of YSZ (left) and alumina (right) at 20,000X magnification. Note that there is some charging visible from the alumina sample.

Figure 20. SEM micrographs of (a, left) uncoated alumina ceramic B and (b, right) YSZ + Al_2O_3 -coated ceramic B.

Figure 21. SEM micrographs of (a, left) uncoated alumina ceramic C, (b, center) YSZ + Al_2O_3 -coated ceramic C, and (c, right) Al_2O_3 -coated ceramic C at 1000X magnification.

Task 5 Results. Preliminary Studies on Scale-up and Process Automation.

No studies were performed on scale-up due to the lack of sufficient results in the thin film investigations of the Phase I work. From the perspective of the nanopowder-based coating, however, even though nanopowder production was not part of this proposed work and no nanopowder synthesis was done under this contract, note that the production of nanomaterials at MCT has reached rates of 0.1-1 kg/hr in pilot-scale facility and order of magnitude higher rates in scaled version. Efforts are currently underway to scale nanopowder production to ton quantities. The expected price of NanoSpray-made nanopowders will be in the range \$50-\$200/kg.

Task 6 Results. Pre-commercialize CCVD Process.

MCT worked with Solar Turbines throughout the Phase I work, as summarized under Task 4 Results. They were consulted on better-suited application areas of interest to them for the CCVD process or nanopowder-based coatings, resulting in the work done on the thicker nanopowder-based coatings.

Task 7 Results. Final Report.

Completed in this document.

Estimate of Technical Feasibility. MCT's reassessment of the originally proposed work after the investigations described in this report concluded that the thin coatings were not feasible for the application. After consultation with the industrial collaborator, Solar Turbines, in this Phase I, a new strategy was proposed and thicker coatings were considered. Vapor deposition techniques like CVD and CCVD are not generally amenable to depositing thick and dense coatings of most materials, including alumina and yttria. The NanoSpraySM technology using the Nanomiser[®] device, however, can be used to deposit much larger quantities of materials as nanopowder particles, which can then be sintered, usually at much lower temperatures than traditionally associated with larger size powder particles.

The initial investigations of nanopowder-based coatings showed technical feasibility in smoothing of a rough substrate and in sintering at relatively low temperatures. Much additional work needs to be done to investigate the economic feasibility of such an approach.