

DOE/OR/22242--T1

**ADVANCED THERMAL BARRIER  
COATING SYSTEM DEVELOPMENT**

CONTRACT # DE-AC05-95OR22242

TECHNICAL PROGRESS REPORT

to the

U.S. DEPARTMENT OF ENERGY

Oak Ridge Operations Office

Oak Ridge, Tennessee

June 10, 1996

Submitted By

WESTINGHOUSE ELECTRIC CORPORATION

Power Generation Business Unit

4400 Alafaya Trail

Orlando, Florida 32826-2399

DISTRIBUTION OF THIS DOCUMENT IS LIMITED

*h*  
**MASTER**

## DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

**DISCLAIMER**

**Portions of this document may be illegible  
in electronic image products. Images are  
produced from the best available original  
document.**

# Advanced Thermal Barrier Coating System Development

## Program Objectives

The objectives of the program are to provide an improved TBC system with increased temperature capability and improved reliability relative to current state of the art TBC systems. The development of such a coating system is essential to the ATS engine meeting its objectives.

The base program consists of three phases:

Phase I: Program Planning - Complete

Phase II: Development

Phase III: Selected Specimen - Bench Test

Work is currently being performed in Phase II of the program. In phase II, process improvements will be married with new bond coat and ceramic materials systems to provide improvements over currently available TBC systems. Coating reliability will be further improved with the development of an improved lifing model and NDE techniques. This will be accomplished by conducting the following program tasks:

- II.1 Process Modelling
- II.2 Bond Coat Development
- II.3 Analytical Lifing Model
- II.4 Process Development
- II.5 NDE, Maintenance and Repair
- II.6 New TBC Concepts

Phase III of the program will proof test the best of the newly developed TBC systems on airfoil sections in a combustor test passage at the Westinghouse Science and Technology Center.

## Technical Progress Report

### Task II.2 Bond Coat Development

The Advanced Thermal Barrier Coating System Development program is designed to provide a coating system capable of meeting ATS engine operating requirements. Since it is known that there is considerable interaction between the superalloy substrate composition and the coating performance, it is imperative that the coatings be developed and tested on the alloys being considered for the engine. Three alloys are being considered in the program, two blade alloys CMSX-4 and MarM002, and one vane alloy IN-939. CMSX-4 was selected as the base material for this study.

Substrate machining is continuing for all development tasks.

#### *Task II.2.1 Bond Coat Deposition Process*

Electron beam physical vapor deposition (EB-PVD) and low pressure plasma spray (LPPS) are high temperature vacuum processes for depositing bond coat materials to turbine components. EB-PVD provides a high density coating free of internal oxides. High process temperatures, low chamber pressure and high coating particle velocities in LPPS bond coats provide coatings nearly as good as EB-PVD. Due to high capital equipment costs, however, these processes are inherently expensive. Shrouded plasma spray (SPS), Gator Gard (GG), and high velocity oxy-fuel (HVOF) are three cost effective alternatives to the vacuum processes. To date, little process optimization has been performed for these alternatives.

Coating optimization consists of a statistical design of experiment approach to optimization. Optimization for the HVOF, SPS, and GG techniques is being conducted in two parts, study 1 and study 2. Study 1 consists of an initial set of experiments with a broad range of process variables based on coating vendor history. Based on study 1 results, a refined set of experiments, referred to as study 2, will be conducted to yield a final, optimized set of process parameters. Study 1 coatings have been deposited for the HVOF and the SPS deposition techniques.

The HVOF study 1 examined two levels for each of the process variables shown in Table 1. Coating trials consisted of 16 process variation (a quarter factorial design) plus a baseline setting. These parameters resulted in a significant range of bond coat microstructures. The HVOF microstructure analysis is nearly complete and the data is being reviewed for further optimization in study 2.

The design of experiments for the Shrouded Plasma Spray study 1 was modified from that originally proposed. The primary focus of the experiment is to examine the effect of the shrouding in improving coating quality. The two shrouds investigated are the Miller shroud and the Drexel shroud. A smaller partial factorial experimental design was then used for each of these shroud types. Metallography is currently being conducted on the SPS coated test coupons.

**Table 1: Optimization Process Variables**

High Velocity Oxy-Fuel	Shrouded Plasma Spray	Gator Gard
Fuel Flow	Shroud Type	Powder Size (3 levels)
Fuel to Oxygen Ratio	Shroud Gas Flow	Gun Nozzle
Powder Size	Primary Gas Flow	Power
Powder Feed Rate	Anode Type	Gas Flow
Powder Orifice Size	Current	Shrouded/Unshrouded
Carrier Gas Flow		

The experimental approach for optimizing the Gator Gard deposition process has been finalized. Deposition is scheduled for June, 1996.

The LPPS deposition process is considered a more forgiving process. The quality of these coating are surpassed only by EB-PVD (perhaps). As a result, a single optimization study is sufficient. As with the prior methods, a factorial design of experiment has been generated. Test pins have been prepared and are awaiting coating.

#### *Task II.2.2 Evaluate Bond Coat Chemistry*

The bond coat chemistries must possess inherent oxidation resistance, compatibility with the substrate alloy and provide an appropriate surface for ceramic top coat adherence. In the previous report, it was indicated that seven of the ten program chemistries had been identified. The remaining three chemistries have since been identified and LPPS powders of all 10 chemistries have been manufactured. Bond coat powder manufacturing was conducted using inert gas atomization. Praxair also performed the necessary classification of the powder according the coating vendor specifications. These powders will be deposited during the next reporting period using LPPS.

#### *Task II.2.2.7 Diffusion Modified Bond Coats*

Diffusion modification of overlay bond coats allows one to place specific alloying additions in the coating where the addition provides the most benefit. In this way, the coating can be tailored to address system specific issues. A series of coatings and coating modifications have been identified for investigation. The modifications are based on using slurry platinum-aluminides and platinum-silicon-aluminides to modify the bond coat chemistry. These coating will be used in conjunction with APS ceramic top coats. The details of applying these coatings are being worked through. Process variables being considered in the experimental design include diffusion coating chemistry, basecoat chemistry, diffusion parameters, and top coat application process. In addition, due to the high degree of uncertainty, associated with applying and APS topcoat to modified bond coat, a preliminary proof of concept experiment has been initiated. This proof of concept consists of a set of four deposition conditions using an APS bond coat, a slurry modification system, and an APS zirconia top coat. This work is continuing.

#### *Task II.2.2.8 Sol-Gel Bond Coats*

The effort to utilize sol-gel as a means of applying an oxygen barrier in lieu of or in conjunction with a conventional bond coat is continuing. Several coating trials have been performed with variable degrees of success. However, the large volumetric shrinkage associated with drying and densifying the coating continues to hinder successful coating deposition. Possible solutions to the issue are being considered.

### Task II.3 TBC Analytical Lifting Model

#### *Task II.3.1. Evaluate Existing Lifting Models*

Evaluation of existing lifting models, NASA, GE, Pratt & Whitney and Garret, were evaluated as a foundation to developing the SwRI lifting model. Consideration was given to the findings of these efforts and the availability of baseline data within the reports.

#### *Task II.3.2 Model Development*

The modeling approach and equations associated with the individual failure mechanisms to be addressed were evaluated and finalized. Bond coat oxidation will be modeled using an equation, which under expected conditions, reduces down to the well known parabolic oxidation equation. An Arrhenius temperature dependence is assumed. Fatigue equations were derived and the constitutive equations for the TBC behavior were established. The inelastic behavior of the system will be modeled using the Bodner-Partom approach. Equations for the effect of sintering of the TBC ceramic were also finalized.

Strategies for collecting the data to support the model were established. Whenever possible, data will be extracted from the literature. All available Westinghouse mechanical and physical data relevant to the program will be forwarded to SwRI. Data not available in the open literature or available within Westinghouse will be derived from tests performed by Westinghouse. A test matrix was established which focuses on the cyclic testing of thin wall cylindrical specimens coated with TBC as seen in figures 1 and 2. The output of these tests will be used in the individual fundamental equations to derive unknown parameters. The test matrix is designed to clearly quantify the effect of TGO thickness, stain range, temperature and sintering effects.

Various routes to fabricate the thin wall specimens have been explored, and suitable vendors have been identified. Substrate material was acquired, and the fabrication of the thin wall substrates is now under way. Suitable vendors for the coating work have been identified and final costing is underway.

### Task II.4 Manufacturing Process Development

#### *Task II.4.2 Cooling Hole Masking Technology*

Application of coatings to turbine component surfaces can cause restriction of cooling holes and alter the heat management of the engine. Altered cooling air flow will lead to increased component temperatures and will shorten the life of the part. Therefore, it is

critical to understand the extent of hole restriction caused by the coating process and to 1)account for the restriction in cooling hole design, 2)prevent cooling hole restriction during TBC deposition, or 3)remove the coating material from the holes after deposition.

A number of techniques for eliminating cooling hole restriction were reviewed. Several of those techniques have been selected for coating trials (see table 2). Progress was made in the areas of polymer masking and programmed spray automation.

**Table 2: Techniques for eliminating cooling hole restriction**

Masking Technique	Advantages	Disadvantages	Status
Paste masking (hole filling)	easy to apply paste	•contamination	initial masking trial performed
Programmed spray path	automated (high speed) no contamination	•requires robotics •requires programming	discussion with vendors
Programmed spray angles	automated (high speed) no contamination	•requires robotics •requires programming	discussion with vendors
Air flow	no contamination no complex automation	•requires optimized air flow •difficult to control	discussion with vendors

The current polymer masking consists of application and cure of a polymer, cleanup of the component surface, deposition of coatings, and removal of the mask after coating. Preliminary polymer masking trials were performed on sections of engine hardware; five different polymers were examined. The polymers were applied to rows of cooling holes and any excess material was wiped from the surface of the component. The polymers were then cured in a laboratory oven. On completion of the cure cycles, it was noted that several of the polymers had protruded out of the holes. The excess mask material was removed to avoid shadowing; the excess mask was left on several holes as a comparison. Grit blasting with alumina was used to remove any remaining polymer from the component surface. Compressed air was used to clean the residual grit from the surface in final preparation for the application of coatings.

A ceramic coating, having a nominal .12 mil thickness, was applied to the components using air plasma spray; no bond coat was used for these initial trials. The spray gun was oriented at 90° to the component surface, and a standard gun to part distance was used. The samples used in this study had cooling holes oriented perpendicular to the surface.

Masking was successful in preventing restriction of the cooling holes when the polymer mask was cured correctly. Incomplete cure on some masks lead to extensive polymer volatilization during coating, and hole restriction occurred. Also, soot from burning or volatilization of the polymer on some parts was seen to discolor the APS coating.

For properly cured polymers, no restriction and no over-masking was seen for holes which had the mask trimmed down. Several holes, that did not have the mask trimmed, showed poor edge definition, and the surface of the part adjacent to the hole was not coated.

A burnout cycle was used to remove the polymer mask from the cooling holes. The cycle also served to burn off any residual soot that was trapped in the coating during the spraying process. It was noted that some polymer masks contain a ceramic filler. The ceramic filler particles from the mask were observed to remain in the holes after the polymer was burned out. Processes for removing the filler particles are being investigated. As an alternative, unfilled masking materials are being considered.

Customized spray patterns and angles may be used to reduce cooling hole restriction. Most existing spray coating systems use computer automation to control the coating deposition. The extent of programming, however, has been limited to simple iterative step patterns. The degree of hole closure may be limited by customizing the spray pattern so as to lessen coating thickness in the vicinity of a row cooling holes.

Computer automation is critical to the success of customized spray patterns. The spray pattern must account for the location of cooling holes and the shape of the part. Spray gun robotics appear to be adequate, but the memory and speed of the current control terminal being used by the vendor may be limiting. Coating trials performed using different spray patterns and angles will demonstrate the dependence of hole restriction on spray angle and hole angle. Additionally, the feasibility of reducing the coating thickness (and hole restriction) in the region of a line of cooling holes will be determined.

#### *Task II.4.3 Hole Re-Drilling*

Three machining techniques have been identified for re-shaping cooling holes after TBC deposition. Table 3 shows a list of techniques that are being evaluated. A vendor has been identified for high pressure water-jet cutting. Initial trials are being performed to verify the minimum practical jet size and the positional resolution of the equipment. Upon sufficient verification of the hardware, Westinghouse will supply coated samples for additional verification of the water-jet method. Possible problems with the water-jet method include over-machining that would cause loss of tolerance on the cooling holes, and impingement of the jet on the internal cooling passages.

**Table 3: Cooling hole re-machining techniques**

Machining Technique	Advantages	Disadvantages	Status
Water-jet cutting	compatible with non-conductive materials	<ul style="list-style-type: none"><li>•current resolution</li><li>•under cut on angles</li></ul>	initial trials being performed at vendor
Laser cutting	allows precise positioning of beam	<ul style="list-style-type: none"><li>•thermal stresses</li><li>•heat affected zone</li><li>•ceramic to metal transition</li></ul>	internal discussion
High speed rotary cutting	readily adaptable to CNC machines	<ul style="list-style-type: none"><li>•mechanical stresses</li></ul>	internal discussion

Task II.5 NDE, Maintenance, and Repair

NDE methods are being evaluated for use on TBC's to ensure that the coating meets the Westinghouse quality standards for new equipment, and throughout the life of the coating. Since detailed inspection of the coatings is limited and component refurbishment at every inspection interval is impractical, appropriate NDE methods, sensitive to the types of microstructural features that cause failure, and local repair methods must be established. In addition, on-line monitoring of the TBC during engine operation is essential to limit damage in the event of a coating failure.

*Task II.5.1 Repair and Maintenance*

Localized repair of a coating system offers the potential for considerable cost savings over general stripping and recoating of a component. Based on discussions with coating vendors, it was established that two general classification of repairs need to be considered, major repairs, and minor repairs. Minor repairs are defined as repairs requiring cleaning and top coat application only. This type of repair is intended for a new or nearly new parts with a coating chip, but little if any bond coat degradation. Major repairs, on the other hand, constitute a local TBC and bond coat stripping and refurbishment. Test specimens have been designed for both types of repairs and are being fabricated.

*Task II.5.2 Off Line NDE*

Off line NDE will consist of only commercially available NDE services for the purpose of ranking new coating performance on test coupons. Technologies such as thermal wave imaging and penetrant testing of TBC's will be utilized for newly coated and service exposed specimens as needed.

*Task II.5.3 In Frame NDE*

Since the conception of the in-situ monitor for coating damage, the ability to monitor coating effectiveness during engine operation has gained tremendous interest both here at Westinghouse, as well as in competitive and related industries. Task II.5.3 is scheduled

to begin in the second quarter of 96 and some preprogram activities have been completed in preparation. An internal meeting was held with Design, Materials and Sensors Engineering personnel to both establish the high priority of this work and brainstorm about possible solutions with the goal of leveraging this effort with other programs. The information generated at this meeting was taken to a DOE sponsored ATS Sensors Workshop where related industries reaffirmed the importance of new sensor needs for such measurements. Our subcontractor, Southwest Research Institute is currently scheduling a kick off meeting to formally begin this program on schedule.

#### Task II.6 New TBC Concepts

Yttria-stabilized zirconia is the mainstay of the aero and industrial gas turbine (IGT) TBC coating industries. Significant differences in the operating mode of an IGT relative to an aero engine exist. The long time at temperature in an IGT, has created significant concerns as to whether current zirconia TBC's are capable of operating under ATS conditions.

##### *Task II.6.1 New TBC Chemistry*

Five alternates to YSZ have been identified as having merit for application as a thermal barrier coating. Four of these have been formalized with a fabrication request with Praxair. The fifth composition is being investigated in terms of its economic feasibility and availability. Fabrication and initial deposition trials for these compositions are planned to occur during the next reporting period.

##### *Task II.6.2 Microstructure: Microcracked / Segmented / Columnar*

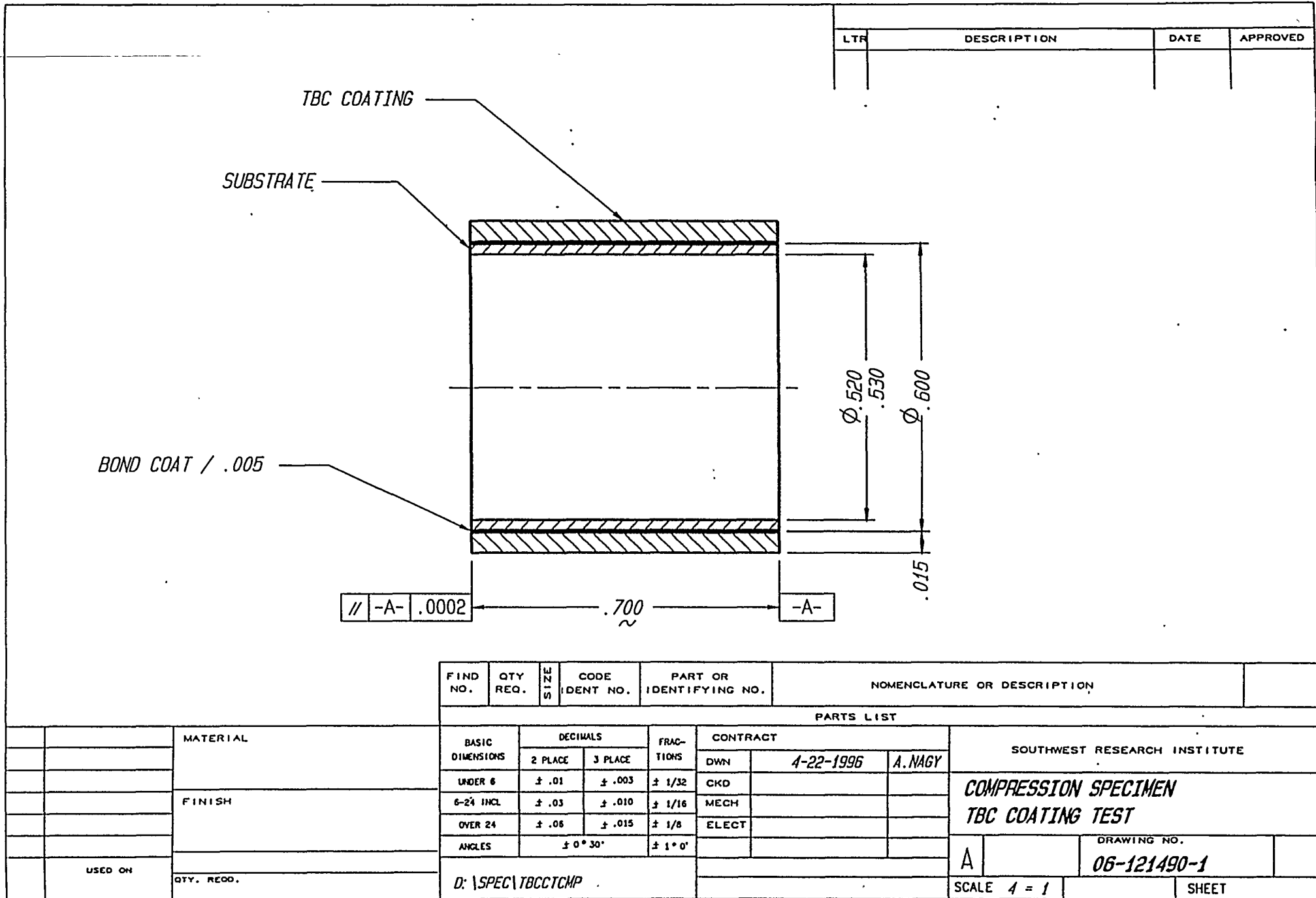
It has been proposed that an increased strain tolerance (and longer coating life) can be achieved in a TBC ceramic by developing a microstructure where a high density of microcracks run perpendicular to the coating surface. This theory has been used to explain increased coating life for EB-PVD coatings over APS coatings for high cycle applications.

Similar benefits are possible utilizing APS TBC deposition techniques. By proper manipulation of the deposition process and thermal treatment, it is possible to mimic the columnar EB-PVD structure using APS.

Work was initiated in this task by reviewing the base technology held by the coating vendor. The experimental design is being developed. This work will continue through the next reporting period with deposition trials.

##### *Task II.6.3 Process Optimization*

Task II.6.3 is intended to optimize the APS deposition of YSZ by investigating the benefits derived from TBC powder characteristics. Four distinct TBC powders have been identified for the optimization study and include two variations of the baseline material, a finer particle size material, and a material with elliptical particles.



**Figure 1**

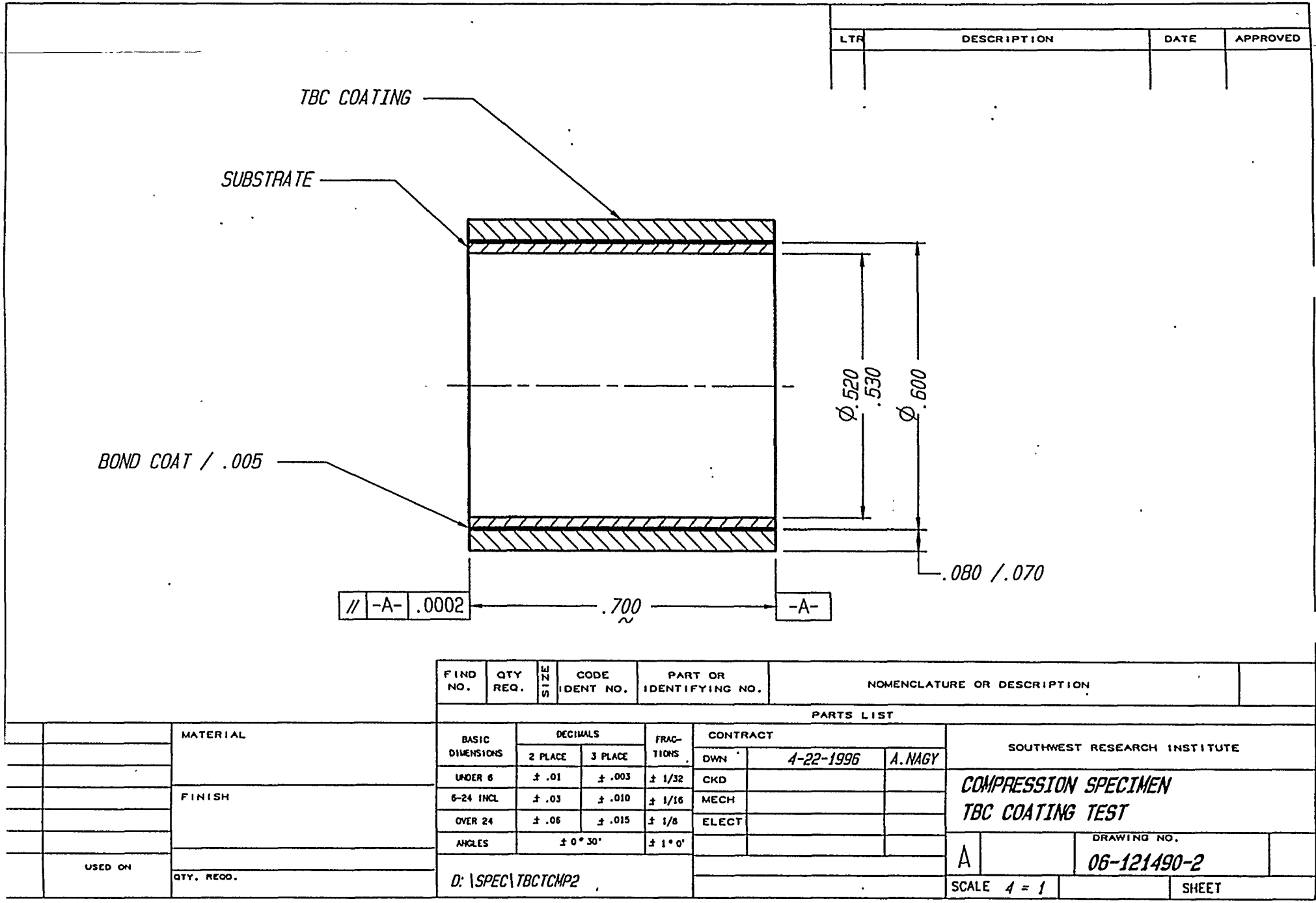


Figure 2