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Fabrication of 0.0075-Scale Orbiter Phosphor Thermography Test Models for Shuttle RTF Aeroheating Studies

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November 2006

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Abstract

This report details the techniques and fidelity associated with aeroheating models constructed in support of the return-to-flight boundary layer transition (BLT) activity for STS-114. This report provides technical descriptions of the methods, materials, and equipment used, as well as the surface quality results obtained with the cast ceramic phosphor thermography models. The subject document is intended to define, from a verification and validation perspective, the quality of the experimental models used to establish the boundary layer transition thresholds within the facilities of the Langley Aerothermodynamic Laboratory. As described within the subject document, many 0.0075-scale cast-ceramic Orbiter models were constructed and tested over the past year, which are believed to be typically better than ± 0.010 -in overall when compared to the current Orbiter CAD definition. The sample ceramic model that was scanned, however, shows the nose region to be raised on the order of 0.020-in. This deviation is not believed to be systematic of all the cast ceramic models tested, but an artifact of the particular model chosen to document the surface verification results. Additionally, an optical surface scan was conducted of other sample ceramic models with and without phosphor coating applied and found to have a surface finish (RMS) roughness on the order of 200 μin uncoated and 400 μin coated. The purpose of this report is to document the methods, materials, and equipment used to fabricate and validate aeroheating test models at NASA Langley Research Center in support of Shuttle Return-to-Flight.

Introduction

The unique capability to rapidly construct and test experimental aeroheating models over a wide range of hypersonic conditions was instrumental during the Columbia accident investigation, and continues to support the “fast-paced” Return-to-Flight activities. This report provides detailed documentation of an application of the technical process and skills that were developed over the past decade and a half, with many lessons learned in constructing high-fidelity aeroheating test models at NASA Langley.

Quantitative aeroheating test methods at Langley, from the early 1980s until the early 90s, required machining of ceramic inserts and application of thin film gages (Schultz and Jones, 1973; Miller, 1981, 1984). Typically, during this period a thin film aeroheating test model with 150 to 250 gages would take a year to fabricate and cost up to \$150K (Miller, 1998). Fast paced programs such as the National AeroSpace Plane and X-33 next generation orbiters in the 1990s required more rapid techniques than this for fabrication and testing of aeroheating configurations.

Two-color thermographic phosphors and imaging systems (Buck, 1988, 1991), together with the described techniques for ceramic slip casting and other rapid model fabrication techniques (Buck, 2000), soon provided test data for complex aeroheating configurations in a matter of days, not months. User-friendly tools to view and analyze the data (Merski, 1998) and an improved temperature calibration technique (Merski, 1999) improved the method even further.

The effects of isolated roughness elements on the boundary layer of the windward surface of the Shuttle Orbiter were experimentally examined in NASA Langley’s hypersonic wind tunnels in two reports by Liechty, Berry and Horvath, 2005, on the effects of protuberances and cavities using phosphor coated ceramic aeroheating test models. These studies were in support of an agency-wide effort to prepare the Shuttle Orbiter for return to flight. Similar aeroheating test models were also fabricated earlier for a JSC/LaRC collaboration (Berry et al., 1998) and for isolated roughness elements of varying heights placed at various locations along the windward centerline (Berry and Hamilton, 2002). During the Columbia accident investigation, some ceramic models were also modified to accept a six-component balance for simultaneous aerodynamic and aeroheating measurements (Brauckmann and Scallion, 2003; Horvath, 2004).

In preparing the Shuttle Orbiter for return to flight, both protuberances above the model surface, simulating possible expanded repair devices, and cavities below, simulating unrepaired tile damage, were examined. Both of which were tested along the centerline and attachment lines at various heights, depths and geometries. Global heat transfer images of the Orbiter windward surface were obtained using phosphor thermography and used to infer the status of the boundary layer. The results of these studies are currently being used to formulate roughness-transition correlations, using predicted boundary layer edge parameters.

The purpose of this paper is to document the methods, materials and equipment used in fabricating the ceramic aeroheating test models used in these experimental studies. The fabrication process includes forming a wax pattern in the shape of the test model, using a lost-wax investment casting process to transform the pattern into a ceramic model, sintering the ceramic model to give it strength, mounting supports, machining cavities, coating with phosphor, marking fiducials and applying protuberances. A typical schedule for performing all these tasks is shown in figure 1, including the one-time task of fabricating the wax injection mold and sting mounting alignment fixture. Over a typical schedule, a week and a half, up to 8 models can be built simultaneously.

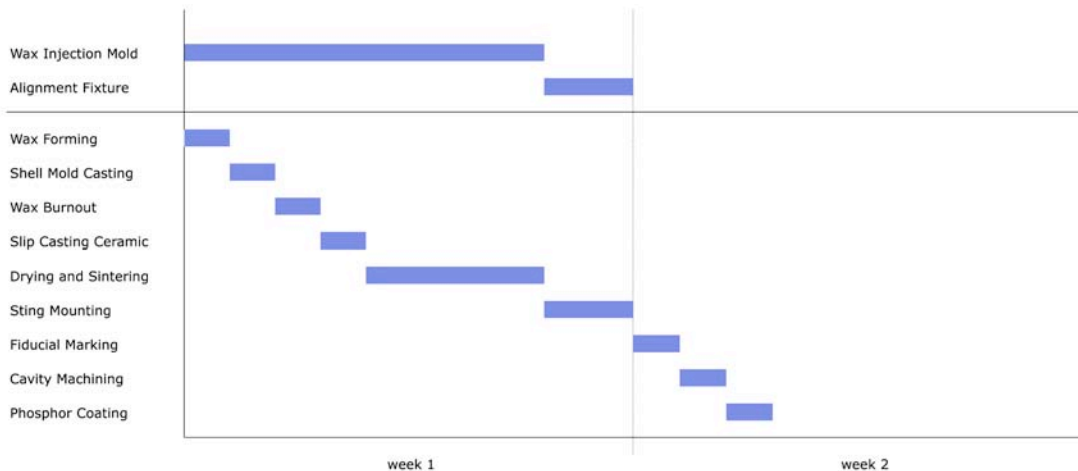


Figure 1. Model fabrication schedule.

Orbiter Model Casting Pattern

The original model pattern used for fabricating the slip-cast ceramic test models for aero-heating studies is a machined stainless steel aerodynamic test model. The Langley model drawing is LE-542183, dated 1-21-87. The project title for this model was "0.75% Shuttle Ascent Configuration LTV Model". The drawing is a model detail and assembly with three other drawings of external tank details, model arrangement, and Solid Rocket Boosters (SRB) plume details. The model itself was built from CAD file/milling tapes which have since been lost. The Orbital Maneuvering System (OMS) pods may have been made at a later date as these are not on the drawing (different body flap deflections were made later as well). This model was also later modified, after the Columbia accident, to simulate damage to the left wheel well for accident studies (Brauckmann and Scallion, 2003). Top-side and bottom views of the stainless steel model pattern are shown placed in the wax injection mold in figure 2.



Figure 2. Top and bottom views of machined stainless steel aerodynamic test model/casting pattern and cast formed wax injection mold.

Fabrication of Wax Injection Mold

A lost wax process is used in transferring the surface coordinates from the original model pattern to the slip-cast ceramic. The first step in this process is to form a mold for wax injection over the original stainless steel pattern. This is done using a two-part urethane tooling plastic from Freeman Manufacturing and Supply Company, which is part of their Repro castable plastics line. The particular product used is the Repro-Slow, which has a gel time of 12-14 minutes and demold time of 3-4 hours. The particular advantage to this material, in addition to the extra working time, is that it has the highest flexural and tensile strength and lowest shrinkage (0.0009 in. / in., ASTM D-2566) of the urethanes. It also has the lowest mixed viscosity of the group, which allows it to be formed over detailed surface features and cavities.

The mold itself was formed in three primary sections consisting of a base or windward mold section and two top sections to form around the OMS pods. These were formed using typical casting practices with the Repro material. Other mold pieces include a loose piece at the model base to form the body flap upper surface and OMS pods trailing features and a turned brass core for forming the internal cavity. The brass core also helps in conducting heat away from the hot injected wax part. Sections of this mold are shown in figures 2 and 3. This wax injection mold was fabricated in 1994 and used before the Columbia accident for transition studies (Berry et al., 1998) with approximately 20 wax orbiter patterns fabricated. It was then used during the accident investigation (Horvath, 2004) with an additional 50 or more models fabricated and again for the return-to-flight studies with approximately 106 models in total being fabricated using this one wax injection mold.



Figure 3. Two-part wax injection mold top section with aft insert piece and internal shaped brass core mandrel

Wax Pattern Forming

A high-tech premium pattern wax is used with a paste wax injector for the most accurate forming of investment patterns. The pattern wax used is Kindt-Collins #3807 F (composite filled). This pattern wax is also used in the aerospace industry for larger investment castings to reduce dips and cavities in those castings. In addition to providing higher model fidelity and lower contraction rate over liquid wax injection (0.2% reduction in linear shrinkage to approximately 1.4%) the paste wax process provides a faster cycle time and lower core temperatures, which is of critical importance when using the Repro urethane because of the relatively low heat conduction or dissipation of that material.

The wax injector is a 4,400 lb machine used to clamp the mold or die in place, position and hold an injection nozzle, and then pre-condition and inject paste wax at a constant and accurate temperature and pressure. The system (fig. 4) manufactured by MPI is a Model 55 with a 25 ton clamping force capability, 18-inch maximum clamp opening with a 14-inch stroke. The liquid/paste wax reservoir can condition the wax to any viscosity required. It has a 30 gallon wax reservoir capacity with a maximum 150 cubic inch single shot capacity and an injection pressure range from 50 to 1000 psi. The temperature is controlled in four different zones; the upper tank, lower tank, injector and nozzle; and is capable of temperature changes up to 1°F in 3 minutes for rapid die cycle times.

The injection mold is clamped in the wax injector with a force of 550 pounds (fig. 5) and the paste wax injection pressure is set between 160°F and 200°F. Wax temperatures maintained are 190°F for the upper tank, 160°F for the lower tank, 130°F for the injector, and 130°F for the nozzle. After the wax is injected and allowed to cool to room temperature, the pattern is removed from the mold (fig. 6).

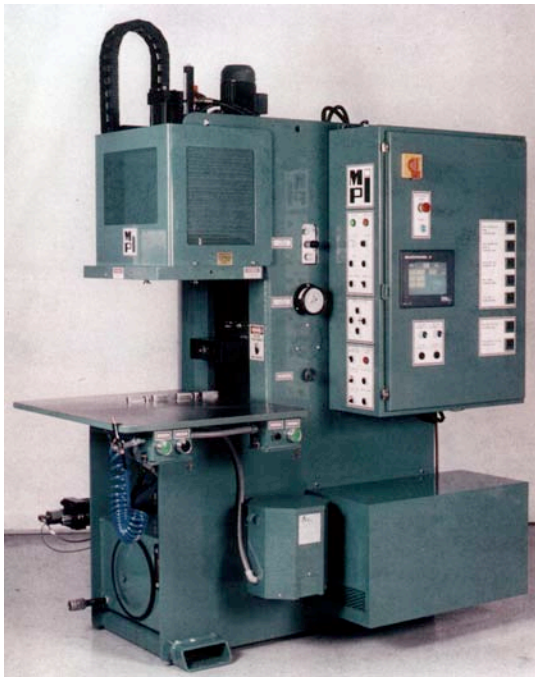


Figure 4. Wax injector



Figure 5. Injection of wax into wax injection mold.

The original wax gates and flashings, residual from the wax injection mold, are manually removed from the injected wax pattern and it is given new gates for pouring the slip (green wax bars) and vents for letting out trapped air (red wax strips) as shown in figures 7 through 9.

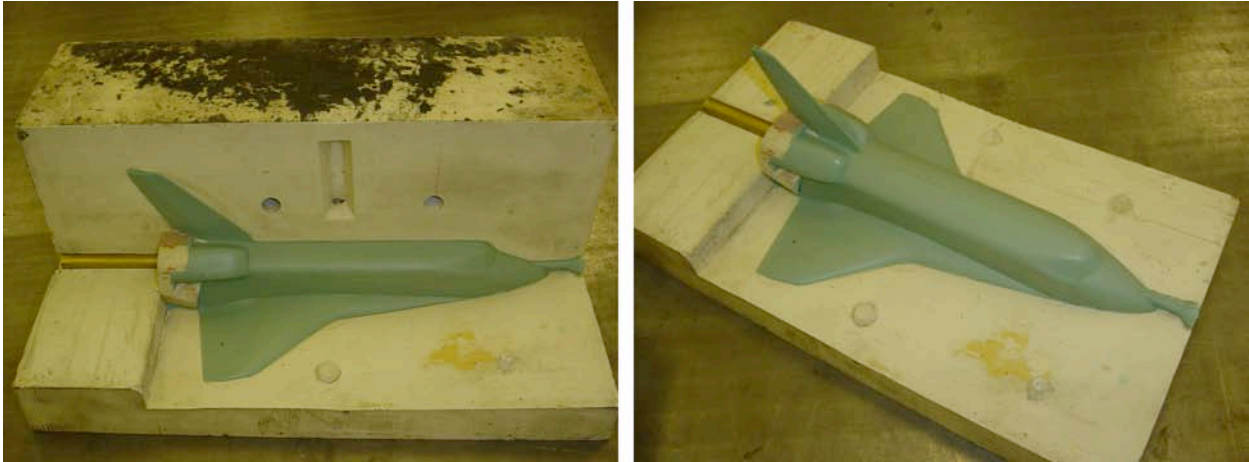


Figure 6. Wax pattern being removed from wax injection mold



Figure 7. Trimming and cleaning of wax pattern.

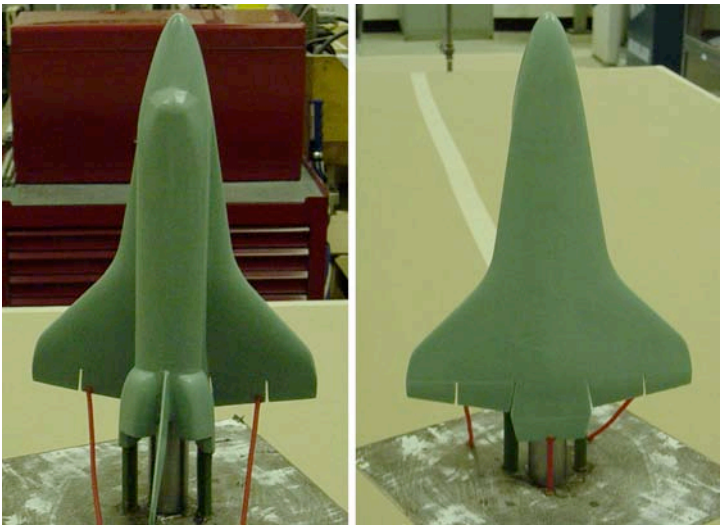


Figure 8. Treeing of wax pattern with vents and risers for shell mold application

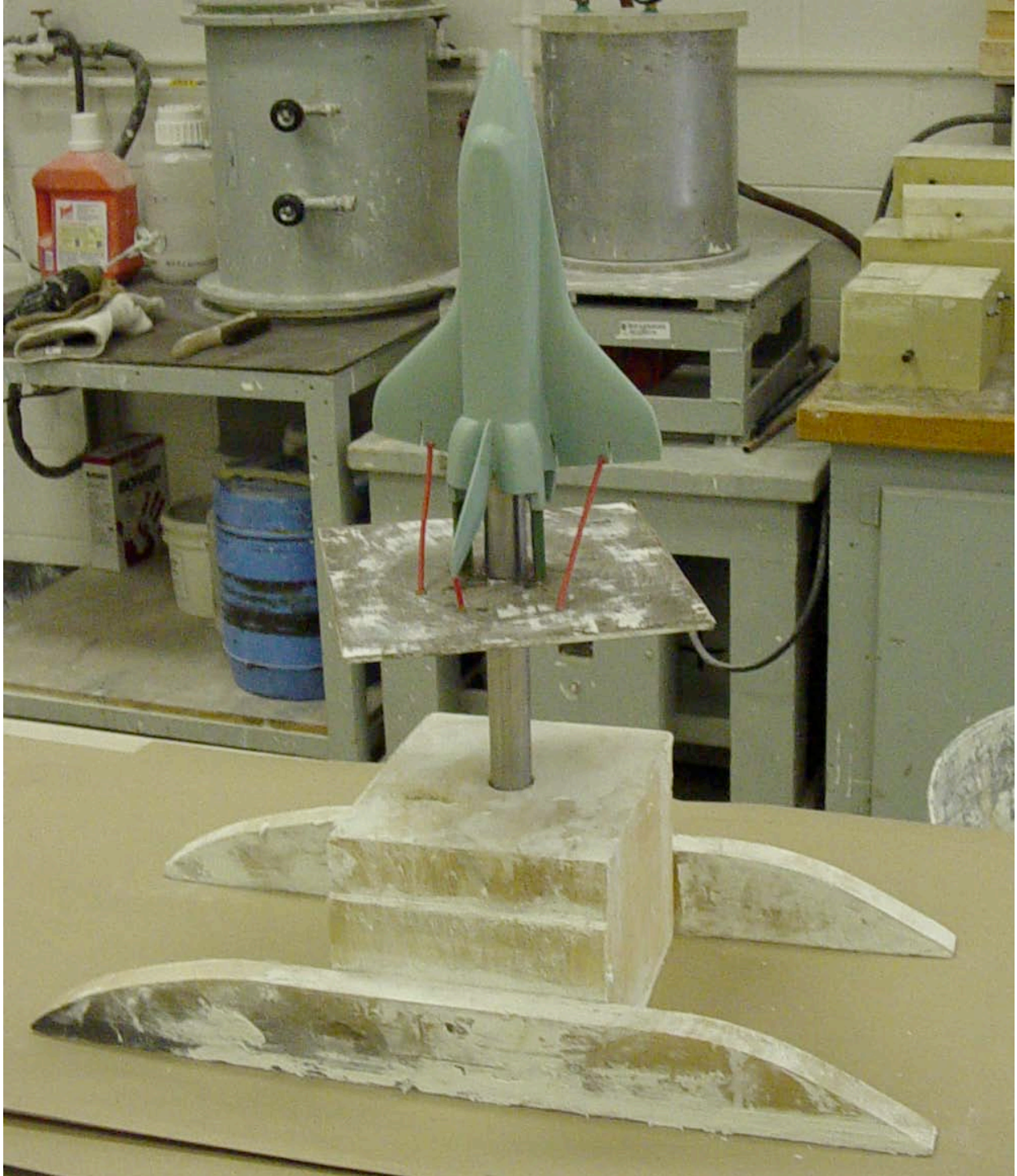


Figure 9. Treed wax pattern in shell mold application and drying stand.

Shell Mold Forming

The process used for slip casting using investment shell molds from lost wax patterns was invented at NASA Langley (Buck and Vasquez, 1989) as a way to provide greater detail in slip castings. This technique facilitates castings with attached fins and wings, properly aligned, and eliminates mold parting lines from leading edges. The shell mold casting process is illustrated in figures 10 through 12. In place of a conventional multipart plaster mold, as used in the art and porcelain industry, an investment shell mold is used. This provides the capability of removing the mold in small sections, as if peeling an eggshell, to release fine and delicate parts such as fins and tails. It also eliminates flashings at parting lines in the slip mold, as the shell mold is seamless.

The material used for the shell mold is a hydraulic setting calcium sulphate bonded investment mixture which contains calcined silica, fiberglass, and various specially graded refractories. It is a castable product from Ransolm and Randolph, Inc., that is part of their line of materials conventionally used for non-ferrous metal castings. In particular, the product used is R&R 910, which has been shown to have the optimum mix of reinforcement materials and fine surface texture. This mold material must withstand temperatures high enough to burn out the wax investment pattern, but is softened when rewetted to be easily removed from delicate slip castings.

The shell mold is formed in several layers to give it strength and volume to absorb slip liquid, but not in one thick layer, so that it can be easily removed again in layers when rewetted. To give it added strength, an open weave or perforated fiberglass cloth is added at strategic locations, such as at the roots of wings and fins and other locations where cracks are expected to form.

The R&R 910 is first mixed with water (>28% by weight to desired consistency) and then poured and spread over the wax pattern using a “buttering” method as illustrated in figures 10 and 11. Four layers of material are applied in this manner, with at least 2 hours drying time between each layer. Fiberglass reinforcement cloth is then placed in strategic locations and a fifth and final layer is applied as shown in figure 12.

Removal of Wax Pattern from Shell Mold

After the finished shell mold is dried overnight it is placed in a gas-fired wax “burn-out” oven. The oven used is a Lindbergh mold pre-heat furnace with a maximum temperature of 2200°F. The oven is forced-air fed to promote cleaner burnout of wax patterns from the investment molds and also has a post-burner on top of the exhaust stack to reduce byproduct emissions into the atmosphere.

The furnace is pre-heated to 1250°F. The shell mold is placed in the furnace on brick spacers with gates pointing downward to drain as shown in Figure 13. The shell molds remain in the furnace overnight at 1250°F until morning when the oven is turned off (~14 hours) and the molds are removed that day after a period of cooling (~2 hours).



Figure 10. Application of slip-casting investment shell mold to wax pattern using a “buttering” method.



Figure 11. Completed first application of slip-casting investment shell mold to wax pattern.



Figure 12. Reinforcement of shell mold with fiberglass cloth between fourth and final coat.



Figure 13. Removal of pattern from shell mold in wax “burn-out” gas oven.

Ceramic Slip Casting

A “slip” refers to a crowded suspension of particles in a liquid. In the process of slip casting the slip is poured into a porous or liquid permeable mold, such as plaster of Paris used with aqueous or water based slips. The mold draws liquid from the slip compacting the powder along the mold surface to form a high-density cast shape. This cast shape is referred to as being in the “green” state. This state has to have some strength so that the mold can then be removed. Intermediate binders are usually added to the slip to give it this green strength. The silica slip is purchased from the Ceradyne Corporation. It comes completely formulated in 75 pound drums. The suspended powder is an amorphous fused silica with a median particle size of approximately 10 microns. Before use, the slip is placed on rollers to keep the ceramic powder from settling. The last two batches purchased were batch numbers 052301-24 and 082001-26, and in the past three years 1,725 pounds of slip were used in casting silica ceramic test models at NASA Langley.

Advantages of the slip cast process include hollow, thin walled castings, high purity materials, void free substrates, smoothness and an accurate reproduction of the mold surface. Accuracy is achieved because of the low shrinkage of the ceramic during drying and sintering. The silica slip used for aeroheating test models is 83% solids and the slip casting process removes most of the remaining liquid to compact the green shape. Silica ceramic also has very low linear shrinkage relative to other ceramic slip castings. From a fully dense casting, with complete sintering, silica has a theoretical minimum linear shrinkage of 0.75%, whereas alumina ceramic has a theoretical minimum linear shrinkage of 3%.

After removal from the wax burn-out oven the shell mold is allowed to cool to room temperature. Any debris which is loose in the mold is removed with blown air. The mold is first supported in a fluidic sand bed and then filled with ceramic slip (fig. 14). After an approximately 3/16 inch thick wall is formed, in about 20 to 30 minutes, the shell mold is removed from the fluidic bed and excess slip is poured out of the shell (fig. 15). The “green” cast ceramic model is then removed from the shell mold immediately, as shown in figures 16 and 17. The model is then allowed to air dry for 24 hours. Final finishing, removing the pour gate, and additional trimming and shaping, if needed, is then done by hand (fig. 18) before firing.

Ceramic Sintering

After removal from the mold, the ceramic model is taken to a high temperature (2150°F for silica) burning out the intermediate binder and bonding or “sintering” the powder, forming inter-particle bonds which give it strength. An electric resistance L&L kiln is used for sintering with a maximum temperature capability of 2350°F (Figure 19).

After drying in room air a minimum of 24 hours, the green model is placed in the kiln, supported evenly by fine zirconia sand as shown in Figure 20. The kiln temperature is ramped at a rate of 12°F per minute to 250°F and held for 4 hours. Next, it is ramped at 5.76°F per minute (5.5 hours) to 2150°F and held for 4 hours. It is then allowed to cool to room temperature before removing the sintered model.

Once the model is sintered it cannot be touched with bare hands. The adsorbed oils affect the luminescent properties and adhesion of the next layer of phosphor coating. Gloves or paper towels are used in handling the sintered models. If the model surface is contaminated, before it is backfilled and supports mounted, it can be refired to 1200°F to burn off impurities.



Figure 14. Adding ceramic slip material into investment shell mold.



Figure 15. Removing ceramic slip from model center after 3/16 inch wall is formed.



Figure 16. "Green" cast ceramic model being removed from shell mold.



Figure 17. "Green" cast ceramic model "as cast."

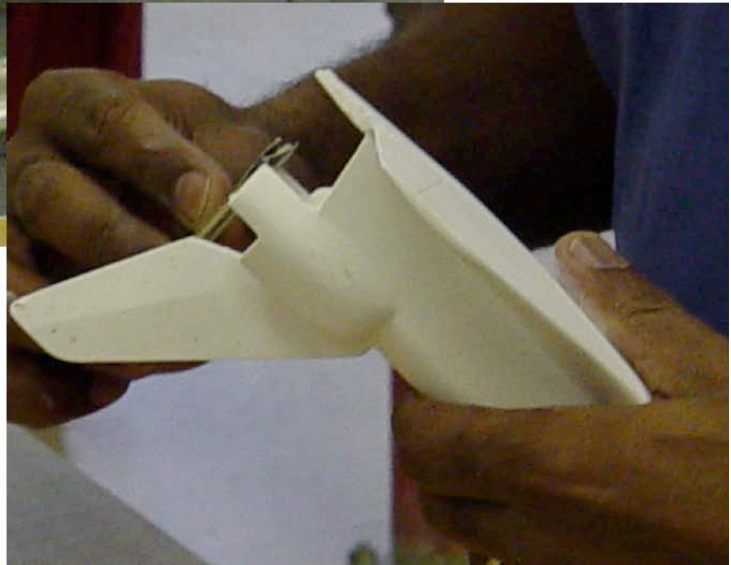
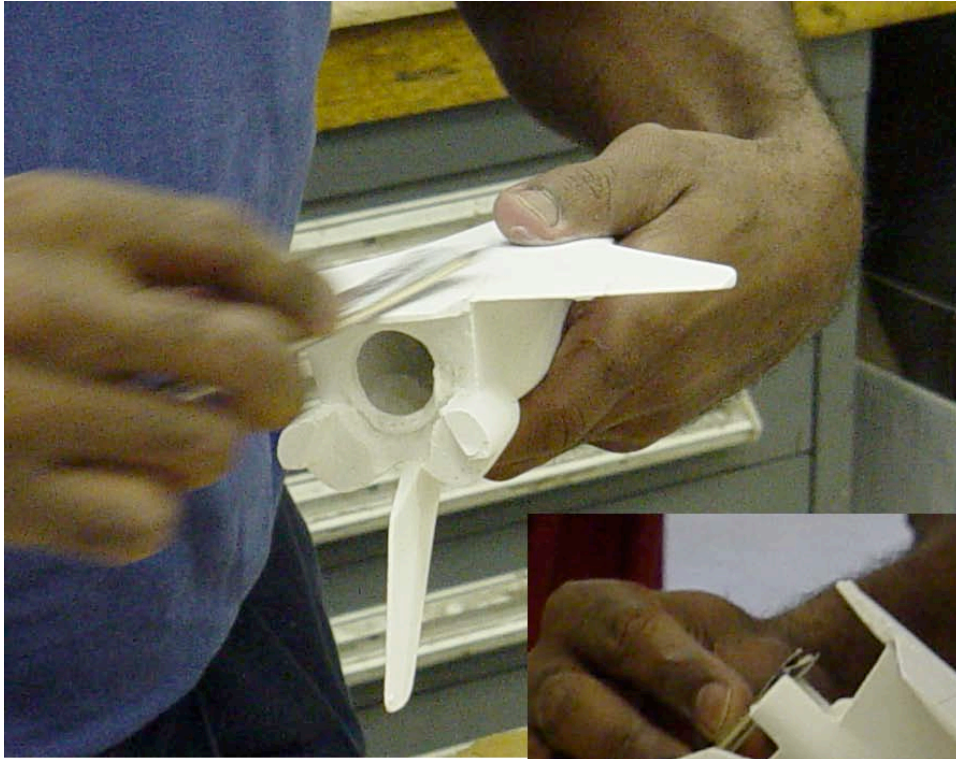


Figure 18. Trimming and additional shaping of “Green” cast ceramic model.

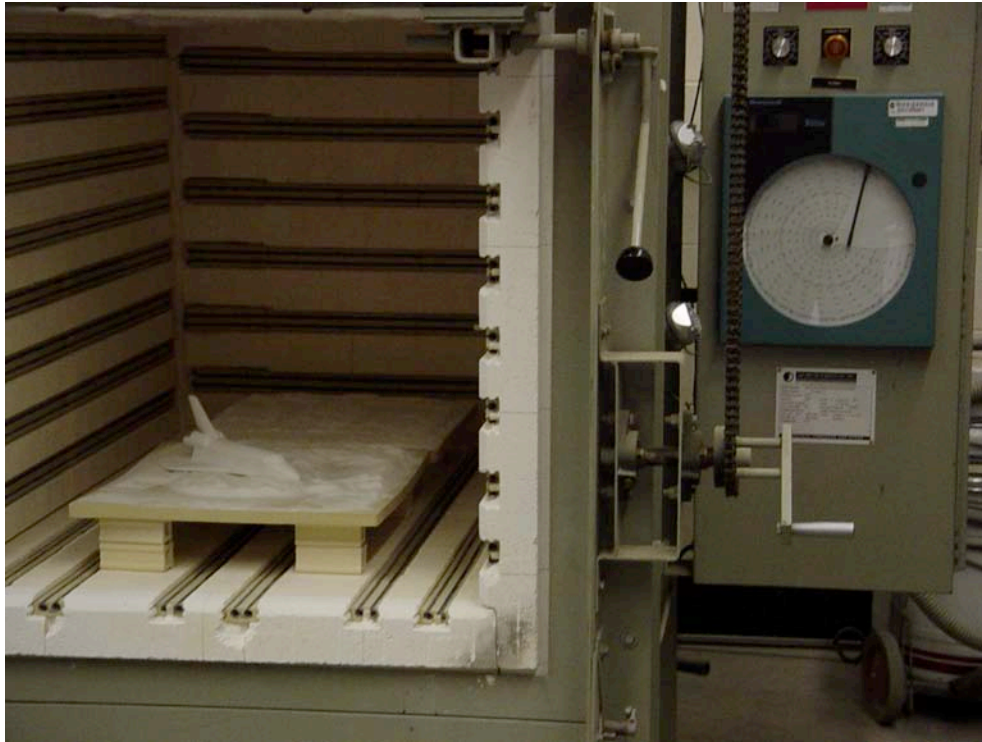


Figure 19. Sintering of cast ceramic model in electric fired kiln.



Figure 20. Sintered ceramic test model.

Fabrication of Alignment Fixture

To position and align the mounting sting in the slip cast ceramic models the original model pattern is first mounted in an aluminum brace as shown in figure 21, and a support or positioning glove is cast around the pattern in such a manner that the pattern can be removed and replaced with a ceramic model. The casting material used is the same Repro two-part urethane tooling plastic that was used to cast the wax injection mold.

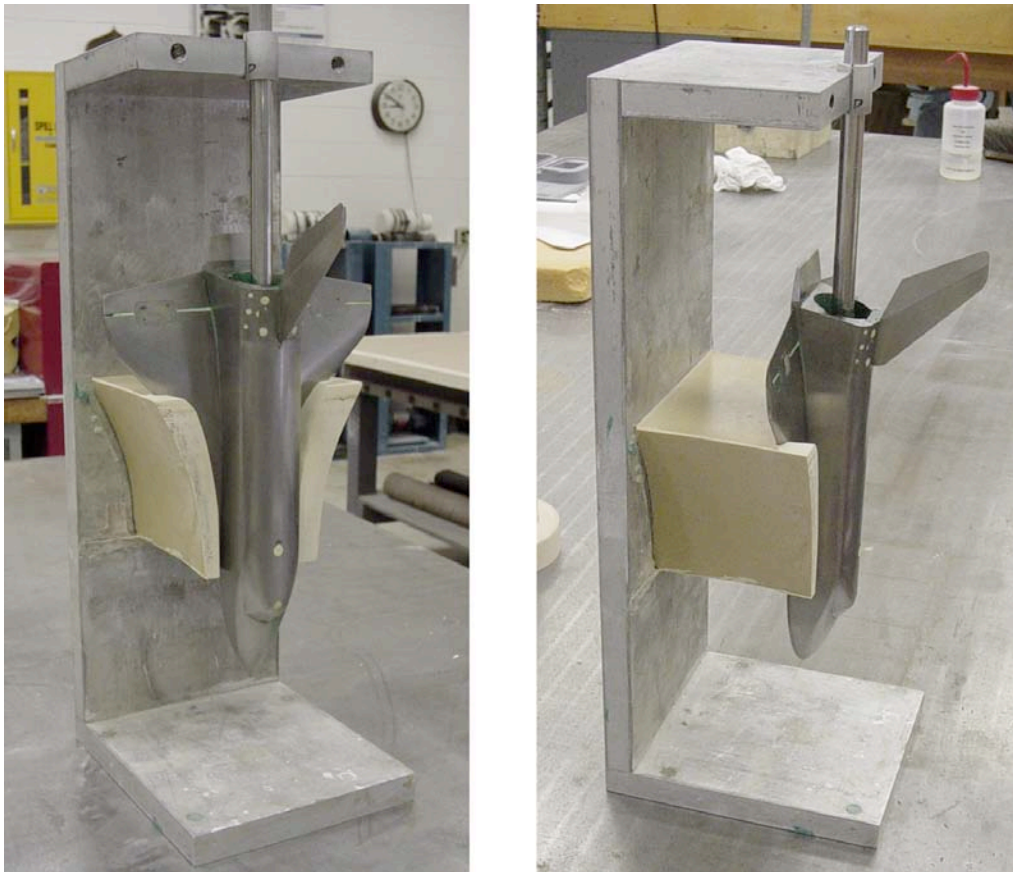


Figure 21. Setting up fixture for positioning support sting in ceramic test model using original model pattern.

Mounting and Cementing Support Stings

Because the sintered ceramic is porous and that various contaminants which find their way into the ceramic effect the luminescent properties of the temperature sensing phosphor coating, it was found to be necessary to seal the inner surface of the ceramic test models before backfilling with hydraulic setting materials. The sealer or liner which was found to be most useful is a two-component, tin catalyzed, RTV silicone rubber which is also used for flexible mold applications. The product used is manufactured by Plastic Tooling Inc. and is called GI-1000.

To securely hold the mounting sting in position a hydraulically setting ceramic cement is used. The mixture is of inorganic ceramic materials consisting mainly of alumina. It is a commercial product manufactured by Aremco called Ceramacast 510. It is also a high temperature castable which can withstand temperatures up to 3200°F.

The sintered ceramic model is internally sealed with GI-1000 silicone rubber (fig. 22) and allowed to cure overnight. It is then placed in the alignment fixture. The Ceramacast 510 is mixed with filtered water, slightly more than 18% by weight, to lower viscosity just enough to fill cavity. The cavity is partially filled, then the mounting sting is positioned and clamped in place (fig. 23) and the cavity is filled completely with Ceramacast 510. The model is left in the alignment fixture for 8 minutes, until the backfill hardens.



Figure 22. Mixing, pouring and draining GI-1000 Silicone liner to/from model cavity.



Figure 23. – Mixing, pouring and positioning hydraulic setting backfill material.

Surface Integrity Measurements

The multiple steps in casting these models impacts the final surface integrity. A portable laser scanning system is used to evaluate model surfaces at multiple steps in the process for a sample slip casting (model #107). The original metal model pattern, the polyurethane wax injection mold, a slip-cast ceramic model before it is fired, and the same slip-cast ceramic model after it has been fired are scanned. These scanned surface points, or “point clouds” are then each compared with a CAD file representation of the vehicle surface to show differences in the fabrication process.

The portable laser scanner used is manufactured by NVISION and is called the Modelmaker system. The system is mounted on an 4 foot articulated coordinate measuring arm manufactured by FARO (fig. 24), and is swept over the model surface manually. The system is capable of capturing complex 3D geometry of objects within the accuracy of +/- 0.002 inches. High density point cloud data is collected in real time, taking only a matter of minutes to acquire millions of x,y,z coordinate data points.

The process of scanning models with the ModelMaker system begins with aligning the scanner head with the Faro Arm probe. A calibrated block is measured, on four sides and the top surfaces, with a series of probe measurements and laser stripes. These measurements are then calculated by the software to give an alignment result. With the alignment complete, the model is then mounted and scanned. The scanning process is a series of passes of the laser across the model. With each pass, stripes of data points are collected in real time and displayed on the computer screen. When all areas of the model have been scanned, the data is exported as an electronic 3D point cloud.

Imageware software is used to compare the ModelMaker data files with the CAD surface file. The data and CAD files are opened together. The two files are first put into the same coordinate system. A series of commands are used to set up the difference scale and color plot. The software then compares the two files to produce a visual comparison showing dimension variances between them. The differences are depicted by colors on the model with a scale on the side. The scale notes the identification of the colors and their numerical value. (See figs 25 and 26.)

The Shuttle Orbiter CAD geometry file used in comparisons was first generated by Boeing/Huntington Beach and delivered to NASA Langley in a compressed file dated July 2, 2002, and represented the “best” CAD model of the Shuttle OML available at the time of the Columbia Accident Investigation. There were a number of missing or simplified areas in this geometry. From an additional CAD geometry file provided by NASA Johnson, Langley was able to recreate missing surfaces. Only minor additional changes were then required to seal the geometry into a watertight solid. The engine bells remained in place, and no gaps were sealed over. This geometry was made available as 2003feb25-ug-step-from-shuttle2002.stp and is documented and controlled by Karen Bibb, 2005, at NASA Langley. An error on the upper wing leading edge in vicinity of RCC Panel 6 was discovered (geometry approximately 0.8” too thin, full scale), after this geometry was used in the Columbia Accident Investigation, but this corresponds to 0.006 inches in the current 0.0075 scale model and is well within the measured surface variation.

Scanned windward surface comparisons with the Shuttle-2002 CAD geometry are shown in figure 25 for the steel pattern, epoxy wax injection mold, pre-fired “green” ceramic model and final sintered ceramic model. Data comparisons show a flexure of the wings in the green cast model, by as much as 0.020 inches at the wing tips, which is somehow corrected in the final sintering process. A difference in surfaces for the windward nose region remains, at +0.015 to +0.020 inches relative to the CAD geometry. Figure 26 shows a comparison with the complete scanned surfaces for the stainless steel aerodynamic test

model/casting pattern, and final sintered ceramic model.

These data show that the windward surface of the test model is mostly within ± 0.010 inches, with the exception of nose and bodyflap. These differences, including the wingtips before firing, were not present in the wax injection mold and therefore must be attributed to either/or both handling of the wax and distortion of the shell mold. Without further samplings and measurements, it is difficult to determine which, or for that matter whether these measurements are typical of the other 106 castings. It is noted, however, that distortion with this type of shell mold has been documented (Buck, 2000) and that another shell mold casting process has been developed with higher dimensional stability, but was not used in these castings. The fact that the wingtips self corrected during the sintering process, however serendipitous, could also indicate the possibility of wingtip distortions in other castings caused by creep. Methods have been developed in slip casting to reduce such creep using organic silica precursors, but similar to the improved casting process was not used for these models.



Figure 24. Portable laser scanner used for capturing pattern, mold and model surface geometries.

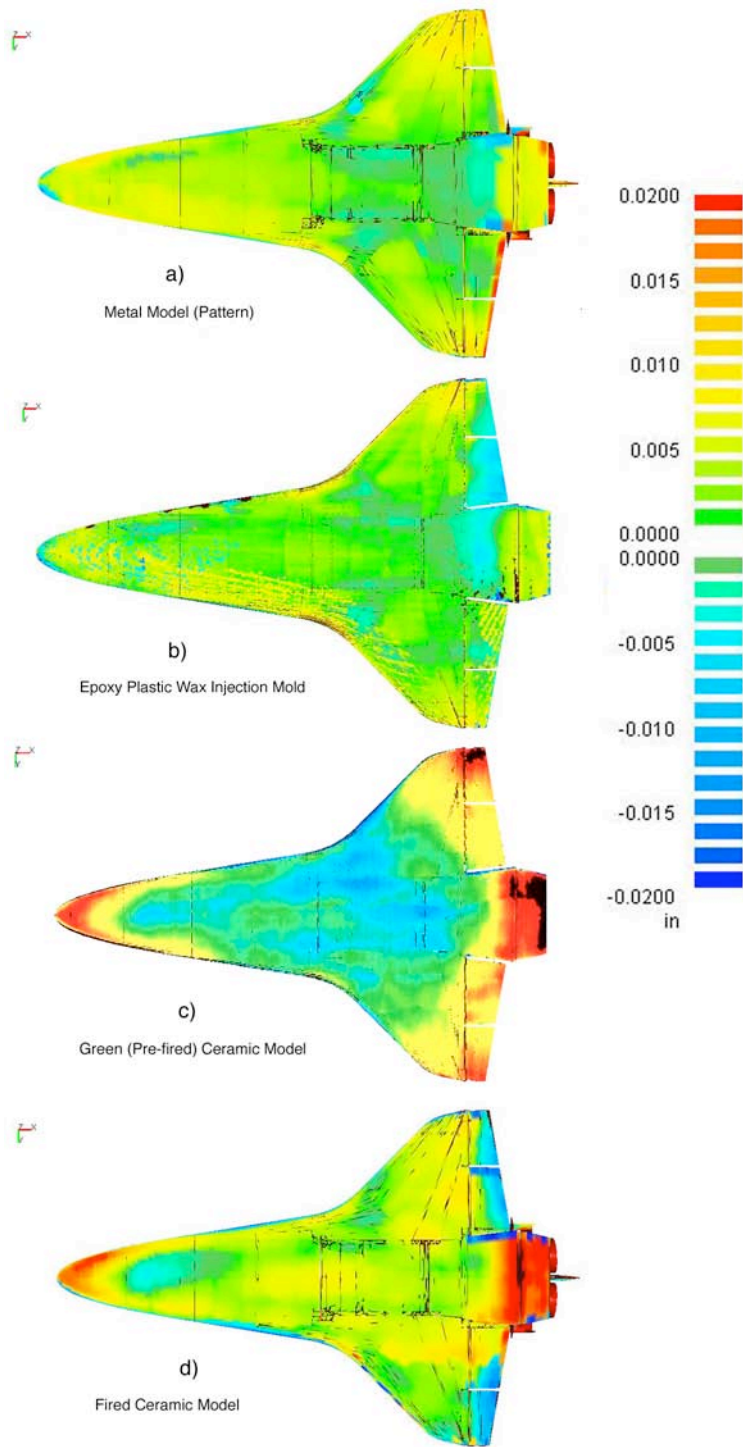


Figure 25. Scanned windward surface comparison with Shuttle-2002 CAD geometry for a) stainless steel aerodynamic test model/casting pattern, b) epoxy plastic wax injection mold, c) pre-fired “green” ceramic model and d) final sintered ceramic model.

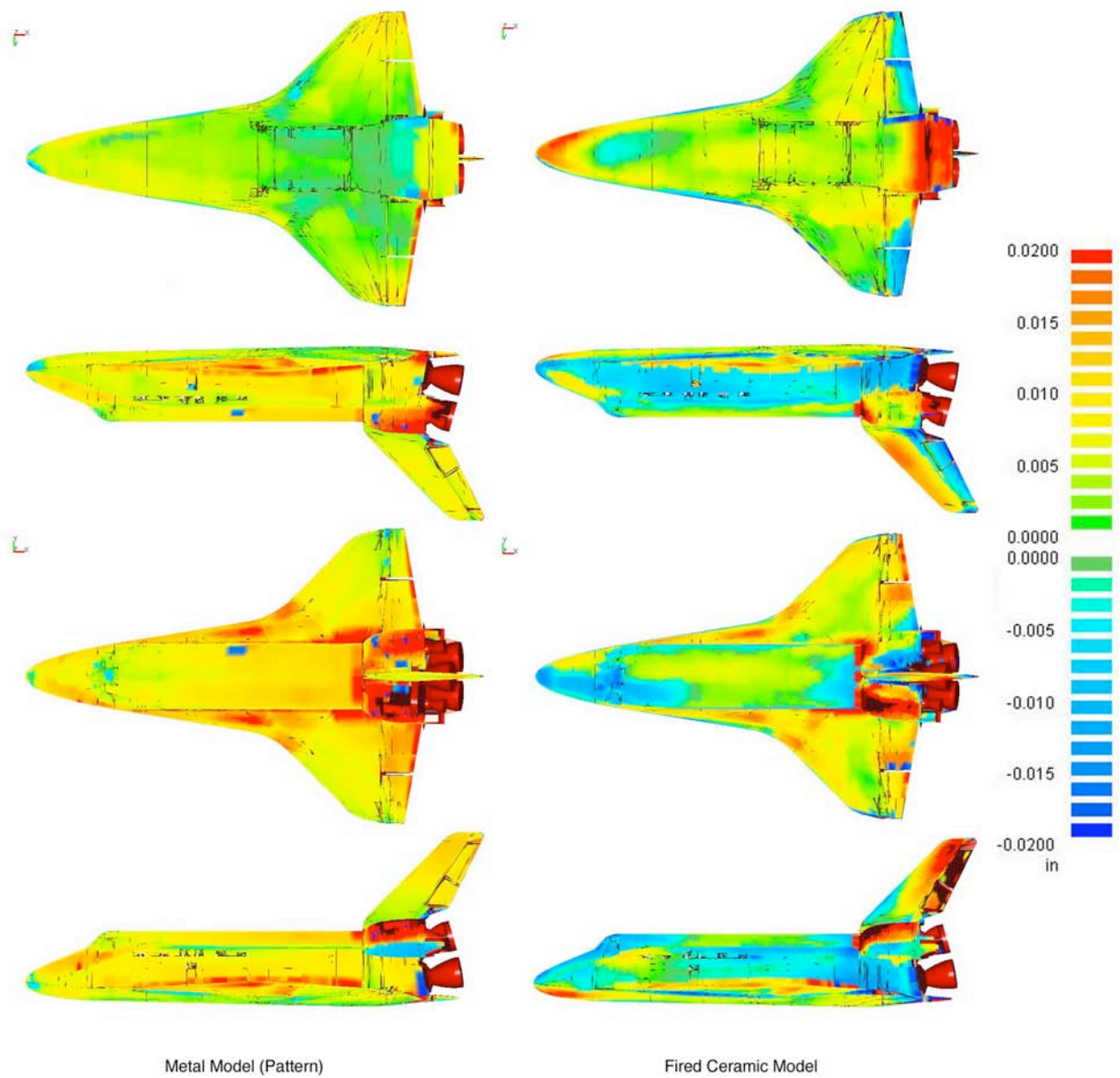


Figure 26. Scanned surface comparison with Shuttle-2002 CAD geometry for left) stainless steel aerodynamic test model/casting pattern, and right) final sintered ceramic model.

Application of Ceramic Phosphor Coating

The two-color phosphor system uses two types of phosphors and a binder in a surface coating. For a measurement, the coating is excited by 365 nanometer (nm) peak ultraviolet radiation from a filtered mercury arc lamp. Emission wavelength characteristics of the combined phosphor coating can be found in Buck, 1991. Two chromatically filtered images are recorded simultaneously using a digital image acquisition system and the relative color intensities, green (500nm to 600nm) and red (600nm to 700nm), are used to measure temperature.

The first of the two types of phosphors used in the coating emits primarily in the green when excited by near ultraviolet. Without ultraviolet excitation it appears light yellow under visible white light. This material is a zinc-sulfide/cadmium-sulfide ceramic compound doped with silver and nickel (ZnCdS: Ag, Ni) known as a metallic-ion phosphor. It had been sold in the U.S. by USR Optonix for several years, until the late 1990s, as number 1807 in their product group of Radelin thermographic phosphors. Today it is obtained from a Russian company called SPF Luminophor and is their K-575 phosphor. The current lot number is 2-2002.

The second of the two types of phosphors used in the coating emits primarily in the red when excited by near ultraviolet. Without ultraviolet excitation it appears white under visible white light. This material is a lanthanum-oxy-sulfide ceramic compound doped with europium (La₂O₂S:Eu ~1% by weight) known as a rare-earth phosphor. It had been sold in the U.S. by USR Optonix and GTE Sylvania for several years until the late 1990s. Today it is obtained from Nichia U.S. and is their number 1121 phosphor. Current lot number is 3.

The binder used to adhere the phosphor mix coating to the silica ceramic model surface is an ionic colloidal silica suspension in water. The binder is obtained from AKZO Nobel Company – EKA Chemicals Division by the product name Nyacol 215.

In a typical spray batch, 10 grams of green phosphor and 50 grams of red phosphor are mixed dry. Filtered water is added to a paste consistency. 100 grams of liquid colloidal silica binder are then added and mixed thoroughly. The material is handled and mixed in a chemical vent hood as shown in figure 27. Before coating the model, the surface is wiped with a dry paper towel and blown with dry compressed air to remove all residue. The coating is applied using a Passche Type H #5 air brush (external mix, large nozzle) and is sprayed in a positive air flow paint booth as shown in figure 28. The first spray coat consists only of colloidal silica binder to promote adhesion and uniform surface absorption of binder liquid in phosphor layers. Five coats of phosphor mixture are sprayed, allowing 45 seconds to 1 minute of drying time between layers. Afterwards, the surface is again wiped with a clean dry paper towel and lightly blown with dry compressed air to remove all residue. The surface is inspected under ultraviolet lighting (fig. 29) and an additional phosphor coat is sprayed on if needed. A final coat of only colloidal silica binder is applied to seal and strengthen the coating.



Figure 27. Vent hood and mixture chemicals for phosphor coating.



Figure 28. Spray booth and Passche Type H #5 air brush for phosphor coating.



Figure 29. Spray coating and wiping excess phosphor coating.

Surface Roughness Measurements

An optical 3D surface profiler is used for capturing high-resolution cavity geometries and making surface roughness measurements. The instrument, shown in figure 30, is the NewView 5000 which is both marketed and in this case operated by Zygo Corporation under contract. This system is based on scanning white-light interferometry, a traditional technique in which a pattern of bright and dark lines (fringes) result from an optical path difference between a reference and a sample beam. The three-dimensional interferogram of the surface is processed by computer and transformed by frequency domain analysis resulting in a quantitative 3-D image.

Both uncoated and phosphor coated sample areas were evaluated. Representative results are shown in figures 31 and 32. Roughness parameters are calculated by the system. R_t is the maximum peak to valley height over the sample. R_a is the average deviation of all points from a plane fit to the test sample. And, R_q is the root-mean-square average of the measured height deviations taken within the evaluation area and measured from the mean linear surface. R_q represents the standard deviation of the profile heights. The standard deviation measurements (R_q) show roughness on an uncoated ceramic sample at 5 microns and on a phosphor coated sample at 10 microns. The results were typical, on average, of the other measurements (6 coated sample areas, not shown).

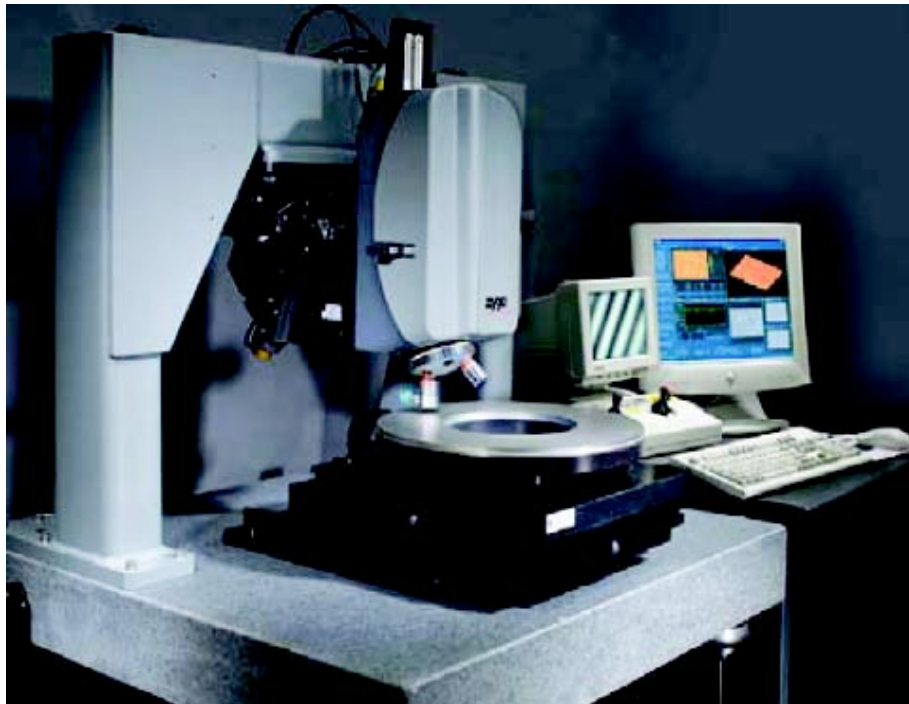


Figure 30. Optical 3D surface profiler for capturing high-resolution cavity geometries and surface roughness measurements.

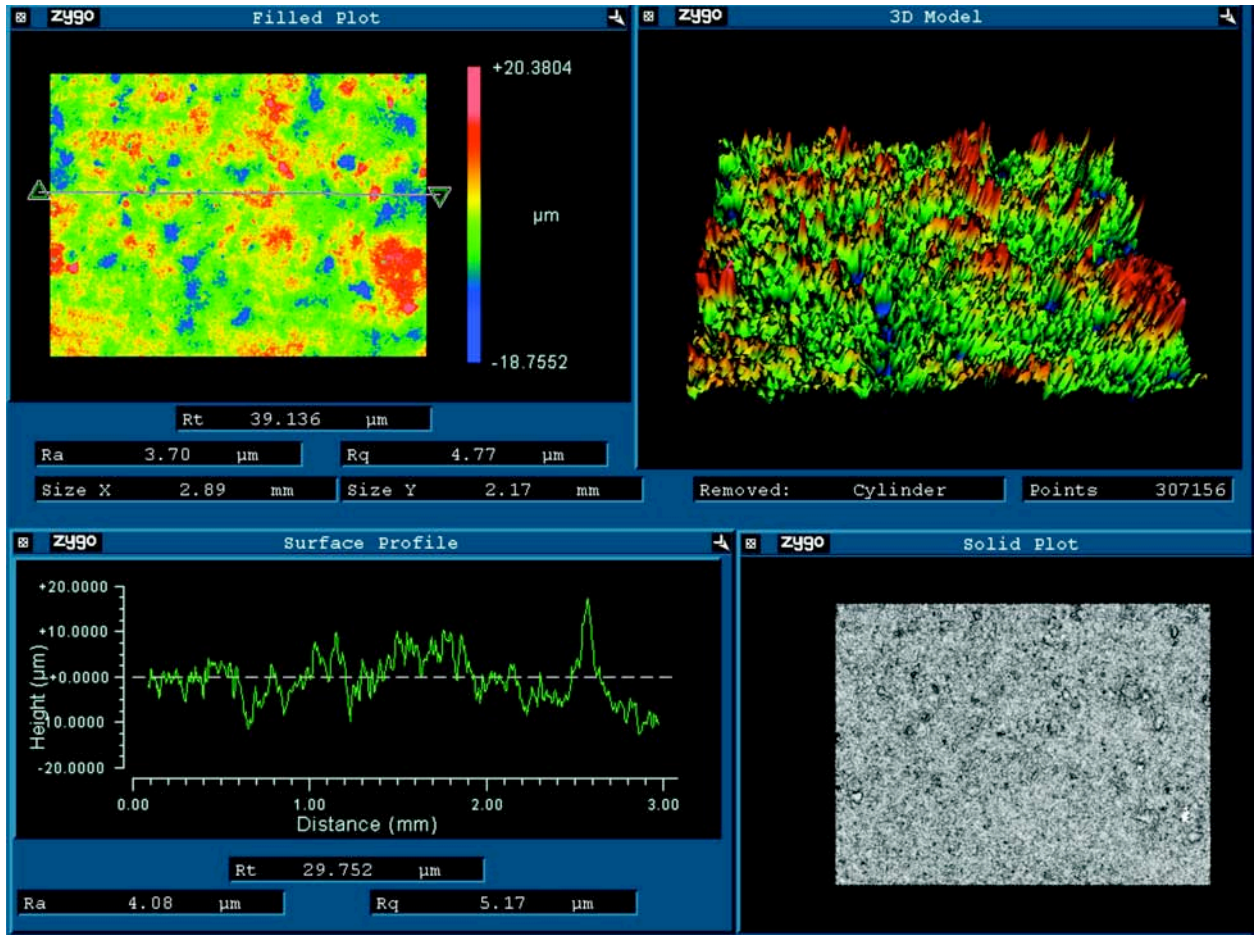


Figure 31. Uncoated ceramic sample area roughness measurements (Rt, Ra, and Rq).

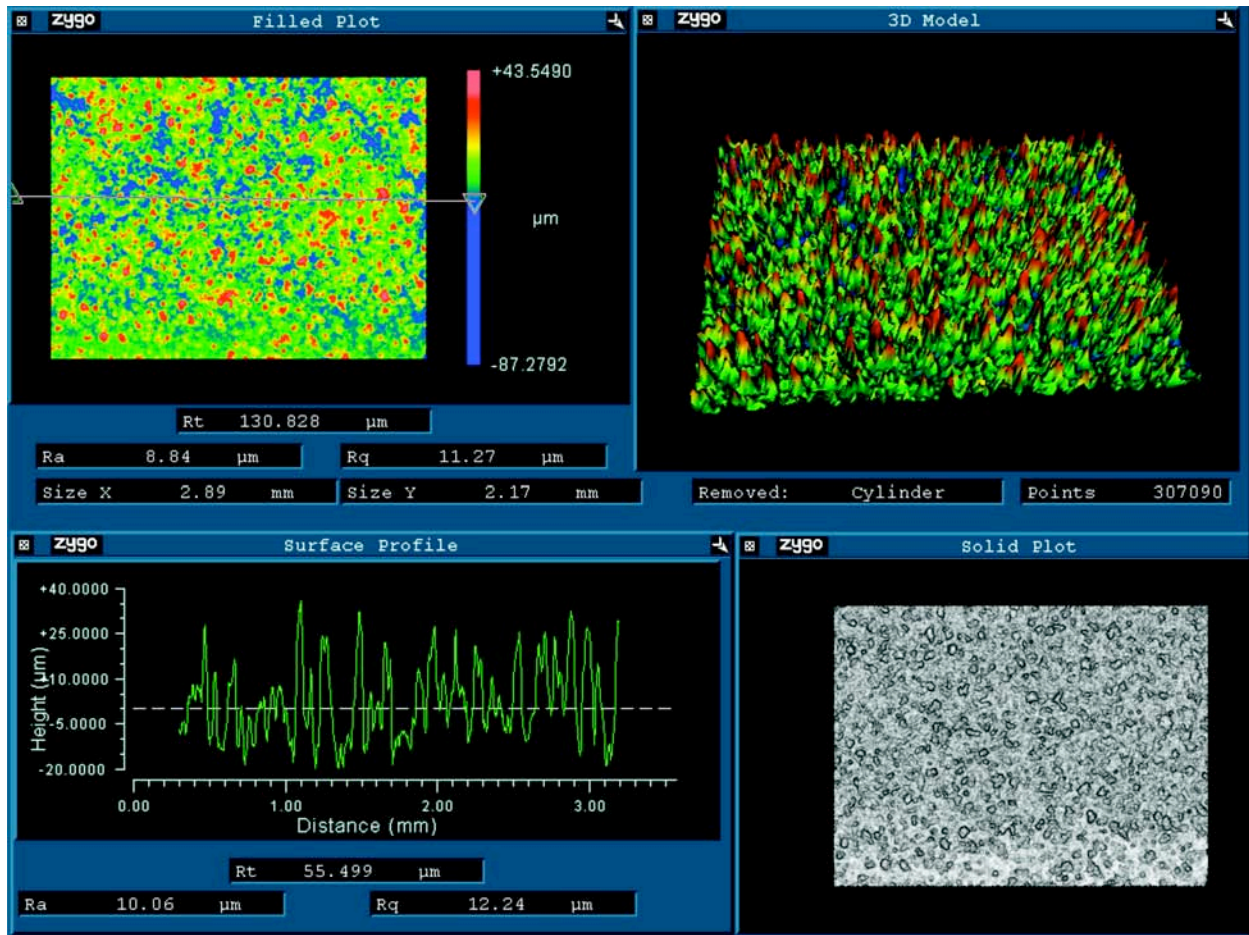


Figure 32. Phosphor coated ceramic sample area roughness measurements (Rt, Ra, and Rq).

Fiducial Marking for Image Registration and Protuberance and Cavity Alignment

A blue colored liquid/paste identified as Hi-Spot Blue and manufactured by a company called Dykem is used to mark fiducials. This material is a petroleum based chemical which has been traditionally used to mark high spots on bearings, gears and other closely fitting assemblies. The properties of this material which make it useful in marking fiducials are slow drying time and readiness in which it transfers from one surface to another.

Fiducial markings are applied to the model surface using a coordinate measuring machine (CMM) with a ruby tipped analog touch trigger probe. The coordinate measuring machine is a Fanamation model number 606040 which was rebuilt in 2003 by Brown and Sharpe to replace the controller, analog scanning probe, control software and computer. The control software used is PC-DMIS which includes Curves and Surfaces software modules. The CMM has a granite base with a 60 inch square x-y and 45 inch vertical measuring range. Its volumetric accuracy is 8.1 microns (0.0081 millimeters). The probe configuration used for applying fiducials is built on a Renishaw PH10M hub using a 30mm to M8 thread converter to attach a TP2 connect probe which is connected to a 20 millimeters long stylus with a 1 millimeter spherical synthetic ruby tip.

The model is positioned nose up on the granite CMM surface using a precision V-block and aligned to the CMM axis. It is situated on the table with the left wing pointing at the operator; this was for concentrating mainly on the left leading edge and landing gear areas during the initial accident investigations, when the programs were originally written, although the point patterns for these tests are typically symmetric. The length (L) is measured from the nose tip to the bodyflap hinge line and X/L values are calculated and drive points determined. A smooth thin coating of Hi-Spot Blue is applied to a metal palette to transfer to the ruby probe tip for application. The coating thickness on the palette determines the size of the fiducial mark applied to the model. The probe tip is automatically backed away from the model after each fiducial mark application to be re-inked manually, with the timing typically 30 seconds per fiducial mark. The resulting turnaround rate is approximately 4 hours per model, plus an initial 2 or more days to write the initial CMM application program.

Figure 33 shows the probe configuration during application of a fiducial point. The lower image in figure 33 shows a final fiducial pattern on a phosphor test model with protuberance trips applied at the 2nd, 4th and 6th fiducial locations along the top row of fiducials in the image. For alignment of cavities, fiducials are applied after only a single layer of colloidal silica binder is applied to the model surface with the phosphor coating being applied later after the cavity is formed using laser ablation. The phosphor is applied after the laser ablation process to keep the phosphor powder from contaminating the laser ablation system and the first coat of colloidal silica is applied prior to marking the first fiducials to keep the ink from absorbing and spreading in the porous ceramic substrate.

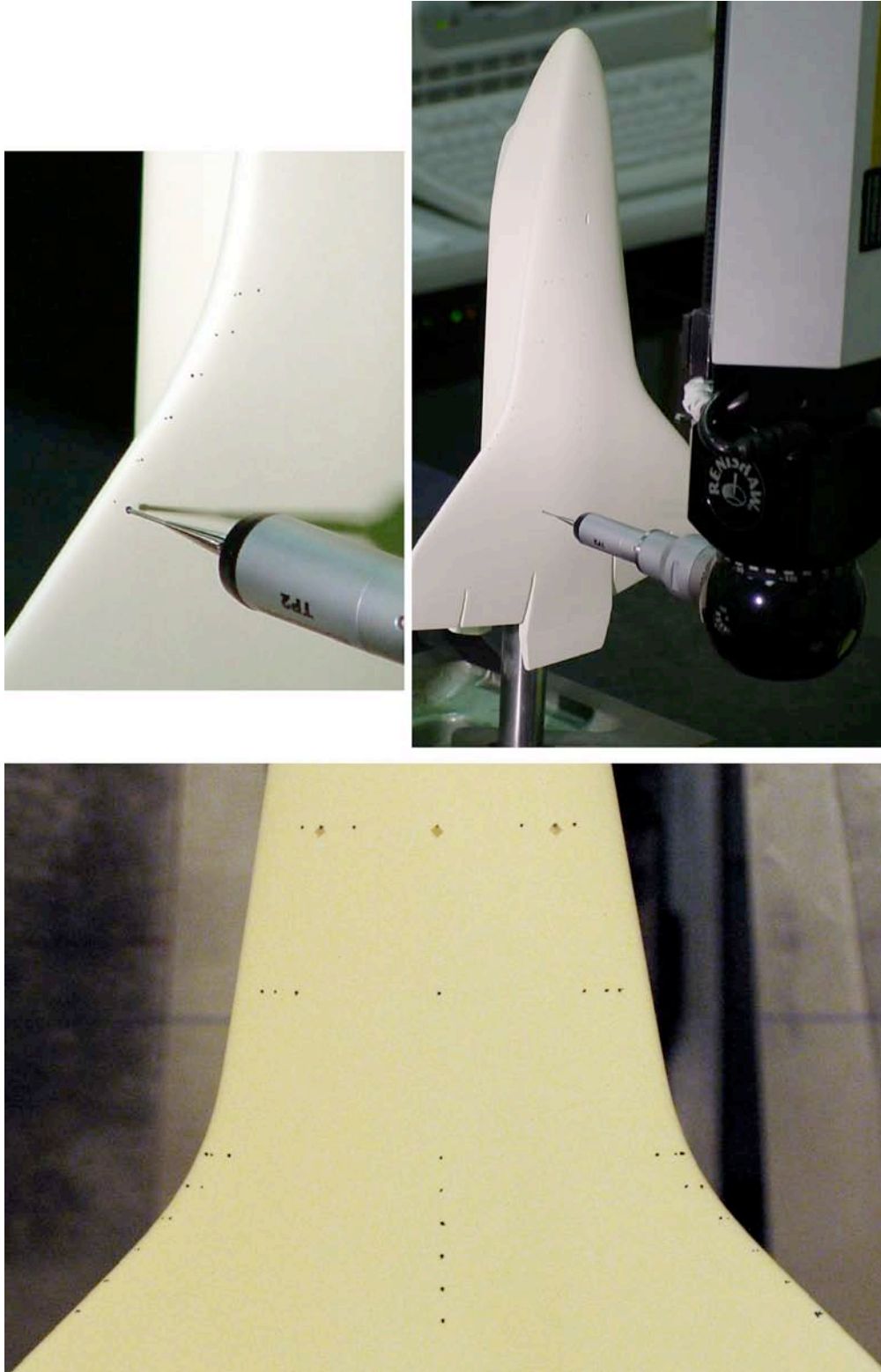


Figure 33. Application of fiducial points on model surface using a coordinate measuring machine.

Laser Ablation of Model Cavities

A laser ablation system was used with a CO₂ laser and galvanometrically driven beam scanners to remove material and form cavities in the fused silica ceramic test models. The system was originally configured to remove or ablate material from flat surfaces or films. The lower half of the system, as shown in figure 34 with an orbiter model in place, was modified using a precision V-block to clamp the model in the focal plane of the laser system, just off the X-Y stage of the positioning system, thus allowing the vertical tail to hang down below the normal working surface.

The system contains two lasers, one a frequency tripled Nd:YAG laser (7-watt output @ 355nm wavelength) and the other an 80-watt, 9-micron CO₂ laser. Whichever laser is used is based on the optical properties of the target material and required power delivery. The system is also equipped with a video camera alignment system to precisely position the laser. Both laser systems are equipped with galvanometrically driven beam scanners to accurately and rapidly ablate material in any pattern within a 6-inch square area. The CO₂ laser is also equipped with a fixed beam lens and can be used with the moveable X-Y stage to move the target material and ablate or cut any pattern within a 24-inch square area.

The orbiter model is first clamped by the sting to the precision V block just off the X-Y stage of the positioning system. A Starrett precision level is placed on lower surface tail section to vertically align the model. Using the video camera alignment system the model is aligned in the x-y plane using fiducial marks on the model. The camera crosshairs are used to locate the desired fiducial mark at the leading edge center of the cavity, as shown in the lower photos in figure 34.

Cavity dimensions are controlled by programming the laser for the desired cavity size and geometry. Typical CO₂ laser parameter settings are 15 percent power, 4 kilohertz frequency, and 100 micro-seconds pulse width. The scanning density is 1429 passes per inch (0.0007-inch step) with a 0.002-inch diameter spot size. Scanning speed is 10 inches/sec. The cavity depth is controlled by the number of passes made by the laser. A typical pass removes about 0.003 to 0.004 inches of surface material. As the cavity depth increases the focal point of the laser must be adjusted to keep the laser spot size consistent. The depth of the cavity is measured with the laser systems vertical height sensor and verified with a depth micrometer. The x-y dimensions of each cavity are verified using the video camera alignment system. Cavity dimensions are further verified using a coordinate measuring machine.

High Resolution Cavity Measurements

Again using the optical 3D surface profiler, high-resolution cavity geometry measurements are made for 130 micron and 420 micron deep laser ablated cavities as shown in figure 35. Absolute measurement accuracy for this data was given as +/- 4.5 microns.

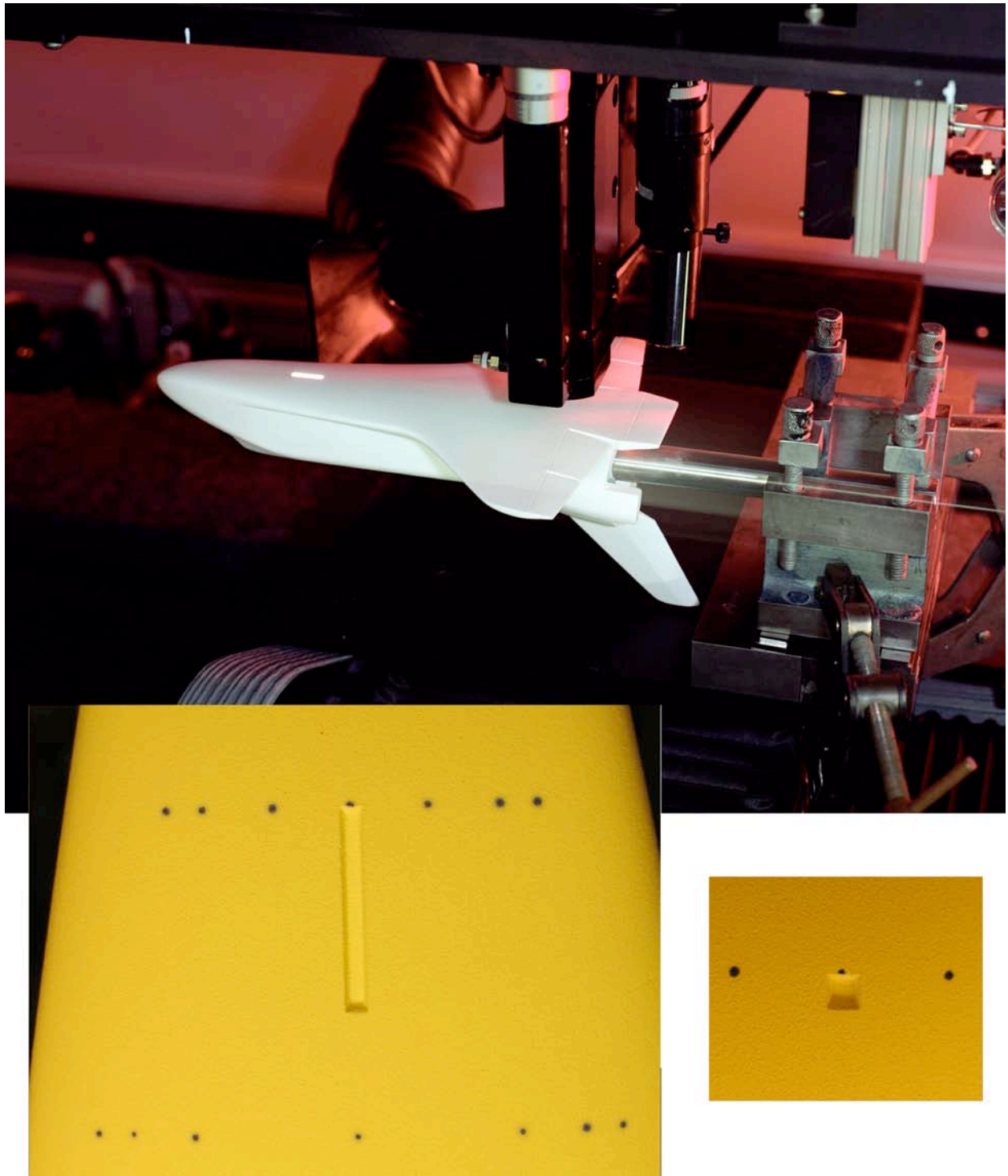


Figure 34. Use of a laser ablation system to machine cavities for transition studies.

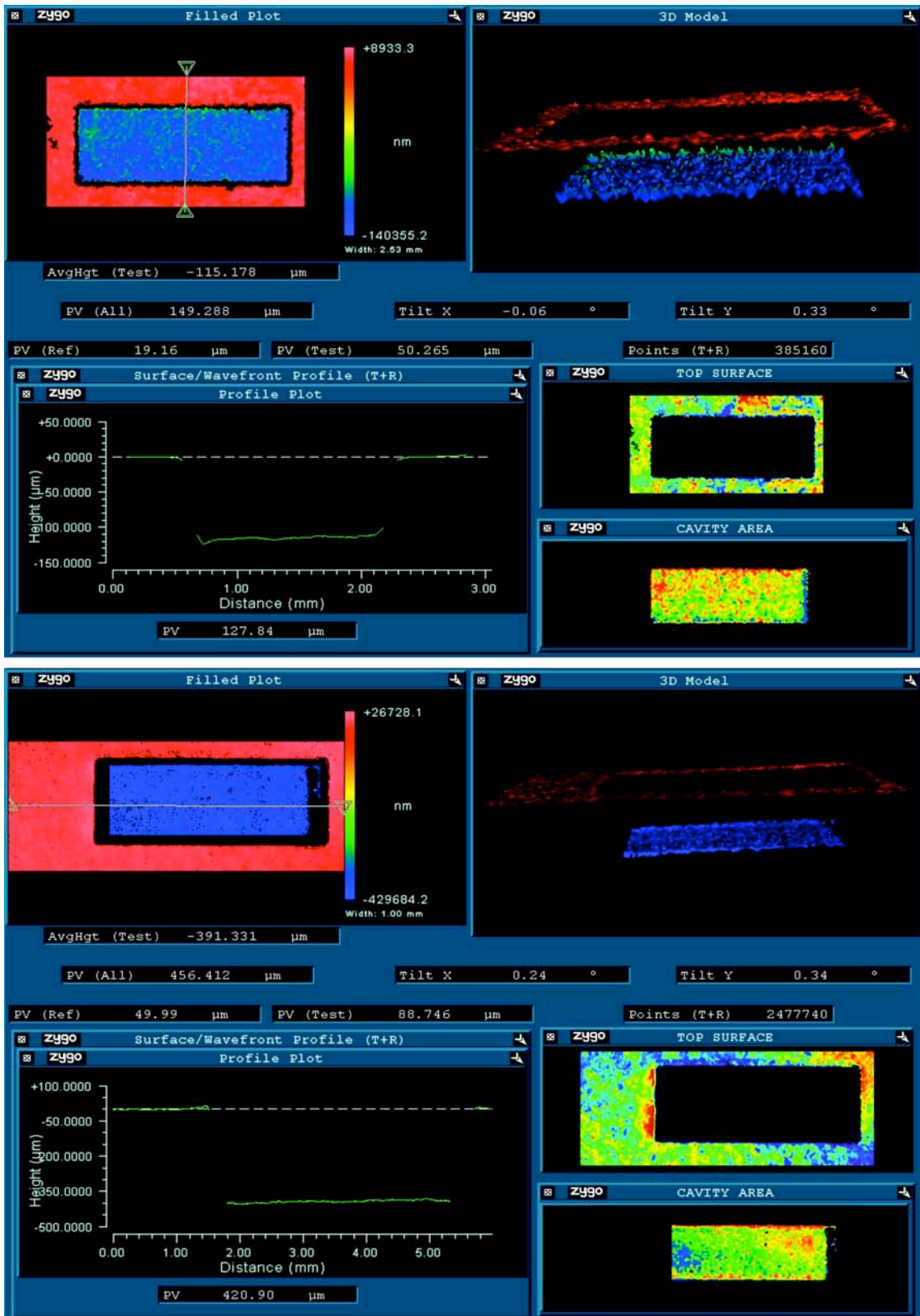


Figure 35. High-resolution cavity geometry measurements for 0.13 millimeter and 0.42 millimeter deep cavities

Application of Protuberance Trips

For return-to-flight experiments both protuberance and cavity effects on boundary-layer transition are tested. Cavities are laser ablated into the model surface before phosphor coating, as described in the last section, and protuberances are applied last, on top of all model coatings.

A high-temperature polymer tape was obtained for the protuberance trips. The polymer, polytetrafluoroethylene (PTFE), is purchased with a pre-applied silicone adhesive. The various tape thicknesses used varied from 0.0035 inches to 0.0115 inches. Of that total thickness the silicone adhesive is 0.0015 inches.

The tape is first scored with a 0.05 inch squared tile pattern using a knife and then later the laser ablation tool described in the last section. Individual squares are then lifted from the tape backing and applied to the model surface. Protuberance trips are shown in figure 33 along the top row of fiducial markings in the bottom image (at fiducials #2, 4 and 6).

Summary

These are the methods, materials and equipment used in fabricating and validating the test models for Shuttle return-to-flight aeroheating experiments at NASA Langley Research Center. Figure 36 shows a boxed set of these models prepared for testing. This document stands as supporting material for Orbiter Entry Aeroheating Notes OEAN-0305-006 and OEAN-0305-008 by Liechty, Berry and Horvath, 2005, documenting those test results.

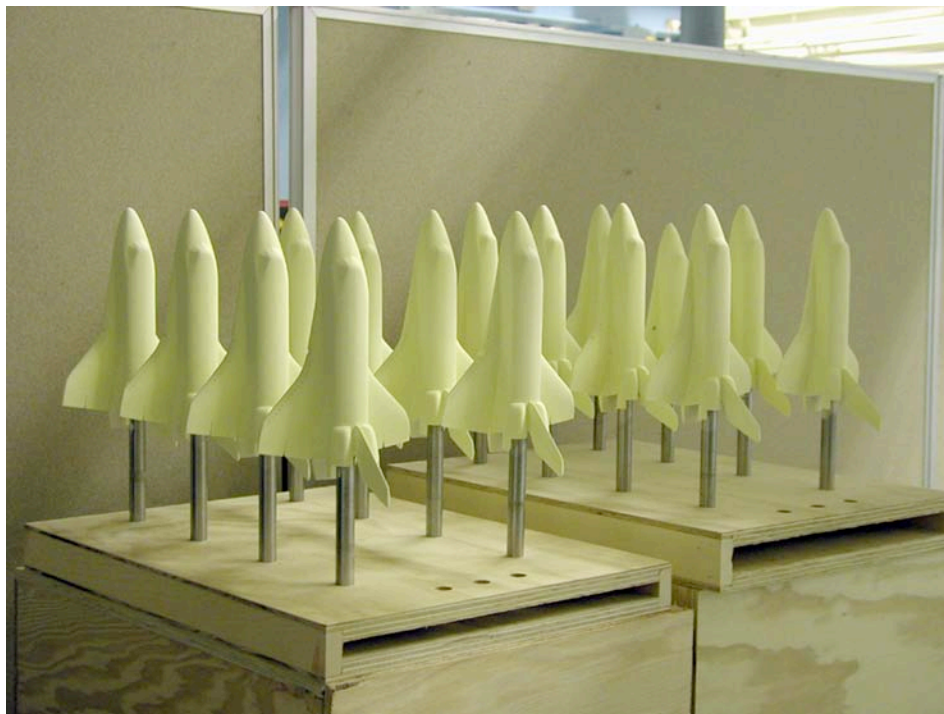


Figure 36. Boxed set of 0.0075 scale Orbiter test. models

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REPORT DOCUMENTATION PAGE

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