42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
9 - 12 July 2006, Sacramento, California

AIAA 2006-4600

Pitting and Repair of the Space Shuttle's Inconel® Honeycomb Conical Seal Panel

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During return to flight servicing of the rudder speed brake (RSB) for each Space Shuttle Orbiter, inspectors discovered numerous small pits on the surface of the #4 right hand side honeycomb panel that covers the rudder speed brake actuators. Shortly after detection of the problem, concurrent investigations were initiated to determine the extent of damage, the root cause, and to develop a repair plan, since fabrication of a replacement panel is impractical for cost, schedule, and sourcing considerations. This paper describes the approach, findings, conclusions and recommendations associated with the investigation of the conical seal pitting. It documents the cause and contributing factors of the pitting, the means used to isolate each contributor, and the supporting evidence for the primary cause of the pitting. Finally, the selection, development and verification of the repair procedure used to restore the conical seal panel is described with supporting process and metallurgical rationale for selection.

I. Approach

The overall approach of the investigation and repair effort was to divide the assessment into tasks along discipline lines, assign them to individual leads, and identify project point-of-contact for each task. These tasks are described as follows:

1. **Risk Assessment:** Document current risk assessment for compromise of RSB conical seal. Determine if complete or requires update.
2. **Root Cause(s) Determination**: Review current Project understanding of pitting root cause(s). If incomplete, then generate listing of potential proximate and root cause(s) in an effort to examine effectiveness of repair.
3. **Damage Tolerance ("Use As Is") Analysis:** Review analysis methodology applied to damaged conical seal for adequacy including inputs, assumptions and resulting damage tolerance criteria. Includes very high level understanding of original certification analysis of hardware.

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4. **Repair Analysis:** Review analysis methodology applied to repaired conical seal for adequacy including inputs, assumptions and resulting capability. Particular emphasis on derivation of repaired hardware material properties.
5. **Project Proposed Repair Techniques:** Review Project approach (evaluation criteria, development approach, verification & validation) used in the selection of proposed methods.
6. **Alternate Repair Techniques:** Examination of alternate methods based on technical requirements. Identify critical performance parameters (dimensional, thermal, structural, material/environmental compatibility, etc.) for use as metric on evaluation of alternate techniques.
7. **Flight Hardware Restoration Readiness:** Review Project readiness to perform repair with lowest risk for irreversible damage to flight hardware. Examine infrastructure (personnel, facilities, documentation, etc.) readiness to affect repair.

II. Background

Concurrent with other return to flight servicing of the RSB, the project decided to reapply the Pyromark coating to the conical seals on all of the orbiters. Pyromark is a siloxane based high- temperature, high-emissivity coating applied to protect the outside surface of the seal panels from the heat of re-entry. OV-105 was the last orbiter, and the right half #4 panel was the last panel to be processed. After removal of the Pyromark coating by sanding, on or about August 16, 2004, during preparations to apply an abrasive compound to prepare the surface for reapplication of the Pyromark coating, the technicians identified and documented the pitting. Visual inspection revealed numerous pits over the surface of the face sheet of the honeycomb panel; including some penetrating the full thickness of the face sheet. Fabrication of a replacement panel is both costly and a significant schedule impact, so the project team developed a repair strategy.

A. Hardware Description

The segmented conical seals are located on the vertical tail assembly as shown in Fig. 1. Each of the five panels has a left and a right half section as pictured in Fig. 2. The purpose of the RSB Conical Seals is to provide a barrier or seal between the RSB rotary actuators and the external environment while permitting the movement of RSB. The RSB Conical Seal consists of the conical panels, panel structural supports, and the spring loaded graphite seal block assemblies. The graphite block assemblies are attached to the RSB segments and ride on the conical panels forming the hot gas seal.

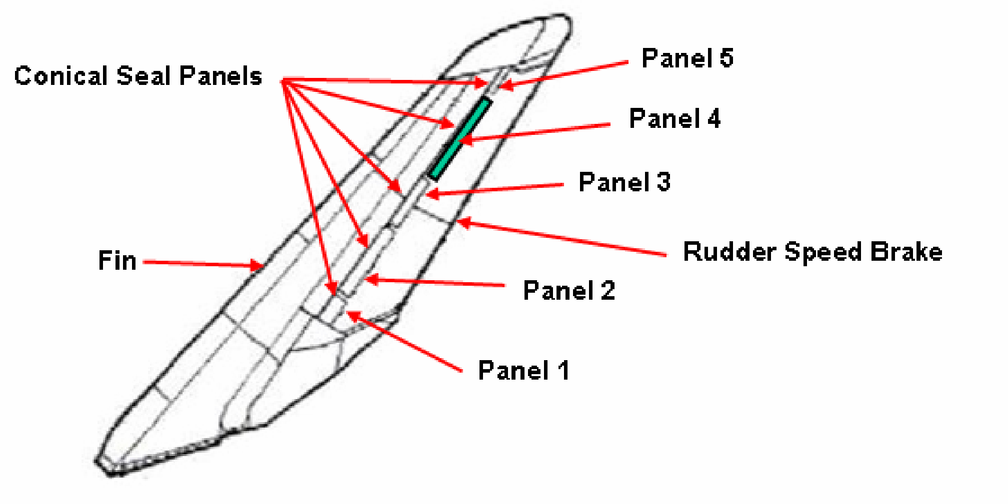


Figure 1. Location of RSB conical seal #4 on the orbiter vertical tail.

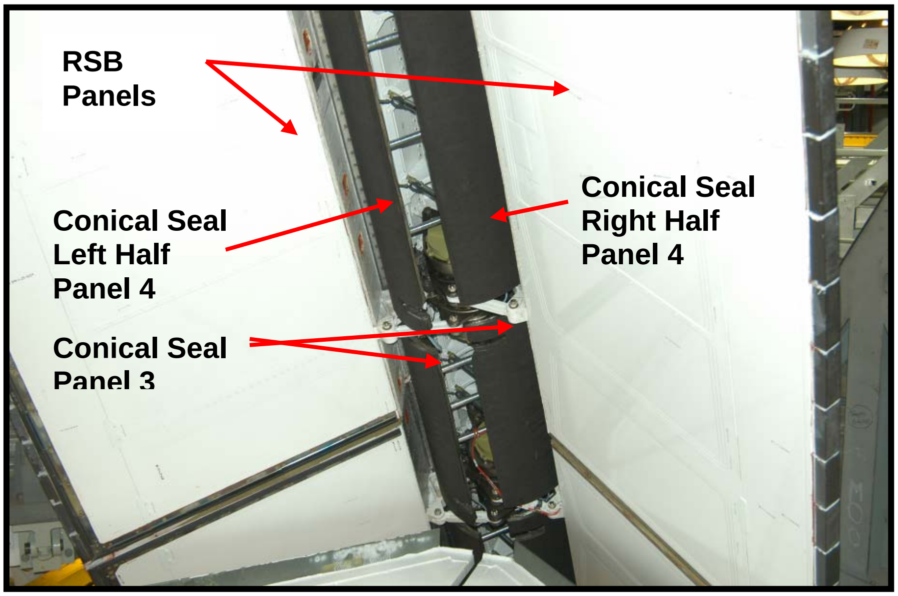


Figure 2. Rudder speed brake (RSB) and conical seal panels, located on the aft side of the vertical tail, in fully open position.

B. Construction

The right hand (RH) #4 panel is mounted in the second from the top location of the conical seal installation as seen in Fig. 2. The conical seals are fabricated from Inconel® 718 consisting of 0.5 inch honeycomb core brazed between 0.01 inch face sheets. The interior face is then covered with a thermal insulation blanket and encased in an Inconel® 718 foil spot welded to the rear face sheet perimeter. A photograph of the RH #4 panel is shown in Fig. 3. Aluminum struts are attached to the panels by integral attach-point fittings which are brazed into the panel structure. The conical seal panels are mounted to the vertical tail assembly by the struts as seen in Fig. 4. Spring loaded graphite seal block assemblies attached to the RSB panel slide (rotating part) and press on the outer surface of the conical panels forming a seal. A portion of the #4 seal block assembly is pictured in Fig. 5.

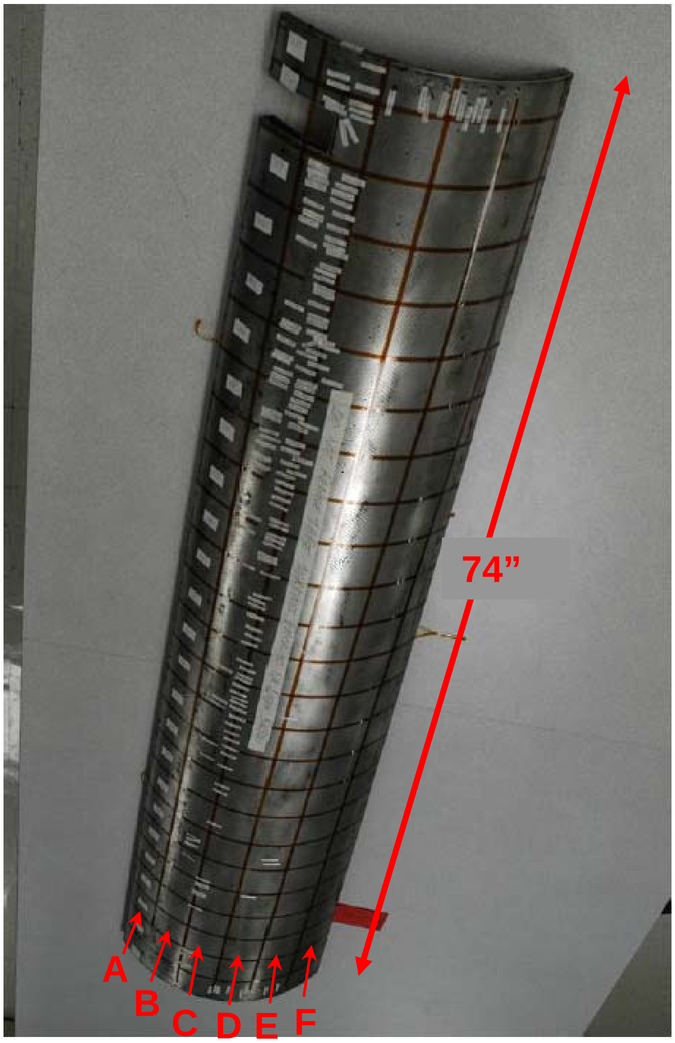


Figure 3. **Photograph OV-105 RSB Conical Seal #4 Right Panel with a tape grid applied. Columns A-E parallel to the length of the panel correspond to columns A-E for the pit depth data in Fig. 9.**

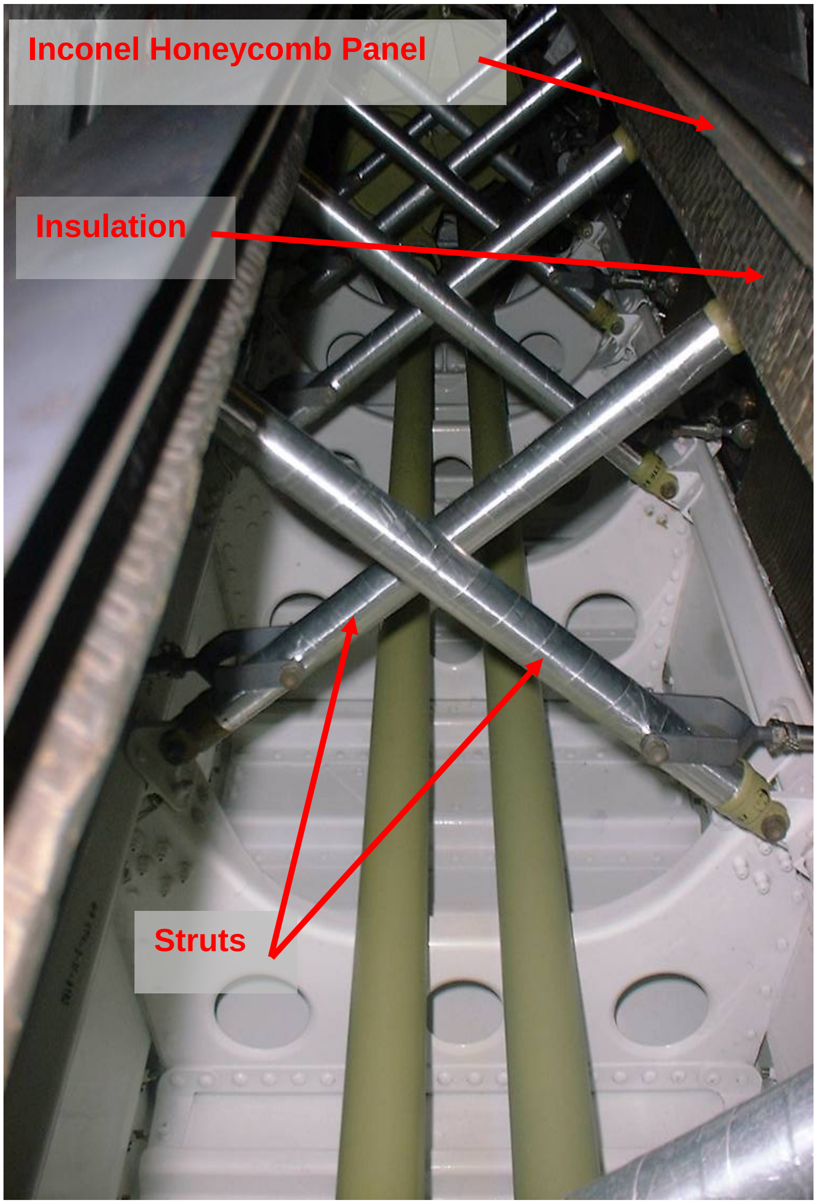


Figure 4. Photograph of OV-103 RSB conical seal #4.

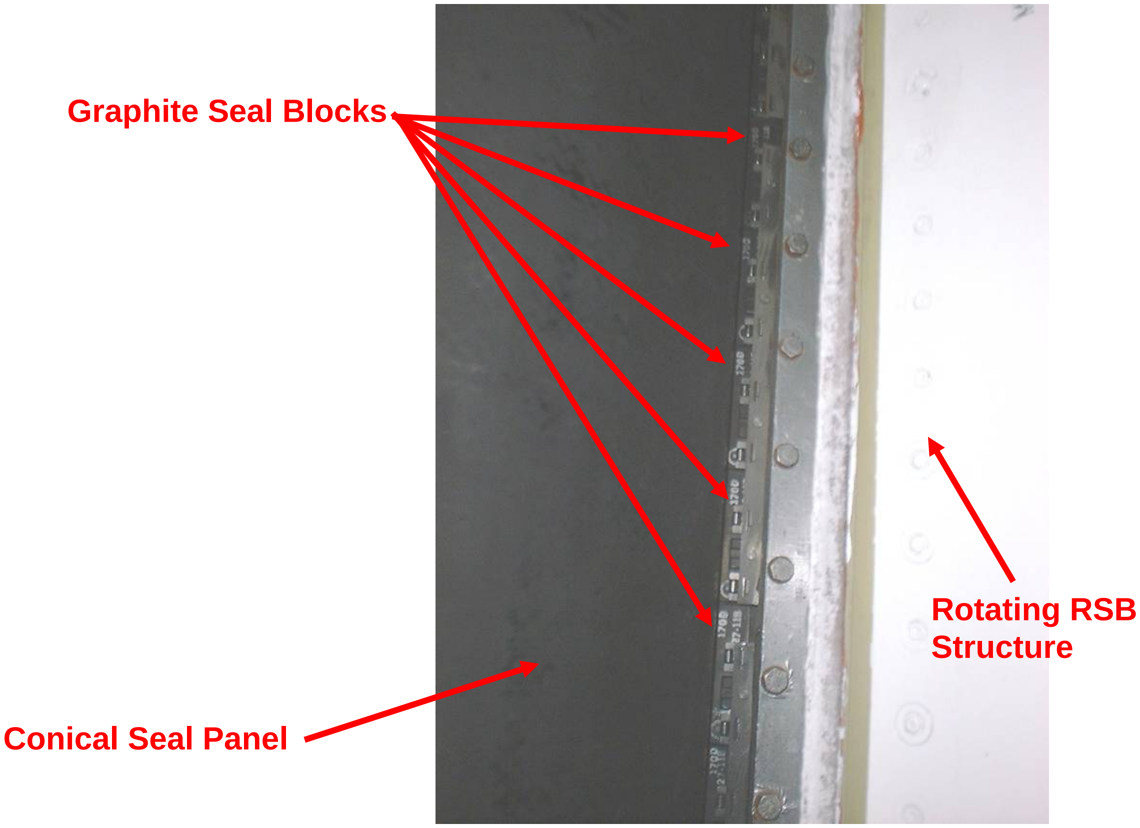


Figure 5. Photograph of Interior of OV-103 RSB graphite seal block assembly.

C. Service History

RSB RH #4 conical seal was fabricated by Fairchild in 1986 as part of a spare set of conical seals. Fabrication of the brazed honeycomb panels was sub-contracted to Aeronca, Incorporated. The seals were maintained as spares until OV-105 was assembled for its first flight in 1992. Certification documentation for the Inconel® used in the fabrication of this panel could not be located during this investigation.

The only maintenance checks routinely performed over the lifetime of the seals are in-place visual inspections following each flight. These inspections are general in nature and not directed at any unique surface or coating acceptance or rejection criteria. The Pyromark coating was the original coating applied by the manufacturer and for OV-105 has experienced 19 flights.

The project reviewed the ground history and the flight protocol to determine the location of the graphite seal blocks on the conical seal as a function of time. The evaluation of the ground operations concluded that the RSB was at the nominal 5 degree open position 65 percent of the time, at the nominal 1.5 degree open position 20 percent of the time, and the nominal 98 degree position 15 percent of the time. The RSB remains in the trail/parked, nominal 1.5 degree, position throughout a majority of the flight cycle. The placement of the graphite seal block for the nominal 1.5 and 5 degree positions can be seen in Fig. 6. The worst case (measured depth) pitting corresponds to the area where the graphite seal blocks are in contact with the conical seal at the nominal 1.5 degree trail/parked position.

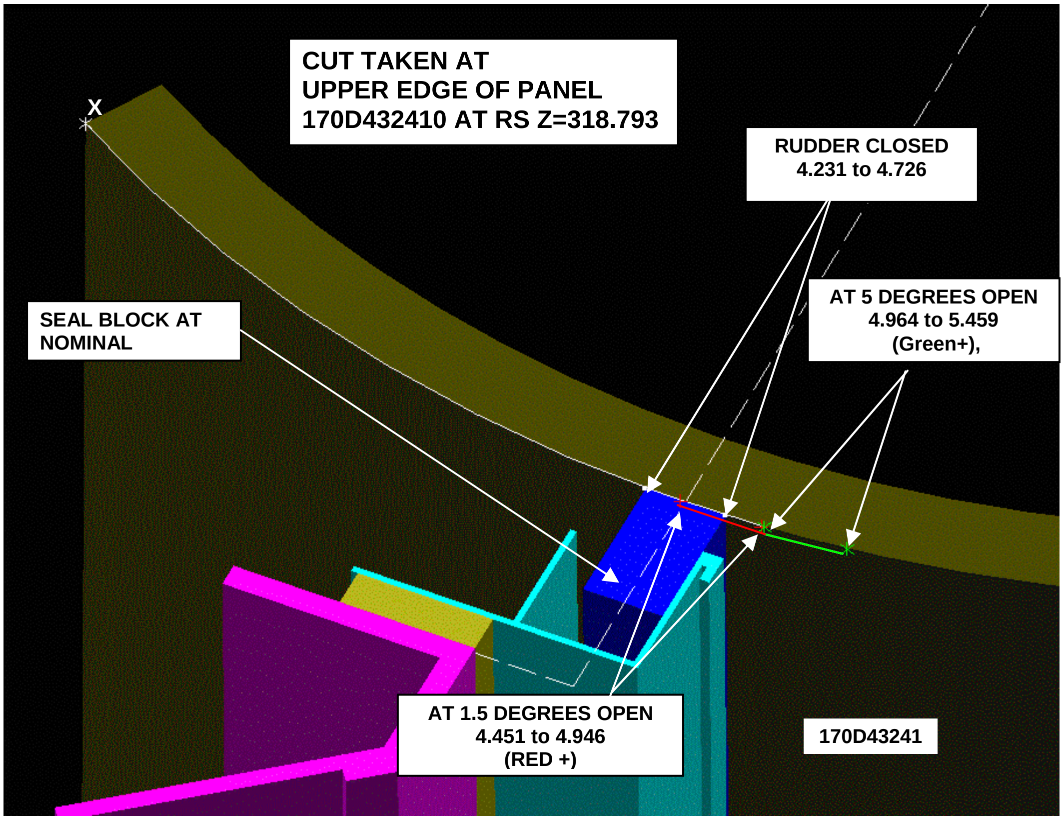


Figure 6. Computer generated drawing of RSB seal position as a function of RSB position.

A summary of all problems reported on the conical seals of all Orbiters from the Problem Reporting and Corrective Action (PRACA) system was reviewed. The most common problems noted were with damage to the foil covered insulating blankets on the rear of the panels, but there were a number of reports of surface contamination on or damage to the Pyromark coating. Corrosion of safety wires, and at least one incident of a suspected micro-meteor strike were reported. Individual reports of interest have been reviewed on conical seal panels from different Orbiter vehicles. There are no reports of surface damage, corrosion, or pitting prior to removal of the Pyromark coating on the RH#4 panel of OV-105, but shallow pitting has been observed across the Pyromark coating and/or substrate from at least one other panel on OV-103.

III. Problem Description

Following removal from the Orbiter, RSB RH #4 conical panel was sent to the NASA Shuttle Logistics Depot (NSLD) for refurbishment of the Pyromark coating. No significant discrepancies were reported during the removal and transport. In accordance with the procedures, the old Pyromark coating was removed using behr-tex (Scotch-Brite$^{®}$ green) pads. No significant discrepancies were noted during the hand abrasive operation. During examination of the panel, the assessment team noted areas where the face sheet was dimpled over individual honeycomb cells, and Pyromark coating was not removed from these dimpled areas.

In accordance with the procedures, the surface was going to be prepared with an abrasive aluminum oxide compound, with the criteria of obtaining a water break free surface. This part of the process was not attempted, as the surface pitting was identified and documented.

Visual inspection of the panel revealed 105 pits with a depth greater than 0.003 inch with some pits appearing to be through the thickness of the face sheet. Photographs of typical pitting and of molds from the pit interiors (replisets) are shown in Fig. 7 and Fig. 8.

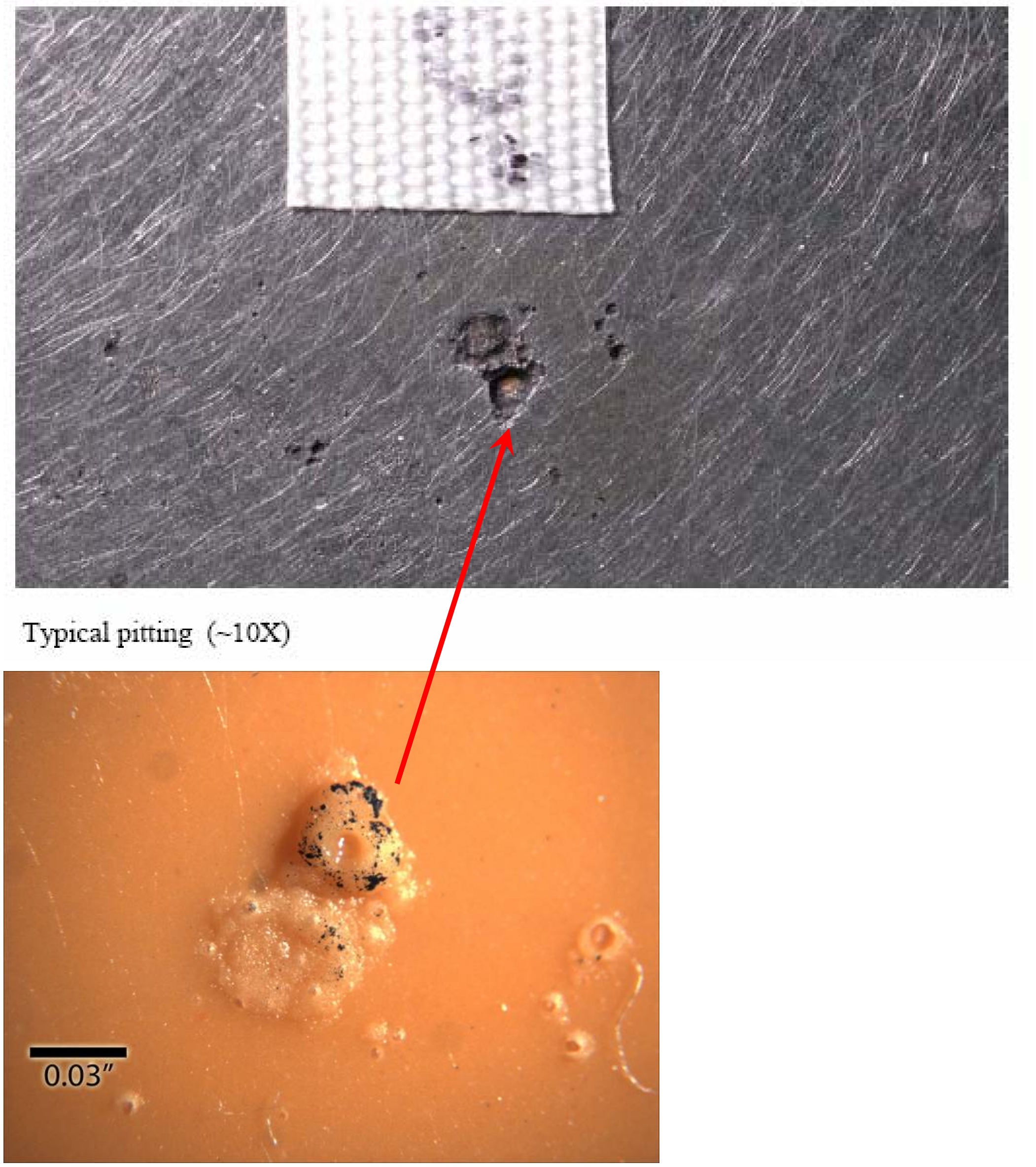


Figure 7. Photograph of typical OV-105 RH #4 conical seal pit (top) and mold of pit interior (bottom).

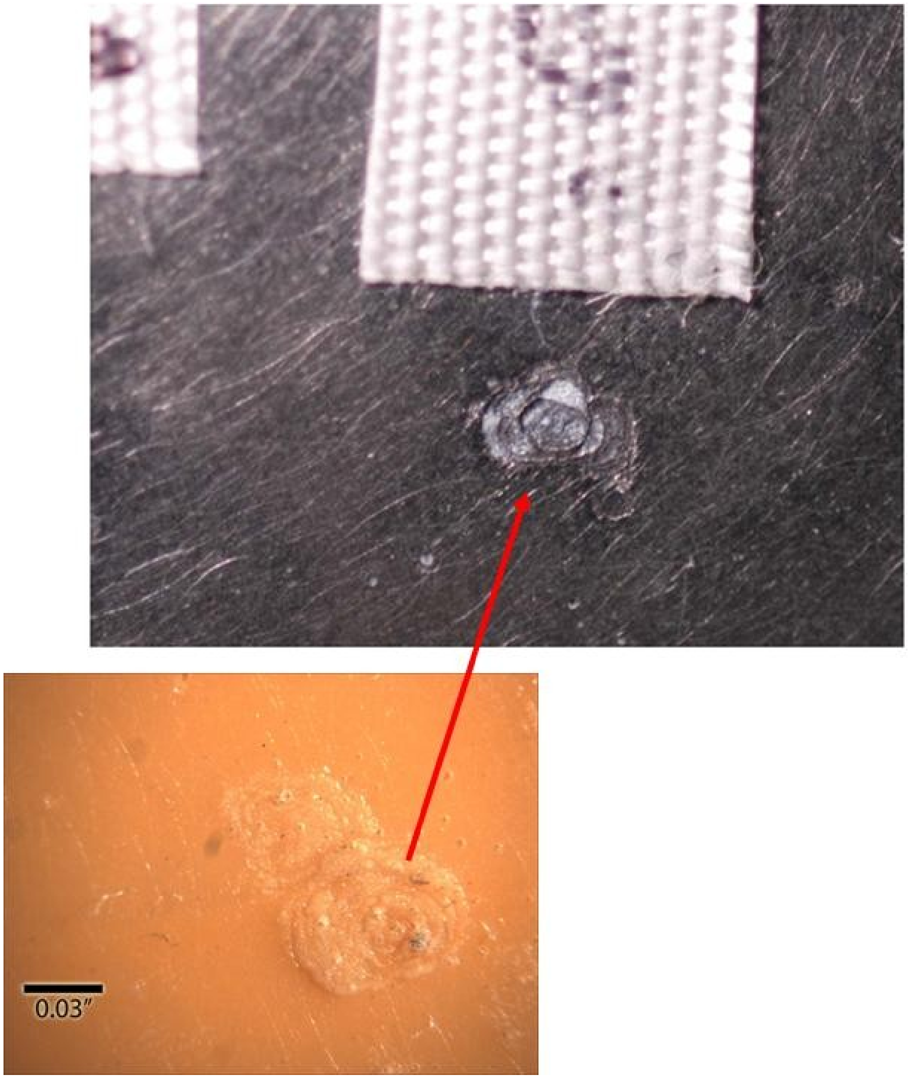


Figure 8. **Photograph of typical OV-105 RH #4 conical seal pit (top) and mold of pit interior (bottom).**

A grid of axial columns (A-F) and circumferential rows was overlaid on the panel with tape, as can be seen in Fig. 3. The grid location and dimensions of all pits greater than 0.003 inch in depth, as measured with an optical micrometer, were documented. The 0.003 inch threshold was selected based on a conservative structural analysis indicating that defects smaller than that depth would be inconsequential and the Material Review Board (MRB) accepted it for unrestricted use “as is.” The majority of the pits were located in the column designated as B; pitting was also clustered at the panel’s ends in columns C, D, and E (see Fig. 3). Figure 9 plots the depth of the pits as a function of grid location.

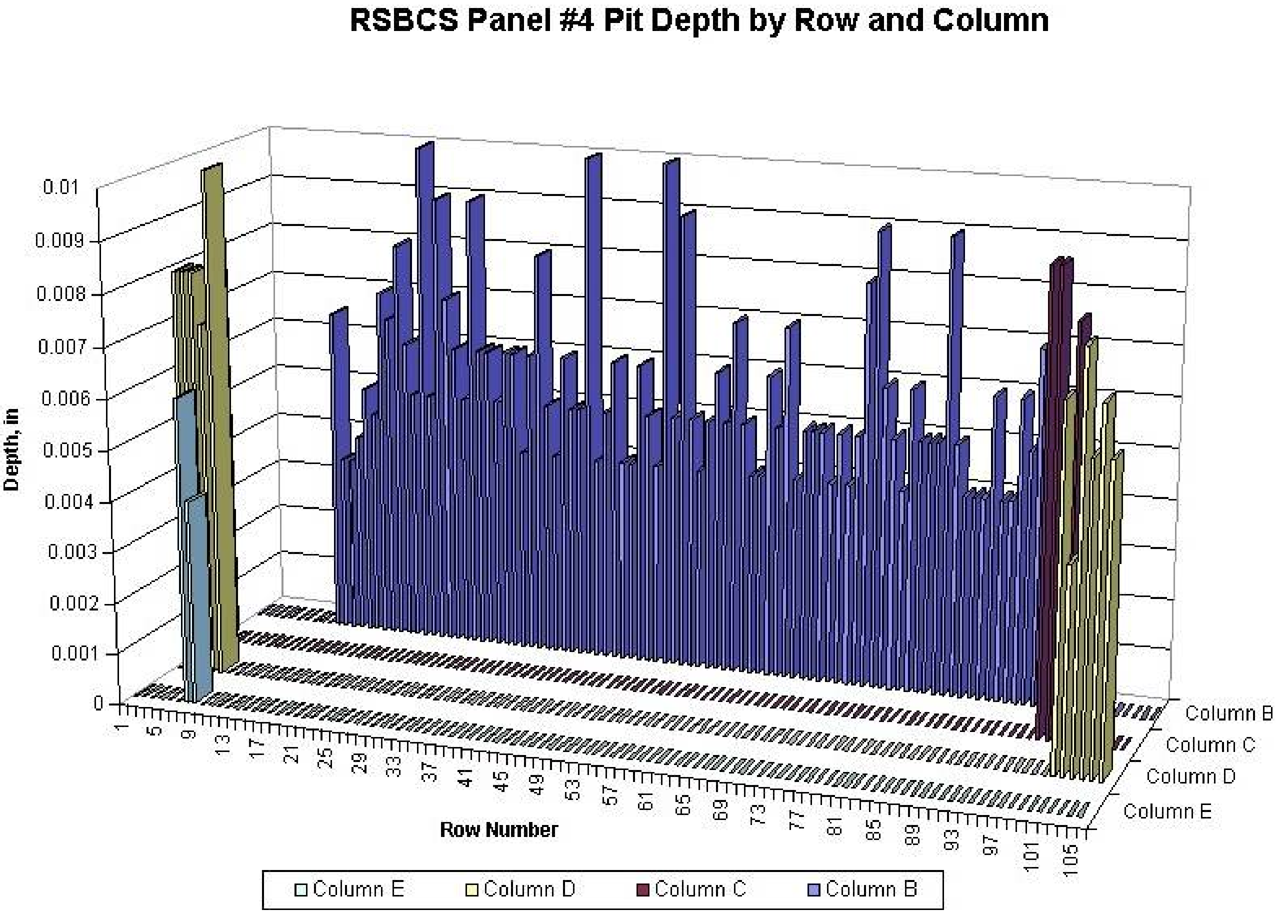


Figure 9. OV-105 RSB #4 conical seal pit depth by grid location.

During examination of the panel, the assessment team noted that there were areas adjacent to the identified pitted areas containing numerous small pits, assumed to be less than 0.003 inch, as well as additional microscopic pits across the entire face sheet, which were only observable at 10-20 X magnification. The assessment team also noted that since there was residue within the pits, as a result of removal of the Pyromark coating, it is possible that all through holes have not been detected; the identification of all through holes may be required if local repair techniques are performed to fill the through holes.

With regard to the condition of the remaining conical seal panels on OV-105 and the other Orbiters, the project infers they do not have any significant pitting as the remaining panels passed the water break free surface test prior to Pyromark coating without any reported discrepancies. No additional inspection has been conducted on the remaining panels as a result of the surface irregularities on RH #4 of OV-105.

IV. Repair Approach

The project had developed a repair rationale based on the position that the conical seals are secondary structure, and if a repair can be shown by analysis to provide adequate strength then it would be acceptable. To this end, the project conducted a structural analysis, and developed the rationale that a minimum 0.006 inch face sheet thickness is required.

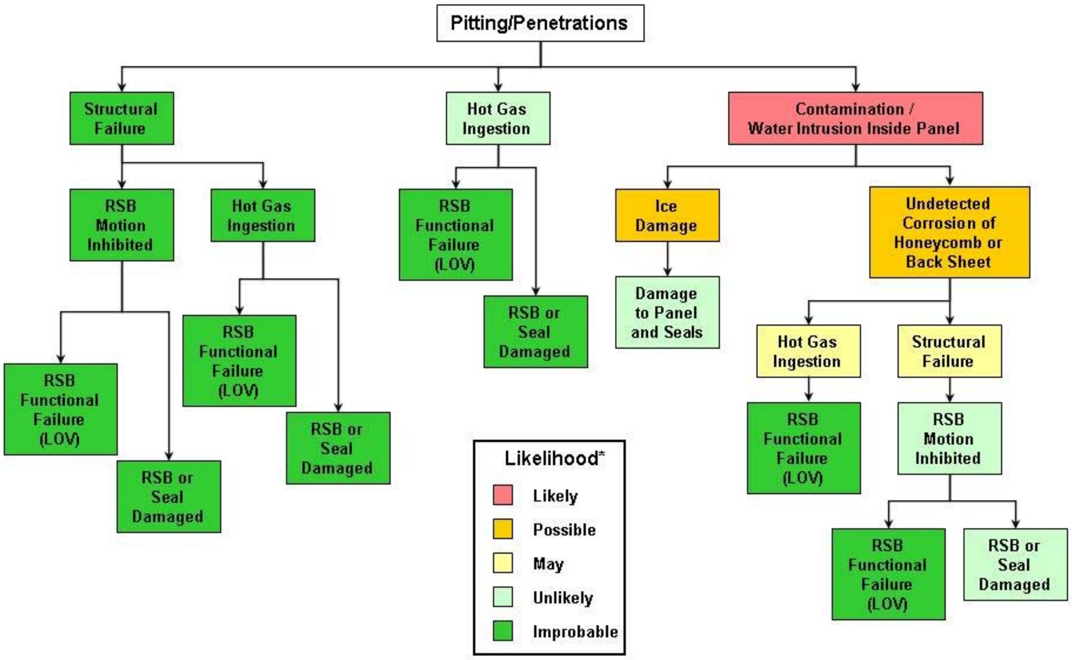
The project considered global, local repair techniques, and a combination of the two. The global technique considered was thermal spray. Thermal spray is the generic term which includes plasma and high-velocity oxy-fuel (HVOF) spray, among many others not evaluated for this program. Thermal spray, can potentially provide a global repair by adding a large doubler that fills or covers the pits and provides 0.006 inch thickness or greater. In the event that thermal spray does not fill the through holes, welding/brazing techniques were considered to fill the through holes alone or with an over coat of thermal spray.

As a proof of concept, the project team fabricated test panels from Inconel® honeycomb of similar materials and construction to the flight panel configuration, and machined grooves and holes into the panel to simulate the pitting on the OV-105 RH #4 conical seal panel. The assessment team noted the simulated defects on the test panel do not accurately represent the majority of the defects on the panel. However, the assessment team considered the test panels acceptable for planned proof of concept testing. One panel was used to test a number of welding and brazing techniques, and the other was used to test HVOF spray.

V. Risk Assessment

The assessment team developed a simplified risk assessment for the “as is” conical panel. Thus the risks considered in this section are for flying the OV-105 RH #4 conical seal panel “as is.” However, they could also be used to consider a repaired part, if it was not fully restored “to print.”

The purpose of the conical seals is to provide a seal or barrier between the rotary actuators of the rudder speed brake, and the external environment. During reentry it provides a thermal seal that withstands reentry temperatures while permitting the RSB to articulate. Thus, two flight failure modes are considered: (1) the seal is breached and contamination, water, or hot gas are permitted to enter the RSB cavity and cause damage to or failure of the RSB assembly, (2) the seal fails structurally and mechanically interferes with the proper operation of the RSB resulting in damage to or failure of the RSB assembly. Also considered were lesser failures which result in degradation or damage to the conical seal panel or graphite seals, and result in cost and schedule impacts associated with increased maintenance or additional repairs. Values of likelihood of occurrence are qualitative judgments based on available information, and the definitions from Risk Management Procedural Requirements (NPR-8000.4) were used as guidance in assessing likelihood. A simplified risk tree summarizing the results is shown in Fig. 10.



* Likelihood definitions per Risk Management Procedural Requirements (NPR-8000.4)

Figure 10. Simplified risk tree for OV-105 RSB RH #4 conical seal panel degradation.

The three top level primary risks considered were structural failure, ingestion of hot gasses, and contamination or water intrusion inside the honeycomb panel cells. The structural failure is applicable to new, "as is," or repaired panel, and was addressed by structural analysis. Based on results from the analysis, structural failure is considered to be unlikely. The possibility of hot gas intrusion exists because the outboard face sheet has been penetrated in approximately 12 locations. Hot gas intrusion would occur only during reentry when vertical tail section temperatures are likely to reach 950°F. It is assumed that the inboard face sheet has not also been penetrated, although not verified except for X-rays. Thus it is unlikely that hot gas intrusion will occur through the panel due to the extent of pitting damage. Aero-thermo dynamic analyses would have to be completed to verify this assumption. It is likely that dust, water, sea spray, or other contaminants could, and may have already entered the honeycomb cells. Once contamination or water enters the cells, then a second tier of risks must be considered. Ice damage considered in this analysis is any damage resulting from the formation of ice within the cell prior to launch, and effects of the ice rapidly turning to steam during reentry in the event that the ice did not sublimate on orbit. The likelihood of this occurring is estimated somewhere between possible and may occur. The resulting damage is believed to be an unlikely flight risk, and would be observable by normal visual inspection during post flight checkout.

As a result contamination, in particular chloride salts which have been shown to cause corrosion of Inconel® under limited conditions, it is possible that corrosion within the panel could occur. Since there is no known method for detecting corrosion within the panel until the damage is sufficient to be detected on an X-ray, this corrosion would be undetectable until it manifested a more serious problem (structural failure or hot gas intrusion). Due to the inherent corrosion resistance of Inconel®, the limited number of flights remaining, and the amount of corrosion that would be required to cause a gas path or structural failure of the panel, it is unlikely that a failure would result from undetected corrosion. If corrosion has already occurred due to contamination entering the panel prior detection of the pitting, this would increase the likelihood of a secondary failure to may occur. Another potential issue is that the corrosion could occur during the Pyromark coating vitrification at 1200 °F for 45-60 minutes, if contaminants have already entered the honeycomb structure.

In summary, beyond restoring the structural characteristics of the panel per the structural analysis, the only significant risk is addressing the potential for undetectable corrosion inside the panel caused by contamination/water intrusion into the panel. Since it is likely that contamination did enter the cells during the sanding operation, if not before, this risk should be addressed in any repair plan.

VI. Proximate and Root Causes(s)

The NESC Assessment Team provided an independent technical assessment of the investigation and repair plan, which included efforts to determine proximate and root cause(s). The purpose of determining proximate and root cause(s) was to maximize the likelihood of a successful repair of the conical seal and minimize the potential for reoccurrence of the pitting anomalies. The approach taken by the NESC Assessment Team was to review the project's current understanding of root cause and to review independently relevant documents, including conical seal panel non-conformance records, data on pitting for the OV-105 right hand #4 conical seal panel, and the specifications for the Pyromark coating application. As part of the technical assessment, the NESC Team reviewed the open literature and contacted industry experts regarding experience with pitting in Inconel® 718. A fault tree analysis was performed and developed for identifying and evaluating contributing events for pitting anomalies. Tests and data-gathering methods were also identified for the elimination of potential proximate and root cause(s).

A. Root Cause Assessment

Initially, a methodical, top-down assessment of possible root cause(s) was not performed by the project, although specific potential events for root cause were investigated. These events included: electric arc (lightning strike or static discharge); micro-meteor damage; chemical spill; Pyromark coating removal; and material identification.

Several experts were consulted by the project for evaluation of potential electric arc events, which would include a lightning strike or static discharge. One expert (Andy Plumer, Lightening Technologies, Inc.) concluded from examination of low magnification photos that the anomalies were not the result of electric arcs, either from lightning attachments or from arcing among parts that have been in contact with each other and in a lightning current path. These electric arc events typically result in a melted and re-solidified appearance with no material loss. Furthermore, the re-solidified areas contain shiny globules of material and a thermal discoloration 'halo' that sometimes appears around a lightning current arc attachment. These features are dissimilar to those observed in the pitted regions of conical seal panel RH #4. Lightning would also be expected to produce more damage on exposed trailing edges of the hardware. This expert suggested that a metallographic cross-section would provide more conclusive evidence. A second expert (Bob Scully, Johnson Space Center) thought the pitting damage might be indicative of a low level attachment based on low magnification photos, but was uncertain without a closer examination. A third expert (Pedro Medelius, Aerospace Corp., Kennedy Space Center) examined the pitting anomalies on the RH #4 panel and indicated that these were unlike typical lightning damage, which usually exhibits bigger, round or oval-shaped areas having a melted appearance with through holes.

The possibility of the pitting being caused by static discharge rather than lightning is being investigated. One expert (Bob Scully, Johnson Space Center) confirmed that precipitation static is a common problem for all aircraft as well as the shuttle, and has three sources: (1) impact and separation of particulate material, which is similar to the static charge created when plastic wrap is pulled from a roll; (2) passing through or near a strong electrical field; (3) passing through an ionized stream which charges the vehicle. The orbiter is regularly exposed to the third source, i.e., an ionized stream, on orbit. The charge buildup dissipates back into the atmosphere or space at the tips and edges of the wings, tail, and etc. This expert also agreed with the assessment team that if the grounding between the RSB panels and the conical seals was degraded the likelihood of static discharge between the conical seals and graphite seal blocks would increase. An ongoing activity by the project is to attempt to reproduce the pitting damage in a Pyromark-coated coupon of Inconel® 718 via experiments with high voltage (~4000 volts), low current static discharge.

A search of the historical database of OV-105 for lightning strikes at the launch site indicated no such events occurred from the first flight of OV-105 in 1992 to the present, while OV-105 was at the launch pad. Since arcing tests are still in progress at the time of this writing, electric arc events must be considered to be open as possible, but unlikely, root cause of the pitting anomalies in RH #4.

Micro-meteor damage was identified as a potential root cause, based on historical documents on other conical seal panels (RH #2, LH #3, and LH #4) on OV-105. These historical documents present no evidence that microstructural examinations beyond low magnification (~10X) imagery were performed.

Chemical spill logs from 1998 to the present have been reviewed for OV-105. No significant findings were noted during this time period. Work is still in progress for the pre-1998 time frame, and tests may be conducted by the PRT on Inconel® 718 with nitrogen tetroxide exposures to determine if the pitting damage can be simulated with the Orbital Maneuvering System (OMS) oxidizer.

The Pyromark coating removal procedure was examined to verify that the procedure was not a contributing factor. The abrasive powder solution #320 was determined to be composed of 320 alumina grit and water only; no corrosive chemicals were contained within the solution. The refurbishment procedure is not considered to be a contributing cause of the pitting anomalies.

Chemical composition of the RH #4 panel was examined with a portable X-ray Fluorescence (XRF) unit. The analysis obtained was considered to a general qualitative match and did not provide a quantitative analysis that conclusively verified Inconel® 718.

Corrosion was not considered by the project to be a contributor because a determination was made that the pitting did not have the characteristics of previously observed corrosion features. Corrosion was also ruled out because the Inconel® 718 material is not readily susceptible to corrosion in a marine environment if the Pyromark coating remains intact. However, residue from within the pits was extracted for analysis which was in progress at the time of this writing.

B. Root Cause Analysis

The assessment team performed a comprehensive, top-down fault tree analysis to aid in identifying and evaluating the contributing events for the pitting anomalies in the conical seal panel RH #4. Four main areas were assessed for potential proximate and root cause(s), which included: original manufacture; storage conditions; service; and refurbishment. Each of these four areas was addressed in detail by the NESC Assessment Team and will be discussed below. A graphical representation of the fault tree is displayed in Fig. 11.

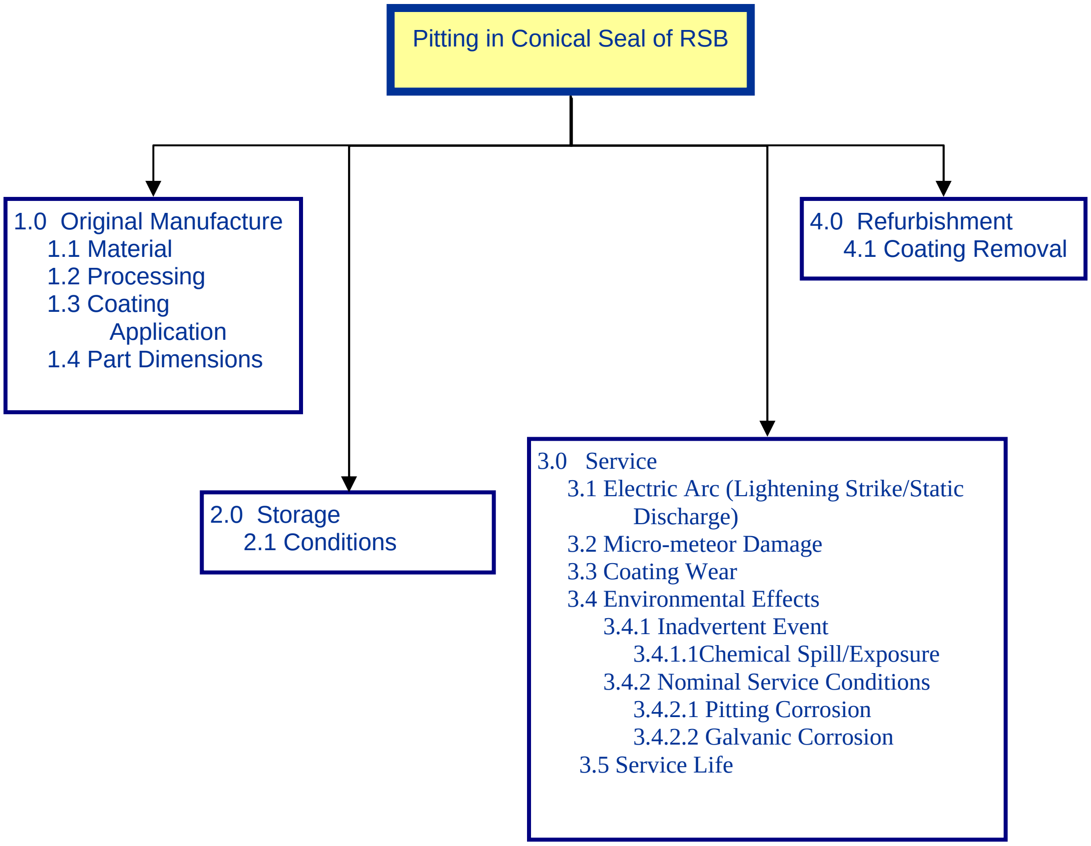


Figure 11. Fault tree for identifying and evaluating contributing conical seal panel pitting anomalies.

1. Manufacture

The assessment team interviewed appropriate personnel and requested relevant documents in an effort to verify that the face sheet material used in RH #4 panel was fabricated from Inconel® 718 or if RH #4 was fabricated from a different "heat" or "lot" of Inconel® 718, as compared to that of the other panels. Many of the requested documents relevant to the original material were not available, and as such, specific questions regarding the composition specifications and actual pedigree of the RH #4 face sheet material have remained unanswered. The intent was to look for deviations from material specifications, as well as for differences in material between RH #4 and other panels in which pitting has not been observed.

The composition of the RH #4 panel was examined with a portable XRF unit. Although this technique may be sufficient to provide data for a general match to Inconel® 718, deviations in the chemistry of RH #4 from certified chemical analyses or deviations between face sheets in OV-105 are likely to be very difficult to determine. Errors in analyzed chemistry data are introduced if the analyzed surface is not flat and if known reference standards are not used to verify that the portable instrument is functioning properly. Analysis of low atomic weight elements and low weight percents are difficult to obtain reliably by portable XRF techniques. The portable XRF technique should be distinguished from other more reliable methods of chemical analyses, such as Wavelength Dispersive XRF or Inductively Coupled Plasma (ICP), which provide improved accuracy of the analyzed major and minor elements. To employ these latter analysis techniques to verify material composition and deviations in chemistry from other panels, small plugs of face sheet material would need to be extracted from flight hardware.

A review of the relevant literature on the processing and resultant microstructure of Inconel® 718 was performed by the assessment team. The literature demonstrates that Inconel® 718 is well known to be corrosion-resistant,[2] but limited cases of pitting in Inconel® 718 have been reported.[3] Pitting in Inconel® 718 has been

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[2] Klopp, W. D. "Ni-4100, IN 718." *Aerospace Structural Metals Handbook*. Code 4104, Purdue Research Foundation, West Lafayette, IN, January (1995): 1.

[3] Groh, J. R., and R. W. Duvelius, "Influence of Corrosion Pitting on Alloy 718 Fatigue Capability." *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592. and
Simon, H., and M. Thoma. "Attack on Superalloys by Chemical and Electrolytic Processes," *Product Finishing,* October (1981): 34-39. and

associated with the segregation of alloying elements, particularly niobium[4] and, to a lesser extent, chromium.[5] Elemental segregation can lead to the precipitation of second phases, such as carbides, nitrides, carbonitrides, and delta phase, which can serve as sites for local attack under certain environmental conditions.[6]

Homogenization practice has a profound effect on the macrostructure and microstructure of both as-cast and wrought products and can affect banding of deleterious phases, dendritic segregation, and grain size control.[7] Incomplete homogenization of the alloy will produce the non-uniform precipitation of second phases during working or aging treatments. Although the homogenization cycle at elevated temperatures is the key to producing a uniform material for forging,[8] bulk diffusion during the homogenization cycle does not completely eliminate segregation in the material prior to working.[9] Intermediate temperature anneals have also been reported to affect the pitting corrosion resistance in Inconel® 718 due to the precipitation of second phases.[10]

Pitting in Inconel® 718 has been attributed to the use of oxidizers and acid etchants during both chemical and electrolytic processing of components.[11] These chemicals include NaOH, which is used in alkaline rust removers, descaling agents, and electrolytic degreasing solutions, as well as acids, which are used in chemical and electrolytic solutions during pickling, cleaning, and electropolishing operations.[12]

Kolts, J. “Alloy 718 for the Oil and Gas Industry.” *Superalloy 718 – Metallurgy and Applications*. Proc. of the Int’l. Symp. on the Metallurgy and Applications of Superalloy 718, E. A. Loria, ed. The Minerals, Metals & Materials Society, Pittsburgh, PA,\ (1989): 329-344.

[4] Groh, J. R., and R. W. Duvelius, “Influence of Corrosion Pitting on Alloy 718 Fatigue Capability.” *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592.

[5] Kolts, J. “Alloy 718 for the Oil and Gas Industry.” *Superalloy 718 – Metallurgy and Applications*. Proc. of the Int’l. Symp. on the Metallurgy and Applications of Superalloy 718, E. A. Loria, ed. The Minerals, Metals & Materials Society, Pittsburgh, PA,\ (1989): 329-344.

[6] Groh, J. R., and R. W. Duvelius, “Influence of Corrosion Pitting on Alloy 718 Fatigue Capability.” *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592. and
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Kolts, J. “Alloy 718 for the Oil and Gas Industry.” *Superalloy 718 – Metallurgy and Applications*. Proc. of the Int’l. Symp. on the Metallurgy and Applications of Superalloy 718, E. A. Loria, ed. The Minerals, Metals & Materials Society, Pittsburgh, PA,\ (1989): 329-344. and
Poole, J. M., K. R. Stultz, and J. M. Manning. “The Effect of Ingot Homogenization Practice on the Structure of Properties of Wrought Alloy 718.” Superalloy 718 – Metallurgy and Applications, Proc. of the Int’l. Symp. on the Metallurgy and Applications of Superalloy 718, E. A. Loria, ed. The Minerals, Metals & Materials Society, Pittsburgh, PA (1989): 219-228.

[7] Radavich, J.F. “The Physical Metallurgy of Cast and Wrought Allow 718.” *Superalloy 718 – Metallurgy and Applications*. Proc. of the Int’l Symp. On the Metallurgy and Applications of Superalloy 718. E.A. Loria, ed. The Minerals, Metals & Materials Society. Pittsburgh, PA (1989): 229-240. and
Poole, J. M., K. R. Stultz, and J. M. Manning. “The Effect of Ingot Homogenization Practice on the Structure of Properties of Wrought Alloy 718.” Superalloy 718 – Metallurgy and Applications, Proc. of the Int’l. Symp. on the Metallurgy and Applications of Superalloy 718, E. A. Loria, ed. The Minerals, Metals & Materials Society, Pittsburgh, PA (1989): 219-228.

[8] Radavich, J.F. “The Physical Metallurgy of Cast and Wrought Allow 718.” *Superalloy 718 – Metallurgy and Applications*. Proc. of the Int’l Symp. On the Metallurgy and Applications of Superalloy 718. E.A. Loria, ed. The Minerals, Metals & Materials Society. Pittsburgh, PA (1989): 229-240.

[9] Couts, W. H. and T. E. Howson. “Wrought Alloys.” *Superalloys II*, C. T. Sims, et al, eds, John New York: Wiley & Sons (1987): 450.

[10] Kolts, J. “Alloy 718 for the Oil and Gas Industry.” *Superalloy 718 – Metallurgy and Applications*. Proc. of the Int’l. Symp. on the Metallurgy and Applications of Superalloy 718, E. A. Loria, ed. The Minerals, Metals & Materials Society, Pittsburgh, PA,\ (1989): 329-344.

[11] Simon, H., and M. Thoma. “Attack on Superalloys by Chemical and Electrolytic Processes,” *Product Finishing,* October (1981): 34-39. and
Groh, J. R., and R. W. Duvelius, “Influence of Corrosion Pitting on Alloy 718 Fatigue Capability.” *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592.

[12] Simon, H., and M. Thoma. “Attack on Superalloys by Chemical and Electrolytic Processes,” *Product Finishing,* October (1981): 34-39.

Therefore, based on the literature review, material and processing are possible contributing factors to the pitting that has been observed in RH #4. As a result, both processing specifications and actual processing data for OV-105 face sheet panel assemblies were requested. The intent was to identify deviations from specifications and for differences between RH #4 processing and that of other panels in which pitting has not been observed. These records have not been located, but may provide useful information toward evaluating proximate and root cause(s). To examine the hardware directly for evidence of non-uniform elemental segregation, small plugs of face sheet material would have to be extracted from flight hardware.

Additionally, the processing of RH #4 includes brazing of the honeycomb panel to the outboard and inboard face sheets. If microstructural examinations are performed on selected plugs of hardware material and indicate anomalies associated with the diffusion of elements into the face sheet from the brazing material, then the brazing specifications and any possible deviations may also require examination.

A Pyromark coating is applied to the conical seal panel for high emittance during Orbiter re-entry. An in-depth review of the Fairchild specifications for the Pyromark coating application used during the original manufacture of the Inconel® 718 panel assembly has been conducted. Based on a top-down examination of potential proximate and root causes of the pitting anomalies in RH #4, the application of the Pyromark coating provides a possible contributing factor for the observed pitting. For example, it is possible for a higher density of defects to be present in the coating of an isolated panel(s) due to the actual preparation of that substrate and subsequent application steps for that coating. A specified size and density of defects are allowed in the Pyromark coating, and scratches in the coating that penetrate through the coating to the bare metal surface of the substrate are allowed within certain limitations. Even with defects extending down to the bare metallic substrate, the panel may still meet the required (average) emittance levels for the coating, but in fact may be detrimental to the pitting corrosion resistance of the underlying metal. Small coating defects, such as a scratch or a pin hole extending down to the bare metal substrate, may promote locally high concentrations of corrosive species to collect, thereby favoring locally high dissolution rates of the metallic substrate.[13]

The Fairchild Pyromark Coating specifications indicate that logs were kept for the Pyromark coating application in terms of batch number, manufacturer, amount of thinner used, and environmental controls. Measurements of the applied coating thickness and adhesion tests were performed on test panels of Inconel® 718 or Incoloy® 903 that were processed at the same time as the flight hardware. Protection of flight hardware during transport to vendors has sometimes been an issue with respect to condensation of moisture and collection of dust on the components.[14] The coating application data and information on how the panels were protected during transport and prior to the actual coating application, if retained and located, may aid in the review of any potential deviations in the original coating application for RH #4 compared to that for other panels on OV-105. Furthermore, the metallographic examination of the coated test panels, if located, would be instructive in terms of providing representative examples of past coating quality. Microstructural examination of the Inconel® 718 in the test panels would also enable the assessment of typical levels of segregation Inconel® 718 manufactured about the same time as that used in the orbiter conical seal panels.

Fairchild coating specifications also allow repair of damaged areas of certain dimensions. The specified repair includes a final coating cure via a heat lamp at 450-500^{o}F for one hour minimum. Coating manufacturing logs would enable a determination if such repairs were performed on RH #4, or any other panels on OV-105, as this final temperature step does not allow for vitrification of the coating. Again OV-105 panel-to-panel variability, if present, with regard to coating repairs during manufacture may aid in the root cause determination.

Part dimension was added to the fault tree to incorporate any potential discrepant dimensional feature(s) of the conical seal panel and graphite seal blocks for RH #4, which may cause preferential wear of the Pyromark coating, the underlying panel surface, and/or the graphite seal blocks. Dissimilar wear of the RH #4 seal panel assembly may either degrade the coated surface, thereby enabling potentially corrosive media to reach the Inconel® substrate, or may have directly caused the pitting anomalies. An out-of-roundness condition or high point in the conical seal panel may cause more friction and wear. Measurements of the profiles of the panels were obtained using Coordinate Measurement Machines (CMM), so these data collected after manufacture may be available for

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[13] Fontana, M. G., and N. D. Greene. *Corrosion Engineering*. New York: McGraw-Hill Book Company (1967): 48-54.

[14] Korb, L. J. "Corrosion in the Aerospace Industry," *Metals Handbook*, Ninth Ed., Vol. 13, Corrosion. Metals Park, OH (1987): 1075-1079.

examination. The assessment team requested that some of the graphite seal blocks in contact with RH #4 be examine by electron microscopy to determine the surface condition of those blocks.

Some isolated surface finish and contour issues have been cited in conical seal panels. For example, dimples on the face sheet surface of RH#4 were observed after Pyromark coating removal, and some of these dimples contained adherent coating material that was not removed. Deviations to the contour of a conical seal panel from OV-104 necessitated a repair to be made after manufacture to restore the part to print.

2. Storage

The conical seal panel set for OV-105 was delivered in 1986 and placed in storage until OV-105 was assembled for its first flight in 1992. The assessment team requested documents that detailed the storage conditions of the panels, including if the OV-105 panels were all stored in the coated or uncoated condition. Protection of the panels during transport to the storage facility may also be examined. Records detailing other relevant storage conditions of each conical seal panel for OV-105 may reveal any potential differences in storage that could have contributed to the pitting anomalies in RH #4.

3. Service

No on-pad lightning strikes to OV-105 have been documented. Thus, a potential lightning strike would more likely be a re-entry event. Another more probable electric arc event is a static discharge due to inadequate grounding. The Orbiter is subject to a build up of a static charge while moving through the atmosphere. Static discharge events are more likely to produce small surface anomalies rather than large surface anomalies.

The assessment team concurs that melting of the Inconel® 718 would have occurred if an electric arc event, either lightning strike or static discharge, affected the conical seal panels. Microstructural analysis of selected pit(s) should reveal evidence of melting, if an electric arc event occurred, and should aid in root cause determination.

KSC documents indicate that three OV-105 panels (RH#2, LH#3, and LH#4) exhibited damage that was described as micro-meteor or meteor strikes. These identifications were made without subsequent detailed analyses. Any documentation detailing the nature of this damage may aid in root cause determination.

For a micro-meteor event to have damaged the conical seal panels on OV-105, the panels would have to be exposed during flight. It should be noted that the panels are not exposed during a large fraction of the time in flight, and some of the areas where pits formed are outside of the travel of the seal blocks and thus are never exposed in flight. Furthermore, the highest density of pits was axially aligned along two lines parallel to the length of the panel, which seems inconsistent with a micro-meteor event. The assessment team concurs with the initial conclusion that a micro-meteor event is not a likely cause of the pitting. To examine the hardware directly for evidence of foreign impact damage from a potential micro-meteor event, small plugs of face sheet material would have to be extracted from flight hardware.

The highest density of pitting was concentrated along two axial locations corresponding to the nominal trail/parked, or 1.5 degree open positions of the seal blocks in the RSB, which represents the seal block positions for a majority of the flight cycle. Coating wear is expected. It is expected coating wear to be maximized along locations where the graphite seal blocks and the face sheet are in direct contact for a long period of time. As a result of the correlation between the pitting density and the location in which wear of the coating would be expected, coating wear was added to the fault tree as a possible contributing event for the pitting anomalies. It should be noted that pitting was also observed, although to a lesser extent, on the conical seal panel in positions outside of the travel of the graphite seal blocks, and therefore, in locations where coating wear would not be present.

Inconel® 718 is well known to be a corrosion-resistant material.[15] However, defects in the Pyromark coating may be detrimental to the pitting corrosion resistance of the underlying Inconel® 718. Although the intent of the Pyromark coating is to provide high emittance for the conical seal panel, it is possible that a sufficiently thick coating may be serving as a chemical barrier or a moisture barrier. Wear of the coating, or defects in the coating, may entrap moisture that contains salt from the marine environment at KSC. This condition may promote high concentrations of corrosive species, such as sodium chloride, in localized areas, thereby favoring high dissolution rates of the Inconel® 718 face sheet in these localized regions.

It should be noted that the assessment team observed after only one flight that the coated conical seal panel (RH #4) on OV-103 exhibited contrast or surface roughness changes in the coating along the axial positions corresponding to the nominal trail/parked, or 1.5 degree open positions. It is unknown specifically how the

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[15] Klopp, W. D. “Ni-4100, IN 718.” *Aerospace Structural Metals Handbook*. Code 4104, Purdue Research Foundation, West Lafayette, IN, January (1995): 1.

accumulation of flight service affected the coating along the nominal trail/parked positions of the RSB of OV-105, as detailed records documenting the condition of the Pyromark coating prior to refurbishment were not obtained. The Pyromark coating has since been removed from all panels in the fleet and thus can no longer be examined directly. Nonconformance records for RH #4 of OV-105 do indicate, however, that Pyromark coating was missing in numerous locations prior to refurbishment. The documentation of surface irregularities should be updated during Orbiter flow inspections to address and document changes in the coating surface after flight.

The assessment team performed a literature search which showed that oxidizers and some acid etchants cause pitting in Inconel® 718.[16] This particular branch of the fault tree was added specifically to represent an inadvertent chemical event during or after installation on the orbiter, as opposed to chemical exposures that may occur under nominal environmental conditions while the orbiter is in service.

The chemical spill logs from 1998 to the present were examined, and no significant findings were noted for OV-105 during this time period. In addition, the KSC engineering personnel, responsible for the maintenance and servicing of the hypergolic Ground Support Equipment and flight hardware, were questioned with regards to any memory of a hypergolic spill or release on OV-105. There were no recalled incidents of any hypergolic releases on OV-105.

Thus, an inadvertent chemical spill or exposure is not a likely candidate for the root cause of the pitting anomalies.

The literature indicates that Inconel® 718 is well known to be resistant to general overall corrosion,[17] but limited cases of pitting in Inconel® 718 have been observed and attributed to chemical and electrolytic exposures containing aqueous chloride,[18] oxidizers,[19] and acids.[20] Pitting has also been intentionally reproduced in Inconel® 718 material by forward and reverse polarization scans in tap water. Second phase particles in the alloy provided sites for local attack.[21] The pits were determined to debit fatigue life of the component. [22]

Because oxidizers and other chemicals are also released during nominal operations of the orbiter, the assessment team examined these occurrences as possible contributing events. The thrusters on the OMS pods are known to leak small amounts of oxidizer (nitrogen tetroxide), but due to their distance from the conical seal panels, it seems that the thrusters are an unlikely source for providing chemical exposures. The Auxiliary Power Unit (APU) exhaust ports are in the vicinity of the RSB; the vapor from the exhaust ports may contain minor amounts of hydrazine, with higher concentrations of ammonia, hydrogen, and nitrogen byproducts. However, no significant amount of APU fuel vapor is known to have been released in the tail area during the past six years. Solid rocket boosters (SRBs) also release chemicals that come into contact with the vertical tail section, thereby similarly

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[16] Simon, H., and M. Thoma. "Attack on Superalloys by Chemical and Electrolytic Processes," *Product Finishing,* October (1981): 34-39. and
Groh, J. R., and R. W. Duvelius, "Influence of Corrosion Pitting on Alloy 718 Fatigue Capability." *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592.

[17] Klopp, W. D. "Ni-4100, IN 718." *Aerospace Structural Metals Handbook*. Code 4104, Purdue Research Foundation, West Lafayette, IN, January (1995): 1.

[18] Groh, J. R., and R. W. Duvelius, "Influence of Corrosion Pitting on Alloy 718 Fatigue Capability." *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592.

[19] Ibid. and
Simon, H., and M. Thoma. "Attack on Superalloys by Chemical and Electrolytic Processes," *Product Finishing,* October (1981): 34-39.

[20] Ibid. and
Kolts, J. "Alloy 718 for the Oil and Gas Industry." Superalloy 718 – Metallurgy and Applications. Proc. of the Int'l. Symp. on the Metallurgy and Applications of Superalloy 718, E. A. Loria, ed. The Minerals, Metals & Materials Society, Pittsburgh, PA,\ (1989): 329-344.

[21] Groh, J. R., and R. W. Duvelius, "Influence of Corrosion Pitting on Alloy 718 Fatigue Capability." *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592. and
Simon, H., and M. Thoma. "Attack on Superalloys by Chemical and Electrolytic Processes," *Product Finishing,* October (1981): 34-39. and
Kolts, J. "Alloy 718 for the Oil and Gas Industry." Superalloy 718 – Metallurgy and Applications. Proc. of the Int'l. Symp. on the Metallurgy and Applications of Superalloy 718, E. A. Loria, ed. The Minerals, Metals & Materials Society, Pittsburgh, PA,\ (1989): 329-344.

[22] Groh, J. R., and R. W. Duvelius, "Influence of Corrosion Pitting on Alloy 718 Fatigue Capability." *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592.

exposing all conical seal panels. Thus, nominal operations of the OMS thrusters, APUs, and SRBs do not appear to be contributing to proximate and root causes of the pitting anomalies.

The general corrosion literature indicates that most pitting corrosion is caused by chloride and chloride-containing ions, which are present in varying concentrations in most water solutions.[23] The salt fog and moisture inherent to KSC exposes the Orbiters to an environment where pitting corrosion from nominal service conditions seems to be a likely proximate cause. However, other factors are expected to be contributors to explain the sole occurrence of pitting in the RH #4 conical seal panel. Wear or defects of the coating may entrap moisture from the marine environment, thereby exposing the Inconel® face sheet in localized regions. This condition may promote locally high concentrations of corrosive species, thereby favoring high dissolution rates in localized regions of the metallic substrate. Although delta phase was found within the pits of the Inconel® 718[24] after aqueous chloride attack, it is not clear that the material has to be improperly processed or inadequately homogenized for the second phases to be sites for localized attacks. Inconel® 718 processed under optimum conditions would still have some degree of niobium segregation present.[25] However, to explain the presence of pitting only in RH #4, material and/or processing issues could be involved, thereby further predisposing RH #4 to such anomalies.

Some similarity in the general morphology of the pits was observed in another nickel-base superalloy after coating the alloy with magnesium, sodium and potassium sulfate salts and performing high temperature exposures. In this case, sulfides formed beneath the oxides in the pits.[26]

Analysis of residues collected and analyzed from three pits in RH #4, is still in-progress. The preliminary results indicate that the residues contain chlorine and potassium. These results appear consistent with the microstructural analyses performed on cross-sections of Inconel® 718 pits after aqueous chloride attack, where chlorine, potassium, calcium, and silicon-rich corrosion products were found within the pits.[27] In the residue from RH #4 conical seal panel pits, elements associated with the abrasive coating removal process were also identified. Although these results on RH #4 and their interpretation are preliminary, the data represent a first step in determining what may be contained within the pits, which will assist in the identification of proximate and root cause(s). Examination of metallographic cross-sections will more definitively determine the presence of any corrosion products through the pitted region(s).

Galvanic corrosion can occur when dissimilar metals are in contact while being immersed in a corrosive or conductive solution. The severity of attack depends on a number of factors, including the potential difference between the dissimilar metals, solution conductivity, area ratio between the cathode and anode, and the distance from the junction between the dissimilar metals.[28] Graphite behaves electrochemically like a noble metal, which suggests that this material may be cathodic to most metals upon galvanic coupling.[29] Because of the direct contact between the graphite seal blocks and the coated Inconel® face sheet, it was conceivable that galvanic coupling could occur, especially with the marine environment at KSC. If coating flaws existed on the RH #4 conical seal thereby exposing the bare metal substrate, a potentially unfavorable area ratio could exist between the large cathode (seal blocks) and the small anode (exposed Inconel® 718). This could be exacerbated by segregation in the Inconel® 718 alloy which could introduce small areas that are more anodic locally relative to the overall alloy. Galvanic currents

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[23] Fontana, M. G., and N. D. Greene. "*Corrosion Engineering*." *Corrosion Engineering*. New York: McGraw-Hill Book Company (1967): 48-54.

[24] Groh, J. R., and R. W. Duvelius, "Influence of Corrosion Pitting on Alloy 718 Fatigue Capability." *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592.

[25] Radavich, J.F. "The Physical Metallurgy of Cast and Wrought Alloy 718." *Superalloy 718 – Metallurgy and Applications*. Proc. of the Int'l Symp. On the Metallurgy and Applications of Superalloy 718. E.A. Loria, ed. The Minerals, Metals & Materials Society. Pittsburgh, PA (1989): 229-240. and
Couts, John, W. H. and T. E. Howson. "Wrought Alloys." *Superalloys II*, C. T. Sims, et al, eds, New York: Wiley & Sons (1987): 450.

[26] *Gabb, T. P., NASA Glenn Research Center, unpublished research, Sept. 19, 2005.*

[27] Groh, J. R., and R. W. Duvelius, "Influence of Corrosion Pitting on Alloy 718 Fatigue Capability." *Superalloys 718, 625, 706, and Various Derivatives*. E. A. Loria, ed. TMS (2001): 583-592.

[28] Fontana, M. G., and N. D. Greene. *Corrosion Engineering*. New York: McGraw-Hill Book Company (1967): 48-54.

[29] Danford, M. D., and R. H. Higgins. "Galvanic Coupling Between D6AC Steel, 6061-T6 Aluminum, Inconel® 718, and Graphite-Epoxy Composite Material: Corrosion Occurrence and Prevention." NASA TM-2236, 1983.

have also been demonstrated to perforate paint coatings between some dissimilar metals.[30] Thus, galvanic corrosion was added to the fault tree as a potential mechanism for the cause of the pitting anomalies.

A literature search on galvanic coupling with Inconel® 718 was conducted by the assessment team. Studies have been performed on galvanic couples between steel, aluminum, Inconel® 718, and graphite-epoxy composite material in salt water with 3.5 percent NaCl.[31] Inconel® 718 was shown to be compatible when galvanically coupled to graphite epoxy in salt water. Since epoxy is non-conductive, coupling graphite to Inconel® 718 in salt water may have a slightly different effect. Nonetheless, galvanic corrosion between the conical seal panel and the block seal is not supported by the data found in the literature.[32] Other papers indicate galvanic incompatibility between Inconel® 718 and aluminum[33] and between Inconel® 718 and carbon steel[34], but these dissimilar metals are not in contact with each other in the conical seal panel assembly. Based on the available data in the literature, galvanic coupling does not appear to be the most likely corrosion mechanism for explaining the pitting anomalies in the conical seal panel, but this mechanism cannot be ruled out entirely without further examination.

OV-105 had accumulated the lowest number of flights at 19 of the orbiters in the fleet. Thus, service life does not appear to contribute to the formation of the pitting anomalies in RH #4. The assessment team considers service life as not probable for the root cause.

4. Refurbishment

Intermetallic phases or inclusions in Inconel® 718 can be dragged across surfaces during machining and torn out by grinding, leaving behind shallow pores (approximately 0.0008 inch deep) and features resembling "comet-tails" in the machined surface.[35] It is possible that the abrasive removal of the coating may have contributed to the appearance of swirls on the face sheet surface (Fig. 7 and Fig 8.), but the formation of the circular through pits (0.010 inch deep) is difficult to rationalize as having been produced from the abrasive removal process. Additionally, pitting anomalies in panel RH #5 of OV-103 have been observed with the Pyromark coating still in place. Earlier investigation also determined that the Pyromark coating removal procedure on RH #4 did not include the use of corrosive chemicals. The assessment team concurs with earlier findings that the refurbishment procedure does not appear to be a probable cause of the pitting anomalies.

C. Cause Scenarios

The critical assumption made is that the anomalies are isolated only to RH #4. If similar pitting anomalies are determined to be present in other panels, then the proximate and root cause analysis will need to be reconsidered. The available evidence suggests a synergistic events chain:

> Pitting corrosion and/or material/processing issues in conjunction with inadequate Pyromark coating coverage from original application or subsequent coating wear.
>
> Electrical discharge evaluation is also underway.

VII. Damage and Repair Assessment

During the initial project assessment, the only requirements established in the evaluation of the hardware for form, fit and function were the structural requirements. Therefore, analysis was conducted to determine if the RSB conical seal could maintain required margins of safety in the damaged condition. This analysis was a fairly

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[30] Korb, L. J. "Corrosion in the Aerospace Industry," *Metals Handbook*, Ninth Ed., Vol. 13, Corrosion. Metals Park, OH (1987): 1075-1079.

[31] Danford, M. D., and R. H. Higgins. "Galvanic Coupling Between D6AC Steel, 6061-T6 Aluminum, Inconel® 718, and Graphite-Epoxy Composite Material: Corrosion Occurrence and Prevention." NASA TM-2236, 1983.

[32] Ibid. and
Military Standard: *Dissimilar Materials*, MIL-STD-889B, Department of Defense, 7 July 1976.

[33] Roach, T. A. "Alloy 718 Fasteners: Versatility and Reliability for Aerospace Design." Superalloys 718, 625, 706, and Various Derivatives. E. A. Loria, ed. TMS (2001): 381-389.

[34] Champagne, V. K., G. Wechsler, M. S. Pepi, and K. J Bhansali. "Failure Analysis of an Alloy 718 Barrel Nut from an Army Attack Helicopter." Superalloys 718, 625, 706, and Various Derivatives. E. A. Loria, ed. TMS. (2001): 813-824.

[35] Simon, H., and M. Thoma. "Attack on Superalloys by Chemical and Electrolytic Processes," *Product Finishing,* October (1981): 34-39.

straight forward update to the original RSB analysis conducted in 1985. Maximum applied compressive stress was taken from the 1985 analysis and a margin was recomputed for the specific failure modes of interest, including cell dimpling, intercell bucking and flatwise strength.

The original RSB analysis conducted in 1985 was not reviewed in detail as a part of this assessment. The maximum applied compressive stress was established from an 8000 degrees of freedom (DOF) finite element model that utilized QUAD4 and TRIA3 elements in NASTRAN to model the Inconel® honeycomb panel. CBAR elements were used to represent other elements in the assembly, such as the struts, links and attach fittings. The analysis incorporated the temperature dependent properties of the material, as the design limit load cases for this panel had thermal environments approaching 1000 °F. Stresses were established based on the review of many thermal conditions which maximized chordwise gradient, inner/outer skin gradient, adjacent node gradient and temperature. Thermal loads were combined with pressure and inertial loads, as appropriate, to produce maximum stresses in different phases of ascent and descent.

The maximum applied compressive stress from the 1985 analysis was combined with a factor of safety of 1.4 to produce a zero-margin critical load. This load was then used with standard intercell buckling equations to back-calculate minimum face sheet thickness necessary to prevent elastic, intercell buckling. This methodology is a simplified, conservative, analysis technique, based on a uniform thinning of the skin. The analysis resulted in a finding that a minimum of 0.006 inch thickness of face sheet was required to ensure that intercell buckling did not occur. This minimum face sheet thickness was then used with standard flatwise strength equations to ensure that the sandwich compressive strength margin remains positive. These data resulted in a decision to pursue a total surface repair.

The assessment team reviewed the data, and recommended that the previous structural analysis team revisit the analysis with two specific objectives. First, establish a more appropriate criterion for determining the critical face sheet thickness for local buckling modes than uniform thinning. Second, evaluate failure modes other than local, cell-level, elastic buckling modes as critical failure modes. Plastic buckling, multiple contiguous cell failure and global failure modes were identified as the modes that could potentially affect the RSB system functionality. This type of analysis approach does have some precedent in the Shuttle Program, and is a more realistic approach for corrosion which manifests itself as local, isolated pitting as opposed to general corrosion which does result in global thinning of the structure. It was also recommended that the loads analysis group look into the design load cases to ensure a better understanding of the driving loads. This would assist the analysis team if the application of case consistent loads was required to establish additional capability. This approach was reviewed and concurred to by the Boeing analysis subsystem manager and the structures NASA Subsystem Engineer (NSE) at JSC.

In its final implementation, the methodology proposed resulted in multiple criteria for the evaluation of pitting damage to the conical seal. These criteria are as follows:

1. Pitting to 0.004 inch depth is acceptable
2. Pitting beyond 0.004 inch depth up to 0.007 inch should be evaluated by "equivalent volume method." The sum of the volumes of all pits within a single cell cannot exceed 20 percent of the total volume.
3. Pitting beyond 0.007 inch depth should be evaluated as a through hole: Structurally acceptable if through hole does not exceed 10 percent on area in one cell (assumes no other pits present). If there is non-through pitting and through hole in one cell, this would need to be evaluated separately.
4. Pitting that is unacceptable by rules 2) and 3) above for a single cell can be evaluated over three adjacent cells (worst two adjacent cells "in a line") on an individual basis.

The first criterion is consistent with the original, conservative assessment of uniform skin thickness loss and a critical face sheet thickness of 0.006 inch for intercell buckling. The second criterion has its basis in some simple finite element modeling to establish the sensitivity of cell buckling to loss of skin volume. This criterion is somewhat conservative, as the pit volume is conservatively represented as the area multiplied by the maximum depth, and ignoring the taper of the pit walls. The third criteria, for through holes, is based on fundamental relationships of stress and capability for buckling of simply supported plates with and without through holes as established in Roark.[36] This process supports the conversion a 40 percent reduction in thickness (the 0.006 inch critical skin thickness) to an acceptable area loss of approximately 10 percent for a through hole. Finally, for pitting that does not pass the first three criteria, a multicell analysis can be used on a case by case basis.

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[36] Young, Warren C., and Richard G. Budynas. *Roark's Formulas for Stress and Strain*. McGraw-Hill Professional Publishing (2001): 832.

These criteria were implemented, and their use substantially reduced the number of damage sites which required detailed stress analysis. Ultimately, the final stress analysis indicated that eleven sites required repair.

VIII. Repair Approach

Hardware performance drives repair requirements, which drive repair process(es) selection. As a minimum, repair only what is necessary (local rather than global repair). However, the repair selection should be based on a number of other considerations; principal among them is "do no harm." The risk versus requirements trade is driven by repair requirements and by the processing considerations associated with each process.

- Is any repair required?
- If so, how much repair is required?
- Is the risk of executing the required number of individual repairs higher or lower risk that a single global?
- What are final part/surface requirements?
- Can excess sprayed deposited "doublers" be left on or machine to original contour?
- Is it better to adapt the existing approved processes or qualify new process?
- Which processes should be considered for qualification?

There are various means for depositing materials for applications such as those presented here; i.e., filling of pits. The critical requirements for the process include:

- Proper surface preparation
- Thermal control/monitoring during processing of thin section
- Potential distortion associated with process
- Proper surface finish or finishability (post processing polishing) of the repair
- Low dust environment (proper dust removal as per industrial practice)
- Robotic control to achieve uniform spray torch motion and nominal perpendicularity to substrate for thermal spray application

A. Primary Repair Techniques

The project team has been focusing on a return-to-print approach employing a global spray process augmented, if necessary, with a local weld/braze repair for those penetrations that can not be bridged by spraying. In addition, the project team examined electroplating, and ceramic fill. Electroplating was not further developed due to concerns of elevated temperature durability. The project has used epoxy fill for penetrations outside thermal exposed areas, and continues to explore the possible use of Dow Corning® 93-104 as a fill for the through pits.

The primary approach of using thermal spray (plasma & others) is an accepted industrial practice for this type of surface restoration. While, there is no specific call-out for pitting repair, clearly, current technology is available to satisfy the above stated requirements. There are a number of critical issues that must be recognized relative to spray-repair techniques. Independent of the thermal spray technique employed, the central concerns are:

- Proper thermal spray equipment condition and up-to-date maintenance
- Pure gases for plasma/combustion and powder carrying as per best practice
- Appropriate spray parameter settings – for specific powder feed-stock.
- Powder size distribution (as tight as possible), morphology (spherical) and chemistry must be to-specification (various aircraft specifications are acceptable)
- Powder to be dry and flowable
- Substrate surface preparation must be suitable for spray process (HVOF versus plasma spray)
- Spray torch-workpiece distance constant and nominal normal angle-to-workpiece to be assured by robotic control
- Post-spray surface quality (e.g., can be upgraded with controlled glass bead peening)

Metco 443 or Praxair PS036136, and similar powders, (the powder preparation method should be gas atomization in order to achieve a chemically uniform and spherical powder which flows well) are suitable for "self-bonding" purposes. Although a clean surface is required prior to spray application, it is not generally required to have a high profile "anchor" substrate surface (i.e., heavy deformation-inducing grit blasting to assure proper adhesive bonding is not necessary). Surface cleaning (without abrasion) is an industry standard for bonding to nickel-based alloys and is approved for repair of the panels by fabrication/repair specifications. It is preferable to use this material-type for the given repair application. It is essential for the case of plasma spraying that sufficient melting of particles occurs to achieve a satisfactory adhesive bond. In the case of high-velocity oxy-fuel (HVOF) thermal spray, there is sufficient velocity (supersonic) to yield excellent coating density and superior bonding to the substrate. The pre-spray substrate surface profile is far less demanding for the case of HVOF, which is a major advantage for the process, especially in the case of the honeycomb-backed Inconel® 718 sheet, the integrity of which may be compromised by the hot plasma spray torch.

However, it is important to note that through-holes present a more complex situation because they are virtually impossible to spray-fill. This is further complicated by the honeycomb structure that prevents access to the backside, and precludes the application of a backing over the hole that could serve as deposit surface. In contrast, shallow pits greater than several mils in diameter can likely be spray-sealed.

Aeronca Incorporated originally fabricated the honeycomb panels and specified plasma spray as an approved technique for in process repairs. A non-conformance review identified at least one panel that had been subjected to this repair technique for a local contour violation. A review of the Aeronca plasma spray procedure identified three limitations which prevented its direct application to the RH #4 conical seal panel. The conical seal panel pitting damage exceeded all of the dimensional limitations established for the in-process plasma spray restoration/repair including:

- Total area of the repair
- Maximum repair depth
- Minimum remaining thickness

It may be suitable for repairs beyond those constraints, particularly with regard to the total area of repair constraint. This aspect requires verification by process qualification based on performance requirements. As a minimum the verification should include those requirements used to qualify the original plasma spray. The project's approach to address these limitations was the fabrication of honeycomb test panels with drilled holes of various sizes to simulate the pits in a feasibility study of both thermal spray and welding/brazing techniques.

The project conducted both a welding/brazing test and a HVOF spray test and have noted preliminary results/observations. The welding test included 6 attempts at repair of through holes with gas tungsten arc welding (GTAW) – labeled as "TIG" in Fig. 12, micro plasma transfer arc (MPTA), and hydrogen torch techniques. The welds were executed by a qualified welder who has performed MPTA crack and pinhole repairs on the thin walled (0.008 inch) A286 coolant tubes of the Space Shuttle Main Engine (SSME) nozzle. The resulting welds are shown in Fig. 12. The project selected only MPTA welding/brazing for further consideration due to the level of technical maturity for similar Shuttle hardware and low heat input to the face sheet.

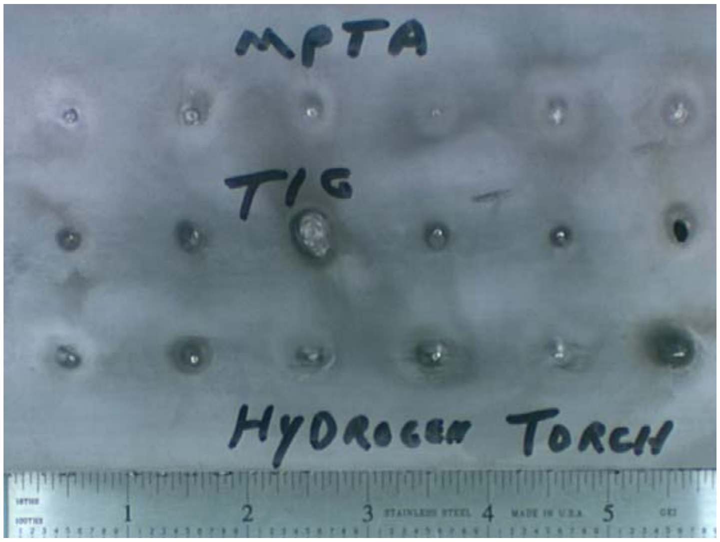


Figure 12. Conical seal welding test panel

The HVOF tests were completed with initial observations indicating the spray deposit maintained the contour and size of the simulated pits. The spray did not fill or bridge the holes, which remained the same size as before coating. Two conclusions may be drawn from the HVOF testing:

1. The HVOF process will deposit material into the pits and fill them at the same rate as material is deposited onto the surrounding surface. Sufficient thickness must be applied to fill the pits to a minimum depth. Thickness measurements before and after spray will verify the deposit thickness.
2. Penetrations through the panel thickness will have to be filled before, after, or instead of HVOF coating.

B. Alternate Repair Techniques

A survey was performed among various candidate deposition processes. The processes in the following matrix (Table 1) are the most favorable when considered as an alternate or accompaniment to plasma spray. The identified processes all have established technology maturity for aerospace applications. Processes shown are all believed to be applicable to the size and nature of the hardware as a means of filling pitting of various depths. They are not considered effective methods for repairing through holes in the face sheet, except in combination with welding or brazing to fill the penetrations.

Process	**Plasma Spraying**	**HVOF**	**Kinetic/Cold Spray**	**Two-Wire Electric Arc**	**Electro-spark Disposition**	**Laser/Powder Glazing Deposition**	**Plating**
Production of Depositing	Plasmas	Combustion	Cold Gas	Electric Arc	Electric Arc	Laser Melting	Solution
Deposition Rate	Very High	High	Low	High	Low to High	Medium	Low to Medium
Depositing Species	Splats/ Droplets	Spray/ Droplets	Solid Particles	Splats/ Droplets	Ions	Molten Droplets	Ionic
Complex Shaped	Good with robotics	Robotic Ready	Robotic Ready	Robotic Ready	Good	Good	Good
Blind Holes?	Very Limited	Limited	Limited	Very Limited	Limited	Possible	Poor
Metal/Alloy Deposition	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Refractory Compounds/ Ceramic	Yes	Limited	No	No	Limited	Yes	No
Energy of Deposit Species	Can be High	Very High	Extremely High	Medium to High	Can be High	Low	Low
Surface Finish	Poor As-sprayed	Good	Good	Poor	No	Medium	Good
Substrate Heating	Sometimes	Low	None	Yes	No	Controllable	Yes
Specifications	Use aircraft	Use aircraft	None	None	None	None-DOD Certified	Available
Local or Global Technique	Both/ For Fine Can Mask	Global/ Can Mask	Global/ Can Mask	Global	Local/Global	Local Generally	Global

Table 1. Comparison of alternate repair techniques

C. Repair Readiness Level

The importance of a correct repair to the OV-105 RSB Right Hand #4 conical seal panel cannot be over emphasized. There are no spare conical seal panels available and the manufacture of replacement units is expected to be prohibitive from an Orbiter retirement standpoint. Irreversible damage to this panel would require repetitive hardware removal from other Orbiters (cannibalization) for OV-105 flight. Each successive removal and replacement of the RSB components from vehicle to vehicle increases the potential of collateral damage. Additional attrition to the RSB conical seal fleet set would further aggravate the removal/replacement process.

It is anticipated the repair will be a unique or low frequency occurrence. The absence of direct acceptance documentation requires inference that the magnitude and frequency of the surface indications is not systemic to the remainder of the fleet RSB conical seal panels. Any future instances of conical seal panel face sheet damage will be structurally and thermally assessed and restored using the existing epoxy repair technique in low thermal exposure area or with the techniques developed for the OV-105 RH #4 conical seal panel.

The development of restoration technique(s) must provide a comprehensive consideration of variables associated with the test panels and the flight hardware. The vendor setup and geometry limitations must be compared to the conical seal panel size and number of surface indications. The development of a repair technique that is successfully demonstrated on a test coupon, but is not feasible on the actual hardware would not be productive. The following is a partial listing of parameters and considerations that should be evaluated during the development process:

- Surface preparation prior to repair and Pyromark coating application.
- Ability to bridge the face sheet penetrations.
- Post repair thermal treatments.
- Adhesion compatibility of the repair method with the Pyromark coating.
- Preservation of (structural and thermal) certification.
- Retention of configuration form, fit, and function.

Following completion of the development effort to identify repair method(s), a thorough review of data should be accomplished from a systems perspective. This would include an objective examination of the completed inspections, tests, and analyses with respect to the applicability to the flight hardware. All areas of data interpolation and extrapolation should be examined to ensure the development effort is sufficiently conservative or does not extend beyond the limits of sound engineering judgment. A critical aspect of this review is the generation of definitive success/rejection criteria. The predetermined identification of hardware acceptance metrics is invaluable in avoiding iterative repair attempts and the potential for exceeding the development parameters.

The final aspect of readiness process is adherence to NASA procedures by conveying the crucial development parameter requirements into applicable work instructions. All work associated with the planned repair will be documented in accordance with established Space Shuttle operating procedures and non-conformance reporting system. The thorough characterization of the repair development effort with respect to the flight hardware and proper translation of these requirements into clear and concise work instructions with defined acceptance/rejection criteria should maximize the success of the planned restoration process and minimize the risk of unforeseen anomalies and hardware attrition.

D. Repair Process Selection and Verification

The final, refined stress analysis showed eleven sites that required repair. These defects were pits, holes, or a combination in close proximity, and scattered across the panel. Global repair was deemed unnecessary and inappropriate for the identified defects. Repair process selection focused on to welding and brazing techniques to fill individual holes and pits with a suitable alloy, after which they would be ground flush with the surrounding face sheet.

Risks to the hardware were identified for each technique and its operations. These risks guided the selection and development of a process that would minimize them while providing the best chance of a successful initial repair. Risks include thermal distortion of the face sheet, incomplete or cracked fill of the defect, “burn through” or a melting through of the face sheet, melting the original braze, and “blow out” where gas trapped in a honeycomb cell by the repair would push through before the metal solidifies. Initial success was found to be critical for all candidate processes because during development, re-working of unsuccessful repairs rarely improved the final product, leaving a condition that was worse than the original defect.

Two processes were selected for preliminary evaluation on hardware (panels and honeycomb structures) with drilled holes that simulated defects on the conical seal panel: GTAW and MPTA, which is simply a smaller, lower power version of the more common plasma transferred arc process. MPTA was the preferred process, but because it deposits only powder filler alloys, GTAW was kept as an option for alloys that were only available in wire or rod forms. Alloy selection was based on those known to be compatible with Inconel® 718, with preference to those with experience and heritage.

Fifty MPTA simulated repairs were produced using BAu-4 alloy (82% gold – 18% nickel) powder on two nickel alloy X750 panels with no anomalies noted. Alloy X750 was used because it was the closest alloy composition to Inconel® 718 that was readily available in the same 0.010 inch thickness as the conical seal face sheet. The braze alloy has been demonstrated on the Inconel® 718 in manufacturing the nozzle jacket of the Space Shuttle Main Engine. Liquid metal embrittlement (LME) in Inconel® 718 weldments contaminated with gold base braze alloy is well known. Every effort was made to prevent overheating of the parent metal during these tests.

Seventeen (17) repairs were also produced honeycomb verification panels of Inconel® 718. Two of the repair attempts on the verification panel resulted in blow-outs at the repair site. The blow-outs caused holes up to 0.10 inches in diameter. Attempts to repair the blow-out areas resulted in heat affected zone (HAZ) and LME cracking of the 718 cover sheet. Metallography confirmed LME of 718 grain boundaries (Fig.13). After grinding six of the fifteen successful repairs flush to the panel surface, porosity was observed up to 0.008 inches in diameter within the braze deposits. The BAu-4 braze alloy was removed from further consideration because of the risk of LME cracking of the face sheet. Consequently, nickel-base braze alloys were evaluated to eliminate the cracking risk.

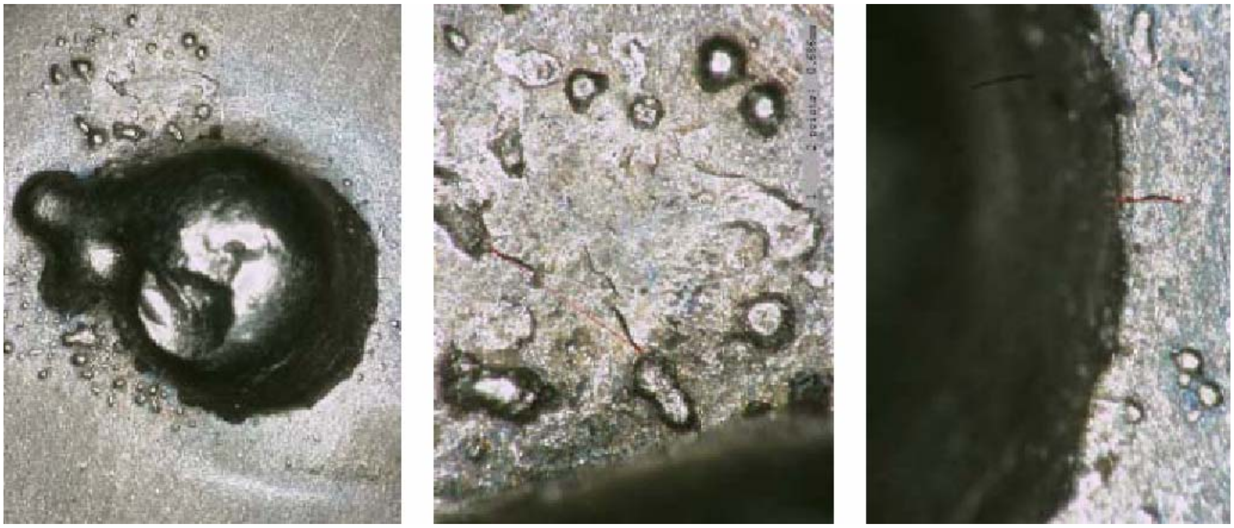


Figure 13. Photographs at increasing magnification from left to right showing an MPTA repair with BAu-4 braze, and LME cracking in the heat affected zone of the MPTA braze repair.

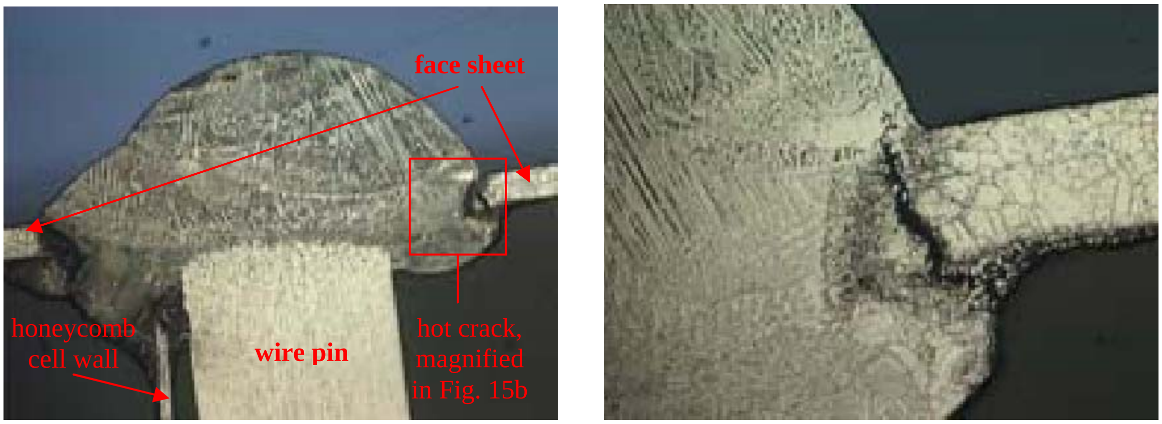
The first alloy identified was Hastelloy®-W, a nickel-base weld filler which was selected for this application because the original manufacturer specified it for various standard repairs during manufacture of the honeycomb panels. Because this alloy is generally produced only in wire form, standard GTA welding was used in place of MPTA. To minimize heat to the face sheet, an unusual technique was used to melt and flow the filler wire into the simulated defects of the Inconel® 718 honeycomb verification panels. A short (approximately 0.5 inch) piece of the wire or “pin” was cut and placed through a hole in the face, all the way into the honeycomb and resting on the opposite sheet. Wire diameters of 0.062 inch and 0.040 inch were evaluated.

The welder melted the end of the wire protruding through the hole in the face sheet to form a ball that dropped down as the wire was consumed, covering the hole. This reduced the amount of heat that had to be put into the face sheet compared to a more traditional welding technique. Figure 14 shows the top side of the completed repair and the condition of the unconsumed pin in the honeycomb core.


(a) (b)

Figure 14. (a) Macrograph showing top surface of a repair made using a Hastelloy®-W “pin”. (b) Unfused bottom of wire “pin” protruding into honeycomb cell

Figure 15 shows a cross section from one repair. Cracking was noted in most of the repairs. The defect observed was a hot crack caused by contamination of the weld pool by the preexisting nickel braze alloy that attaches the core structure to the top and bottom sheets. Given the disparity of the melting ranges between the nickel alloy and the Hastelloy®-W, no effective means to prevent the hot cracking could be found.



(a) (b)

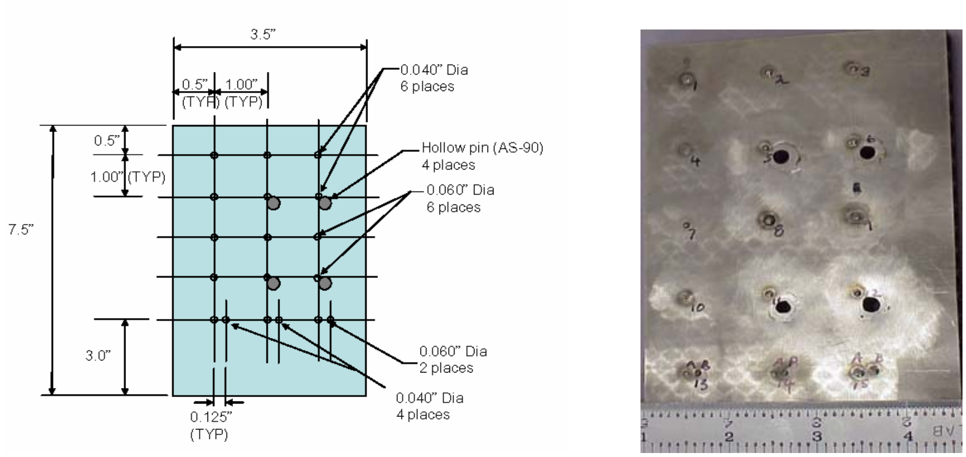
Figure 15. (a) Cross section of welded Hastelloy®-W pin repair. Note honeycomb cell wall just left of the unfused bottom of the wire “pin”. (b) Hot cracking caused by pre-existing nickel based braze alloy. Similar cracking was observed in all sections.

A review of potential nickel base braze alloys that would have better compatibility with the existing honeycomb braze alloy, and not produce LME in the Inconel® 718 face sheet, identified AMS 4777 nickel based alloy. Its melting temperature was in the same range as the original braze alloy. The overlap of the melting temperatures was expected to eliminate the hot cracking observed in the Hastelloy®-W repairs. Table 1 shows the compositions and melting ranges of both alloys.

Alloy	Melting Point	Composition
AMS 4777	1830 °F	82Ni – 7.0Cr – 4.5Si – 3.1B – 3.0Fe
Hastelloy®-W	2510 °F	63Ni – 24Mo – 6.0Fe – 5.0Cr – 2.5Co(max) – 1.0Si(max) – 0.6V(max)

Table 1. Melting temperature and composition of two candidate repair alloys

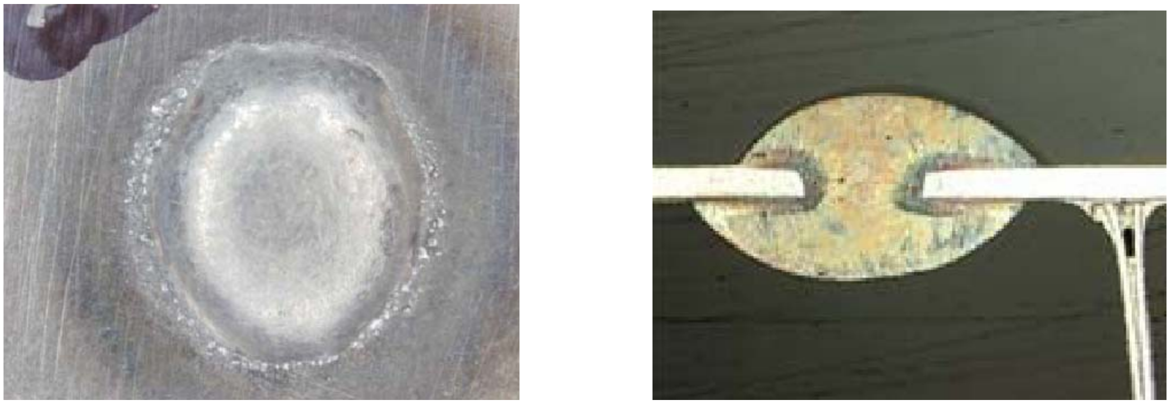
Honeycomb verification panels were prepared by drilling 0.040 and 0.060 inch diameter holes in the top and bottom face sheets. The configuration of the honeycomb verification test panel is shown in Fig. 16a. The drilled and repaired panel is displayed in Fig. 16b. The holes were repaired using the AMS 4777 alloy with the MPTA process, similar to that used with the BAu-4 previously. A typical deposit is shown in Fig. 17. Test deposits were free from the type of hot cracking observed in the Hastelloy®-W repairs.



(a) (b)

Figure 16. **(a) Configuration of verification test sample. (b) Completed verification sample**

A more detailed metallographic analysis was also performed on all repair locations in the as-welded condition. Several internal defects were revealed by metallography that would have been found after grinding the deposits flush to the panel surface. Based on these results, it was decided to make additional samples that would be completed through flushing prior to metallography. Any defects visually detected after grinding would be repaired and the location re-ground. A sample containing 24 repairs was used to develop grinding and repair techniques. Grinding was accomplished using stone bits and a hand "mini-grinder". A repair technique was developed and demonstrated on the sample. The procedure required grinding of a new through hole to remove the defect, followed by re-fill with the standard MPTA process.



(a) (b)

Figure 17. **(a) Typical MPTA repair using AMS 4777 braze alloy. (b) Micrograph of a typical cross section of MPTA braze repair.**

E. Hardware Repair

On March 2, 2006 the Space Shuttle speed brake conical seal panel was repaired at the Pratt & Whitney Rocketdyne manufacturing facility in Canoga Park, CA. Prior to shipment to Pratt & Whitney, the eleven defects requiring repair on RH #4 were marked and prepared. Ten of the pitting locations were drilled before repair to remove debris in the defect and to provide a repair geometry consistent with that in the development samples. Drilled diameters of 0.040 inch were obtained in order to match the smaller holes repaired during the repair development effort. No pre-repair preparation was performed on the eleventh location, which was the site of a pre-existing repair made during original fabrication of RH #4. The repairs were performed using the MPTA process and AMS 4777 nickel base braze alloy filler using the procedures described previously.

Ten holes were successfully repaired in a single attempt with no problem or rework. One repair attempt was made on a “lack-of-fusion” defect (unrelated to the pitting) near a pre-existing repair made during initial fabrication. That repair was not completed due to lifting of the face sheet resulting from heating during the arc braze operation. Details and final disposition of this repair are available in NASA documents currently in work.

Eleven defects were marked and prepared prior to shipment to Pratt & Whitney Rocketdyne. Ten of the pitting locations were drilled just as the development and verification samples. The pits and holes were drilled before repair to remove debris in the pit and present a repair geometry consistent with the development samples.

To verify the repair process on RH #4, a brazed honeycomb panel was used as a process control sample and was prepared in parallel by drilling a series of 0.040 inch diameter holes in the Inconel® 718 face sheet. Six locations were repaired using the same MPTA process and AMS 4777 alloy filler as RH #4. The completed welds were visually inspected with magnifications up to 30x. No cracking in the deposit or heat affected zones was noted. The six deposits were manually ground flush to the face sheet surface and were re-inspected at the same magnifications. Based on the visual inspection, all deposits appeared sound and free of rejectable defects. The six deposits were then sectioned, cold mounted, polished and etched for metallographic inspection. Figure 18 shows a typical deposit.

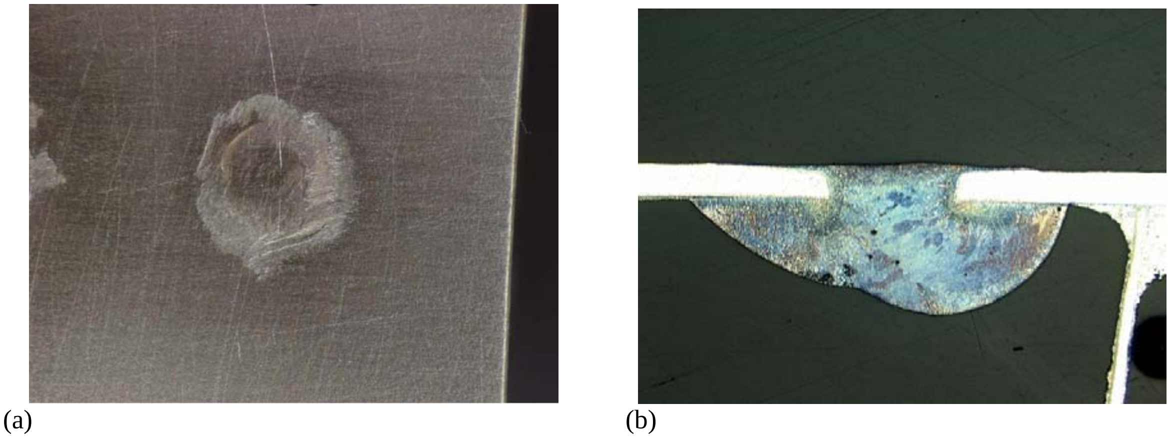

(a) (b)

Figure 18. (a) Macrograph showing a typical repair location on the in-process weld sample. Repair has been manually flushed after welding. (b) Micrograph of typical cross section of a flushed repair.

After metallographic examination each sample was re-etched with an electrolytic process using 10% oxalic acid, Fig 19. This procedure causes fully aged Inconel® 718 to stain while annealed areas remain shiny and unstained. The edge to edge distance observed on the etched samples was used to determine the diameter of the fusion and HAZ zones. The maximum allowable combined fusion and HAZ diameter is 0.187 inch, according to the repair work authorization. Figure 19 shows a repair cross section after oxalic acid etching.

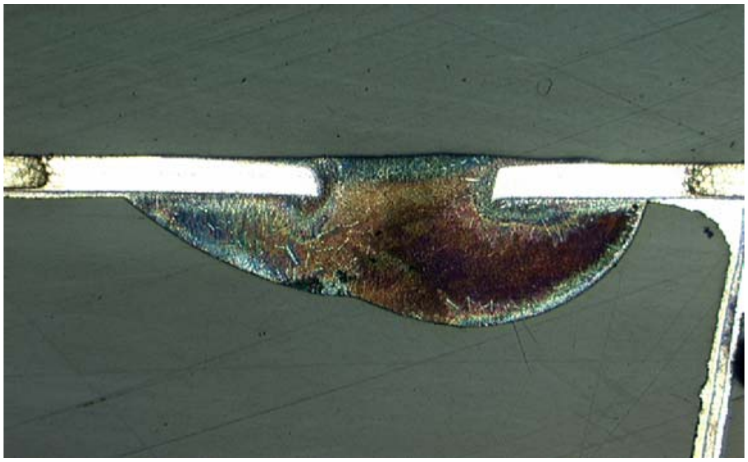


Figure 19. Typical repair (same section as in Fig. 18b previously) after electrolytic etch with 10% oxalic acid. The area of Inconel® 718 face sheet not stained was annealed by the MPTA process. Such micrographs were used to measure the fusion zone and heat affected zone, which are required to be under a specified size.

Sample Number	Fusion Zone & HAZ Diameter (in)	Max Pore Diameter (in)	Cracks	Lack of Fusion
1	0.144	0.001	none	none
2	0.165	None	none	none
3	0.153	0.001	none	none
4	0.148	0.001	none	none
5	0.116	0.001	none	none
6	0.125	0.0014	none	none

Table 2. Summary of metallographic measurements and observations for process control sample repairs.

Table 2 lists the combined fusion/HAZ sizes for each repair as well as any defects noted in the repair. These data indicate that the process control samples met the requirements of the repair procedure.

IX. Conclusions

The OV-105 conical seal panel RH #4 was successfully repaired and returned to service. The success of the repairs is due in large part to the thorough screening of available methods and materials, followed by detailed process verification. Structural analysis shows the parts are suitable for flight, and the remaining pits do not pose a risk to the hardware. The repair process was affected by the existing braze used to fabricate the honeycomb panel, heat input from the torch, and metallurgical interaction between the Inconel® 718 face sheet and the braze alloy used for repair. This compatibility problem exists despite the fact that the same braze alloy was used on the Inconel® 718 nozzle jacket of the SSME, although it was applied by different means (furnace rather than torch braze). Root and proximate cause(s) of the pitting have not been definitively identified, although a list of specific recommendations for completing the proximate and root cause analysis was provided to the project. The depth and extent of pitting that occurred on the OV-105 conical seal panel RH #4 is unique among the conical seal panels in the Space Shuttle fleet. Based on available evidence, the cause is likely a synergistic events chain that includes pitting corrosion and/or material/processing issues in conjunction with inadequate Pyromark coating coverage. Continued study of the mechanism is warranted for this application, and for the wider use of Inconel® 718 because of its perceived resistance to corrosion.

Acknowledgments

The authors gratefully acknowledge the efforts of Mr. Steve Leonard (Pratt & Whitney Rocketdyne) for developing the methods and parameters used for the arc braze repairs, and for skillfully effecting repair of the OV-105 RH #4 conical seal repairs, and Mr. Art Turner (Pratt & Whitney Rocketdyne) for adeptly preparing the development samples and performing the post weld flushing operation of the conical seal repairs. Mr. Bill Smith (Pratt & Whitney Rocketdyne) is recognized for the expeditious metallographic preparation and examinations of the development and verification samples that appear in this paper.

List of Acronyms

CS	Cold Spray
ESD	Electro-Spark Deposition
FMEA	Failure Modes and Effect Analyses
GRC	Glenn Research Center
GTAW	Gas Tungsten Arc Weld
HVOF	High Velocity Oxy-Fuel Thermal Spray
ICP	Inductively Coupled Plasma
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
LISI	Laser Induced Surface Improvement
LOV	Loss of Vehicle
MPTA	Micro Plasma Transfer Arc
MRB	Material Review Board
MSFC	Marshall Space Flight Center
MTSO	Management Technical Support Office
NASA	National Aeronautics and Space Administration
NASTRAN	NASA Structural Analysis System
NDE	NESC Discipline Expert
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
NSE	NASA Subsystem Engineer
NSLD	NASA Shuttle Logistics Depot
OMS	Orbital Maneuvering System
OPO	Orbiter Project Office
PAR	Problem Action Report
PRACA	Problem Reporting and Corrective Action
PRT	Problem Resolution Team
PTR	Performance Test Review
SSME	Space Shuttle Main Engine
USA	United Space Alliance
XRF	X-ray Fluorescence

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