Application of Fiber-Reinforced Bismaleimide Materials to Aircraft Nacelle Structures

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ABSTRACT

Existing aircraft engine nacelle structures employ advanced composite materials to reduce weight and thereby increase overall performance. Use of advanced composite materials on existing aircraft nacelle structures includes fiber-reinforced epoxy structures and has typically been limited to regions furthest away from the hot engine core. Portions of the nacelle structure that are closer to the engine require materials with a higher temperature capability. In these portions, existing nacelle structures employ aluminum sandwich construction and skin/stringer construction. The aluminum structure is composed of many detail parts and assemblies and is usually protected by some form of ablative, insulator, or metallic thermal shield.

A one-piece composite inner cowl for a new-generation engine nacelle structure has been designed using fiber-reinforced bismaleimide (BMI) materials and honeycomb core in a sandwich construction. The composite structure is 9 feet in length and 10 feet wide in cross section. The new composite design has many advantages over the existing aluminum structure. Multiple details have been integrated into the one-piece composite design, thereby significantly reducing the number of detail parts and fasteners. The use of lightweight materials and the reduction of the number of joints result in a significant weight reduction over the aluminum design; manufacturing labor and the overall number of tools required have also been reduced.

Several significant technical issues were addressed in the development of a BMI composite design. Technical evaluation of the available BMI systems led to the selection of a toughened BMI material which was resistant to microcracking under thermal cyclic loading and enhanced the damage tolerance of the structure. Technical evaluation of the degradation of BMI materials in contact with aluminum and other metals validated methods for isolation of the various materials. Graphite-reinforced BMI in contact with aluminum and some steels was found to degrade in salt spray testing. Isolation techniques such as those used for graphite-reinforced epoxy structures were shown to provide adequate protection.

The springback and producibility of large BMI structures were evaluated by manufacturing prototype hardware which had the full-scale cross section of the one-piece composite structure. A female tooling approach was adopted to control critical aerodynamic surface tolerances. Composite tooling and laminate design were successfully combined to minimize springback.

INTRODUCTION

Existing aircraft engine nacelle structures employ advanced composite materials to reduce weight and thereby increase overall performance. Use of advanced composite materials on existing aircraft nacelle structures includes fiber-reinforced epoxy structures and has typically been limited to regions furthest away from the hot engine core. Portions of the nacelle structure that are closer to the engine require materials with a higher temperature capability. In these portions, existing nacelle structures employ aluminum sandwich construction and aluminum skin/stringer construction. The aluminum structure is composed of many detail parts and assemblies and is usually protected by some form of ablative, insulator, or metallic thermal shield.

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The usage of advanced composite materials in aircraft nacelle structures, specifically the engine thrust reverser, is illustrated in Figure 1. The thrust reverser has two concentric cowls which together form the fan duct flowpath. The outer cowl or translating cowl moves aft during landing and deploys the blocker doors which reverse the fan duct flow. The resulting reverse thrust helps to slow the aircraft. Since the translating cowl is in a region furthest away from the hot engine core, many translating cowls in service today are constructed of fiber-reinforced epoxy.

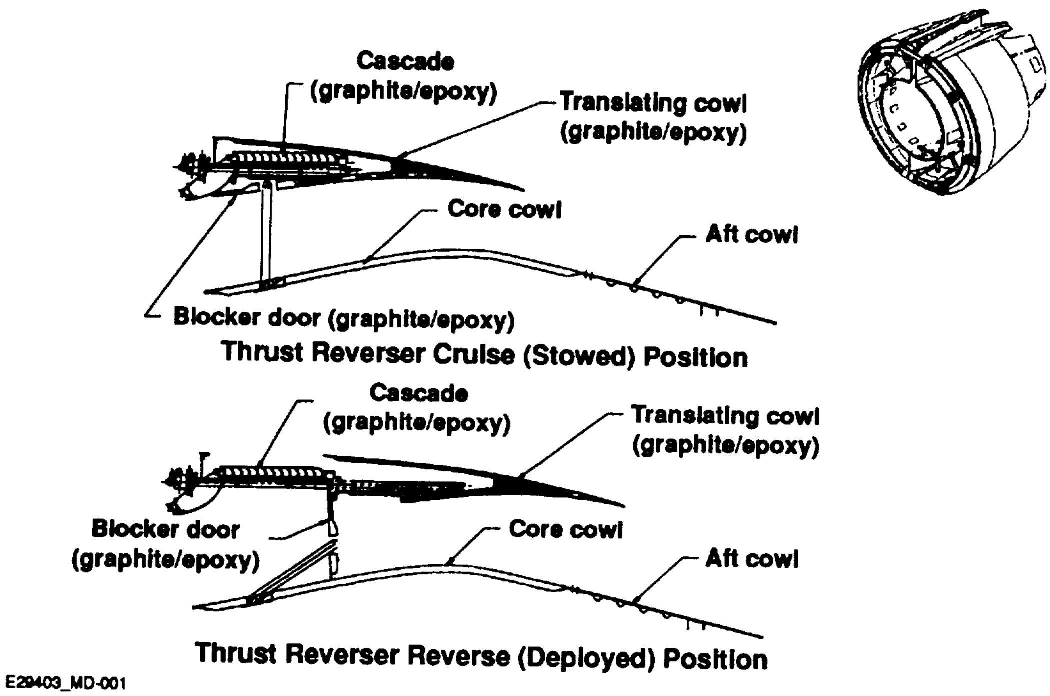

Figure 1. Existing use of composite materials in nacelle structure

The inner cowl of the thrust reverser, however, is stationary and surrounds the hot engine core. The inner cowl provides the primary attachments of the thrust reverser to the engine, access to engine components through a series of access doors, and inlets for airflow for various engine or aircraft systems. The reverser is attached to the engine pylon at the hinge beam at the upper edges of the inner cowl. The two reverser halves are latched together at the latch beam, which is attached to the lower edges of the inner cowl. The reverser is also attached at its forward and aft ends to the engine.

Many of the inner cowls in service today consist of a core cowl, upper and lower bifurcations, and an aft cowl, as shown in Figure 2. The core cowl and bifurcations are assembled into one subassembly and the aft cowl is another. Several recent designs in service have incorporated the core cowl and bifurcations into one integral metallic structure. Various fairings and inlets are subsequently attached to the inner cowl. These assembly operations involve many detail parts and a significant number of fasteners. Therefore, during the last decade, work has focused on the use of advanced composite materials for portions of the inner cowl. Composite structures utilizing high-temperature materials such as bismaleimides and polyimides have been considered [1,2]. Development efforts on a one-piece composite inner cowl were started by Martin Marietta Aero & Naval Systems in 1985. Continuation of the effort into detail design, certification, and production of the one-piece composite inner cowl has been funded by Pratt & Whitney since 1990.

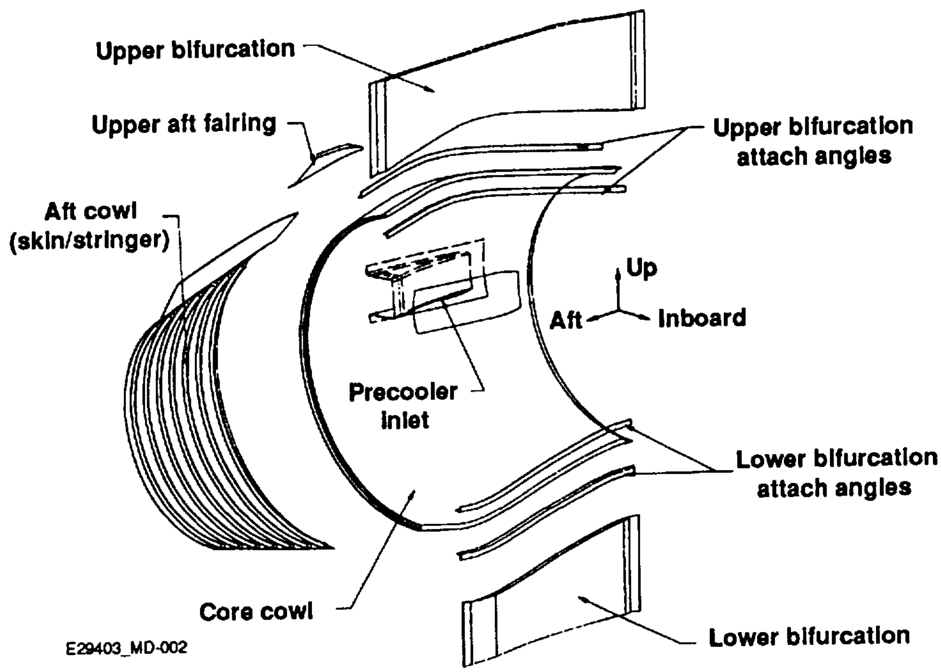

Figure 2. Present aluminum inner cowl design

The inner cowl, or fixed-structure bondment, of a new-generation engine nacelle structure features a composite sandwich construction with fiber-reinforced bismaleimide (BMI) skin materials and honeycomb core. The design employing composite materials has several advantages over the existing aluminum structure, including lower weight and fewer parts. Several significant technical issues were resolved in the development of a BMI composite design. These issues include microcracking of BMI laminates due to thermal cyclic loading, degradation of BMI laminates in contact with or in close proximity to aluminum and other metals, and springback of a large composite structure due to its cure cycle. The design, materials selection, and manufacture of the BMI one-piece inner cowl are discussed in the following sections.

DESIGN

The one-piece composite inner cowl design, shown in Figure 3, is approximately 9 feet in length and 10 feet wide in cross section. The design integrates many of the individual components of the present inner cowls into one structure. Initial trade studies focused on integration of the core cowl, upper bifurcation, and lower bifurcation. As the trade studies proceeded, the inner cowl was extended to include the aft cowl as well as the upper aft fairing. The final design incorporated the turbine case cooling inlet as well as the precooler inlet and associated reinforcing structure.

The one-piece composite design significantly reduces the number of detail parts and the number of fasteners compared to the aluminum design. The use of lightweight materials, the ability to tailor laminate construction, and the reduction of the number of joints results in a considerable weight reduction. Trade studies show that the BMI inner cowl design is 30 to 35 pounds lighter than the aluminum design.

The one-piece inner cowl design also has manufacturing advantages over the aluminum design. The reduced number of detail parts and joints and fasteners results in reduced manufacturing labor for the inner cowl. Many manufacturing operations are consolidated into one operation by the transfer of the majority of the manufacturing to a traditionally more efficient area of production in the bonding facility. In addition, the overall number of tools required is reduced significantly.

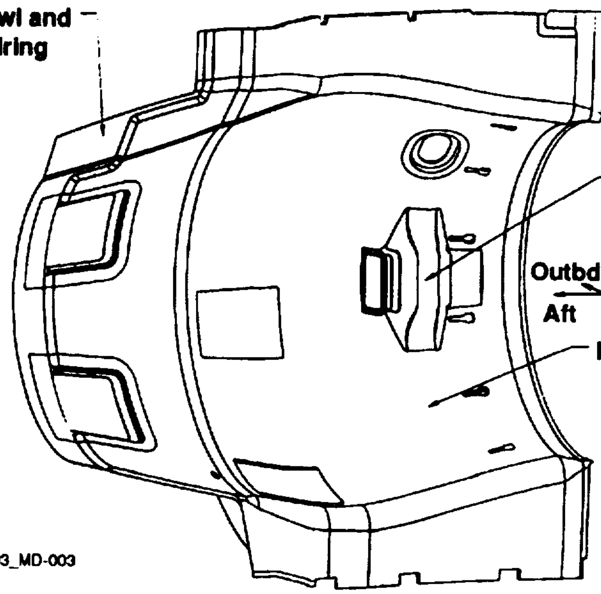

Figure 3. One-piece composite inner cowl

The longitudinal cross section of the BMI inner cowl is shown in Figure 4. The inner cowl consists of a precured outer skin, local precured reinforcing doublers, honeycomb core, and a precured inner skin. Because the forward section of the inner cowl is part of the sound-suppression system for the engine, this portion has a perforated BMI outer skin. Since the aft portion of the inner cowl is beyond the fan duct where no sound suppression is required, this portion has a solid BMI outer skin. Local BMI doublers are employed to reinforce cutouts and attachments. These doublers fit into recessed areas of the core.

Figure 4. Longitudinal cross section of one-piece composite inner cowl

The solid inner skin is continuous over the full length of the inner cowl and incorporates edge closeouts. The skin is tailored to minimize weight while meeting the load requirements. Hence, local integral doublers are precured as part of the inner skin. These doublers are placed on the inner surface of the inner skin, thereby eliminating the need for recesses for doublers in the core. As a result, the core has a smooth surface for improved fitup of the core to the skin. Finally, the inner cowl is protected by a reinforced silicon thermal insulator sprayed onto its inner surface.

A typical circumferential cross section is shown in Figure 5. The inner cowl is continuous from the upper bifurcation to the lower bifurcation. At the bifurcation-to-core cowl joint is a 3-inch radius with local doublers for reinforcement. The integral precooler inlet, also shown in Figure 5, provides an effective circumferential load path across the large precooler cutout, which for previous designs has required significant reinforcing structure. Both the core cowl-to-bifurcation joint and the integral precooler inlet result in weight reduction.

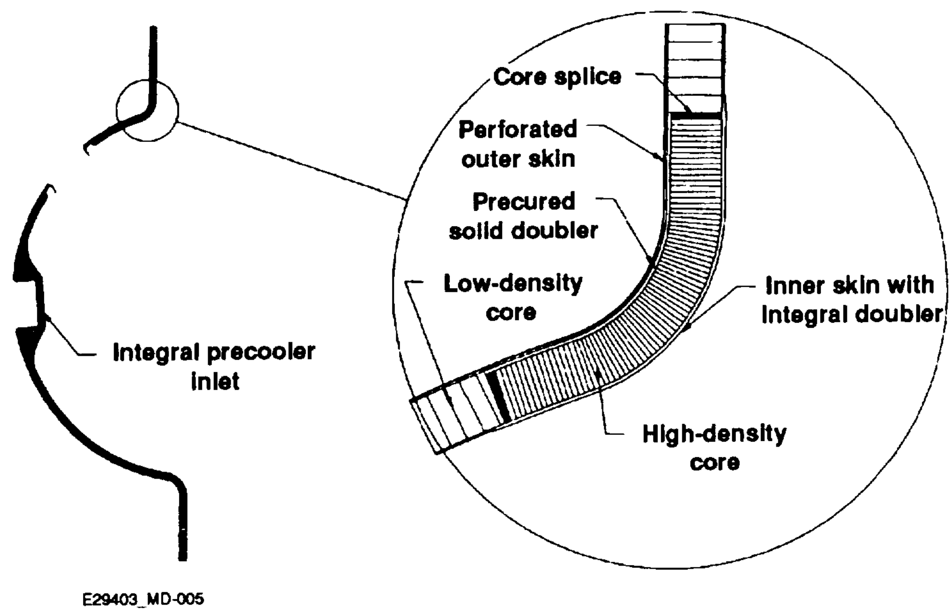

Figure 5. Circumferential cross section of one-piece composite inner cowl

Controlling the temperature of the inner skin below the design limit of 350° F proved to be a key technical issue and was highly dependent on the choice of honeycomb core material. Various honeycomb core materials were considered, including glass/polyimide, glass/phenolic, and aluminum. Figure 6 shows the temperature profile versus engine station for the aluminum and glass/polyimide cores. The glass-reinforced core materials have low thermal conductivity, resulting in inner skin temperatures above the design limits. Significant weight penalties are projected for the glass-reinforced core design due to the need for increased thermal protection. The aluminum core, which has the best conductivity, results in the lowest inner skin temperatures. Graphite-reinforced polyimide core resulted in inner skin temperatures slightly higher than those for the aluminum core design. A comparison of the cost of the various core options showed that the glass and graphite-reinforced core options were considerably more expensive than the aluminum core design.

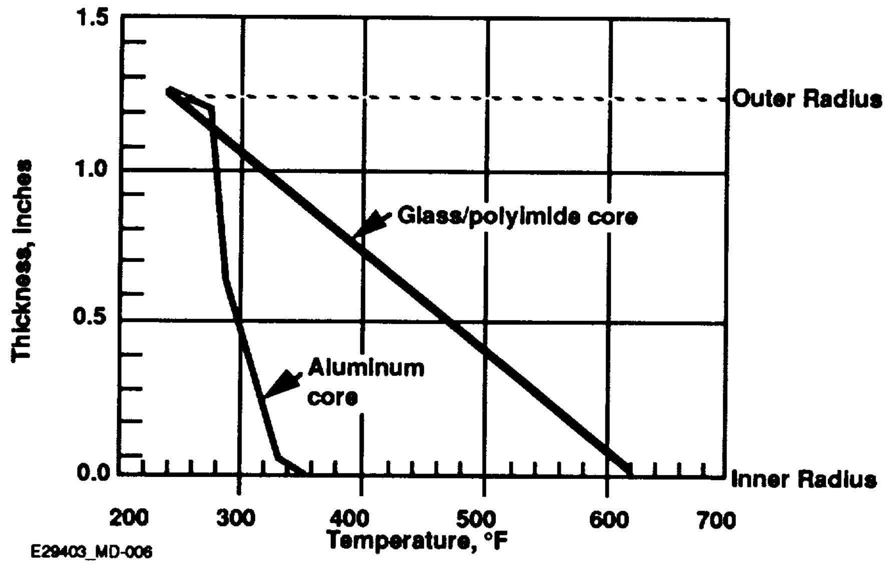

Figure 6. Effect of core material on temperature distribution

Corrosion protection of the inner cowl materials is another key technical issue. Moisture ingress is possible in some areas of the inner cowl due to the perforated outer skin. Both corrosion of the aluminum core and degradation of the graphite/BMI laminates were addressed. Figure 7 shows the typical isolation techniques for the inner cowl. Aluminum core is isolated from both the inner and outer graphite/BMI skins by a glass/BMI isolation layer. A glass/BMI layer is also placed on the outer surface of the perforated skin to isolate it from the stainless steel screen required for sound suppression. In addition, the aluminum core is treated with a protective coating to enhance its corrosion resistance.

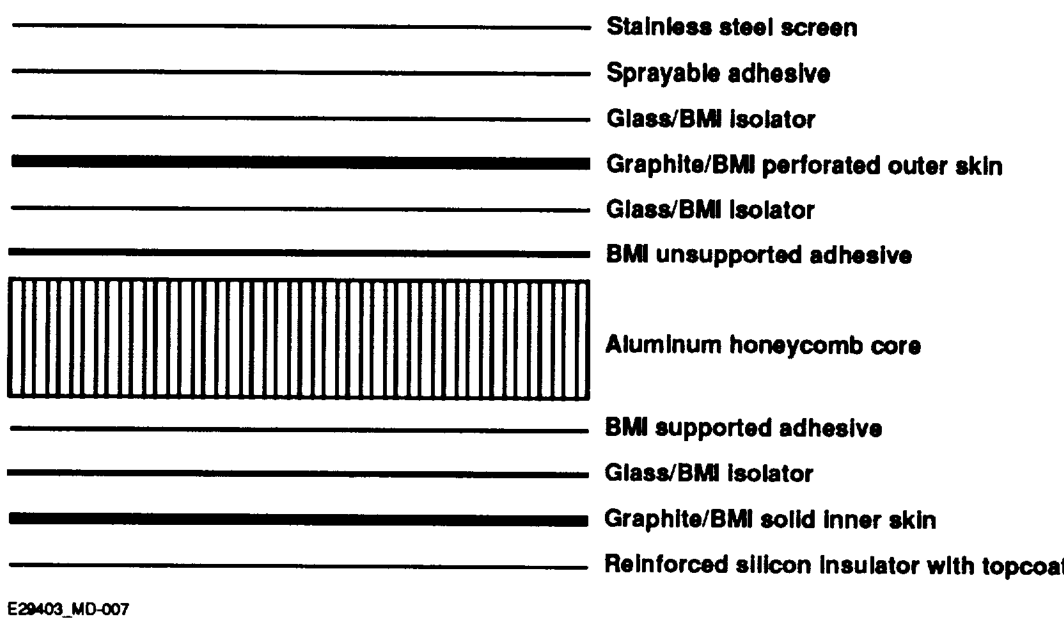

Figure 7. Isolation of aluminum core and steel screen

Attachments to the inner cowl are also designed with corrosion protection in mind. A typical attachment to the inner cowl is shown in Figure 8. Glass/BMI layers are placed locally on the BMI skins to isolate them from aluminum attachment hardware, and titanium inserts are used to further prevent BMI degradation. Titanium fasteners are used for attachments in areas of the inner cowl which consist only of laminate.

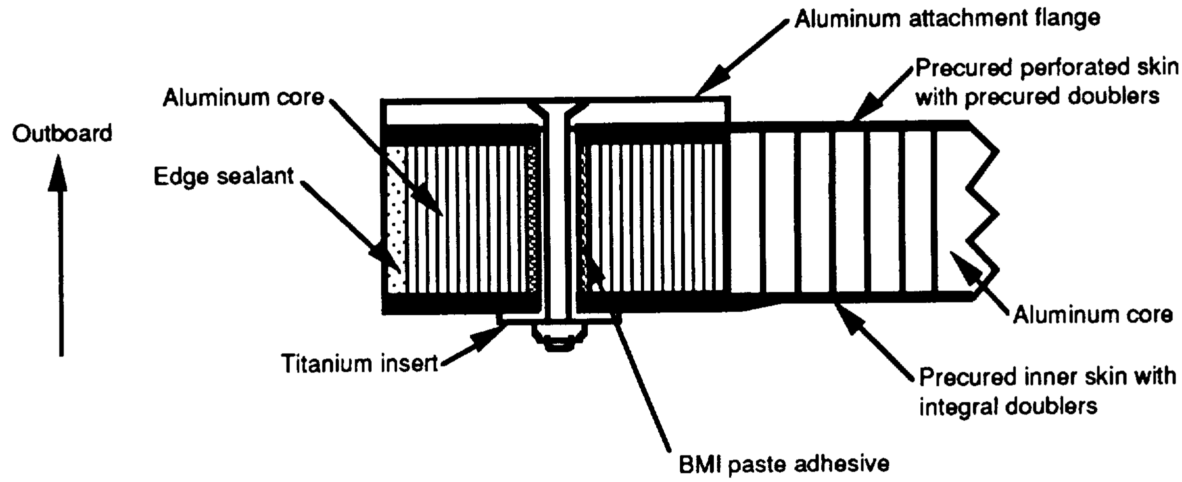

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Figure 8. Insert design for composite inner cowl

MATERIALS

Several technical material issues had to be addressed to incorporate the fiber-reinforced BMI materials in conjunction with aluminum core into the composite inner cowl design. Major issues, as previously stated, included BMI microcraking, BMI degradation, and aluminum core corrosion.

BMI Microcracking

First-generation BMI systems, toughened BMI systems, and high-temperature epoxies were evaluated for laminate mechanical properties after thermal cycling and for laminate microcracking as a function of thermal cycling and isothermal aging. A thermal cyclic profile, shown in Figure 9, was developed to represent the thermal loading of the inner cowl. It includes cycles from -67° F to 375° F and from 11° F to 375° F with heatup rates of 20 degrees per minute, typical of the engine thrust reverser. The laminate used was a mix of fabric (f) and unidirectional tape (t), $[90_f,90_t,45_f,-45_f,90_t,90_f,90_t,-45_f,45_f,90_t,90_f]$. Panels with this laminate construction were fabricated and inspected. Specimens were prepared and exposed up to 1000 thermal cycles. The first-generation BMI and the epoxy systems exhibited an increase of microcracking as a function of thermal cycles while the toughened BMI systems essentially showed no evidence of microcracking.

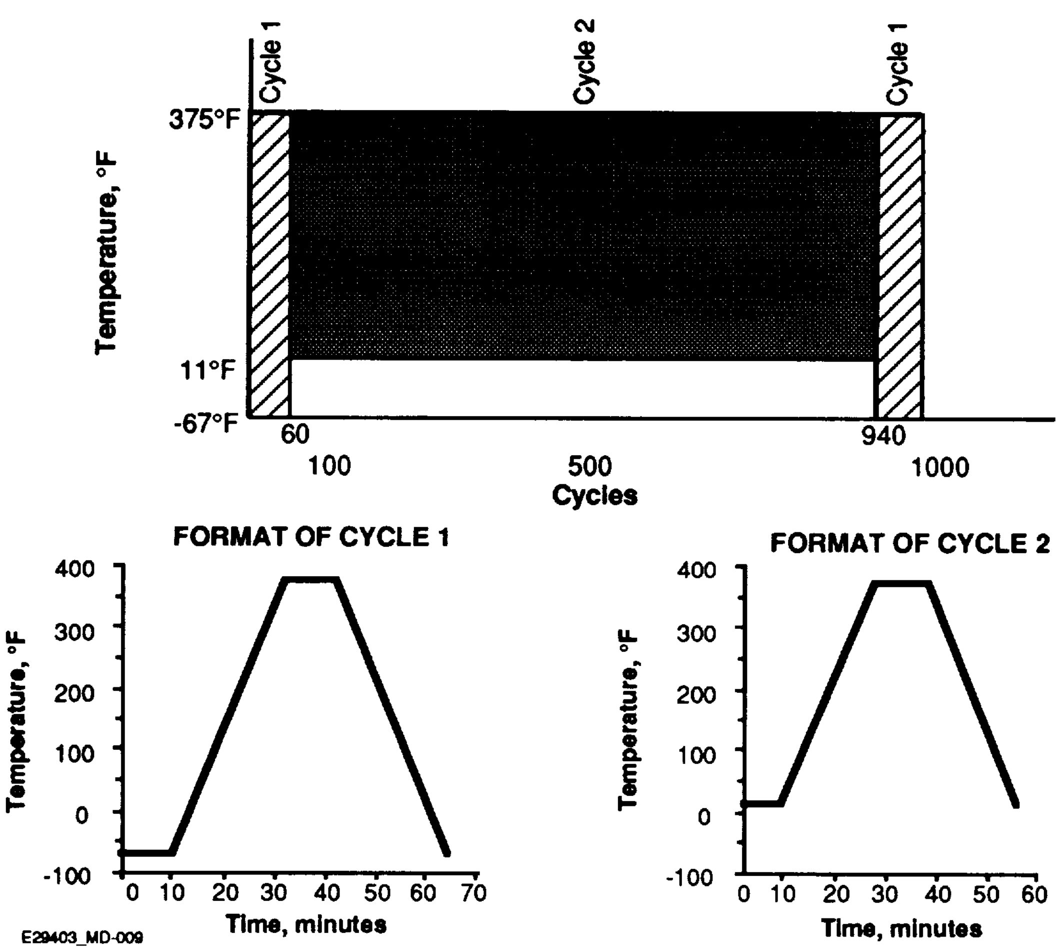


Figure 9. Thermal cycle profile for microcracking evaluation

In addition to the visual examination for microcracks, the residual compressive and interlaminar shear strength of the laminate after thermal cycling was measured. The specimens were tested at 350° F after 240 hours exposure at 160° F and 97 percent relative humidity. Compressive testing was performed using an IITRI (Illinois Institute of Technology Research Institute) fixture in accordance with the ASTM for Compressive Properties of Unidirectional or Cross-Ply Fiber-Resin Composites (D3410-82). Interlaminar shear testing was performed in accordance with the ASTM for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short Beam Methods (D2344-84). Test results showed approximately a 10 percent drop in strength after 1000 thermal cycles. Isothermal aging of specimens with the laminate construction discussed above was also performed. Specimens exposed to 375° F for 800 hours showed no evidence of microcracking.

In addition, the performance of the perforated BMI outer skin was evaluated. Testing focused on the perforated skin because of the potential for the increased surface area to cause increased microcracking. Isothermal aging tests were performed to study the effect of temperature and the effect of perforations on the BMI outer skin; however, the design temperature for the perforated outer skin was only 300° F. Solid and perforated laminate specimens with a $[(90)_4]$ laminate construction, the downselected configuration, were fabricated and inspected and isothermally aged at 300° F. Solid laminates were also isothermally aged at 350° F. The results of weight loss measurements are shown in Figure 10. Weight loss was less than 1 percent after 1500 hours at 300° F for both the solid and perforated laminates.

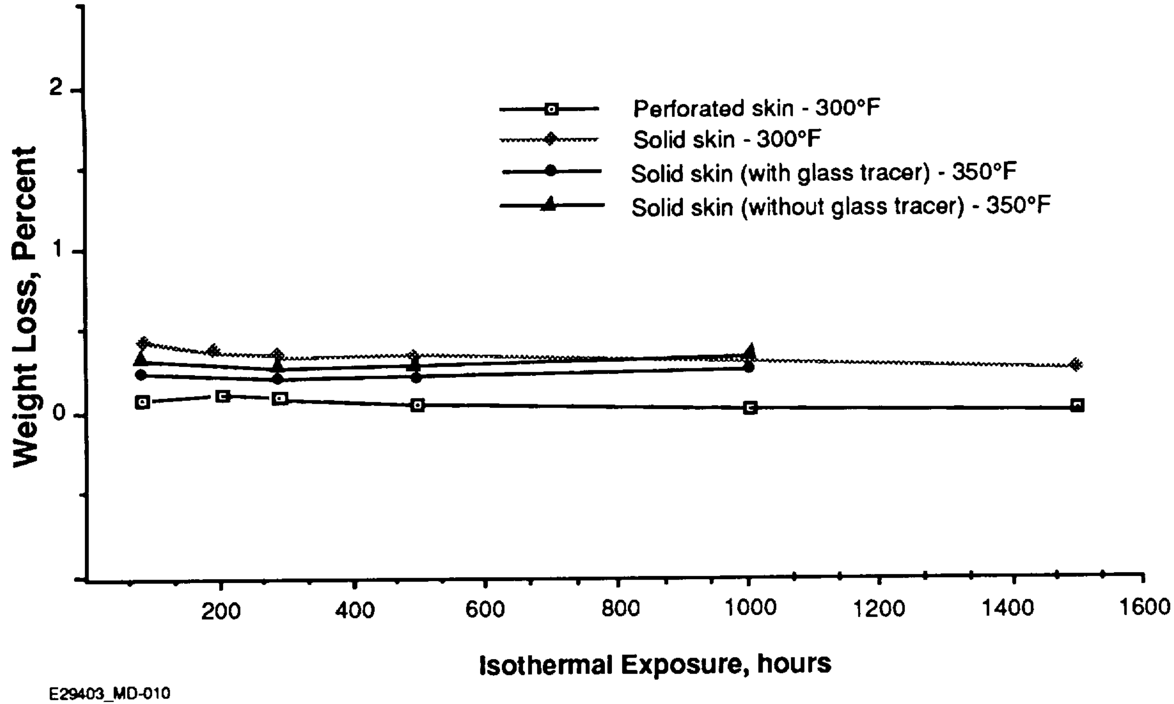


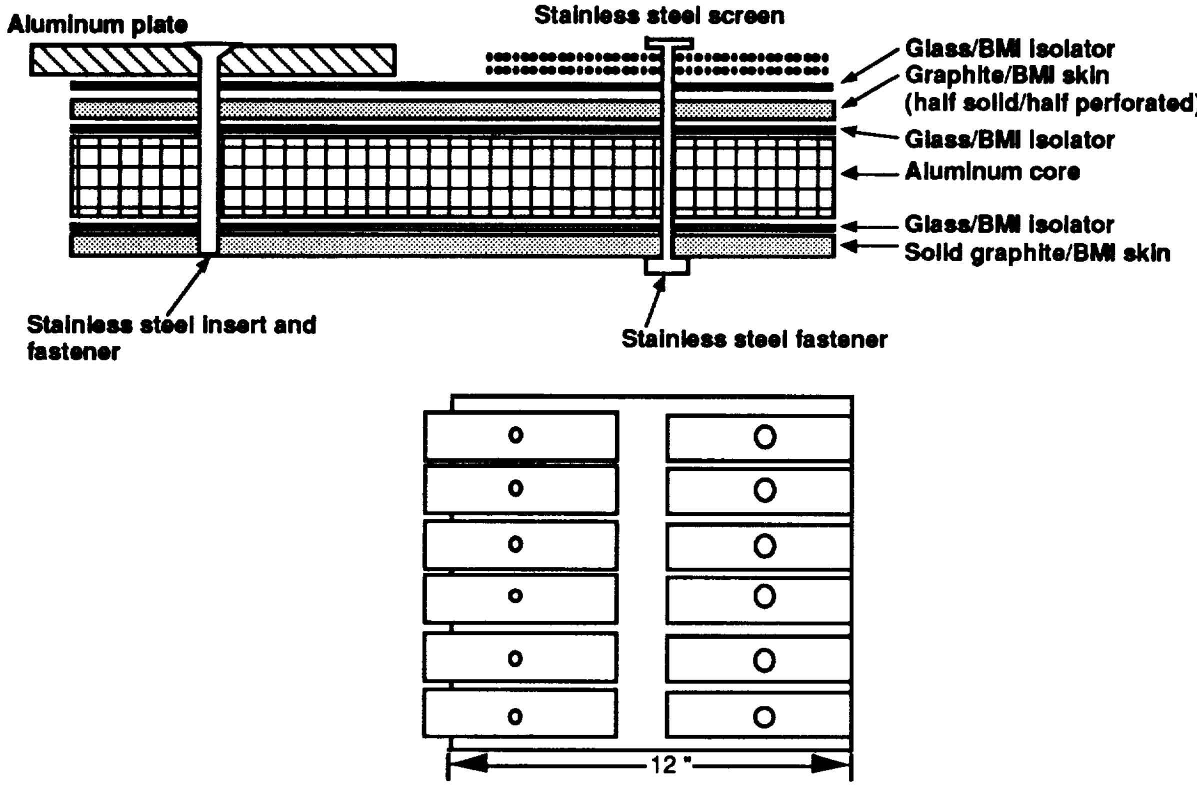
Figure 10. Weight loss results for BMI microcracking evaluation

A toughened BMI material was selected for the composite inner cowl based on these results. Besides its higher resistance to microcracking under thermal cyclic loading and isothermal aging, the toughened BMI material produces an improved damage-tolerant structure.

BMI Degradation

Recent studies have shown that graphite/BMI laminates can degrade when in contact with aluminum and various other metals under certain conditions. The degradation is caused by hydrolysis of imides by hydroxide ions [3]. The phenomenon will not be described further; rather, it is evaluated and suitable methods to prevent it are presented. This effort was performed in two parts. The first part was performed by exposing laminates to an electrolyte solution (salt water) while in contact with various other materials. Graphite-reinforced BMI laminates degraded when coupled with aluminum and some steels, but no degradation was observed in laminates in contact with titanium and glass-reinforced BMI materials.

The second part of the evaluation was performed using panels representative of the inner cowl and its attachments. These sandwich construction panels, shown in Figure 11, were salt spray tested in accordance with the ASTM for Salt Spray (Fog) Testing (B117-85). These sandwich construction panels had perforated BMI outer skins and solid BMI inner skins. Aluminum core was evaluated with and without glass/BMI isolation layers. All panels had a steel screen bonded to the perforated skin and an aluminum plate attachment. However, none of the panels had the insert design which is incorporated in the final design. Instead, fasteners were installed directly through the core, representing a conservative test scenario.



Test Panel Type	Hinge Plate Type - Isolator	Fastener Installation	Core Isolator	Screen Isolator	BMI Type
I	Bare No	Dry	No	No	First Generation
II	Anodized Yes	Wet	Yes	Yes	First Generation
III	Anodized Yes	Wet	Yes	Yes	Toughened

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Figure 11. BMI degradation sandwich panel configuration

The results of the salt spray tests up to 2000 hours are shown in Figure 12. The BMI laminates in the panels without isolation degraded. In contrast, results for the isolated panels showed that isolation techniques such as those used for graphite-reinforced epoxy structures protect adequately against BMI degradation.

TEST PANEL TYPE	EXPOSURE TIME			
	150 HOURS, NOMINAL	500 HOURS, NOMINAL	1000 HOURS, NOMINAL	2000 HOURS, NOMINAL
WITHOUT ISOLATOR	MODERATE DEGRADATION BETWEEN ALUMINUM AND STAINLESS STEEL AND ON BACK OF BOTTOM SKIN	SEVERE DEGRADATION BETWEEN ALUMINUM AND STAINLESS STEEL AND ON BACK OF BOTTOM SKIN	SEVERE DEGRADATION ON ALL EXPOSED SURFACES	SEVERE DEGRADATION ON ALL EXPOSED SURFACES
WITH ISOLATOR	NO BMI DEGRADATION	NO BMI DEGRADATION	NO DEGRADATION ON PROTECTED SKIN, SLIGHT ON UNPROTECTED BACK OF BOTTOM SKIN	NO DEGRADATION ON PROTECTED SKIN, MODERATE ON UNPROTECTED BACK OF BOTTOM SKIN
WITH ISOLATOR AND TOUGHENED BMI	NO BMI DEGRADATION	NO BMI DEGRADATION	NO BMI DEGRADATION	NO DEGRADATION ON PROTECTED SKIN, MODERATE ON UNPROTECTED BACK OF BOTTOM SKIN

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Figure 12. Graphite/BMI degradation tests results

Aluminum Core Corrosion

Methods to enhance the corrosion resistance of aluminum core were investigated. As discussed previously, aluminum core was selected for the composite inner cowl due to its favorable thermal properties, in addition to weight and cost considerations. Aluminum core has been successfully used in the aircraft industry with graphite/epoxy solid skins, protected by glass/epoxy isolators and corrosion-inhibiting sealants and coatings. However, the case is different for the composite inner cowl since the perforated outer skin allows moisture ingress into the structure. The structure is also different due to the BMI skins and the required post cure for the BMI adhesives.

Aluminum cores with various protective coatings were considered in an effort to enhance corrosion resistance for this application. Both aluminum cores dipped in chromated epoxy primers and aluminum cores with phosphoric acid anodize were evaluated. In addition, both types of aluminum cores were also coated with a second layer of epoxy primer. This secondary layer was considered a sacrificial layer to improve corrosion resistance.

Testing was performed to evaluate the effects of the post cure on the aluminum core and the various protective coatings. Specimens of aluminum core with various protective coatings were prepared and exposed to post cures ranging from none to up to 450° F. Core shear tests were performed in accordance with the ASTM for Shear Test in the Flatwise Plane of Flat Sandwich Constructions or Sandwich Cores (C273-80). Salt spray tests were performed in accordance with the ASTM for Salt Spray (Fog) Testing (B117-85). Results showed that the higher post cure temperatures caused a reduction in mechanical properties and adversely affected the protective coatings. An optimum post-cure temperature less than 450° F was selected and any strength reductions were reflected in the design allowables. The aluminum cores *with a secondary* epoxy primer layer performed the best, exhibiting no coating degradation after 1000 hours of salt spray exposure.

Salt spray testing of sandwich panels with aluminum core and the various protective coatings is currently in process. These sandwich panels include the isolation techniques incorporated into the composite inner cowl design and the optimized process parameters described above. Results of these salt spray tests will provide validation of the design and the optimized processing parameters.

MANUFACTURING

A major manufacturing concern was the springback of the large BMI structure. Minimization of springback of the one-piece inner cowl would assure dimensional control of the contour of the external flow surface. In addition, dimensional control would facilitate the assembly of other hardware to the inner cowl. Springback and producibility of the one-piece inner cowl were evaluated by manufacturing prototype hardware. The prototype selected was a 3-foot-long segment with the full-size cross section and contour of the inner cowl.

Two prototypes were fabricated early in the design process using both male and female tooling approaches to evaluate the effects of tooling on springback. The first prototype was fabricated utilizing a male composite tooling approach. A master model was manufactured and a graphite/epoxy splash was constructed; the splash was then used to fabricate the graphite/epoxy tooling. Photogrammetric inspection was successfully employed to verify the contour of the tool.

Precured inner and outer skins and precured doublers were fabricated and inspected. The precured details were assembled on the male tool along with a coremat into a final assembly. The assembly was cured at autoclave temperature and pressure and then postcured freestanding in an oven. Springback was measured using photogrammetric inspection and found to be larger than desired.

The second prototype was fabricated utilizing a female composite tooling approach, which allowed more control of the flow surface, the outer surface of the inner cowl. Composite female tools were manufactured and inspected. The design of the prototype was revised to incorporate lessons learned from the first prototype. The local reinforcement at attachments was redesigned to minimize the warping effect of unidirectional tape plies. All doublers of the inner skin were moved to the inner surface, so that coremat fitup with doublers was now required only on the outer surface of the coremat. The final assembly, shown in Figure 13, was fabricated, cured at autoclave temperature and pressure, and post cured freestanding in an oven. Springback, measured by photogrammetric inspection, was found to be acceptable.

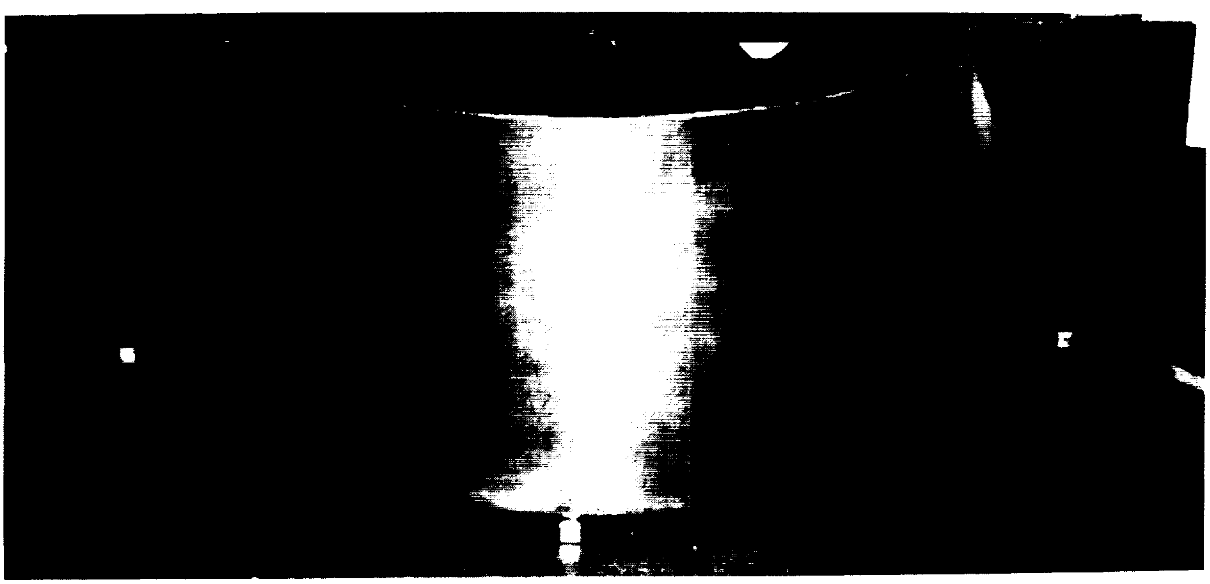

Figure 13. Prototype BMI inner cowl hardware.

Based upon the results with the two prototypes, a female tooling approach was adopted for the one-piece inner cowl. The definition of flow surface contour, prepared using CATIA, was used to prepare full-scale master models for left- and right-hand inner and outer skin tools. Splashes fabricated on these master models using graphite/epoxy materials were utilized to fabricate the graphite/epoxy tools shown in Figure 14. Photogrammetric inspection of models, splashes, and tools was successfully performed to verify flow surface contours.

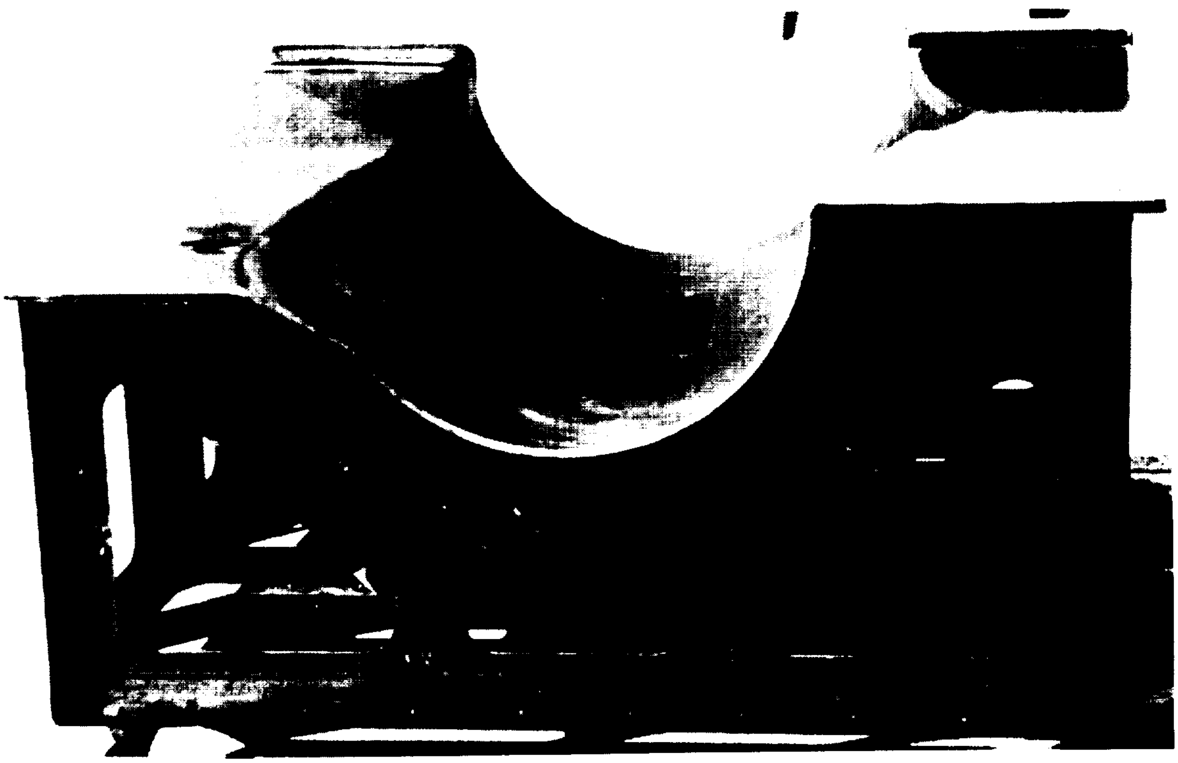

Figure 14. Full-scale composite tooling for inner cowl.

During the prototyping effort, Martin Marietta Aero & Naval Systems developed a proprietary process for the fabrication of large perforated BMI skins. Conflicting acoustic and structural requirements had to be simultaneously satisfied since the outer skin had to be perforated to meet the acoustic requirements and also had to have adequate compressive strength at elevated temperature to perform as a load-carrying member of the sandwich construction. The process for fabrication of the perforated BMI skins provides uniform hole diameter and spacing, minimizes the reduction in compressive strength due to the perforations, and can be applied to complex contoured geometries.

SUMMARY AND CONCLUSIONS

A one-piece composite inner cowl for new-generation engine nacelle thrust reversers has been designed using fiber-reinforced bismaleimide (BMI) materials and aluminum honeycomb core in a sandwich construction. The design employing composite materials has many advantages over the existing aluminum structure. Multiple details have been integrated into the composite design, thereby significantly reducing the number of detail parts and the number of fasteners. The use of lightweight materials and the reduction of the number of joints have resulted in a significant weight reduction over the aluminum design. Trade studies show a reduction in weight of 30 to 35 pounds per reverser for the BMI design over the aluminum design. The manufacturing labor and the overall number of tools required have also been reduced. Many manufacturing operations are consolidated into one operation by the transfer of the majority of the manufacturing to a traditionally more efficient area of production in the bonding facility.

Many significant technical and manufacturing issues were identified and resolved, including microcracking of BMI laminates due to thermal cyclic loading, degradation of BMI laminates in contact or in close proximity to aluminum and other metals, and springback of a large composite structure due to its cure cycle. Technical evaluation of microcracking of BMI laminates showed no cracking of the toughened BMI material after 1000 thermal cycles and after 800 hours of isothermal exposure at 375° F. Testing of perforated BMI laminates showed no microcracking after 1500 hours of isothermal aging at 300° F.

Technical evaluation of the degradation of BMI materials in contact with aluminum and other metals validated methods for isolation of the various materials. Graphite-reinforced BMI in contact with aluminum and some steels was found to degrade in salt spray testing. Glass-reinforced BMI materials and titanium did not cause the degradation. Isolation techniques such as those used for graphite-reinforced epoxy structures were shown to provide adequate protection.

Minimization of springback of the one-piece inner cowl was achieved through composite tooling and laminate design modifications and was demonstrated on prototype hardware. A proprietary process to manufacture BMI perforated skins was developed and validated by full-scale hardware fabrication.

Testing towards completion of certification is continuing. Tests for BMI microcracking, BMI degradation, and aluminum core corrosion are being continued to additional cycles and/or hours to obtain additional engineering information. Core corrosion tests are also focused on the effect of local impact damage and the establishment of maximum operating time before repair. The one-piece composite inner cowl is presently being manufactured and will be certified in 1993.

ACKNOWLEDGMENTS

The authors wish to thank all members of the Fixed Structure Bondment Integrated Product Team, one of several concurrent engineering teams of the Pratt & Whitney 4168 Thrust Reverser Program at Martin Marietta Aero & Naval Systems. Special thanks are extended to Robert Kline and Lawrence Kline for their efforts in design and manufacturing, respectively. Special thanks are also extended to Mark Alberding and Rick Sirian for their efforts in BMI microcracking and aluminum core corrosion, respectively. The authors thank Matt Patterson and all members of the Pratt & Whitney staff for their support and guidance throughout the program. The authors also wish to thank the technical staffs of the many material suppliers for their significant efforts and assistance in material screening and evaluation.

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