POLYMER MATRIX COMPOSITES RESEARCH AT NASA LEWIS RESEARCH CENTER

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CURRENT PROGRAM THRUSTS

The objective of the polymer matrix composites research at the NASA Lewis Research Center is to develop technology for new generations of polymer matrix composites intended for application in advanced aeropropulsion systems. Other applications for the newly developed technology are in airframe and space structures. Research is performed in the following areas: 1) monomer/polymer synthesis, 2) polymer/composites characterization, 3) cure/degradation mechanisms, 4) polymer/composites processing, 5) environmental effects, and 6) thermo-mechanical properties. Emphasis is given not only to developing improved materials, but also to achieving a fundamental understanding of materials' behavior at the molecular level.

The current thrusts of the Lewis polymer matrix composites program are listed in figure 1. In keeping with the Lewis role as the lead center for propulsion research, the major emphasis of the Lewis program is in the area of engine applications. Research is also being conducted to develop matrix resins with improved toughness to support the inter-center program, with the lead center responsibility at the Langley Research Center, to develop improved composites for airframe applications. Highlights of recent progress in each of the program thrusts are discussed with the exception of the thrust to develop a 700° F matrix resin. Emphasis is given to reviewing key advances in improving the processability of PMR polyimides and the application of PMR-15 composites in engine static structures.

ENGINE APPLICATIONS

- DEVELOP MATRIX RESINS FOR USE AT 700° F
- DEVELOP PMR POLYIMIDES WITH IMPROVED PROCESSABILITY
- DEVELOP COMPOSITES MECHANICS METHODOLOGY TO PREDICT LIFE/DURABILITY OF COMPOSITES IN ENGINE ENVIRONMENTS
- ESTABLISH FABRICATION TECHNOLOGY FOR ENGINE STATIC STRUCTURES

AIRFRAME APPLICATIONS

- DEVELOP TOUGHER MATRIX RESINS

Figure 1

LEWIS PMR POLYMIDE TECHNOLOGY

Studies conducted at the Lewis Research Center led to the development of the concept and class of polyimides known as PMR (for in situ polymerization of monomer reactants) polyimides (refs. 1 and 2). The PMR concept has been adopted by other investigators, and PMR polyimide materials are being offered commercially by the leading suppliers of composite materials. Figure 2 outlines some salient features of the PMR polyimide approach for the fabrication of composites. The reinforcing fibers are hot-melt or solution impregnated with a mixture of monomers dissolved in a low-boiling-point alkyl alcohol. Following fiber impregnation, in situ polymerization of the monomers is caused by heating at temperatures in the range of 250° to 450° F. The final polymerization, an addition reaction, occurs at temperatures in the range of 525° to 660° F without the evolution of undesirable reaction by-products, making it possible to fabricate void-free composite structures. The highly processable polyimides are now making it possible to realize much of the potential of high-temperature polymer matrix composites.

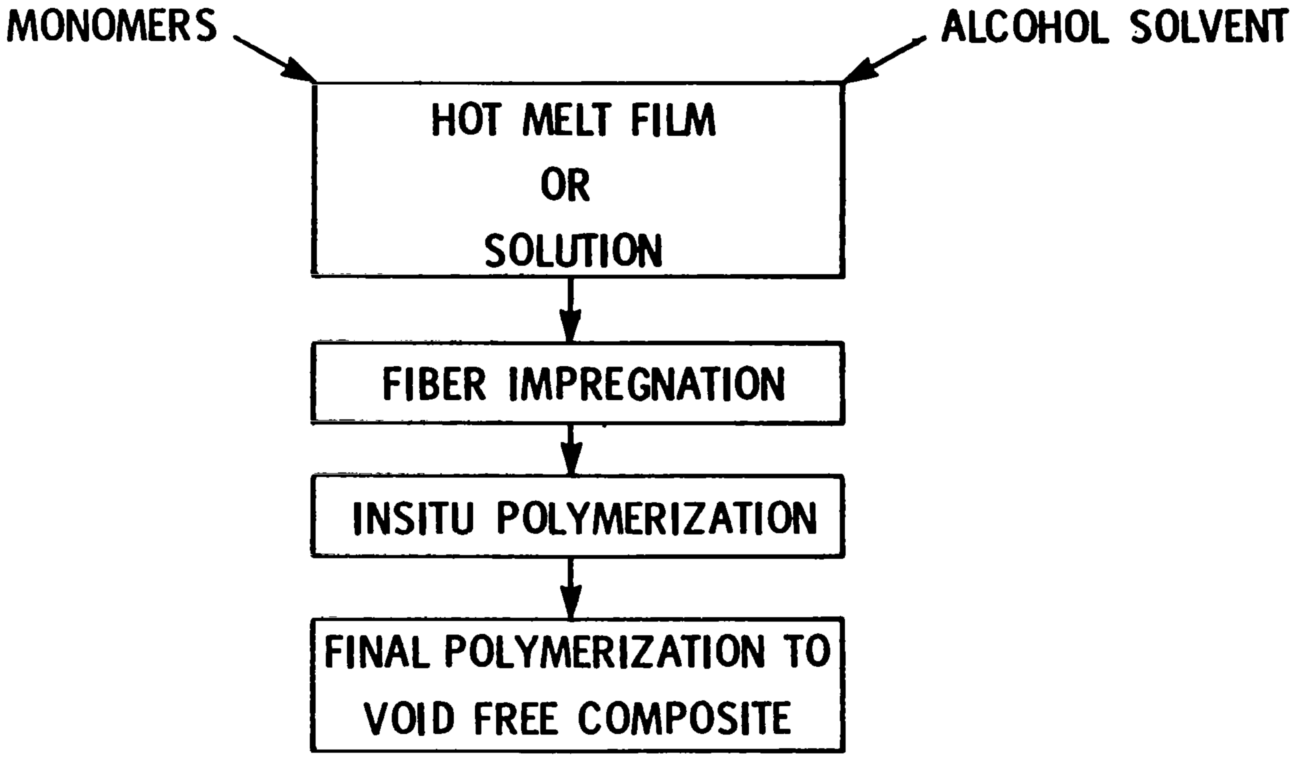


Figure 2

MONOMERS USED FOR PMR-15 POLYIMIDE

The excellent elevated temperature properties and processability of PMR polyimide composites based on the PMR matrix known as PMR-15 have led to their acceptance as viable engineering materials for high-performance structural applications. The structures of the monomers used in PMR-15 are shown in figure 3. The number of moles of each monomer reactant is governed by the following ratio: 2:n:(n + 1), where 2, n, and (n + 1) are the number of moles of NE, BTDE, and MDA, respectively. In PMR-15 the value of n is 2.087, corresponding to a formulated molecular weight of 1500. This PMR composition was found to provide the best overall balance of processing characteristics and thermo-oxidative stability at 600° F (ref. 3). Solutions having solids contents in the range of 50 to 85 percent are prepared by simply dissolving the monomer reactants in an alcohol such as methanol. Higher solids content solutions are used for psuedo-hot-melt fiber impregnation techniques.

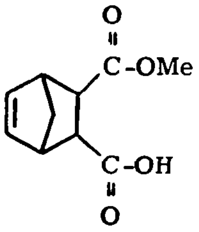
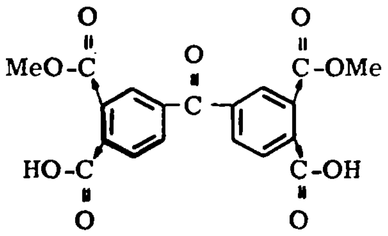
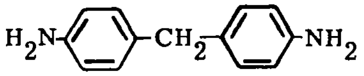
STRUCTURE	NAME	ABBREVIATION
	MONOMETHYL ESTER OF 5-NORBORNENE-2,3-DICARBOXYLIC ACID	NE
	DIMETHYL ESTER OF 3,3',4,4'-BENZOPHENONETETRACARBOXYLIC ACID	BTDE
	4,4'-METHYLENEDIANILINE	MDA

Figure 3

VERSATILITY OF PMR APPROACH

The early studies (ref. 1 and 3) conducted at Lewis clearly demonstrated the versatility of the PMR approach. By varying either the chemical composition of the monomers or the monomer stoichiometry, or both, PMR matrices having a broad range of processing characteristics and properties can be readily synthesized. A PMR composition, designated as PMR-II, has been identified which exhibited improved thermo-oxidative stability compared to PMR-15 (ref. 4). PMR-II has not been accepted as a matrix material because of the lack of a commercial source for one of the monomer reactants used in formulating the resin. A modified PMR-15, called LARC-160, has been developed by substituting an aromatic polyamine for MDA (ref. 5). Other studies (ref. 6) demonstrated the feasibility of using the PMR approach "to tailor make" matrix resins with specific properties. For example, as shown in figure 4, the resin flow characteristics (based on weight of resin flash formed during molding) of PMR polyimides can be varied, or "tailored", over a broad range by simply varying the formulated molecular weight. The higher flow formulations did exhibit decreased thermo-oxidative stability at 550° F.

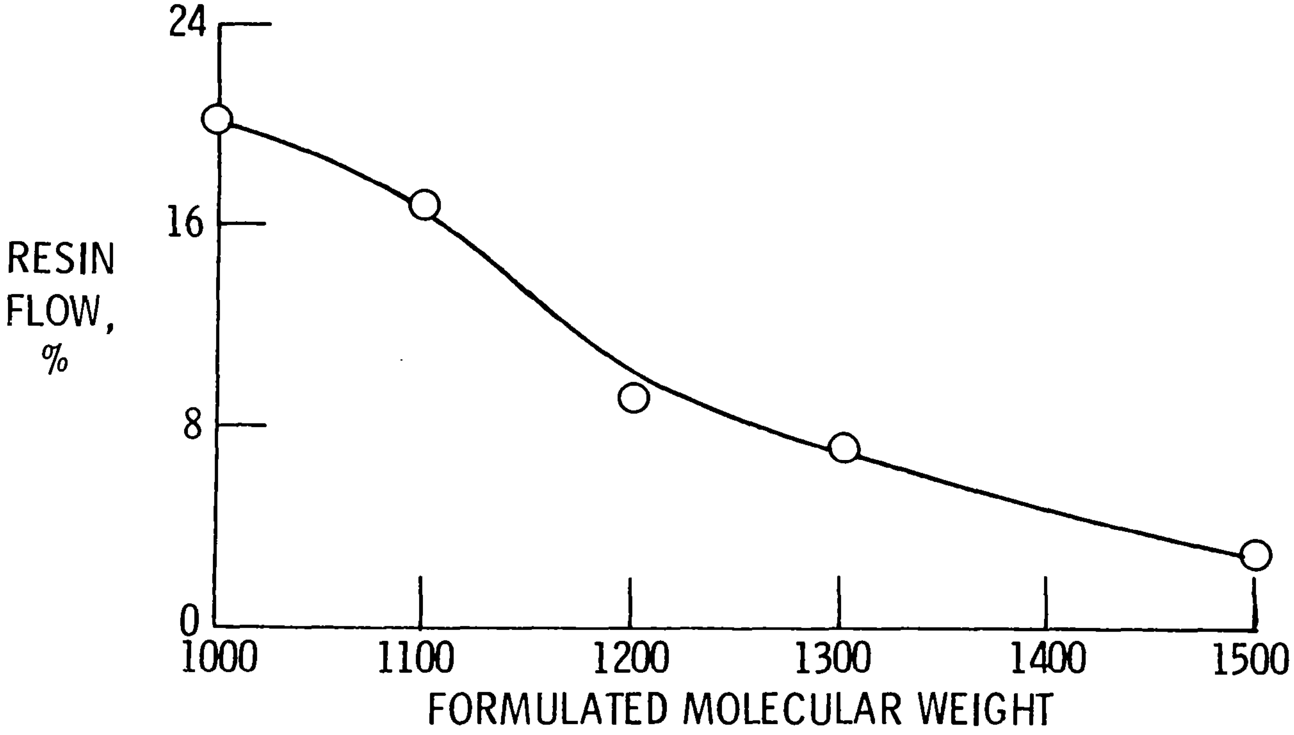


Figure 4

PMR-15 POLYIMIDE MODIFICATIONS FOR IMPROVED PREPREG TACK

Current-technology PMR-15 polyimide prepreg solutions are generally prepared by dissolving the monomer mixture in methanol. Although the volatility of methanol is highly desirable for obtaining void-free composites, it does limit the tack and drape retention characteristics of unprotected prepreg exposed to the ambient. PMR-15 monomer reactants and a mixed solvent have been identified which provide prepreg materials with improved tack and drape retention characteristics without changing the basic cure chemistry or processability (ref. 7). The modifications consist of substituting higher alkyl esters for the methyl esters in NE and BTDE and using a solvent mixture (3:1 methanol/1-propanol) in lieu of pure methanol. As can be seen in figure 5 (left), the ester and solvent modifications extend the tack retention of PMR-15 prepreg to beyond 12 days under ambient conditions. Figure 5 (right) shown that the 600° F interlaminar shear strength (ILSS) properties of Celion 6000 graphite fiber composites made with the modified PMR-15 system are identical to the 600° F (ILSS) properties of composites made with the control, or unmodified, system. The improved tack PMR-15 system should facilitate the fabrication of large complex structures which require long layup times and provide cost savings because of reduced material scrap.

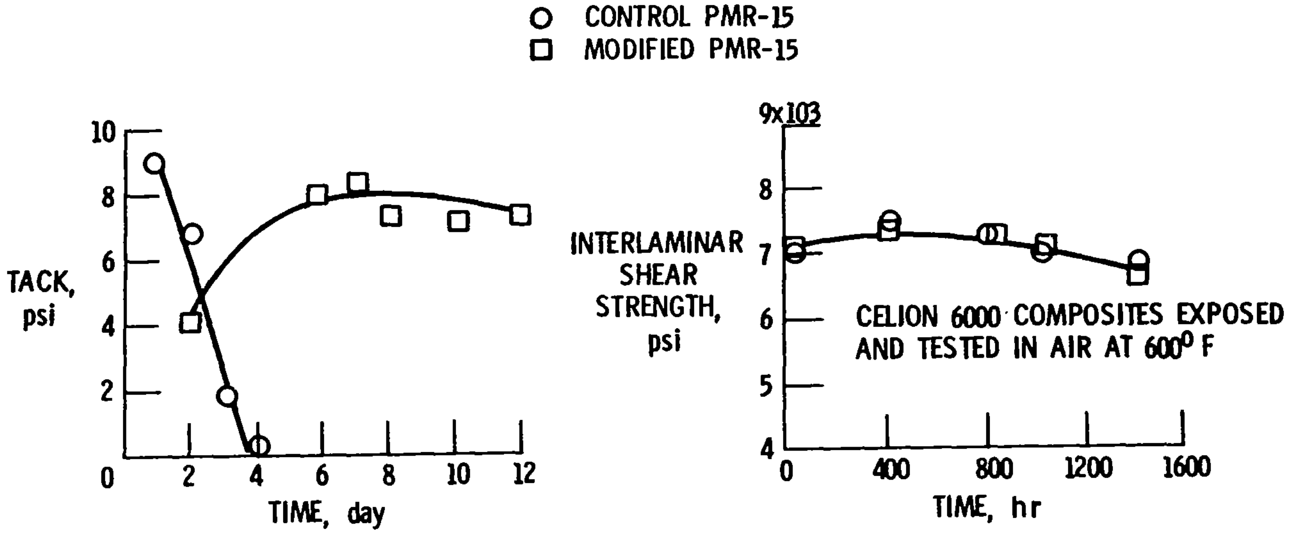


Figure 5

LOWER-CURING-TEMPERATURE PMR POLYIMIDES

The recommended temperature for final cure of PMR-15 is 600° F. This temperature exceeds the temperature capabilities of many industrial autoclave facilities which were originally acquired for curing of epoxy matrix composites. Recent studies (ref. 8) have shown that a significant reduction in cure temperature of PMR-15 can be achieved by replacing 50 mole percent of the NE with p-aminostyrene. Cure studies of the modified system, designated PMR-NV, showed that final cure temperature of PMR-15 could be reduced to 500° F (figure 6, upper left) without sacrificing its 600° F thermo-oxidative stability (figure 6, upper right). As can be seen in figure 6 (bottom), the 600° F interlaminar shear strength (ILSS) properties of Celion 6000 composites made with the PMR-NV matrix are equivalent to the ILSS properties of Celion 6000/PMR-15 composites. The lower cure temperature of the PMR-NV system should be more compatible with existing autoclave facilities and should lead to wider usage of PMR materials.

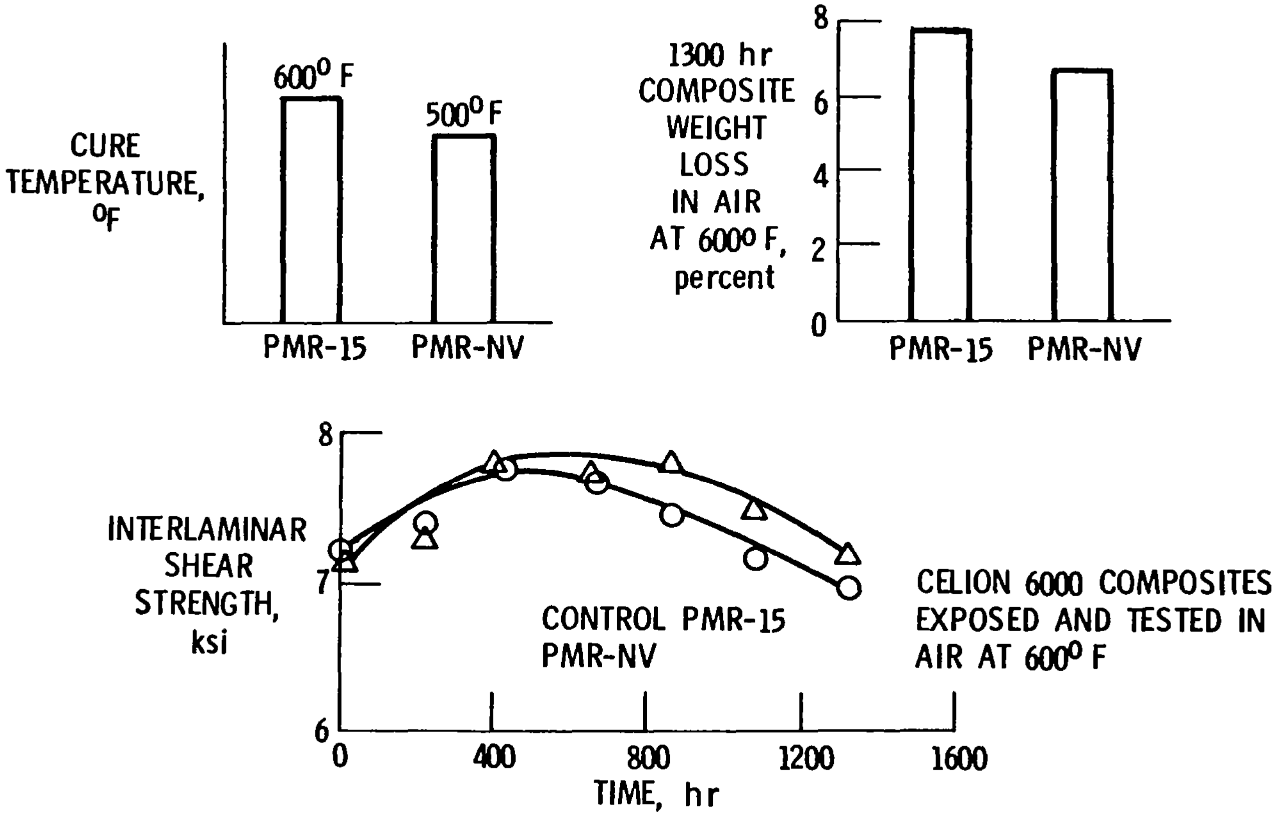


Figure 6

IMPROVED CELION 6000/PMR-15 COMPOSITES

Our continuing research with PMR polyimides has identified a fourth monomer reactant which improved the thermo-oxidative stability and resin flow during composite fabrication (ref. 9). Figure 7 (left) shows the 1500-hour composite weight loss in air at 600° F of Celion 6000 composites made with PMR-15 containing 0 to 20 mole percent N-phenylnadimide (PN). It can be seen that PN levels of 4 and 9 mole percent resulted in improved 600° F thermo-oxidative stability. Figure 7 (right) shows the variation of resin flow during composite processing as a function of PN content. It can be seen that increased resin flow results from the addition of PN. Although the PN-modified PMR-15 composites exhibited lower initial properties at 600° F than unmodified PMR-15 composites, the addition of PN appears to be a promising approach to improve the thermo-oxidative stability of PMR-15.

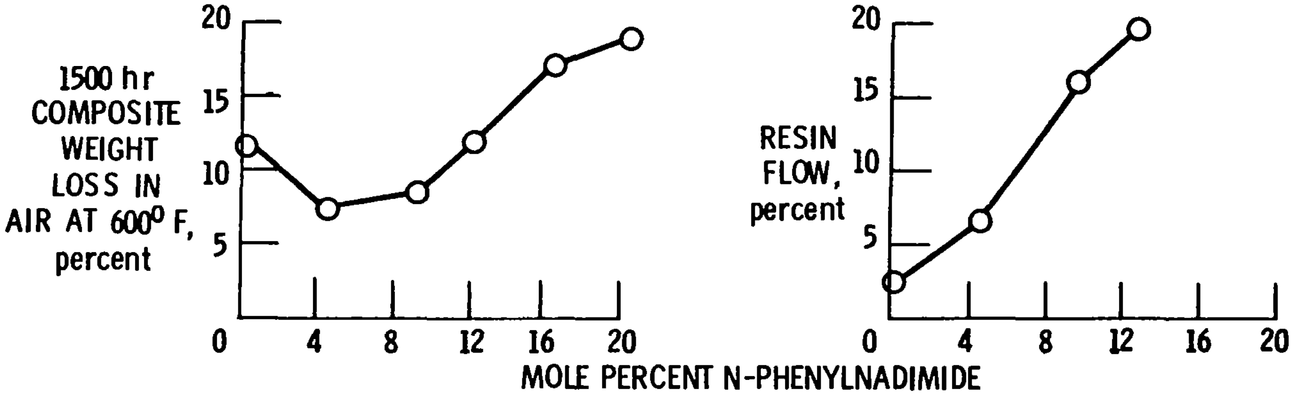


Figure 7

IMPROVED SHEAR STRAIN OF IMIDE-MODIFIED EPOXY

The approach of introducing imide groups into the molecular structure of epoxy resins by reacting epoxy oligomers with novel bis(imide-amine) curing agents was developed by Lewis investigators as a means of improving the thermal characteristics of epoxies (ref. 10). Studies are presently under way at United Technologies Research Center, under contract to NASA, to establish the potential of imide-modified epoxies for improving composite toughness. Figure 8 (left) compares the 10-degree off-axis tensile strengths (ref. 11) of Celion 6000 composite made with a conventional epoxy (A) and an imide-modified epoxy (B). Figure 8 (right) compares calculated resin shear strain for the two composite systems. The resin shear strains were calculated from data generated using 10-degree off-axis tensile tests. It can be seen that the imide-modified resin exhibited more than a two-fold increase in calculated shear strain compared to the conventional epoxy. Studies are currently in progress to establish the correlation between composite toughness and resin shear strain calculated from 10-degree off-axis tensile tests.

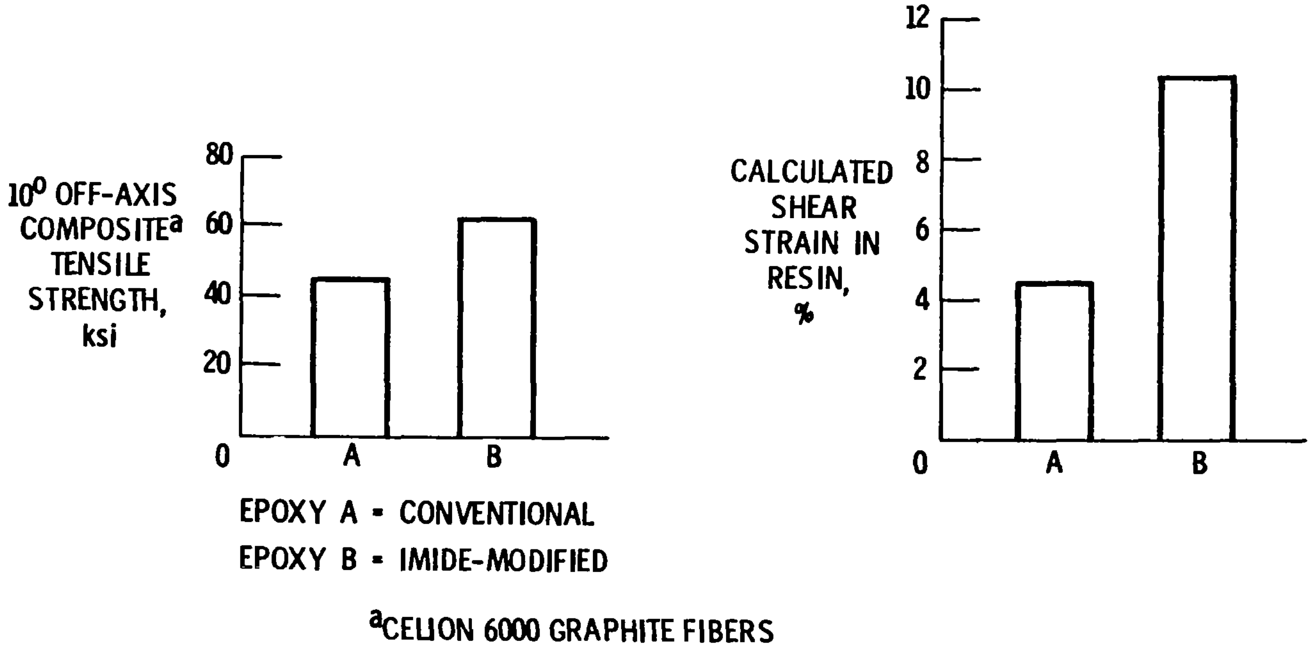


Figure 8

COMPOSITE DURABILITY

Research is being conducted at the Lewis Research Center to develop methodology to predict the life and/or durability of composite structural components in engine service environments. Service environments of major concern are various combinations of temperature, moisture, and mechanical loads. A "generalized" predictive model for predicting the life/durability of graphite fiber/resin matrix composites has been developed (ref. 12). Figure 9 compares experimental data (individual data points) and data predicted by the "generalized" model (parallel lines) for AS graphite/epoxy composites subjected to compression-compression fatigue at room temperature under dry or wet conditions. The important point to note is that the measured data at fracture is above the predicted lines. This indicates the conservative nature of the "generalized" predictive model and should provide credence for its use in preliminary designs.

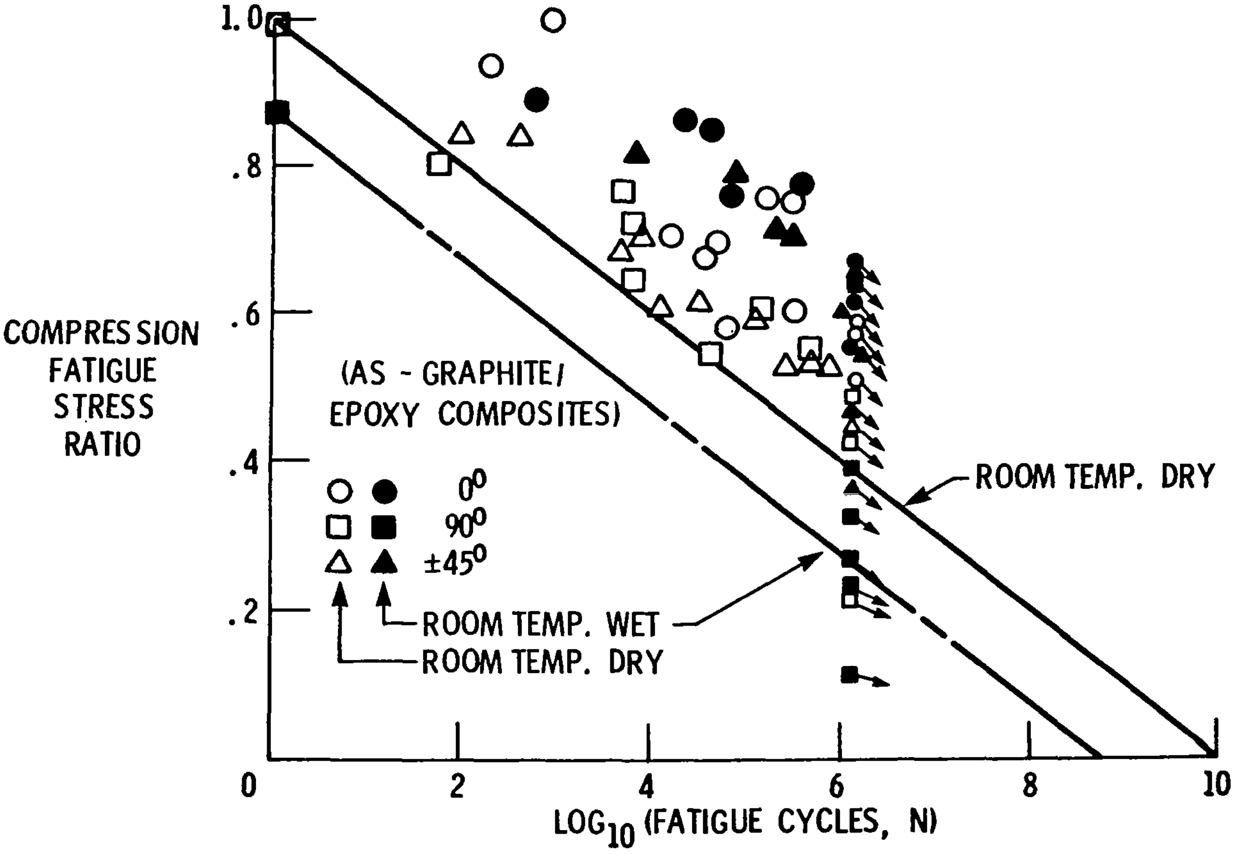


Figure 9

APPLICATIONS OF PMR-15 POLYIMIDE COMPOSITES

One of the most rewarding aspects of the PMR polyimide development has been the successful demonstration of PMR-15 polyimide composite materials as viable engineering materials. Prepregs, molding compounds and even adhesives based on PMR-15 have been commercially available from the major suppliers of composite materials since the mid-seventies. Because of their commerical availability, processability, and excellent retention of properties at elevated temperatures, PMR-15 composites have been used to fabricate a variety of structural components. These components range from small compression-molded bearings to large autoclave-molded aircraft engine cowls and ducts. Processing technology and baseline materials data are being developed for the application of PMR-15 composites in aircraft engines, space structures, and weapon systems. Some representative applications of PMR-15 composites are listed in figure 10. None of the components listed in the figure, with the exception of the ion engine beam shield, are applications in the sense that the components are currently being produced. However, several of the components listed in figure 10 are scheduled for production introduction in the near future. A brief discussion of each of the components listed in figure 10 follows.

COMPONENT	AGENCY	COMPANY
ULTRA-HIGH TIP SPEED FAN FLADES	NASA-LeRC	PWA/TRW
QCSEE INNER COWL	NASA-LeRC	GE
F404 OUTER DUCT	NAVY/NASA-LeRC	GE
F101 DFE INNER DUCT	AIR FORCE	GE
T700 SWIRL FRAME	ARMY	GE
JT8D REVERSER STANG FAIRING	NASA-LeRC	McDONNELL-DOUGLAS
EXTERNAL NOZZLE FLAPS		
PW1120	----	PWA[a]
PW1130	AIR FORCE	PWA
SHUTTLE ORBITER AFT BODY FLAP	NASA-LaRC	BOEING
ION THRUSTER BEAM SHIELD	NASA-LeRC	HUGHES

[a] COMPANY FUNDED

Figure 10

ULTRA-HIGH-TIP-SPEED FAN BLADES

The blade illustrated in figure 11 was the first structural component fabricated with a PMR-15 composite material. The reinforcement is HTS graphite fiber. The blade design was conceived by Pratt & Whitney Aircraft (PWA) for an ultra-high-speed fan stage (ref. 13). Blade tooling and fabrication were performed by TRW Equipment (ref. 14). The blade span is 11 in. and the chord is 8 in. The blade thickness ranges from about 0.5 in. just above the midpoint of the wedge-shaped root to 0.022 in. at the leading edge. At its thickest section the composite structure consists of 77 plies of material arranged in varying fiber orientation. The "line of demarkation" visible at approximately one-third the blade span from the blade tip resulted from a required change in fiber orientation from 40 degrees in the lower region to 75 degrees in the upper region to meet the torsional stiffness requirements. Ultrasonic and radiographic examination of the compression-molded blades indicated that they were defect free. Although some minor internal defects were induced in the blades during low-cycle and high-cycle fatigue testing, the successful fabrication of these highly complex blades established the credibility of PMR-15 as a processable matrix resin.

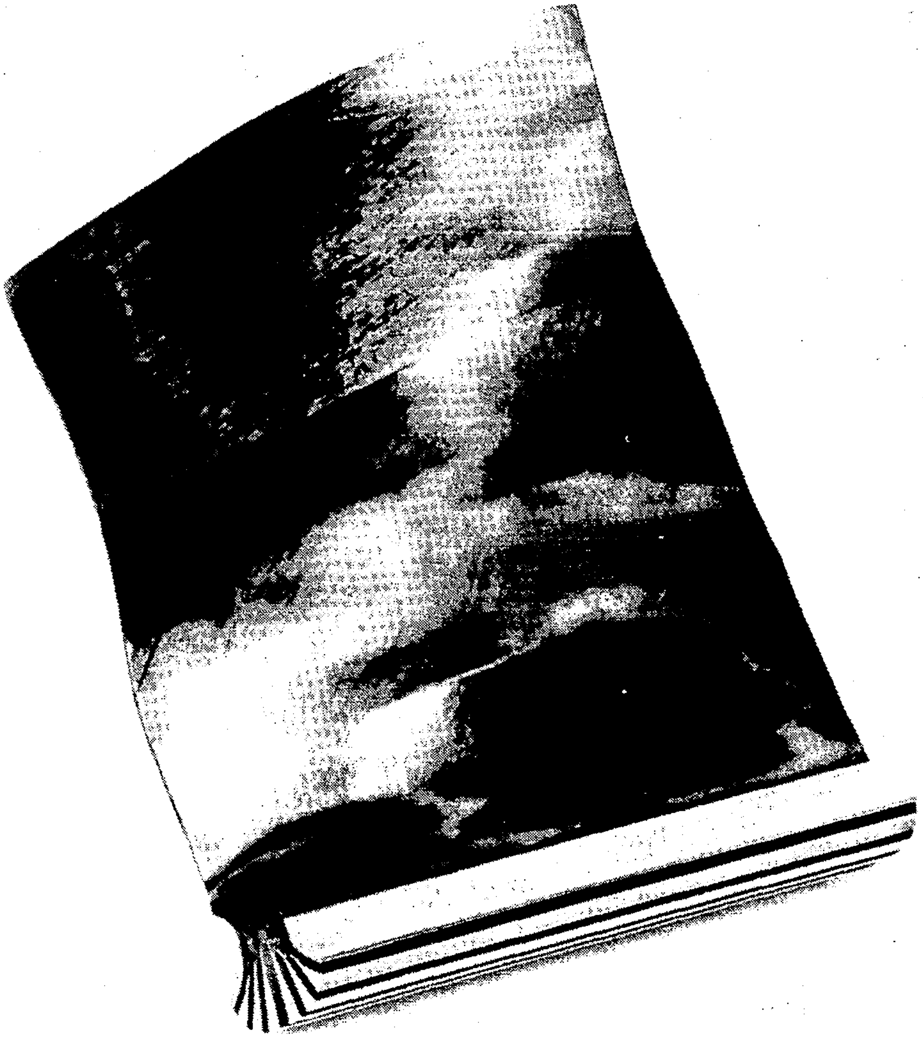


Figure 11

APPLICATION OF COMPOSITES ON QUIET CLEAN SHORT-HAUL EXPERIMENTAL ENGINE (QCSEE)

The Quiet, Clean, Short-Haul Experimental Engine (QCSEE) program was initiated to develop a propulsion technology base for future powered-lift short-haul aircraft. One of the major areas of new technology investigated under the QCSEE program was the application of advanced composite materials to major engine hardware. Figure 12 shows a cutaway drawing of the under-the-wing (UTW) QCSEE engine. Composite materials were used for fan blades, the fan frame, and nacelle components. The blades, frame and all nacelle components with the exception of the inner cowl were fabricated from Kevlar or graphite fibers in an epoxy matrix resin. The inner cowl was made of graphite fibers in PMR-15 polyimide.

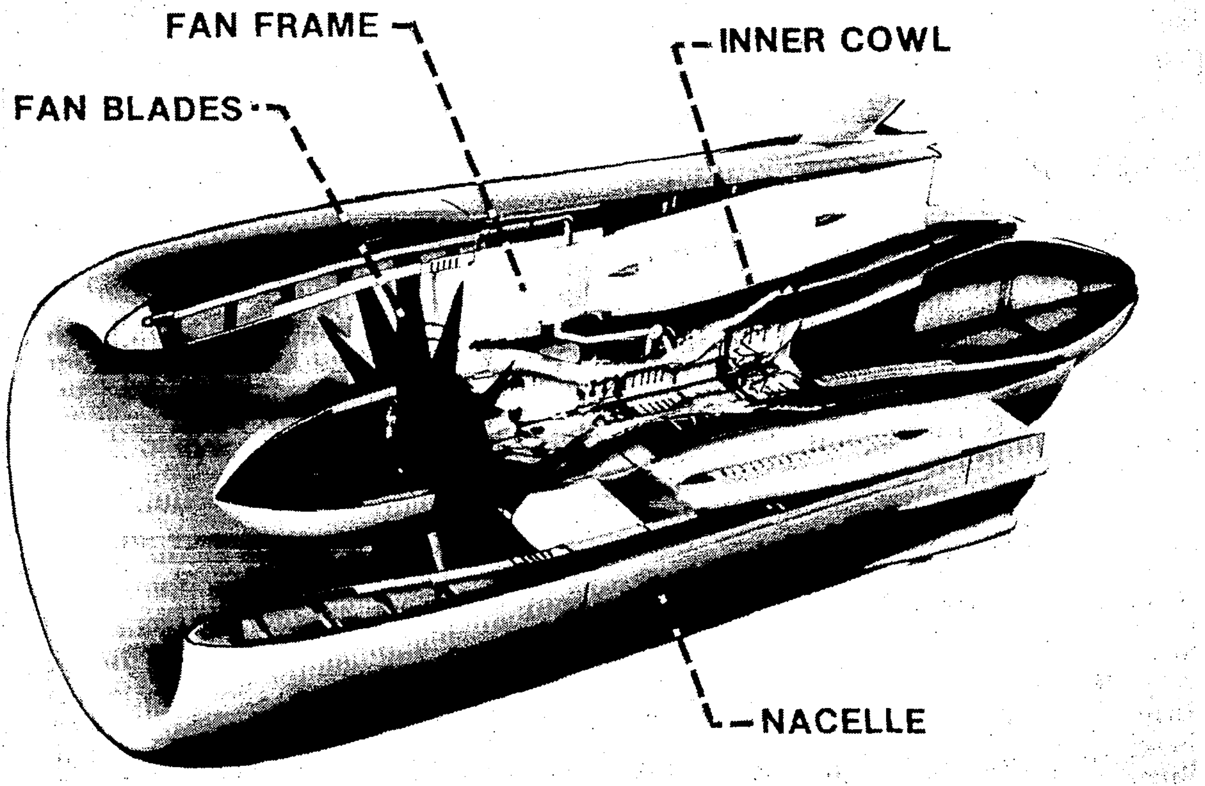


Figure 12

GRAPHITE FIBER/PMR-15 QCSEE INNER COWL

Figure 13 shows the composite inner cowl installed on the UTW QCSEE engine developed by General Electric (GE) under contract with the Lewis Research Center (ref. 15). The cowl defines the inner boundary of the fan air flowpath from the fan frame to the engine core nozzle. The cowl was autoclave-fabricated by GE from PMR-15 and T300 graphite fabric. The cowl has a maximum diameter of about 36 in. and is primarily of honeycomb sandwich construction. HRH327 fiberglass polyimide honeycomb was used as the core material. Complete details about the cowl fabrication process are given in reference 16. The cowl was installed on the QCSEE engine and did not exhibit any degradation after more than 300 hours of ground engine testing. The maximum temperature experienced by the cowl during testing was 500° F (ref. 17). The successful autoclave fabrication and ground engine test results of the QCSEE inner cowl established the feasibility of using PMR-15 composite materials for large engine static structures.

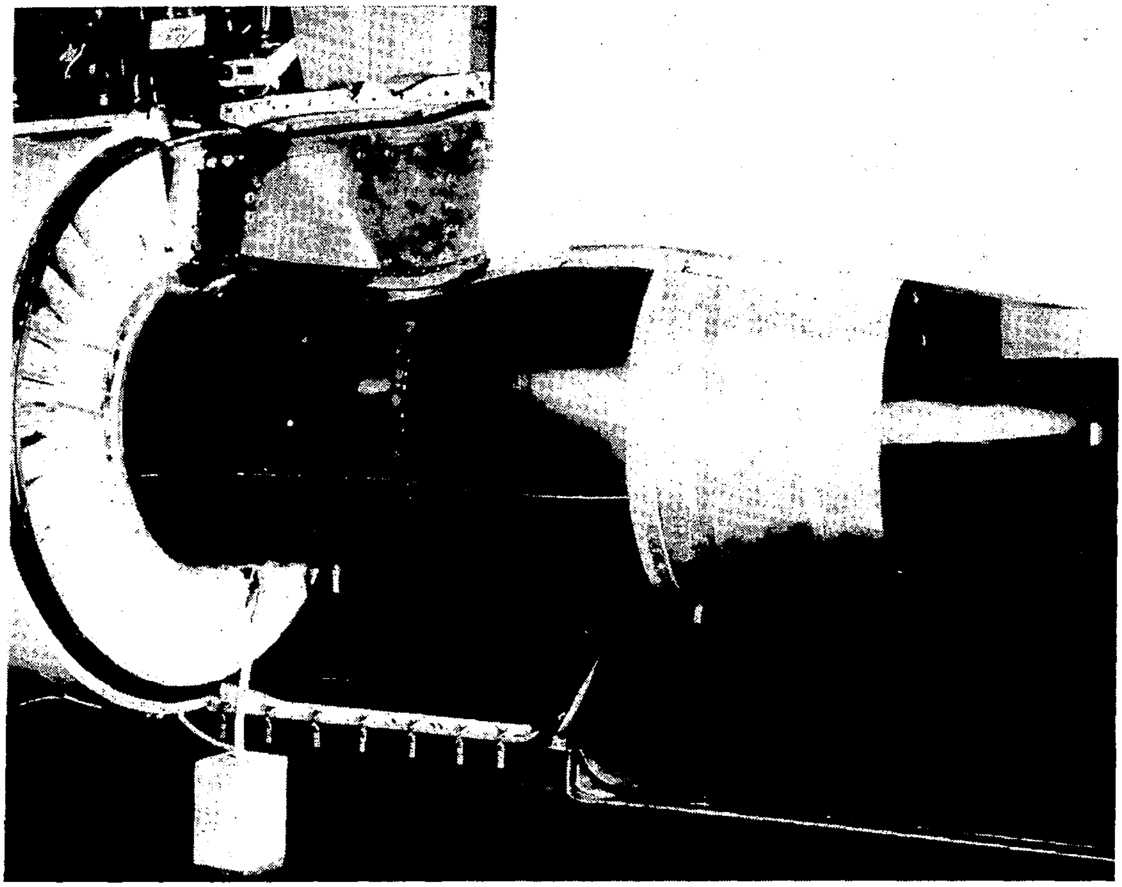


Figure 13

GENERAL ELECTRIC F404-GE-400 TURBOFAN

Under a jointly sponsored U. S. Navy/NASA Lewis program (NAS3-21854), GE is developing a T300 graphite fabric/PMR-15 composite outer duct to replace the titanium duct presently used on the F404 engine, shown in figure 14, for the Navy's F18 strike fighter. The titanium duct (the waffle-like structure) is a sophisticated part made by forming and machining titanium plates followed by chem-milling to reduce weight. A preliminary cost-benefit study indicated that significant cost and weight savings (ref. 18) could be achieved by replacing the titanium duct with a composite duct.

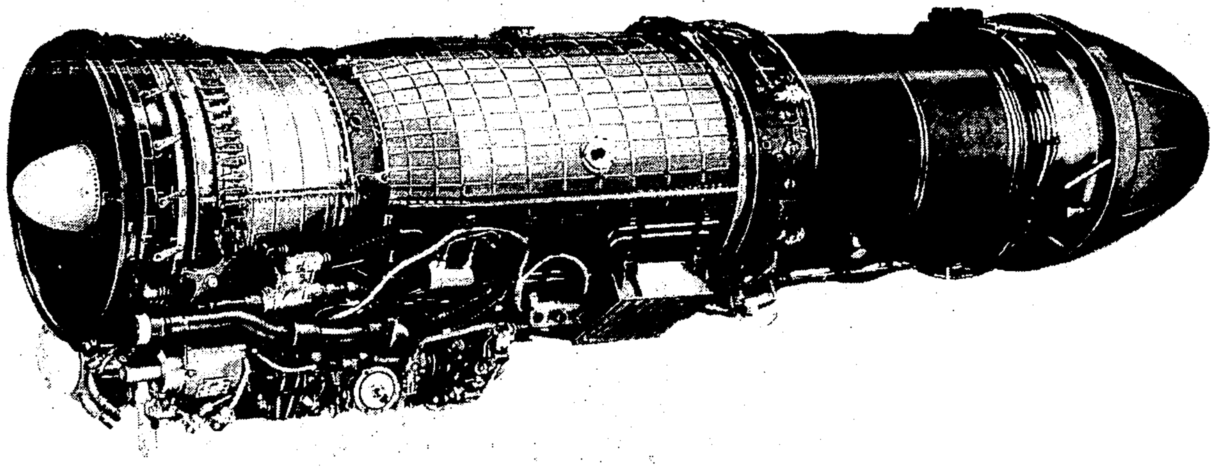


Figure 14

GRAPHITE FIBER/PMR-15 POLYIMIDE OUTER DUCT FOR GE F404 ENGINE

Figure 15 is a photograph of the full-scale composite duct (38 in. diameter x 65 in. length x 0.080 in. wall thickness) that was autoclave-fabricated from T300 graphite fabric and PMR-15 polyimide. The duct was proof pressure checked successfully, prior to ground engine testing, to 108 psi (150 percent of operating pressure). The F404 composite outer duct differs from the QCSEE inner cowl in several important respects. The F404 duct is a monolithic composite structure and needs to withstand fairly high loads, and perhaps most importantly, the F404 duct is to be a production component and not a "one-of-a-kind" demonstration component.

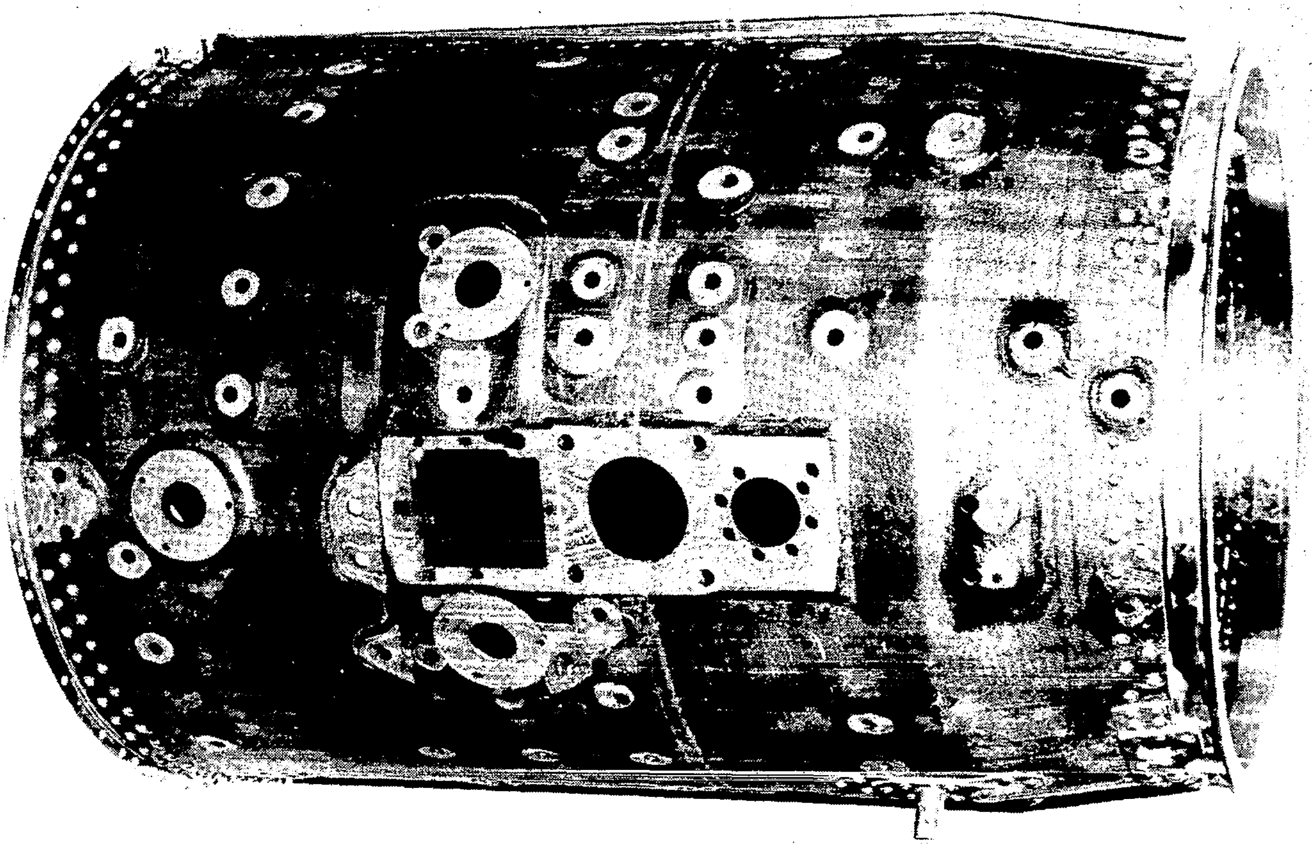


Figure 15

GRAPHITE FIBER/PMR-15 POLYIMIDE OUTER DUCT ON GE F404 ENGINE

Figure 16 shows the composite duct installed on an F404 test engine. The composite duct has successfully withstood over 1000 accelerated mission test cycles during a total engine exposure time of 700 hours. The graphite/PMR-15 polyimide composite duct is scheduled for production introduction in 1985.

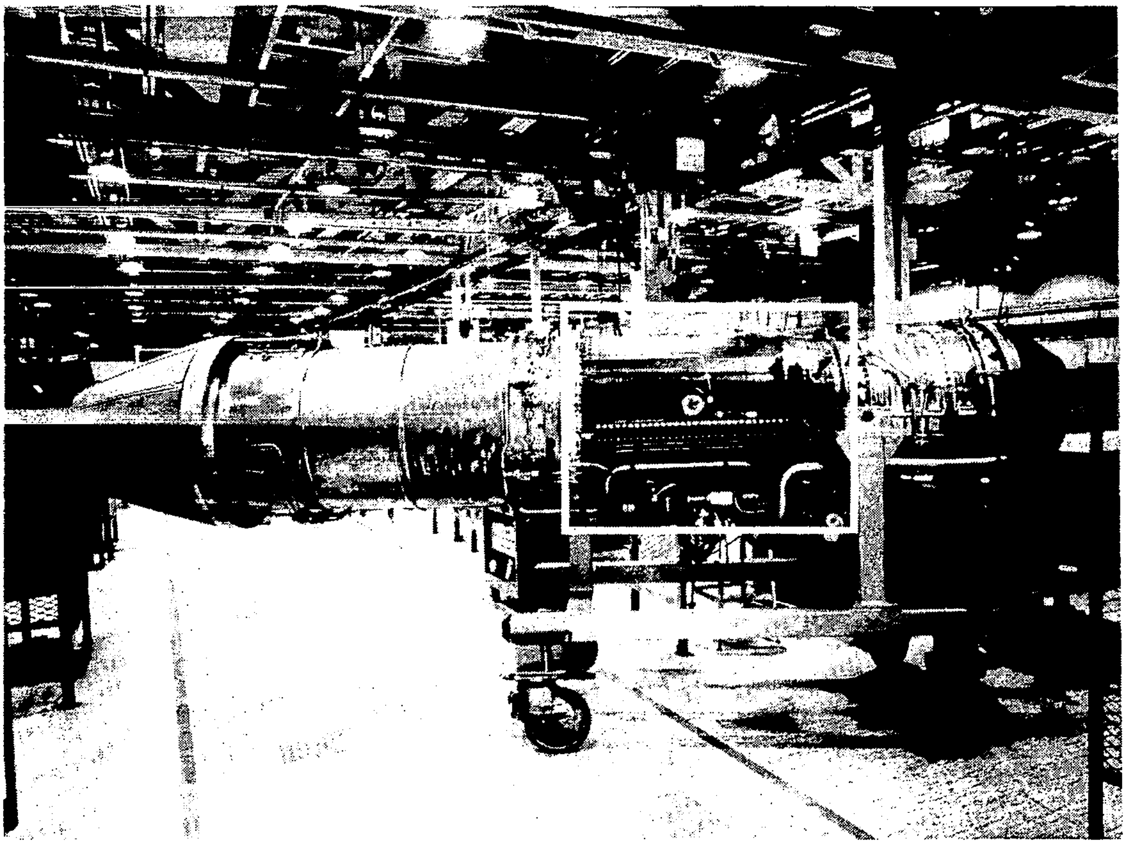


Figure 16

SCHEMATIC OF GE T700 PMR-15 COMPOSITE SWIRL FRAME

The current bill-of-materials inlet particle separator swirl frame on GE's T700 engine is an all-metal part that involves machining, shape-forming, welding, and brazing operations. Design studies conducted under U. S. Army contract number DDAK51-79-C-0018 indicated that the fabrication of a metal/composite swirl frame could result in cost and weight savings of about 30 percent. Figure 17 shows a schematic diagram of a section of the metal/composite swirl frame that was fabricated from 410 stainless steel and various kinds of PMR-15 composite materials. The outer casing uses stainless steel in the flow path area to meet anti-icing temperature requirements and T300 and glass fabric/PMR-15 hybrid composite to meet structural requirements. The T300/glass hybrid composite was selected on the basis of both cost and structural considerations. An aluminum-coated glass fabric PMR-15 composite material is utilized in the inner-hub flowpath to meet heat transfer requirements for anti-icing. The glass fabric/PMR-15 composite utilized for the front edge and front inner surface was selected because of cost as well as temperature considerations. A full-scale (O.D. ~ 20 in.) metal/composite swirl frame has been subjected to sand erosion and ice ball impact tests. The metal/composite swirl frame provided improved particle separation and successfully met the impact test requirements. Fabrication feasibility has been demonstrated, and if the metal/composite swirl frame successfully meets all of the performance requirements, the metal/composite T700 swirl frame will be introduced into production in 1985.

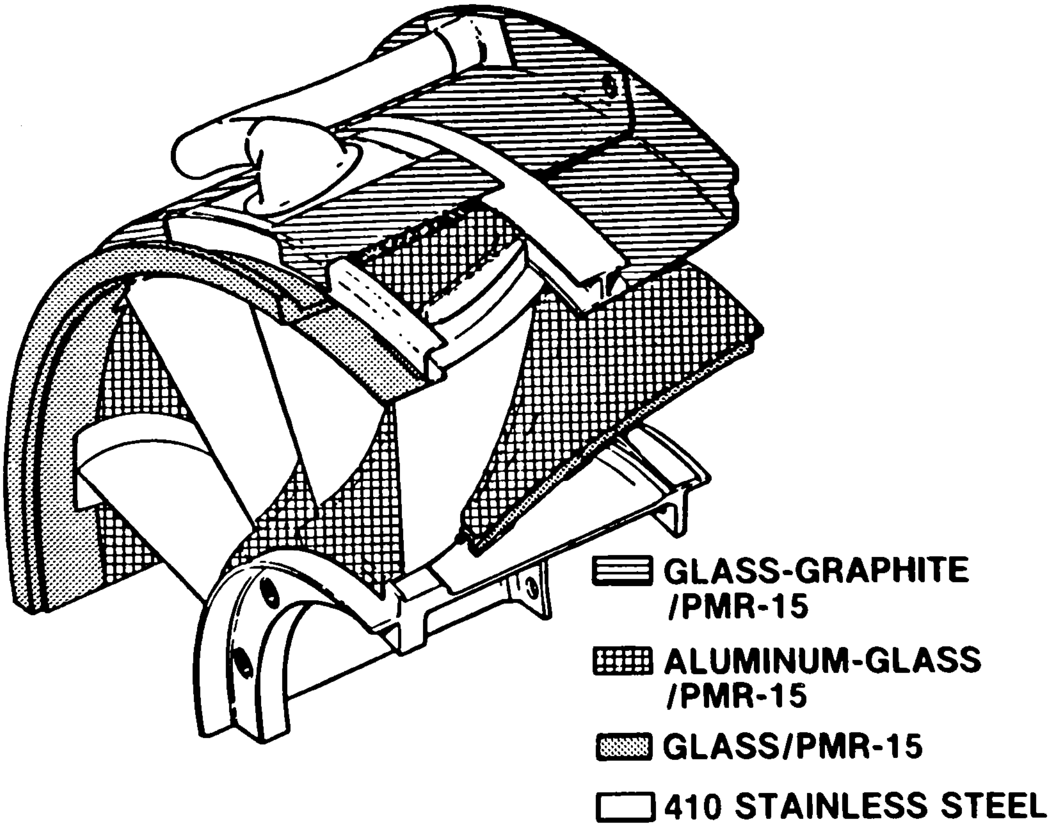


Figure 17

APPLICATIONS OF GRAPHITE FIBER/PMR-15 POLYIMIDE COMPOSITES ON PW1120 ENGINE

Figure 18 is a schematic showing "committed" and "possible" applications of graphite/PMR-15 composite materials on the PW1120 turbojet currently being developed by Pratt & Whitney Aircraft/Government Products Division (PWA/GPD). A committed application is an application for which a metal back-up component is not being developed. The committed applications for graphite/PMR-15 composites on the PW1120 at this time are the external nozzle flaps and the airframe interface ring. PWA/GPD is in the process of completing its assessment of the various "possible" applications and anticipates that many of these will also become "committed", if engine test schedules can be met. The PW1120 engine is currently scheduled for production deliveries in 1986. Graphite/PMR-15 external nozzle flaps have been committed for production by PWA/GPD for its PW1130 turbofan engine. Production deliveries of the PW1130 are scheduled for 1984. Prepregs made from T300 or Celion 3000 uniweave fabrics and PMR-15 are being evaluated for fabrication of the nozzle flaps used on both the PW1120 and PW1130 engines.

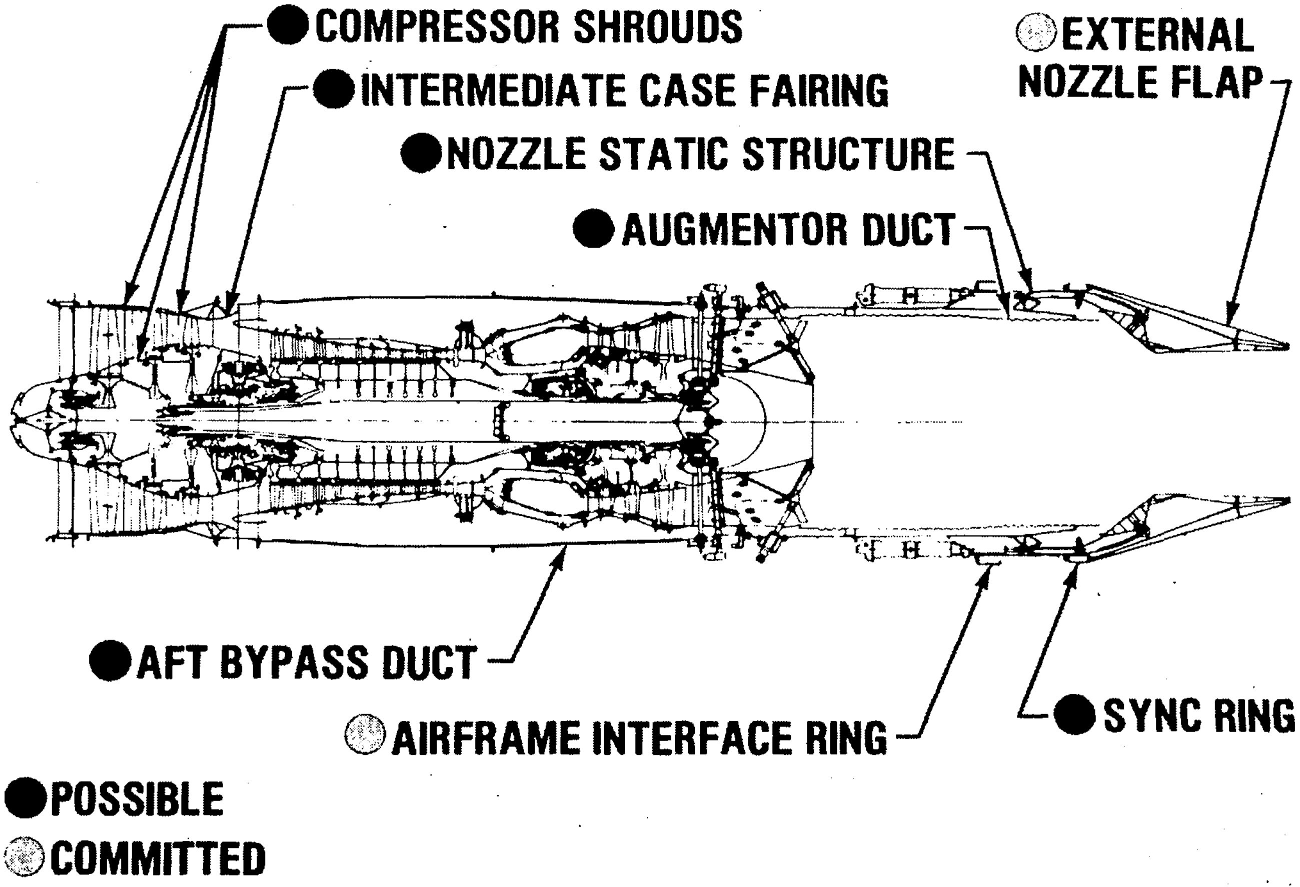


Figure 18

DC-9 DRAG REDUCTION

Figure 19 shows a photograph of a DC-9. The inserts schematically depict the design of the presently used metal reverser stang fairing and a composite redesigned fairing developed by Douglas Aircraft Company under the NASA Lewis Engine Component Improvement Program (ref. 19). Studies had shown that a redesigned fairing provided an opportunity to reduce baseline drag and would result in reduced fuel consumption. The fairing serves as the aft enclosure for the thrust reverser actuator system on the nacelle of the JT8D and is subjected to an exhaust temperature of 500° F during thrust reversal. A Kevlar fabric/PMR-15 composites fairing has been autoclave fabricated and flight tested. Compared to the metal component, the composite fairing resulted in a one percent airplane drag reduction (1/2 percent had been anticipated) and a 40-percent reduction in component weight.

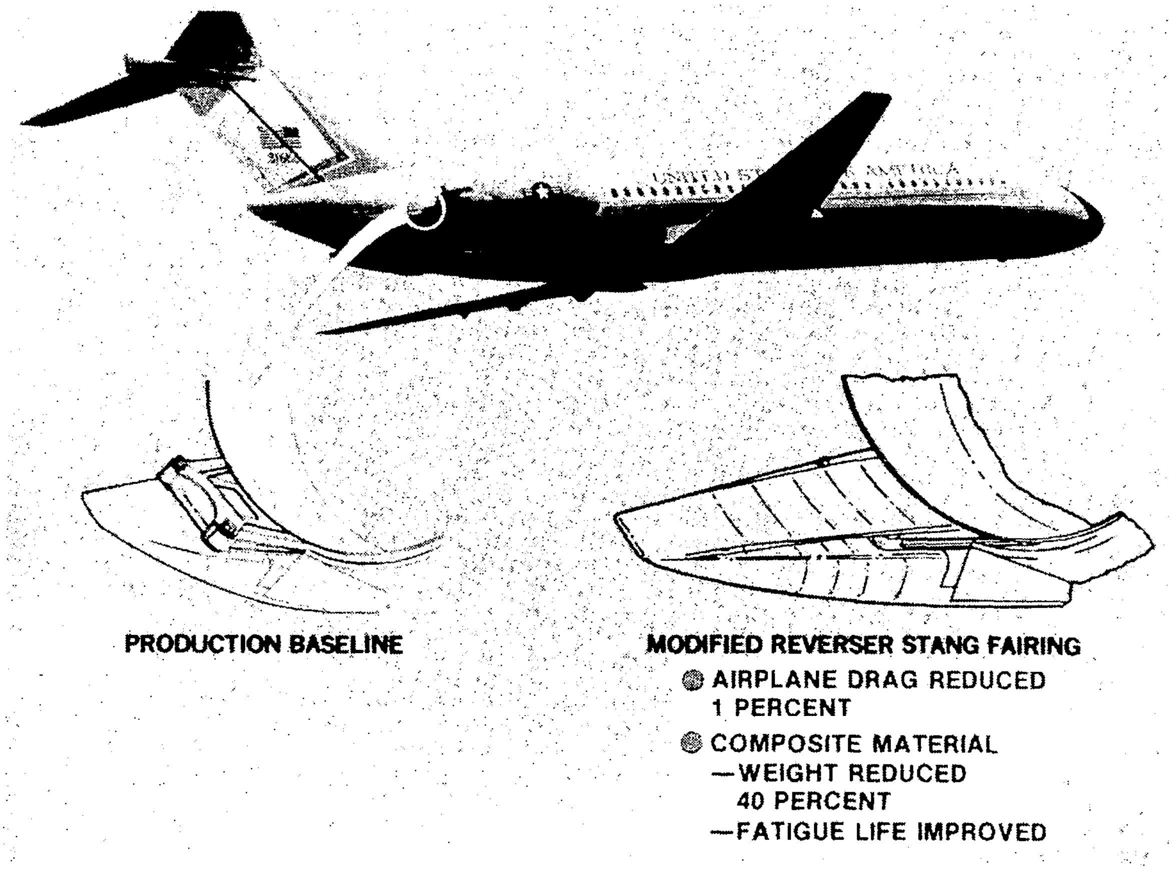


Figure 19

KEVLAR FABRIC/PMR-15 REVERSER STANG FAIRING

Figure 20 shows a photograph of the Kevlar fabric/PMR-15 reverser stang fairing. The weight of the composite fairing was found to be 40 percent less than the calculated weight of a fairing of the same shape made from aluminum.

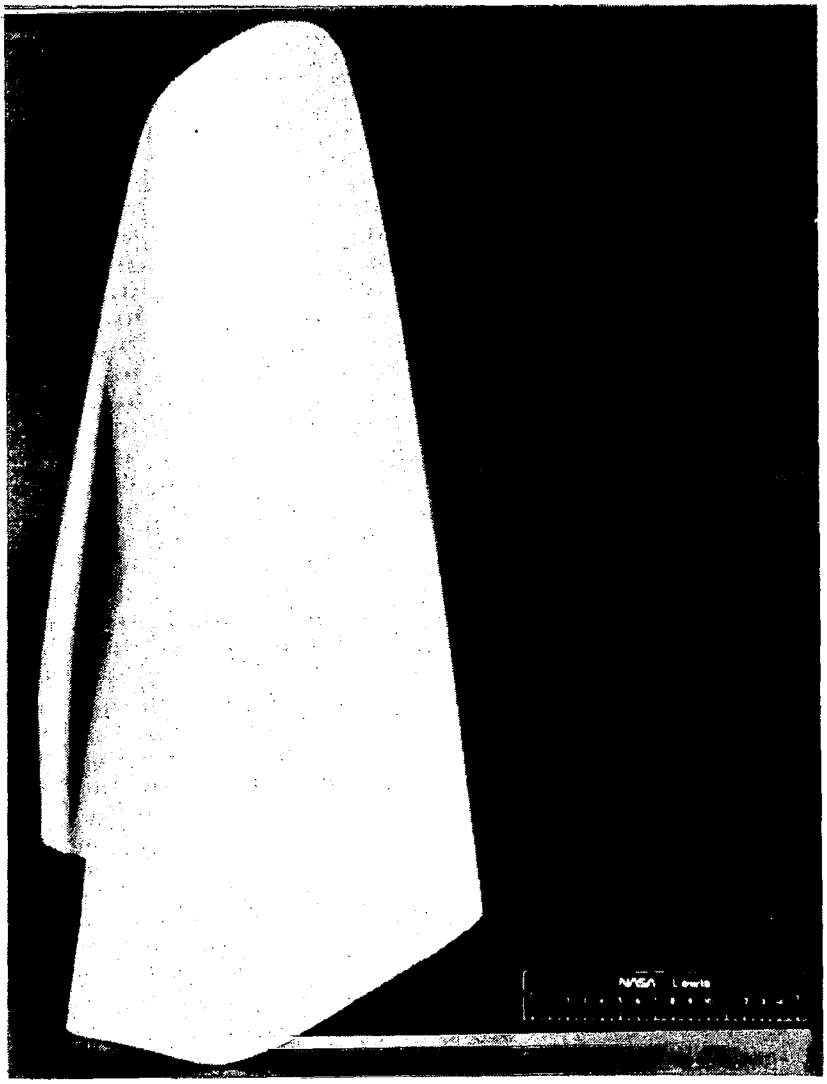


Figure 20

GLASS FABRIC/PMR-15 BEAM SHIELD INSTALLED ON MERCURY ION THRUSTER

Figure 21 shows a mercury ion thruster for an auxiliary propusion system being built by Hughes Space and Communications Group under contract to NASA Lewis. The ion propulsion system is scheduled for launch and testing on a future Shuttle flight. The thruster is equipped with a glass fabric/PMR-15 composite beam shield to protect the solar cell arrays and sensitive instrumentaion on the spacecraft from ion-beam damage. The composite shield (approximate dimensions: 10 in. diameter by 8 in. length by 0.040 in. thickness) was selected over tantalum and titanium because of weight and structural considerations. The feasibility of using a glass fabric/PMR-15 composites shield was initially demonstrated by in-house fabrication and testing of full-scale beam shields.

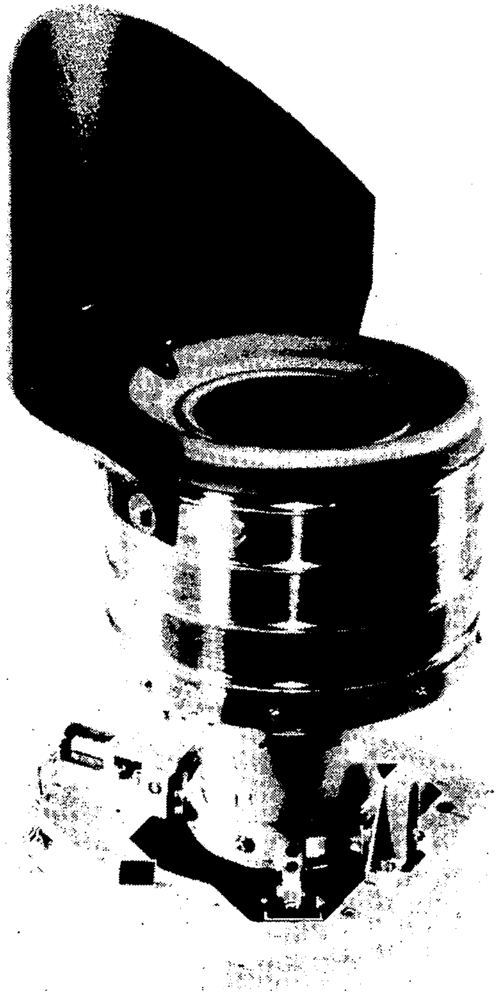
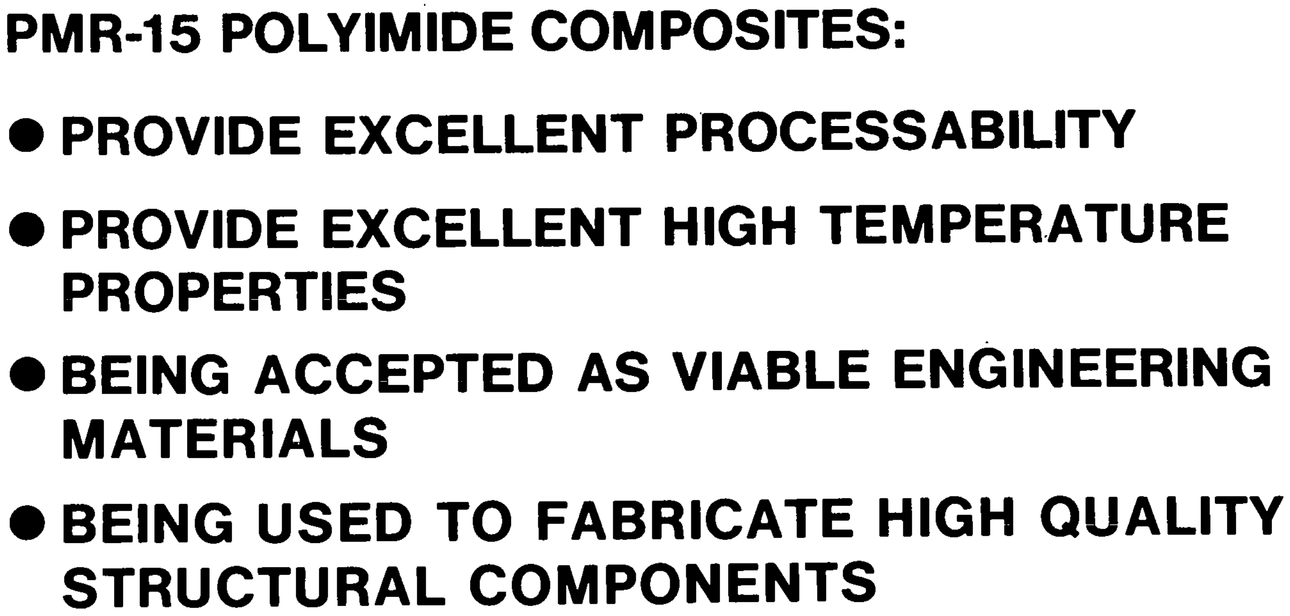


Figure 21

CONCLUDING REMARKS

The in situ polymerization of monomer reactants (PMR) approach has been demonstrated to be a powerful approach for solving many of the processing difficulties associated with the use of high-temperature resistant polymers as matrix resins in high-performance composites. PMR-15, the PMR polyimide discovered in the early seventies, provides the best overall balance of processing characteristics and elevated temperature properties. The excellent properties and commercial availability of composite materials based on PMR-15 have led to their acceptance as viable engineering materials. PMR-15 composites are currently being used to produce a variety of high-quality structural components. Increased use of these materials is anticipated in the future.



PMR-15 POLYIMIDE COMPOSITES:

- PROVIDE EXCELLENT PROCESSABILITY
- PROVIDE EXCELLENT HIGH TEMPERATURE PROPERTIES
- BEING ACCEPTED AS VIABLE ENGINEERING MATERIALS
- BEING USED TO FABRICATE HIGH QUALITY STRUCTURAL COMPONENTS

Figure 22

REFERENCES

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