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Rocketdyne Division
6633 Canoga Avenue
Canoga Park, California 91304

RI/RD82-289

FINAL REPORT
COMPOSITE MATERIAL APPLICATION FOR LIQUID ROCKET ENGINES

December 1982

Contract NAS8-34509

PREPARED BY

Advanced Programs
Canoga Park, California

APPROVED BY

F. M. Kirby
Program Manager

FOREWORD

This final report is submitted for the Composite Material Application for Liquid Rocket Engines Program per the requirements of Contract NAS8-34509. This program was performed by the Rocketdyne Division of Rockwell International for the NASA-Marshall Space Flight Center (MSFC) under Contract NAS8-34509.

The objective of this study was to determine the extent to which composites could be used beneficially in liquid rocket engines to identify additional technology requirements and to determine those areas which have the greatest potential for return.

The NASA/MSFC Project Manager was Dennis R. Gosdin. The Rocketdyne Program Manager was F. M. Kirby, and the Project Engineer was A. W. Huebner.

Principal Rocketdyne personnel contributing to the technical effort of the program were: H. W. Bennett, Advanced Design; J. Lin, Materials & Producibility, Advanced Technology; and T. C. Fan, Advanced & Propulsion Programs Stress. Without these key personnel, the technical effort of the program would have been severely curtailed.

The performance period of the program was December 1981 to August 1982.

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INTRODUCTION

With increasing emphasis on improving engine thrust-to-weight ratios to provide improved payload capabilities, weight reductions achievable by the use of composites have become attractive. However, rocket engine systems impose unique requirements on materials, and these requirements must be considered in the application of composites to these systems. To assess the potential for the application of composites to future rocket engines, a 9-month techical study contract was awarded to Rocketdyne by NASA/MSFC, and is the initial stage of a long-range program intended to advance the state of the art and provide impetus for the use of composites in future liquid rocket engines. Of primary significance in this program was the weight reduction offered by composites, although high-temperature properties and cost reduction were also considered.

Rocketdyne has assessed the potential for application of composites to components of future earth-to-orbit hydrocarbon engines and orbit-to-orbit LOX/H_2 engines. The components most likely to benefit from the application of composites were identified, as were the critical technology areas where future development would be required. Finally, recommendations are made and program outlined for the design, fabrication, and demonstration of specific engine components.

PROGRAM OBJECTIVE

The objective of this Composite Material Application to Liquid Rocket Engines program study was to determine the extent to which composites could be used beneficially in liquid rocket engines, to identify additional technology requirements, then to evaluate those areas which have the greatest potential for return within the technology readiness date of 1987 for orbit-to-orbit engines and 1991 for earth-to-orbit engines.

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PROGRAM SUMMARY

A study program has been completed on application of composites to liquid rocket engines, with recommendations for follow-on effort in design, process development, fabrication, and test evaluation of low-pressure ducting, main fuel valve structures, and nozzle skirts. The program schedule and its constituent tasks are summarized in Fig. 1.

The technical study effort, the initial stage of a long-range program intended to advance the state of the art and provide impetus for the use of composites in future liquid rocket engines, began with the selection and definition of the baseline engine configurations. Two baseline engines served as the basis for this technical study. These engines represent two basic classes of future advanced engines: (1) a reusable orbit-to-orbit engine using LOX/hydrogen propellants in the 15,000-pound-thrust size, and (2) a reusable earth-to-orbit engine using LOX/methane propellants in the 670,000-pound-thrust size. For the purpose of this study, the projected technology readiness date for the orbit-to-orbit engine was 1987 and, for the earth-to-orbit engine, 1991.

Upon completion of the component assessment task, a table was generated summarizing the component environment, design considerations, present material, and limitations for both engines. A table of composite materials substitution was prepared for the earth-to-orbit and orbit-to-orbit engines. The total potential weight saving was estimated to be 91.69 pounds or a 20% weight savings over the original design for the orbit-to-orbit engine, and 1067.6 pounds or a 13% weight savings over the original earth-to-orbit design. In the earth-to-orbit engine, five components were selected for detailed materials substitution conceptual design. These included the actuator struts, the cryogenic ducting, the fuel and oxidizer pump, and the jacket and circumferential nozzle stiffeners.

It was necessary, for the purposes of this program, to predict certain properties of composite materials and to consider both the macroscopic and microscopic features of structural analysis. These subjects are discussed in some detail in Appendixes A and B.

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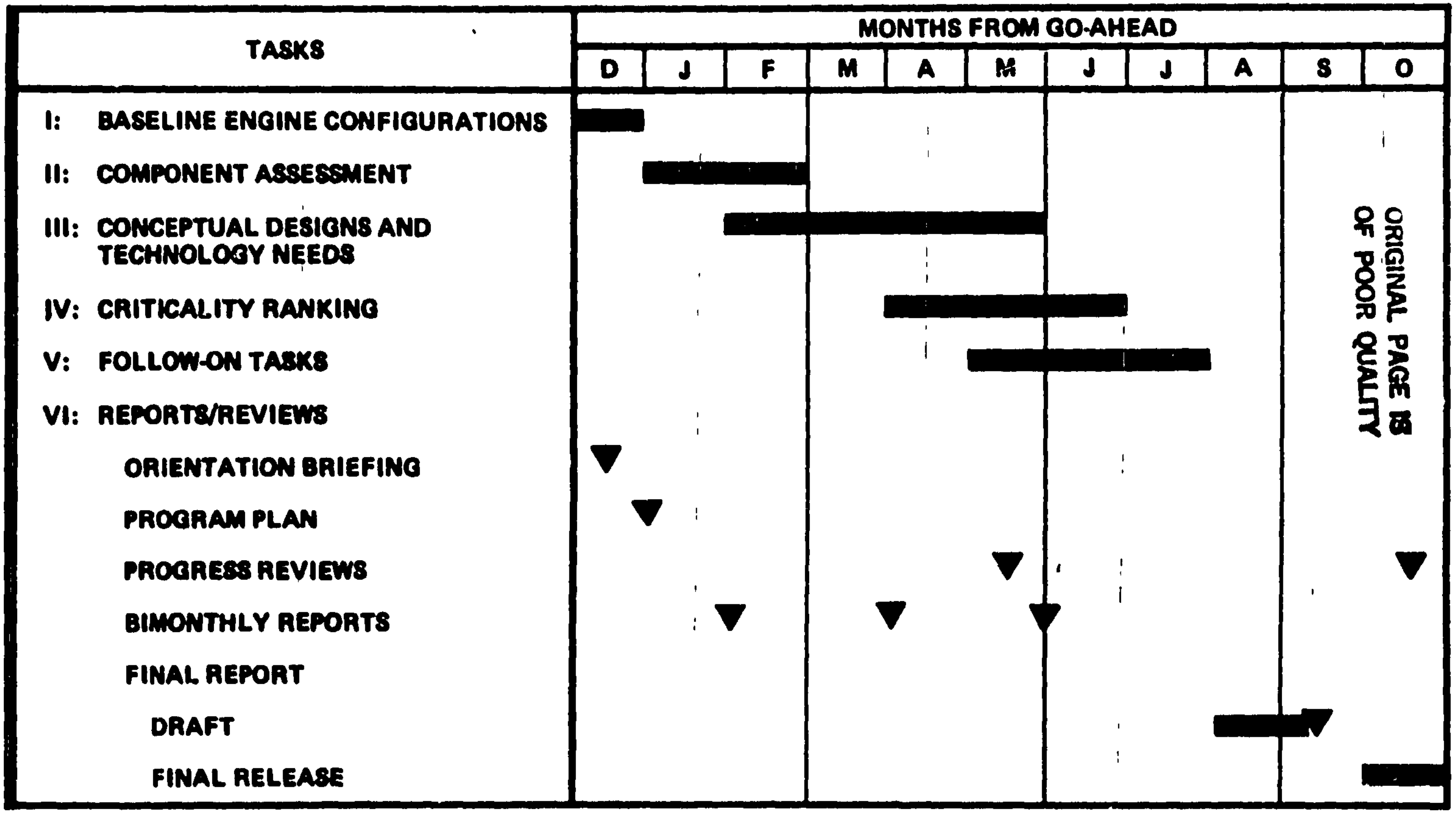

Figure 1. Program Schedule

A review was made of the current state of the art of four metal matrix composite (MMC) materials systems: SiC-whisker, SiC-particulate, SiC-fiber, and Boron fiber-reinforced aluminum alloy. These four material systems are considered the future workhorse of MMC materials. The property data base and fabrication technology needed for the liquid rocket engine application was also addressed.

Compatibility of materials in the operational environment is of major concern. Aluminum alloys are compatible with hydrogen, but not with high-pressure oxygen. Titanium alloys were found to be compatible with hydrogen at a temperature below -150 F, and is currently used, for example, in the Space Shuttle main engine (SSME) high-pressure fuel (hydrogen) turbopump impellers. The matrix obviously must be compatible with the reinforcements. Aluminum is found to be compatible with most of the reinforcement materials such as boron, silicon carbide, and graphite, whereas titanium is very reactive with reinforcement materials, and control of the Ti matrix composite properties is much more difficult. In this study we focused on aluminum matrix MMC, and discussed only briefly the potential application of titanium matrix MMC materials for liquid rocket engines. To evaluate the MMC materials application for liquid rocket engines, three areas were addressed: these were (1) physical and mechanical properties, (2) fabricability, and (3) joining.

The materials properties of MMC were collected from literature surveys and from frequent contact with MMC suppliers. These data, although challengable, were used in establishing the structural integrity of the components selected in the Conceptual Design task. Attempts were made to characterize the available metal matrix composite materials and define the present fabrication methods that were suitable for rocket engine components.

A thorough evaluation of the orbit-to-orbit and earth-to-orbit engine assemblies was conducted. Each component, together with the materials presently used in fabrication, was identified and a corresponding material selected, if applicable.

Areas of concern, due to excessive heat, high stresses/fatigue, weight gains, and fabrication methods required beyond the feasible composite material state of the art, were identified. Both baseline engines share many similar components, but the use of composites in these components is dictated by environmental conditions.

The selection rationale used for determining the components that would be considered in the Conceptual Design task considered:

- Compatibility of the composite material with environmental requirements
- Fabrication success potential
- Production potential
- Interfacing component constraints
- New technology demonstration

Basically, components from the turbomachinery, thrust chamber, valves, controls, and engine systems were selected as candidates for conceptual designs. Among the major technology areas so identified for conceptual design effort were those in the area of ducts and bellows and nozzle extensions. If weight were the sole criteria for deciding additional effort, these areas would be a prime candidate for future effort.

The primary technology needs and ranking of these needs was in the form of a criticality ranking. The components considered for further evaluation were the main fuel valve, low-pressure propellant ducting, the gimbal bearing, and nozzle extensions. The regenerative-cooled nozzle structural jacket was rated second, although a substantial amount of effort has already been expended in this area by Rocketdyne. The main oxidizer valve was a serious contender, although impact tests conducted independently by Rocketdyne in a high-pressure (7000 psi) LOX environment on SiC/Al composite samples indicated an incompatibility problem. From these candidates, the main fuel valve, the propellant ducting, and a nozzle extension are recommended as the best choices for follow-on programs.

DISCUSSION

TASK I - BASELINE ENGINE CONFIGURATIONS

Two baseline engine systems were selected for the purpose of this study. The first was a reusable orbit-to-orbit engine using LO_2/H_2 propellants at a design thrust level of 15,000 pounds. This baseline engine configuration is illustrated in Fig. 2. Figure 3 addresses the major components, and these are tabulated in a subsequent section. The second engine system was a reusable earth-to-orbit booster engine using LO_2/CH_4 propellants with a vacuum thrust of 670,000 pounds. This baseline engine configuration is illustrated in Fig. 4.

These two basic engine configurations represent typical reusable orbit-to-orbit and earth-to-orbit rocket engines. The similarities between booster and space engines are numerous. Both types employ high pressures, high temperatures, and high-speed rotating machinery and use regenerative-cooling techniques. Differences between the two types include pump speed values, thrust level, pump discharge pressure level, nozzle area ratio, weight, NPSH requirements, and design life. A comparison of typical orbit and booster engine operating parameters is shown in Table 1.

Space engines presently envisioned use LOX/H_2 at mixture ratios of 5.5 to 7.0 to obtain maximum specific impulse (440 to 500 seconds) consistent with man-rated operation. Booster engines favor hydrocarbon fuels because their density permits use of smaller tankage. High pressures contribute to reduced weight and envelope; therefore, high chamber pressure levels are chosen for both engine types. The slightly higher chamber pressures of booster engines favor staged combustion or gas generator cycles; however, gas generators are not promising for space application because significant performance losses are caused by t gas generator's poor exhaust specific impulse.

Thrust levels for 65,000- to 100,000-pound gross weight orbit transfer vehicles are selected by a trade of gravity losses versus performance, and lie between

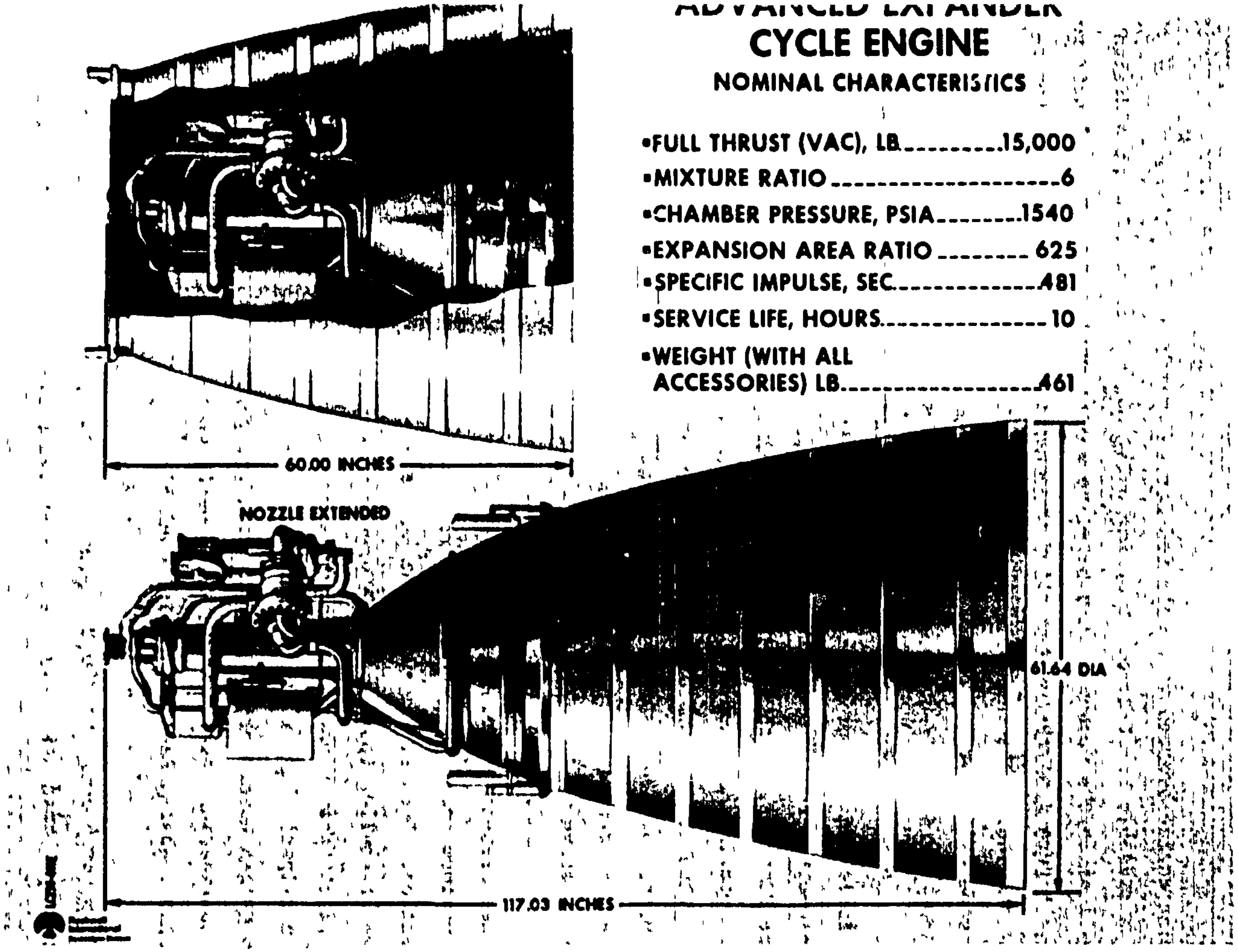

Figure 2. Advanced Expander Cycle Engine, Nominal Characteristics

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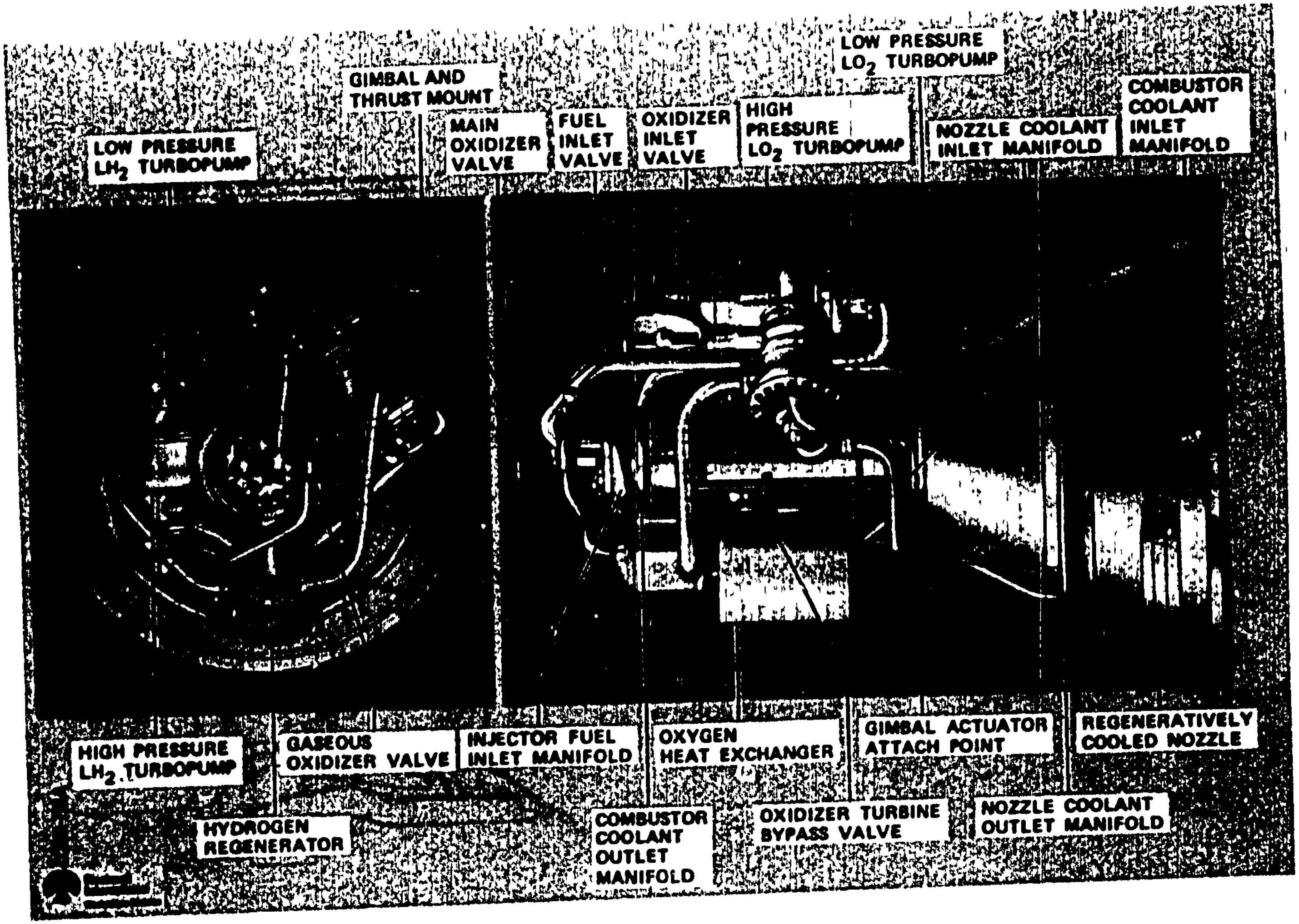

Figure 3. Advanced Expander Cycle Engine Details

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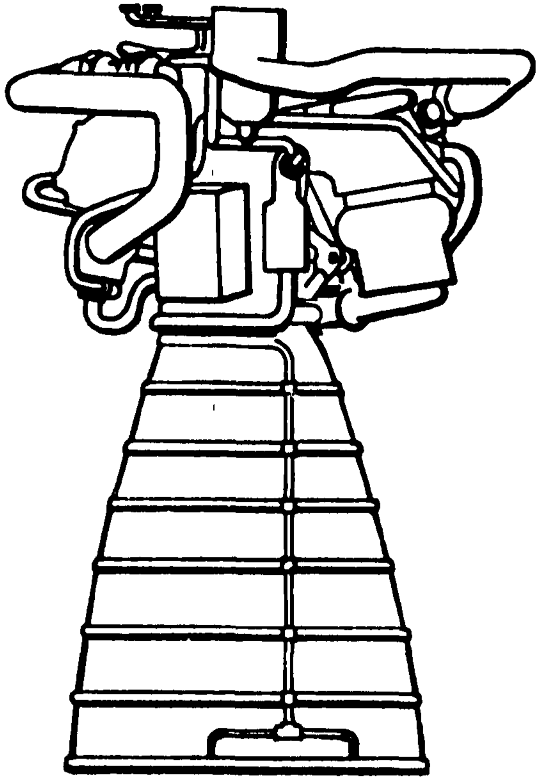

• PROPELLANTS	LOX/CH_4
• THRUST, LBF (VAC)	670K
• CHAMBER PRESSURE, PSIA	3000
• EXPANSION AREA RATIO	77:1
• MIXTURE RATIO	3.5:1
• COOLANT	CH_4
• ENGINE WEIGHT, LB	8564

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Figure 4. LOX/CH_4 Staged Combustion Engine

TABLE 1. COMPARISON OF ORBIT-ORBIT AND EARTH-ORBIT PROPULSION

PARAMETER	TYPICAL VALUES	
	ORBIT TO ORBIT	EARTH TO ORBIT
PROPELLANTS	O_2/H_2	O_2/HYDROCARBON
CYCLE	STAGED OR EXPANDER	STAGED OR GAS GENERATOR
CHAMBER PRESSURE, PSIA	1500 TO 2500	2000 TO 4000
VACUUM THRUST LEVEL, POUNDS	10,000 TO 20,000	600,000 TO 1,000,000
FUEL PUMP DISCHARGE PRESSURE, PSIA	4000 TO 5000	2500 TO 15,000
OXIDIZER PUMP DISCHARGE PRESSURE, PSIA	2000 TO 5000	2500 TO 12,000
FUEL PUMP SPEED, RPM	110,000	15,000 TO 35,000
OXIDIZER PUMP SPEED, RPM	70,000	25,000 TO 30,000
TURBINE INLET TEMPERATURE, R	900 (EXPANDER) TO 2000 (STAGED COMBUSTION)	2000
TURBINE PRESSURE RATIO	1.25 TO 2.5	1.5 TO 2.5 (STAGED COMBUSTION) 10 TO 30 (GAS GENERATOR)
AREA RATIO	400 TO 800	35 TO 80
LENGTH (EXTENDED), INCHES	80 TO 140	150 TO 200
WEIGHT, POUNDS	260 TO 550	6000 TO 10,000
LIFE – SERVICE FREE	2 HR/60 CYCLES	0.15 HR/1 CYCLE
LIFE – BETWEEN OVERHAULS	10 HR/300 CYCLES	7.5 HR/55 CYCLES
NPSH REQUIREMENT	2 FEET (O_2)/15 FEET (H_2)	160 FEET (O_2)/450 FEET (H_2)

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10K and 20K. Booster thrust levels must be much higher because they reflect the larger liftoff weight of the launch vehicle.

High jacket pressure drops along with preburner injector and valve pressure drops for staged combustion boosters can result in significantly higher pump discharge pressure levels than in space engines or gas generator boosters. Some booster engines can, however, have pump discharge pressures comparable to space engines.

The lower thrust levels of space engines produce reduced pump volumetric flowrates and thus reduced pump size. This effect, in turn, leads to higher rotational speeds in the small pumps of orbit-to-orbit engines. Turbine inlet temperatures for space engines can range from 900 R for expander cycles up to 2000 R or more for staged combustion cycles. Booster engines also will use at least 2000 R turbine inlet temperatures. Turbine pressure ratios are in the range of 1.5 to 2.5 for both engine types if topping cycles are employed; gas generator cycle boosters will have much higher pressure ratios because of the low exhaust pressure at the turbine.

A significant difference between space and booster engines lies in the area ratio selected for each. Orbit transfer engine area ratios are selected by a payload trade between performance and weight, typically range from 400 to 800 for peak payload. Booster engines, which must operate within the earth's atmosphere, are constrained to much lower area ratios for optimum mission performance. Engine lengths are similar, with orbital engines tending toward slightly shorter lengths due to orbiter and overall vehicle length limitations. Engine weights are also very different because they reflect the thrust differences. Engine thrust-to-weight values range from 30 to 60 for space engines to approximately 100 for earth-to-orbit engines. Larger engines have proportionately less inert weight, as weight does not scale linearly with thrust.

Life requirements for orbital engines typically have been defined as 2 hours or 60 cycles without service, and 10 hours or 30 cycles between overhauls. Earth-to-orbit engines may have similar life requirements.

Space engines are driven to low NPSH levels by tank weight trades. Booster vehicles may also profit from low NPSH, but present designs employ much higher NPSH levels than do space engines.

An engine mass-pressure-temperature balance computer model was developed at Rocketdyne to conduct engine system tradeoff studies and to define component requirements. Rocketdyne has detailed component requirement and design layouts for the two specified engine systems. In establishing component requirements and design configurations for composite material applications, it is important to realize that component designs intended for composite material applications may be quite different than previous designs developed for conventional metallic fabrication.

TASK II - COMPONENT ASSESSMENT

The objective of Task II was to systematically evaluate each of the components of the two specified engine systems and to identify those which can benefit potentially from fabrication with composites. Prior to this evaluation, a Rocketdyne-developed computer program called TBF81, a Parametric Engine Weight Program, was run to determine the relative component weights that would result from the various hydrocarbon propellant combinations and engine systems. Table 2 illustrates the component weight breakdown and the total weight summary for a LOX/CH_4 staged combustion engine of 670K thrust. Table 3 identifies the nomenclature on the prior table. It was apparent when the various hydrocarbons were evaluated that only subtle changes in component weights were evident and, for the composite material applications effort, these variations were not pertinent to the overall problem. Therefore, the 670K LOX/CH_4 engine was used for this component assessment.

The two baseline engine systems specified in this study result in a wide range of estimated component weights and configurations, providing a good basis for a general evaluation of composite materials in liquid rocket engine applications. Typical engine system weight summaries are presented in Tables 4 and 5 for the two specified engine systems. Although components of greatest weight are associated with thrust chambers and turbopumps, other components such as ducting, gimbal actuators, hot-gas manifolds, control components, and valves also offer significant potential for weight reduction/product improvement through the use of composite materials.

Engine Material Requirements

In the previous section, the performance requirements and parameters were outlined and compared for orbit-to-orbit engines using oxygen/hydrogen propellants and for earth-to-orbit rocket engines using oxygen/hydrocarbon propellants. These engine parameters impose requirements on component materials, some of which are quite unique to rocket engines and which are in some respect different for the two types of engines.

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TABLE 2. LOX/CH_4 STAGED COMBUSTION COMPONENT WEIGHT SUMMARY

#	F	PC	EA	EF	EE	CF	L*	EC	MR	%L	A	WEIGHT WET	WEIGHT B.OUT	WEIGHT DRY
1	670.0	3000.	5.0	77.0	77.0	1.9833	30.4	2.96	3.5	80.0	11.0	9549.	9396.	8564.

TURBOMACHINERY	1941.5
FUEL	830.4
OXIDIZER	1111.1
PREBURNERS	252.3
HOT GAS MANIFOLD	736.8
THRUST CHAMBER	2958.1
GIMBAL BEARING	137.1
INJECTOR	593.4
COMBUSTOR	599.3
FIXED NOZZLE	1628.4
VALVES AND CONTROLS	1004.9
PROPELLANT VALVES	291.1
CONTROL VALVES	207.6
CONTROLLER AND MOUNT	85.0
HARNESS AND SENSORS	132.9
PNEUMATIC CONTROLS	105.0
HYDRAULIC CONTROLS	35.6
ATTACH PARTS	147.7
ENGINE SYSTEMS	1670.7
PROPELLANT DUCTS	1159.2
ATTACH PARTS	126.6
DRAIN LINES	43.8
I.F. OXID. BLEED LINE	13.4
I.F. FUEL BLEED LINE	27.1
I.F. HYDRAULIC LINES	10.1
I.F. GN2/HE LINES	24.9
IGNITION LINES AND IGNI.RS	34.7
PRESSURIZATION SYSTEM	115.3
POGO SYSTEM	115.6

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TABLE 3. IDENTIFICATION OF NOMENCLATURE USED IN TABLE 2

(SC)	STAGED COMBUSTION
(LOXCH4)	PROPELLANTS
(F)	THRUST, POUNDS
(PC)	CHAMBER PRESSURE, POUNDS
(EA)	ATTACHMENT AREA RATIO
(EF)	FIXED NOZZLE AREA RATIO
(EE)	EXT. NOZZLE AREA RATIO
(CF)	THRUST COEFFICIENT
(L*)	CHARACTERISTIC LENGTH, INCHES
(EC)	CONTRACTION RATIO
(MR)	MIXTURE RATIO
(%L)	PERCENT NOZZLE LENGTH
(A)	GIMBAL ANGLE, DEGREES
(WET)	GROSS WEIGHT, POUNDS
(B. OUT)	BURNOUT WEIGHT, POUNDS
(DRY)	EMPTY WEIGHT, POUNDS

The materials used in the engines must be compatible with the environments to which they will be subjected. Thus, materials used in the oxidizer systems (pumps, valves, lines, etc.) of both engines must be compatible with the oxygen, and exhibit no tendency for ignition under normal operating conditions. Materials in the hydrogen system (pumps, valves, lines, combustion chamber, turbine, etc.) of orbit-to-orbit engines, must be compatible with hydrogen at temperatures ranging from cryogenic in components such as pumps to the elevated temperatures associated with turbines. Materials in the fuel system of the earth-to-orbit engines must be compatible with the hydrocarbon fuels, and the combustion chamber and nozzle materials for both engines must be compatible with propellant combustion products at high temperatures. Both types of rocket engines, in particular the orbit-to-orbit engines, will be exposed to the high, infinite pumping capacity vacuums of space. Thus, materials for these engines must not be degraded by such vacuums for the duration of exposure.

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TABLE 4. EARTH-TO-ORBIT 670,000-POUND-THRUST (VACUUM) ENGINE SYSTEM WEIGHT SUMMARY

COMPONENT	EXISTING WEIGHT, LBS	COMPOSITE WEIGHT, LBS	Δ SAVINGS
TURBOMACHINERY	(1941.5)		
FUEL	830.4	760.3	68.6
OXIDIZER	1111.1	1018.4	93.1
PREBURNERS	(252.3)		
HOT-GAS MANIFOLD	(736.8)		
THRUST CHAMBER	(2776.1)		
INJECTOR	583.4		
COMBUSTOR	564.3	506.1	58.2
FIXED NOZZLE	1628.4	1382	253.8
VALVES AND CONTROLS	(1004.9)		
PROPELLANT VALVES	291.1	249.6	41.5
CONTROL VALVES	207.6	179.8	27.8
CONTROLLER AND MOUNT	85	71.7	13.3
HARNESS AND SENSORS	132.9		–
PNEUMATIC CONTROLS	105.0	98.5	6.5
HYDRAULIC CONTROLS	35.6	–	–
ATTACH PARTS	147.7	–	–
ENGINE SYSTEMS	(1670.7)		
PROPELLANT DUCTS	1159.2	765.1	394.1
ATTACH PARTS	128.6		
DRAIN LINES	43.2		
INTERFACE OXIDIZER BLEED LINE	13.4		
INTERFACE FUEL BLEED LINE	27.1		
INTERFACE HYDRAULIC LINES	10.1		
INTERFACE GN_2/He LINES	24.9		
IGNITION LINES AND IGNITERS	34.7		
PRESSURIZATION SYSTEM	115.3	95.5	19.8
POGO SYSTEM	115.6	61.1	54.5
GIMBAL BEARING	(137.1)	109.7	27.4
ACTUATOR STRUTS & LUGS	(45.8)	37.0	8.8
TOTAL	8564.3	7496.7	1067.6

12.5% WEIGHT REDUCTION

The thermal environments of rocket engines range from liquid hydrogen temperatures in the orbit-to-orbit engines and liquid oxygen temperatures in both engines, to gas temperatures in excess of 6000 F in the combustion chamber. Liquid rocket engines are usually regeneratively cooled to reduce the temperature of the combustion chamber wall to a level at which conventional materials can be used, but this imposes a requirements of high thermal conductivity across the hot wall to achieve the desired modest temperature. An expander cycle orbit-to-orbit on the other hand, also requires a high thermal conductivity combustion chamber material but, in this case, to transfer enough heat into the coolant fluid so it can

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TABLE 5. ORBIT-TO-ORBIT 15,000-POUND-THRUST ENGINE SYSTEM WEIGHT SUMMARY

COMPONENT	EXISTING WEIGHT, POUNDS	COMPOSITE WEIGHT, LBS	Δ SAVINGS
THRUST CHAMBER	213.8		
INJECTOR	9.4	–	–
COMBUSTOR	50.7	45.0	5.7
FIXED NOZZLE (1% PASS)	71.0	60.9	10.1
EXTENDIBLE NOZZLE	82.7	55.0	27.7
TURBOPUMPS	113.3		
LOW-PRESSURE H_2	13.8	10.7	3.1
LOW-PRESSURE O_2	18.8	15.1	3.7
HIGH-PRESSURE H_2	37.8	29.5	8.3
HIGH-PRESSURE O_2	40.6	36.6	4.0
PROPELLANT VALVES	23.7	18.0	5.7
CONTROL VALVES	4.9	3.5	1.4
PROPELLANT DUCTS	17.0	6.0	11.0
INTERFACE PURGE AND CONTROL LINES	2.3	–	–
GIMBAL BEARING	6.0	2.5	3.5
ACTUATOR STRUTS	6.5	3.0	3.5
H_2 REGENERATOR	16.0	–	–
O_2 HEAT EXCHANGER	21.0	–	–
HARNESS AND SENSORS	5.2	–	–
IGNITION SYSTEM	3.1	–	–
SYSTEM INSTALLATION PARTS	4.5	–	–
CONTROLLER	24.0	20.0	4.0
TOTAL POUNDS	461.3	369.6	91.7

20% WEIGHT REDUCTION

serve as the turbine drive gas. Materials in hot-gas components in liquid rocket engines are subject to severe thermal transients. This results in thermal shock and high temperature gradients, and high thermal fatigue strains, much higher, for example, than strains that occur in aircraft gas turbines.

The specific strength (strength/density ratio) and specific modulus are very important in the selection of materials for rocket engine systems because of the necessity to reduce weight. (As a rule of thumb, for every pound of engine weight saved, there is a 1-pound increase in payload.) The strength referred to is the limiting strength for the component in question whether it be tensile, high cycle fatigue, low cycle (thermal) fatigue, or creep strength. Comparing rocket engine turbines with aircraft gas turbines, the rocket engine turbines operate at considerably higher speeds resulting in higher tensile creep and high cycle fatigue mean stresses which, combined with the higher thermal fatigue strain, impose more severe requirements on rocket engine turbine materials than on aircraft gas turbine materials. To reduce weight, rocket engine materials are used at conditions close to their strength limits. This, combined with necessary high degrees of reliability, dictates that there be an adequate data base to reliably set the appropriate strength allowables.

Composite materials, because of their high specific modulus and high specific strength, offer an obvious opportunity to reduce engine weight. Both the stiffness and load-bearing ability of conventional alloy components may be increased with no sacrifice in weight by proper use of composites. The characteristics and relative merits of both polymer and metal matrix composites were considered in the component assessment task. The selection criteria included such factors as operating environment (fluid flow, temperatures, and pressures), stress levels, and thermal gradients. Hardware geometry, requirements for removable attachment techniques, and presence of flanges and bolted connections were considered. In general, the most attractive components were those with a significant structural weight, since the primary objective of the composite application was to provide a weight reduction. Previous experience has shown that other benefits may also be derived such as improved cycle life capability, reduced materials and fabrication costs, increased temperature environment, and improved maintainability.

Potential Composite Applications

Examples of potential applications of composites to rocket engine structures are noted in Table 6, together with brief remarks concerning the technical challenges, status, or other key issues which would be faced during development. Figure 5 and Table 7 are summaries of density and mechanical properties data, respectively, on some candidate composite materials.

Table 8 presents orbit-to-orbit expander point design engine components and Table 9 presents earth-to-orbit engine assembly components. These tables tabulate the present material, potential composite material substitute, and their respective weights and weight reduction.

TABLE 6. ENGINE COMPONENTS AND COMPOSITE MATERIAL APPLICATIONS

COMPONENTS	MATERIAL	CONCERNS	COMMENTS
MOUNTING STRUCTURE			
VEHICLE GIMBAL PADS GIMBAL STRUTS ENGINE GIMBAL MOUNTS	ORGANIC MATRIX COMPOSITES	HIGH-TEMPERATURE EXPOSURE FROM RECIRCULATING GASES AND RE-ENTRY	IMMEDIATE WEIGHT SAVINGS POTENTIAL USING AVAILABLE TECHNOLOGY
PROPELLANT SYSTEMS			
DUCTS	ORGANIC MATRIX COMPOSITES	LOW TEMPERATURE	DEMONSTRATED TECHNOLOGY
VALVE HOUSINGS	ORGANIC MATRIX COMPOSITES	COMPLEX SHAPE	COMPLEX SHAPES REQUIRE ADVANCED TECHNIQUES
TURBOPUMPS			
PUMP HOUSINGS	METAL MATRIX	CRYOGENIC TEMPERATURE	GOOD WEIGHT SAVING POTENTIAL, COMPLEX SHAPES REQUIRE ADVANCED TECHNIQUES
TURBINES			
TOPPING CYCLE	METAL MATRIX CERAMIC MATRIX CARBON/CARBON	THERMAL FATIGUE THERMAL SHOCK FATIGUE RESISTANCE	WEIGHT SAVINGS MAY BE LESS IMPORTANT THAN HIGH-TEMPERATURE OPERATING CAPACITY
COMBUSTION DEVICES			
INJECTOR BAFFLES	METAL MATRIX	FATIGUE	INJECTOR FACE IS KNOWN HIGH-VIBRATION AREA
COMBUSTION CHAMBER LINERS	METAL MATRIX	CYCLIC THERMAL STRAIN	MATERIALS AND PROCESSES NEED DEVELOPMENT
COMBUSTION CHAMBER JACKET	METAL MATRIX	STRUCTURAL LOADING	COULD BE INTEGRATED WITH LINER FOR WEIGHT SAVINGS
	ORGANIC MATRIX	TEMPERATURE EXTREMES AND STRUCTURAL LOADING	EXPERIMENTAL PART HAS BEEN MADE
NOZZLE EXTENSIONS	CARBON/CARBON	SEVERE ENVIRONMENT	POTENTIAL DEPLOY-AT-ALTITUDE FOR IMPROVED SPECIFIC IMPULSE
NOZZLE JACKETS	ORGANIC MATRIX	SERVICE DEMONSTRATION	DESIGN AND FABRICATION HAS BEEN PERFORMED SHOWING SIGNIFICANT WEIGHT SAVING
CONTROLS			
CONTROLLER HOUSINGS	ORGANIC MATRIX	HIGH LOAD REQUIREMENT EMP PROTECTION	HIGH POTENTIAL FOR WEIGHT SAVING

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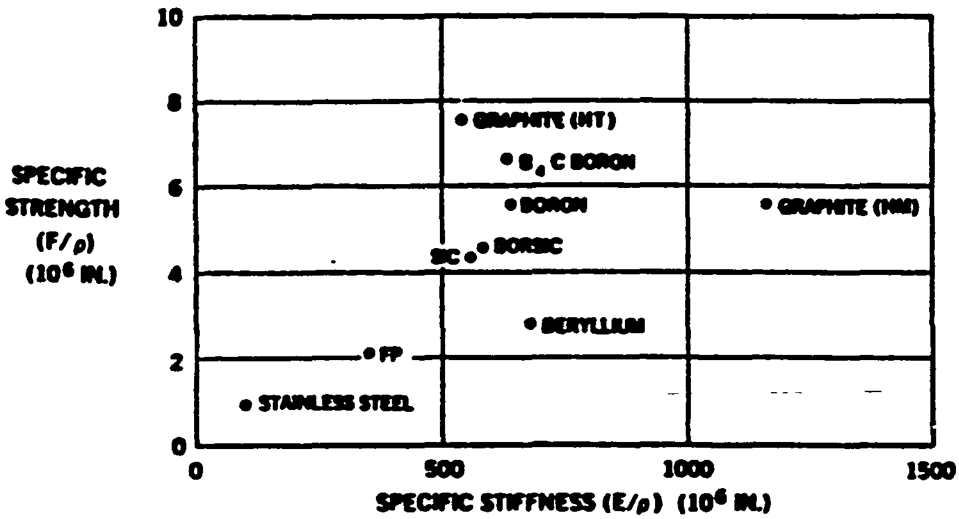

Figure 5. Strength/Stiffness Relationship of Materials

TABLE 7. MECHANICAL PROPERTIES OF COMPOSITES

MATERIAL	VOL (%)	ρ (lb/in^3)	E_L	E_T	G_{LT}	ν_{LT}	F_L^{tu}	F_T^{tu}	F_L^{cu}	F_T^{cu}	F^{su}
			PSI X 10^6				PSI X 10^3				
GRAPHITE, IN 6061 ALUMINUM	45	.088	33	6	3.5	.3	115	8	60	20	9
FP ALUMINA IN ALUMINUM	50	.117	31	20	8.5	.3	85	25	250	90	15
SILICON CARBIDE WHISKER IN 6061 ALUMINUM	25	.104	18	18	5.5	.3	75	75	90	90	40
SILICON CARBIDE PARTICULATE IN 6061 ALUMINUM	30	.104	19	19	5.5	.3	65	65	75	75	35
SILICON CARBIDE IN 6061 ALUMINUM	40	.106	31	19.	6	.25	220	10	220	25	18
6061-T6 ALUMINUM	-	.098	10	10	3.8	.33	42	42	42	42	27
B/Al	45-50	-	30-32	-	-	-	216-236	16-23	-	-	-
SiC WHISKERS/AL	20	-	20	-	-	-	85	-	-	-	-
FP/Mg	50-55	-	30-32	-	-	-	70-80	10-12	-	-	-
G/Mg	30	-	28	-	-	-	120	7	-	-	-

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TABLE 8. ORBIT-ORBIT ENGINE ASSEMBLY COMPOSITE MATERIAL SUBSTITUTION

ENGINE COMPONENT	MATERIAL		WEIGHT, POUNDS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	SAVINGS
PROPELLANT VALVES	CRES	SiC/Al HOUSING	23.7	18.0	5.7
CONTROL VALVES	--	SiC/Al HOUSING	4.9	3.5	1.4
CONTROLLER	--	Gr/EPOXY HOUSING	24.0	20.0	4
HARNESS AND SENSORS	--	(N/A)	5.2	--	--
GIMBAL BEARING	CRES	SiC/Al	6.0	2.5	3.5
ACTUATOR STRUTS AND LUGS	718	SiC/Al	6.5	3.0	3.5
H_2 REGENERATOR	INCO 903	(THERMAL)	16.0	--	--
O_2 HEAT EXCHANGER	INCO 903	(THERMAL)	21.0	--	--
PROPELLANT DUCTS	718	SiC/Al	17.0	6.0	11.0
I.F., PURGE AND CONTROL LINES	CRES	(N/A)	2.3	--	--
IGNITION SYSTEM	INCO 625	(THERMAL)	3.1	--	--
LOW PRESSURE H_2 PUMP (13.8)			--	(10.70)	(3.12)
HOUSING	TENS 50	Gr/Al	5.96	4.5	1.46
COLLECTOR	TENS 50	(WEIGHT)	1.07	--	--
SEAL ASSEMBLY FORWARD	903	(THERMAL)	0.59	--	--
SEAL ASSEMBLY AFT	903	(THERMAL)	0.71	--	--
RETAINER BEARING	A-286	(WEIGHT)	0.60	--	--
NUT - BEARING	A-286	(WEIGHT)	0.10	--	--
NUT - SEAL	A-286	(WEIGHT)	0.08	--	--
INDUCER	5 Al	(WEIGHT)	0.85	--	--
NUT INDUCER	A-286	(WEIGHT)	0.06	--	--
SHAFT	A-286	SiC/Al	1.59	0.53	1.05
NUT - BEARING - FORWARD	A-286	(WEIGHT)	0.04	--	--
SPACERS	K MONEL	(WEIGHT)	0.50	--	--
NUT - TURBINE	A-286	(WEIGHT)	0.07	--	--
WHEEL TURBINE	A-286	B/Al	0.91	0.30	0.61
BEARING	440C	(STRESS)	0.70	--	--
HIGH PRESSURE H_2 PUMP (37.8)		--	--	29.5	(8.30)
BEARING SUPPORT	TENS 50	SiC/Al	3.47	2.31	1.16
HOUSING	718	SiC/Al	11.87	8.0	3.90
DISCHARGE COVER	718	(STRESS)	2.44	--	--
MANIFOLD TURBINE	718	(STRESS)	6.04	--	--
CROSS-OVER NO. 1	718	SiC/Al	2.14	1.07	1.07
CROSS-OVER NO. 2	718	SiC/Al	1.58	0.79	0.79
SPACER	Be	(WEIGHT)	0.20	--	--
BACK RINGS AND SPRINGS	718	(WEIGHT)	0.05	--	--

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TABLE 8. (Continued)

ENGINE COMPONENT	MATERIAL		WEIGHT, POUNDS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	SAVINGS
HIGH PRESSURE H_2 PUMP (Cont.)					
SEAL BEARING RET.	INCO 718	B/Al	1.73	0.87	0.87
BEARING RET.	718	(STRESS)	0.34		
STATOR	903	SiC/Al	1.21	0.70	0.51
NOSE CONE	718	(WEIGHT)	0.36	--	--
CTR. SHAFT BOLT	718	(STRESS)	0.94	--	--
TURBINE WHEELS	ASTROLOY	(STRESS)	1.98	--	--
NUT - BEARING	K-MONEL	(WEIGHT)	0.15	--	--
INDUCER	5Al-2.55	(WEIGHT)	0.12	--	--
IMPELLER NO. 1	5Al-2.55	(WEIGHT)	0.91	--	--
IMPELLER NO. 2	5Al-2.44	(WEIGHT)	0.77	--	--
IMPELLER NO. 3	5Al-2.55	(WEIGHT)	0.87	--	--
BEARING	440C	(STRESS)	0.64	--	--
LOW PRESSURE O_2 PUMP (18.8)				(15.13)	(3.67)
HOUSING - INDUCER	TENS 50	SiC/Al	5.34	4.0	1.3
HOUSING TURBINE	TENS 50	SiC/Al	3.98	3.0	1.0
LINER - INDUCER	K-MONEL	B/Al	1.42	0.50	0.92
LAB. SEAL	K-MONEL	B/Al	0.75	0.30	0.42
NUT - BEARING	A-286	(WEIGHT)	0.38	--	--
NUT INDUCER	A-286	(WEIGHT)	0.22	--	--
INDUCER	TENS 60	(WEIGHT)	0.42	--	--
TURBINE - FRANCIS	K-MONEL	(STRESS)	2.39	--	--
SHAFT	A-286	(STRESS)	1.57	--	--
BEARING	440C	(STRESS)	1.72	--	--
BEARING	440C	(STRESS)	0.09	--	--
SPACER	A-286	(WEIGHT)	0.17	--	--
NUT - BEARING	A-286	(WEIGHT)	0.32	--	--
HIGH PRESSURE O_2 PUMP (40.6)				(36.6)	(4.0)
VOLUTE	TENS 50	(FAB)	2.02	--	--
HOUSING INTER	718	SiC/Al	4.41	3.00	1.40
HOUSING TURBINE	903	(FAB)	15.11	--	--
HOUSING AFT STATOR	903	(FAB)	6.66	--	--
SPACER BEARING	HASTELLOY B	(WEIGHT)	0.25	--	--
NUTS (3)	A-286	(WEIGHT)	0.53	--	--
SEAL ASSEMBLY OXIDIZER	903	SiC/Al	1.73	0.87	0.87
SEAL ASSEMBLY CENTER	903	SiC/Al	0.69	0.35	0.34
SEAL ASSEMBLY TURBINE	903	SiC/Al	1.62	0.90	0.72
SEAL ASSEMBLY TURBINE	903	SiC/Al	1.47	0.80	0.67

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TABLE 8. (Concluded)

ENGINE COMPONENT	MATERIAL		WEIGHT, POUNDS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	SAVINGS
HIGH PRESSURE O_2 PUMP (Cont.)					
INDUCER	K-MONEL	(WEIGHT)	0.13	--	--
IMPELLER	718	(STRESS)	0.65	--	---
NUT IMPELLER	A-286	(WEIGHT)	0.05	--	--
SLINGER	718	(WEIGHT)	0.22	--	--
NUT - BEARING AFT	K-MONEL	(WEIGHT)	0.11	--	--
BEARINGS (4)	440C	(STRESS)	0.60	--	--
SHAFT AND WHEEL	WASPALLOY A-286	(STRESS)	4.36	--	--
WHEEL ONLY (2.28)	WASPALLOY	(STRESS)	--	--	--
THRUST CHAMBER (213.8)					
COMBUSTOR (50.7)	ED NICKEL NARloy Z	ED NICKEL Gr/Cu	50.7	45	5.7
FUEL NOZZLE (70.96)				(60.9)	(10.06)
TUBES	A-286	(THERMAL)	10.09	--	--
BRAZE		(N/A)	1.22	--	--
JACKET	CRES	B/Al	4.15	2.15	2.0
COOLANT INLET MANIFOLD	625	(FAB)	5.2	--	--
COOLANT DISCHARGE MANIFOLD	625	(FAB)	15.73	--	--
BAND	CRES	B/Al	7.59	2.53	5.06
RETURN MANIFOLD	625	(FAB)	12.52	--	--
NOZZLE TIP	Cu	(THERMAL)	3.36	--	--
BRIDGE	718	(WEIGHT)	0.37	--	--
HOUSING	718	(FAB)	4.23	--	--
LUGS AND STRUTS	718	B/Al	6.50	3.5	3.0
EXTENDIBLE NOZZLE (82.70)		CARBON/CARBON		(55.0)	(27.7)
TUBES	A-286	(THERMAL)	38.43	--	--
BRAZE	0.300(CG)	(N/A)	5.38	--	--
JACKET	CRES	B/Al	21.0	--	--
MANIFOLD	625	(FAB)	17.89	--	--
INJECTOR (9.4)		(THERMAL)			
SYSTEM INST. PARTS (4.5)		(N/A)			
WEIGHT TOTAL			461.28	369.59	91.69

NOTE: SUBASSEMBLY CURRENT WEIGHTS APPEAR IN BRACKETS IN THE LEFT-HAND COLUMN, AFTER THE SUBASSEMBLY TITLE.

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TABLE 9. EARTH-TO-ORBIT ENGINE ASSEMBLY - COMPOSITE MATERIAL SUBSTITUTION

ENGINE COMPONENT	MATERIAL		WEIGHT, LBS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	Δ SAVINGS
Valves & Controls			(1004.9)	(915.8)	(89.1)
Propellant Valves	Inco 718, Ti-5AL-2.5 Sn	SiC/Al Hsngs	291.1	249.6	41.5
Control Valves	Inco 718	SiC/AL Hsngs	207.6	179.8	27.8
Controller	6061 AL Hsng	Gr/Ep Hsng	85.0	71.7	13.3
Harness & Sensors	-	(N/A)	132.9	-	-
Pneumatic Controls	7075 AL	SiC/AL Hsngs	105.0	98.5	6.5
Hydraulic Controls	Inco 625	(Weight)	35.6	-	-
Attach Parts	Inco 718	(Stress)	147.7	-	-
Hot Gas Manifold	Inco 718	(Thermal)	(736.8)	(736.8)	-
Preburners	Inco 718	(Thermal)	(252.3)	(252.3)	-
Thrust Chamber			(2776.0)	(2464.0)	(312.0)
Injector	Inco 718	(Thermal)	593.4		
Combustor	Ed Nickel, Narloy Z	Gr/Ep Jacket	554.3	496.1	58.2
Fixed Nozzle					
Tubes	A-286	(Thermal)	338.5	-	-
Braze	-	(N/A)	62.5	-	-
Aft Manifold	Inco 718	(Fab)	120.0	-	-
Mixer Separator Valve	Incoloy 903	(Fab)	51.7	-	-
Forward Outlet	Inco 718	(Fab)	156.3	-	-
Inlet Diffuser	Inco 718	(Fab)	49.3	-	-
Bands	Inco 718	Gr/Ep over 718 Sheath	124.3	339.2	152.8
Rings	Inco 718		174.8		
Hat Bands	Inco 718		192.9		
Drain Lines	Inco 625, 718	(Weight)	70.6	-	-
Transfer Ducting	Inco 718	(Stress)	122.0	-	-
Chamber Bypass Ducts	Inco 718	(Stress)	17.2	-	-
Insulation	-	Less req'd	165.7	64.7	101.0

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TABLE 9. (Continued)

ENGINE COMPONENT	MATERIAL		WEIGHT, LBS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	Δ SAVINGS
High Pressure Fuel Pump			(676.2)	(655.4)	(20.8)
Impellers	Ti-5AL-2.5 Sn	(Weight)	47.5	-	-
Shaft	Inco 718	SiC/Ti	4.7	2.2	2.5
Bearings	440C CRES	(Stress)	4.2	-	-
Impeller Sleeves	Inco 718	SiC/AL	10.7	3.7	7.0
Slinger-Impeller	Inco 718	SiC/AL	1.3	.5	.8
Turbine Disks	Waspalloy	(Thermal)	32.7	-	-
Turbine Blades	MAR-M-246	Tungsten Fib Superalloy	8.7	-	-
Inlet Assembly	Ti-5AL-2.5 Sn	(Fab)	69.2	-	-
Diffusers	Tens 50 AL	(Weight)	86.2	-	-
Volute Housing	Inco 718	(Fab)	234.7	-	-
Bearing Supports	Inco 718	(Thermal)	5.2	-	-
Pump Housing Seals	-	(N/A)	27.9	-	-
Thrust Bearing Housing	Hastelloy B	SiC/AL	17.9	7.4	10.5
Bearing Ring Assembly	A-286	(Stress)	2.5	-	-
Turbine Nozzles	MAR-M-246	(Thermal)	8.2	-	-
Seal - 1st Rotor	Rene 41	(Thermal)	2.3	-	-
Seal - Turbine Bearing	Inco 718	(Thermal)	2.0	-	-
Ring Spacer	Incoloy 903	(Thermal)	9.1	-	-
Seal-OD 1st Stage	Inco 600	(Thermal)	2.8	-	-
Shields - Turbine Inlet	H-188	(Thermal)	17.2	-	-
Rings - Turbine Inlet	Incoloy 903	(Thermal)	23.4	-	-
Shrouds - Turbine Inlet	H-188	(Thermal)	2.0	-	-
Bellows - Turbine Inlet	Incoloy 903	(Thermal)	5.4	-	-
Turbine Seals	H-188, Rene 41	(Thermal)	10.0	-	-
Turbine Bearing Cover	Inco 718	(Thermal)	1.5	-	-

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TABLE 9. (Continued)

ENGINE COMPONENT	MATERIAL		WEIGHT, LBS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	Δ SAVINGS
Low Pressure Fuel Pump			(154.2)	(105.4)	(48.8)
Inducer	Ti-5AL-2.5 Sn	B/AL	22.1	12.4	9.7
Spacer	K-Monel	SiC/AL	1.9	.6	1.3
Nut-Bearing	A-286	(Weight)	.2	-	-
Nut-Shaft	A-286	(Weight)	.1	-	-
Bearings	440C CRES	(Stress)	5.2	-	-
Inducer Closure	321 CRES	(Weight)	.6	-	-
Turbine Wheel	A-286	B/AL	3.2	1.0	2.2
Shaft	A-286	SiC/AL	2.3	.8	1.5
Nut-Turbine Shaft	A-286	(Weight)	.1	-	-
1st Stage Rotor	A-286	B/AL	1.9	.6	1.3
2nd Stage Rotor	A-286	B/AL	1.9	.6	1.3
Pump Housing	Tens 50 AL	(Fab)	44.6	-	-
Carrier - Pump End	Inco 718	(Weight)	1.6	-	-
Turbine Nozzle	A-286	SiC/AL	7.0	2.5	4.5
Stator	A-286	SiC/AL	.4	.1	.3
Stator Shroud	A-286	SiC/AL	.7	.3	.4
Manifold Housing	Inco 718	SiC/AL	48.0	24.7	23.3
Liftoff Seal	-	SiC/AL	2.2	1.0	1.2
Pump Seal	-	SiC/AL	1.0	.5	.5
Turbine Seal	-	SiC/AL	2.4	1.1	1.3

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TABLE 9. (Continued)

ENGINE COMPONENT	MATERIAL		WEIGHT, LBS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	Δ SAVINGS
High Pressure Oxidizer Pump			(326.3)		
Main Impeller	Inco 718	(Fab)	27.1	-	-
Bearings	440C CRES	(Stress)	6.2	-	-
Lab. Seal	K-Monel	Compatibility	2.3		
Retainer	Inco 718	Compatibility	5.6		
Turbine Disks	Waspalloy	(Thermal)	32.4	-	-
Turbine Blades	MAR-M-246	Tungsten Fib Superalloy	10.7	-	-
Interstage Seal	Incoloy 903	(Thermal)	2.3	-	-
Shaft	Waspalloy	(Thermal)	21.6	-	-
Main Pump Volute	Inco 718	(Fab)	77.8	-	-
Main Pump Inlet	Inco 718	(Fab)	123.5	-	-
Mounting Flange	Inco 718	(Thermal)	138.7	-	-
Drains	Inco, CRES	(Weight)	7.1	-	-
Inlet Vanes	K-Monel	Compatibility	28.8		
Bearing Supports & Seals	Inco 718	Compatibility	44.2		
Nut-Inlet Volute	Inco 718	(Weight)	5.1	-	-
Impeller Inlet Seals	Silver	(Thermal)	9.2	-	-
Seal Retainers	K-Monel	Compatibility	5.6		
Turbine Inlet Shell	Incoloy 903	(Thermal)	30.4	-	-
Turbine Inlet Bellows	Incoloy 903	(Thermal)	28.2	-	-
Strut Support	Incoloy 903	(Thermal)	29.0	-	-
Fairing	H-188	(Thermal)	9.2	-	-
Shield - Turbine	H-188	(Thermal)	7.0	-	-
Jet Ring	A-286	(Thermal)	2.4	-	-
Struts	Incoloy, H-188	(Thermal)	30.0	-	-
Turbine Nozzles	MAR-M-246	(Thermal)	22.6	-	-
Box-Inner & Outer	Waspalloy	(Thermal)	8.0	-	-
Flange	Rene 41	(Thermal)	6.6	-	-

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TABLE 9. (Continued)

ENGINE COMPONENT	MATERIAL		WEIGHT, LBS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	Δ SAVINGS
HPOP (continued)					
Boost Pump Volute	Inco 718	(Fab)	54.7	-	-
Boost Pump Impeller	Inco 718	(Fab)	8.7	-	-
Boost Pump Seals	Silver	(Thermal)	3.5	-	-
Seal Retainers	K-Monel	Compatibility	2.3		
Low Pressure Oxidizer Pump			(285.2)	(192.1)	(93.1)
Inducer	K-Monel	B/AL	59.6	17.7	41.9
Rotor	K-Monel	B/AL	29.7	8.8	20.9
Cap	K-Monel	SiC/AL	3.5	1.2	2.3
Volute/Housing	Tens 50 AL	(Fab)	111.2	-	-
Flange	Tens 50 AL	(Fab)	11.3	-	-
Sleeve	K-Monel	SiC/AL	9.1	3.0	6.1
Stator Segments	K-Monel	SiC/AL	5.2	1.7	3.5
Bearings	440C CRES	(Stress)	7.2	-	-
Nozzle	Inco 718	SiC/AL	8.8	3.0	5.8
Housing	Inco 718	SiC/AL	6.7	3.5	3.2
Bearing Support	Inco 718	SiC/AL	15.3	7.9	7.4
Ring Rotor Seal	Silver	(Thermal)	5.2	-	-
Turning Vanes	356 AL	(Weight)	.7	-	-
Spacer Sleeve	347 CRES	SiC/AL	1.0	.4	.6
Inducer Nut	A-286	(Weight)	.9	-	-
Nut-Outer Race	A-286	(Weight)	1.2	-	-
Nut Retainer	A-286	SiC/AL	2.2	.8	1.4
Nuts - Inner Race	A-286	(Weight)	1.5	-	-

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TABLE 9. (Concluded)

ENGINE COMPONENT	MATERIAL		WEIGHT, LBS		
	PRESENT	COMPOSITE	PRESENT	COMPOSITE	Δ SAVINGS
Engine Systems			(1852.2)	(1348.4)	(503.8)
Propellant Ducts	Inco 718, 21-6-9 CRES, Incoloy 903	SiC/AL	1159.2	765.1	394.1
Attach Parts	Inco, CRES	(Weight)	126.6	-	-
Drain Lines	Inco 625	(Weight)	43.8	-	-
Interface Lines	Inco, CRES	(Weight)	75.5	-	-
Ignition System	-	(Thermal)	34.7	-	-
Pressurization System	Inco 718	SiC/AL	115.3	95.5	19.8
Pogo Accumulator	Inco 718	SiC/AL, Gr/Ep	50.8	19.2	31.6
Pogo Accum. Baffles	321 CRES	SiC/AL	11.3	4.0	7.3
Pogo Inlet Baffle	Inco 625, 718	SiC/AL	22.3	6.7	15.6
Pogo System	Inco, CRES	(Weight)	30.6	-	-
Gimbal Bearing	Ti-6AL-6V-2 S	SiC/AL	137.1	109.7	27.4
Actuator Struts & Lugs	Ti-6AL-4V	B/AL	45.0	37.0	8.0
TOTAL WEIGHT			8564.1	7496.7	1067.6

The composite material column of these tables include a one-word rationale in parenthesis; i.e., thermal, weight, fabrication, stress, compatibility, or N/A in thsoe instances where a composite material was not considered applicable to that particular component. Further definition of the one-word rationale is as follows:

(Thermal):	The design temperatures go beyond the limits of presently known composite materials.
(Weight):	The weight differential would not justify further investigation.
(Fab):	The present state of the art does not encompass a fabrication method for the required geometry of the design.
(Stress):	The design loads are incompatible with composite material properties.
(N/A):	Not applicable (i.e., wire harness, etc.).
(Compatibility):	Incompatible with composite material at elevated pressures.

Component Applications of Composites

Typical engine system weight summaries for the two specified engine systems show the heaviest members to be concentrated in the areas of thrust chambers, nozzles, and turbopumps. Other components also offer opportunities for weight reduction through the use of composite materials, particularly in valves, controls, and ducting systems.

The OTV nozzle is typically constructed of a tube bundle wall constrained by structural jackets, bands, rings, and hatbands. Thrust loads, hoop tension, shear, and bending loads are carried through the combustion chamber and nozzle structural members. The chamber liner does not typically carry high mechanical loads, and its primary function is to provide a means of heat exchange between the regenerative coolant and the hot combustion gases. Therefore, by further breaking down the thrust chamber weight, it can be anticipated that the greatest weight savings can be obtained by applying composite materials to the combustion chamber, nozzle extensions, and nozzle structural jackets. However, the possibility of innovative designs that integrate the structural jacket and chamber liner through the use of the advanced composite materials and fabrication techniques should not be overlooked.

A recent Rocketdyne IR&D study investigated the potential weight savings that could be achieved on a 40K LOX/H_2 regeneratively cooled thrust chamber with the use of composite materials. (See Appendix C.)

All engine components were considered and evaluated from the standpoint of their structural requirements, manufacturing peculiarities, operating environments, and the potential for weight reduction. Components such as ducts, lines, and housings are typical. Several screening processes were conducted, and five of the most promising candidates were selected for more detailed studies: (1) combustion chamber jacket, (2) nozzle jacket and support rings, (3) pump and valve housings, (4) actuating arms and ducts, and (5) nozzle extensions. For these selected components a review of potential advanced materials was conducted and design approaches were studied. After further design study, the list was narrowed to the most promising candidates for advanced composites. The estimated weight savings are shown in Tables 8 and 9 for the selected composite for each of the components. These results show that the combustion chamber structural jacket weight can be cut in half and the largest weight savings is made in the nozzle structural jacket and support rings. A significant potential weight savings was also identified in pump housings and propellant ducting for both engine assemblies. In the orbit-to-orbit engine assembly, the results show that the extendible nozzle weight can be reduced substantially by using a carbon/carbon composite.

TASK III - CONCEPTUAL DESIGNS AND TECHNOLOGY NEEDS

Component Selection of Composite Materials

Composite materials conceptual designs of each individual component in the two baseline engines were beyond the scope of work. Thus, a screening method was developed to select representative components for conceptual design. In Table 4, a summary of a typical earth-to-orbit, LOX/CH_4, 670,000-pound-thrust (vacuum), engine system weight is listed. For the component selection, each of the categories was reviewed, viz., the turbomachinery, preburners, thrust chamber, valves and controls, and the engine systems and components were selected for conceptual design. The selection of the components was based on:

1. Compatibility of composite materials with environmental requirements
2. Potential for successful fabrication
3. Current industrial activity
4. Interfacing component constraints to minimize the impact of interfacing components
5. Requirements for new technology
6. Cost effectiveness

In the following paragraphs, the general technology needs for composite materials applications are discussed. Then, the specific technology needs for each of the component conceptual designs are examined.

Generic Technology Needs

Design Allowables. An effort should be made to establish design allowables, particularly for the MMC materials, as most of the materials systems are still in a development stage, with property values still improving and evolving. In the continuous fiber composite systems, the fabrication or consolidation method has great impact on the performance of the part. It requires a very close working relationship between the designer and the supplier. In the whisker SiC-reinforced aluminum alloy system, forging or extrusion is required after the P/M consolidation of the composite. These processes, however, tend to create anisotropy of the materials. The particulate-reinforced composites, however, are less sensitive to the fabrication process, and it has been found that working, such as forging or extruding, generally improves their mechanical properties.

Compatibility with Propellants. The compatibility of MMC materials with rocket engine propellants is largely undefined, although some data are available on the basic matrix alloys (e.g., titanium, aluminum, ferrous, and nickel-base alloys).

Thermal Cycling Under Active Loading. This is a generic concern for liquid rocket engine components which suffer stringent thermal cycling service conditions (e.g., combustion chamber liners and turbine blades). Under another contract, Rocketdyne is investigating the application of fiber-reinforced superalloy composites to turbine components, and the findings of that program should shed some light on this subject.

Design and Analysis. Because of the anisotropic behavior of composite materials, and because they fracture in a brittle mode, it is most important to approach composite structures as a team effort involving design, structural analysis, and materials disciplines.

Joining and Consolidation. Bonding and joining of composites to themselves and to mating structures is a key issue. Much can be adopted from techniques developed for airframe structures, but much of that work which has been directed at polymer-matrix materials may not be suitable for metal-matrix structures.

In Table 10 the technology needs for the component designs described are listed. For each category of the engine components listed, conceptual designs of the applicable component were conceived, and the technology needs for these designs were identified.

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TABLE 10. COMPONENT TECHNOLOGY NEEDS

COMPONENT	COMPOSITE MATERIALS	CRYOGENIC PHYSICAL & MECHANICAL PROPERTIES	COMPATIBILITY LOX >1500 PSI	FIBER ORIENTATION DESIGN & ANALYSIS	CONSOLIDATION METHOD	ANALYSIS (FAILURE MODES)	JOINING BY TRANSITION PIECES	DISSIMILAR METAL BRAZING (AL/718)	WHISKER ORIENTATION AFTER WORKING	DISCONTINUOUS COMPOSITE WELDING	SUPERPLASTIC FORMING	CURRENT PRACTICE
ORBIT-TO-ORBIT	ENGINE ASSEMBLY											
Propell.Valves	SiC/Al Housings	X	X		X	X			X	X	X	
Cont'l. Valves	SiC/Al Hsngs	X	X		X	X			X	X	X	
Controller	Gr/Epoxy Hsng.			X	X	X						
Gimbal Bearing	SiC/Al					X						
Act. Strut & Pump Lugs	B/Al						X	X				
Propell. Ducts	SiC/Al	X	X		X	X	X	X		X	X	
Low P Fuel Pump												
Housing	Gr/Al			X		X						
Shaft	SiC/Al	X			X	X			X			
Wheel Turb.	B/Al			X	X	X						
High P. Fuel Pump												
Brg Supp	SiC/Al	X			X	X						
Housing	SiC/Al	X			X	X	X	X	X	X		
Crossover	SiC/Al	X			X	X	X	X		X		
Seal Brg. Ret	B/Al	X			X	X	X					
Stator	SiC/Al	X			X	X	X			X		
Low P. Ox Pump												
Housing Inducer	SiC/Al	X			X	X	X	X	X	X		
Turb Housing	SiC/Al	X			X	X	X	X		X		
Liner Inducer	B/Al	X		X	X	X	X					
Lab. Seal	B/Al	X		X	X	X	X					
High P. Ox Pump												
Housing	SiC/Al	X	X		X	X	X	X		X		
Seal Ass'y	SiC/Al	X	X		X	X						
Thrust Chamber												
Combustor	Gr/Cu			X	X	X	X					

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TABLE 10. (Continued)

COMPONENT	COMPOSITE MATERIALS	CRYOGENIC PHYSICAL & MECHANICAL PROPERTIES	COMPATIBILITY LOX >1500 PSI	FIBER ORIENTATION DESIGN & ANALYSIS	CONSOLIDATION METHOD	ANALYSIS (FAILURE MODES)	JOINING BY TRANSITION PIECES	DISSIMILAR METAL BRAZING (AL/718)	WHISKER ORIENTATION AFTER WORKING	DISCONTINUOUS COMPOSITE WELDING	SUPERPLASTIC FORMING	CURRENT PRACTICE
Jacket	B/Al			X	X	X	X					
Band	B/Al			X	X	X	X					
Lug & Struts	B/Al			X	X	X	X					
Nozzle	Carbon/Carbon			X	X	X	X					
EARTH-TO-ORBIT	ENGINE ASSEMBLY											
Propell. Vanes	SiC/Al Hsngs	X	X		X	X	X	X				
Control Valves	SiC/Al Hsng	X	X		X	X	X	X				
Controller	Gr/Ep Hsng			X	X	X						
Pneum. Cntrl	SiC/Al Hsng	X			X	X						
Thrust Chamber												
Combustor	Gr/Ep Jacket	X		X	X	X						X
Bands	Gr/Ep over 718 sheath	X		X	X	X						X
Rings												—
Hat bands												
Hi Press Fuel Pump												
Shaft	SiC/Ti	X		X	X	X						
Impel Sleeves	SiC/Al	X			X	X			X			
Impel Slinger	SiC/Al	X			X	X			X			
Blades	W fiber	X		X	X	X	X	X				
Brg Hsng	SiC/Al	X			X	X			X			
Low Press Fuel Pump												
Inducer	B/Al	X		X	X	X	X	X				
Spacer	SiC/Al	X			X	X			X			
Wheel	B/Al	X		X	X	X	X					
Shaft	SiC/Al	X			X	X						
Rotor	B/Al	X		X	X	X						
Nozzle	SiC/Al	X			X	X						

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TABLE 10. (Concluded)

COMPONENT	COMPOSITE MATERIALS	CRYOGENIC PHYSICAL & MECHANICAL PROPERTIES	COMPATIBILITY LH2 >1500 PSI	FIBER ORIENTATION DESIGN & ANALYSIS	CONSOLIDATION METHOD	ANALYSIS (FAILURE MODES)	JOINING BY TRANSITION PIECES	DISSIMILAR METAL BRAZING (AL/710)	OPTIMIZED ORIENTATION AFTER WORKING	DISCONTINUOUS COMPOSITE WELDING	SUPERPLASTIC FORMING	CURRENT PRACTICE
Stator	SiC/Al	X			X	X						
Shroud	SiC/Al	X			X	X	X					
Hsng	SiC/Al	X			X	X	X	X		X	X	
Seals	SiC/Al	X			X	X						
Low Press Ox Pump												
Inducer	B/Al	X		X	X	X						
Rotor	B/Al	X		X	X	X						
Cap	SiC/Al	X			X	X						
Sleeve	SiC/Al	X			X	X			X			
Stator	SiC/Al	X			X	X	X		X			
Nozzle	SiC/Al	X			X	X	X					
Housing	SiC/Al	X			X	X	X		X			
Brg. Supp	SiC/Al	X			X	X			X			
Spacer	SiC/Al	X			X	X						
Nut	SiC/Al	X			X	X						
Eng Systems												
Propell Ducts	SiC/Al	X			X	X	X	X	X		X	
Press Syst	SiC/Al	X			X	X	X	X	X		X	
Accumulator	SiC/Al Gr/Ep	X			X	X	X	X	X		X	
Baffles	SiC/Al	X			X	X	X				X	
Gimbal Brg	SiC/Al				X	X						
Act Struts	B/Al				X	X	X					

Turbomachinery

A sketch of a high-pressure fuel pump is shown in Fig. 6. In this assembly, several subcomponents were identified as potential condidates for composite materials application, as discussed below.

1. Thrust bearing housing - A discontinuous SiC-reinforced aluminum is suggested. The current material is Hastelloy B. A discontinuous SiC-reinforced aluminum composite can be extruded and machined to replace the current material and result in an approximate 30% weight saving.

2. The sleeve - The sleeve is operated in compression; therefore, a SiC/Al composite can be used. Composite materials generally exhibit very high compressive strength when compared to their tensile properties. Composite materials should be favored in compressive loading areas. The current sleeve material is Inconel 718.

3. The shaft - A high-strength fiber SiC/Ti composite material could be used. The titanium matrix composite has higher strength than the aluminum matrix composite. The use of titanium composites avoids dimensionally changing the shaft. The detail fiber arrangement and consolidation method requires some major technology development. Avoiding fiber breaking of the hoop (or ±45°) fibers during consolidation by diffusion bonding could be a major concern. The current shaft material is Inconel 718.

4. Turbine blades - A tungsten fiber-reinforced superalloy could be used in this application. The primary advantage of using this type of composite material is not for weight saving; rather, it is for higher performance and longer service life. The current blade material is DS-MAR-M-246.

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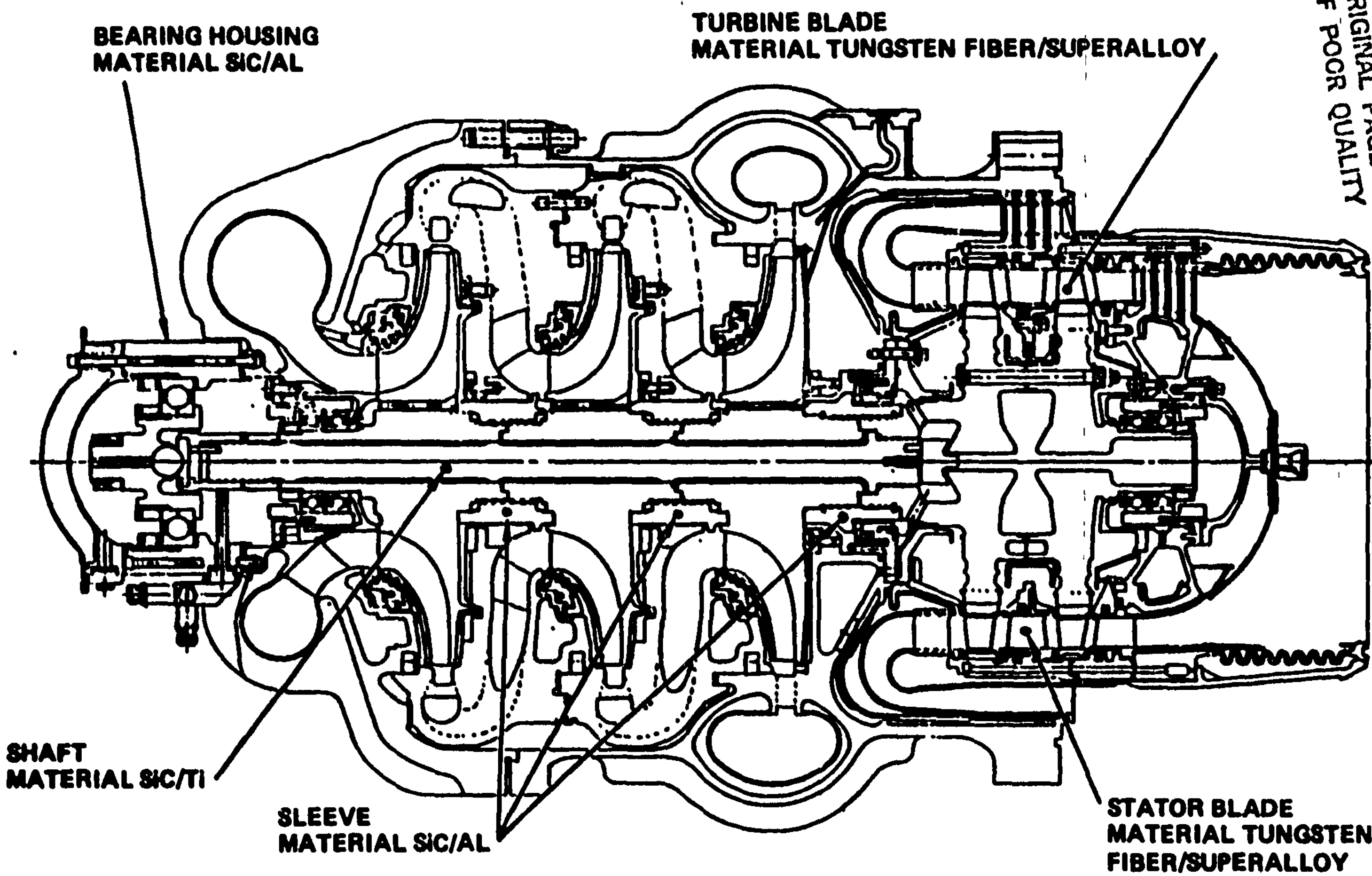

Figure 6. High Pressure Fuel Pump

Low-Pressure Fuel Turbopump (LPFTP)

A LPFTP manifold housing could be made of discontinuous SiC/Al composites. The housing is symmetrical with an open section and, therefore, could be forged and machined. The stiffeners and the bellows could be brazed. The SiC/Al is compatible with the gaseous hydrogen. The brazing would require some development work for this geometry. The housing-to-bellow joint brazing could be a problem because of pressure-containing requirements. The current material used is Inconel 718.

Thrust Chamber

In this category, three components were studied: the gimbal bearing, the thrust chamber jacket, and the strut actuator assembly.

Gimbal Bearings. In Fig. 7, an earth-to-orbit engine gimbal bearing is shown. Discontinuous SiC/Al composites could be used for this application. If, as expected, the composite materials also reduce surface frictional loads, better performance will result from this substitution. The geometry of the gimbal bearing makes it a prime candidate for discontinuous composite application.

Combustion Chamber Jacket. A graphite epoxy structural jacket has been designed and a 40K thrust chamber has been built by Rocketdyne, as shown in Appendix C, Fig. C-1 and C-2. Another design using MMC materials such as Boron/aluminum (B/Al) is illustrated in Fig. 8. In this design, two B/Al fiber-reinforced clam shells are joined by welding. This structural jacket is bonded with titanium transition pieces to facilitate brazing to the Inconel 718 manifold fittings. Obviously this structural jacket is designed to carry bending. The internal pressure, however, is still handled by the chamber section itself. The technology needs lie in the area of the welding the clam shells and brazing the shells to the Inconel 718 manifold fittings.

Strut Actuator Assembly. The strut actuator assembly, AP82-084 (Fig. 9) is mounted on the earth-to-orbit baseline engine. It is an adaptation of the

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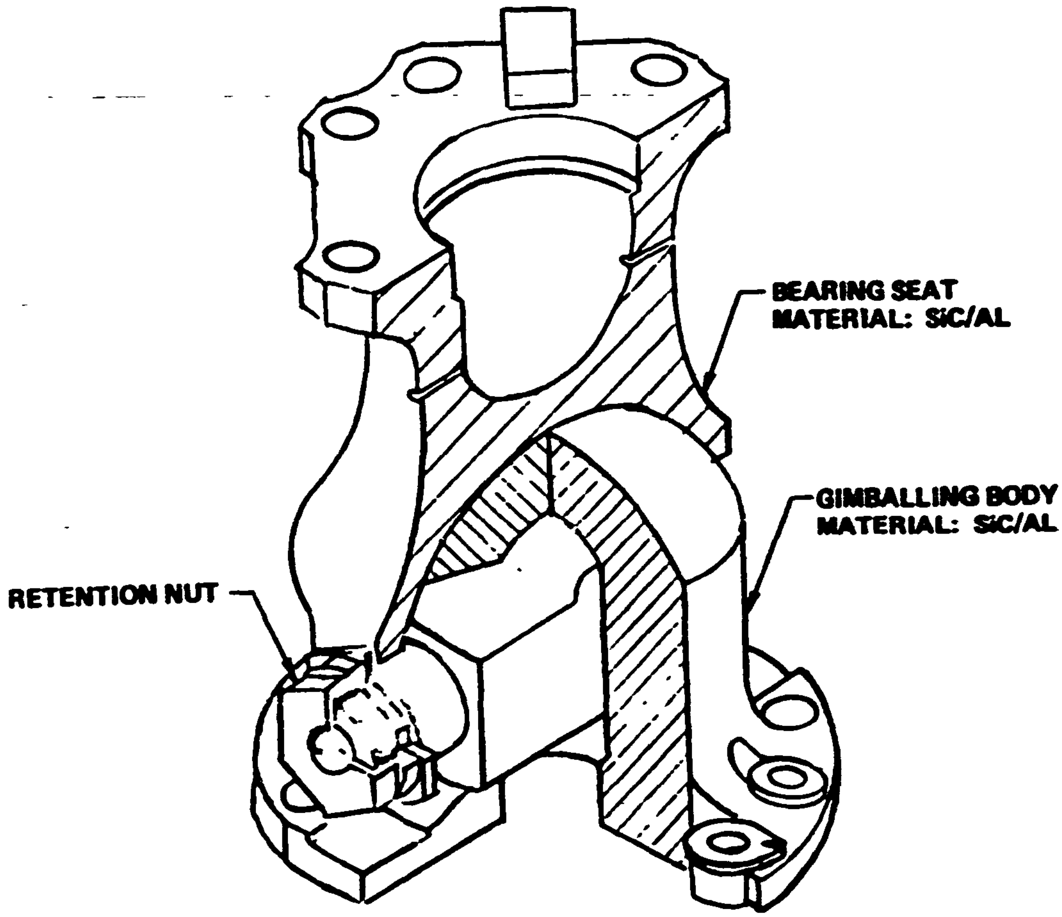

Figure 7. Gimbal Bearing Assembly

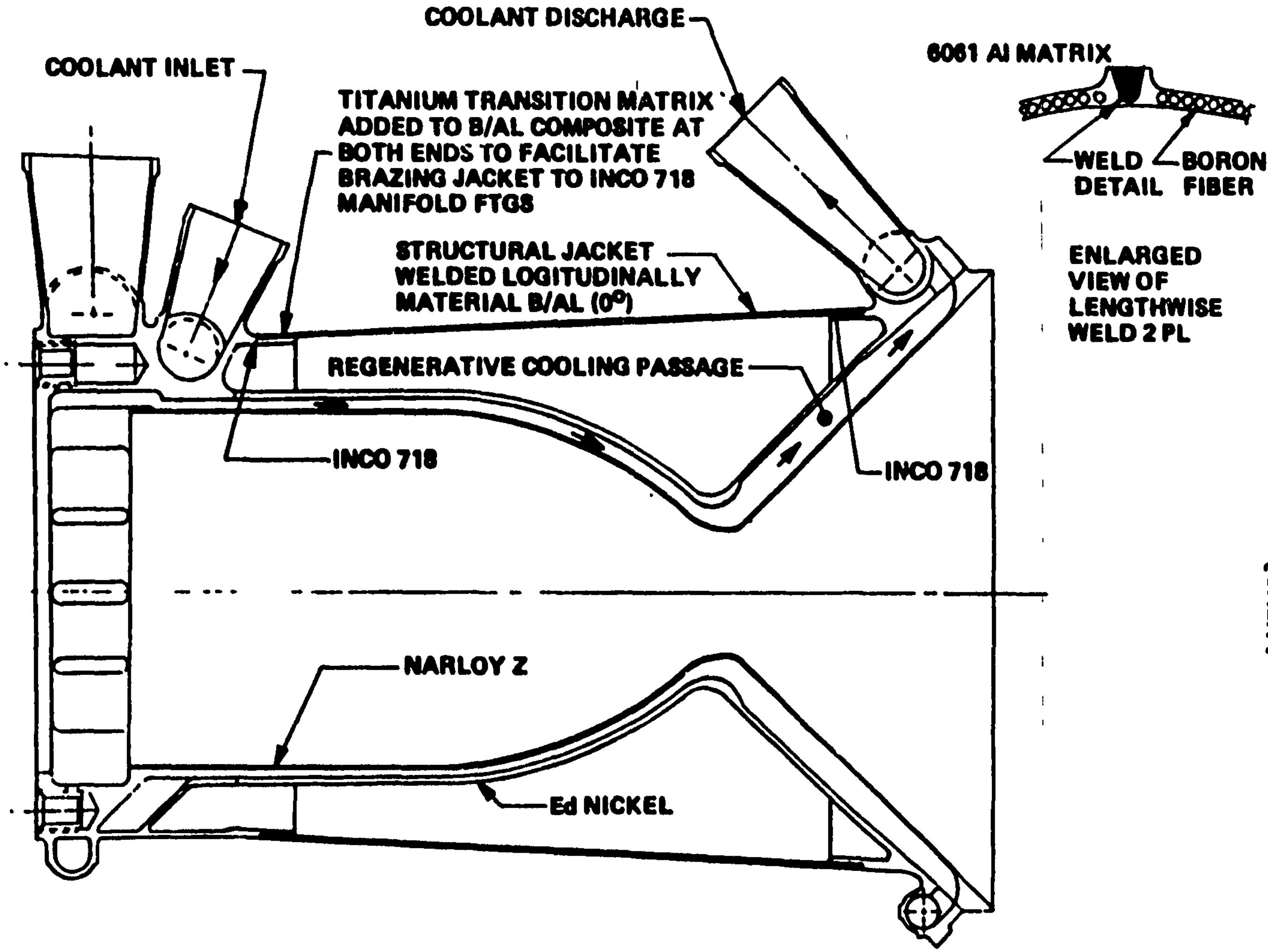

Figure 8. Regenerative Chamber Structural Jacket

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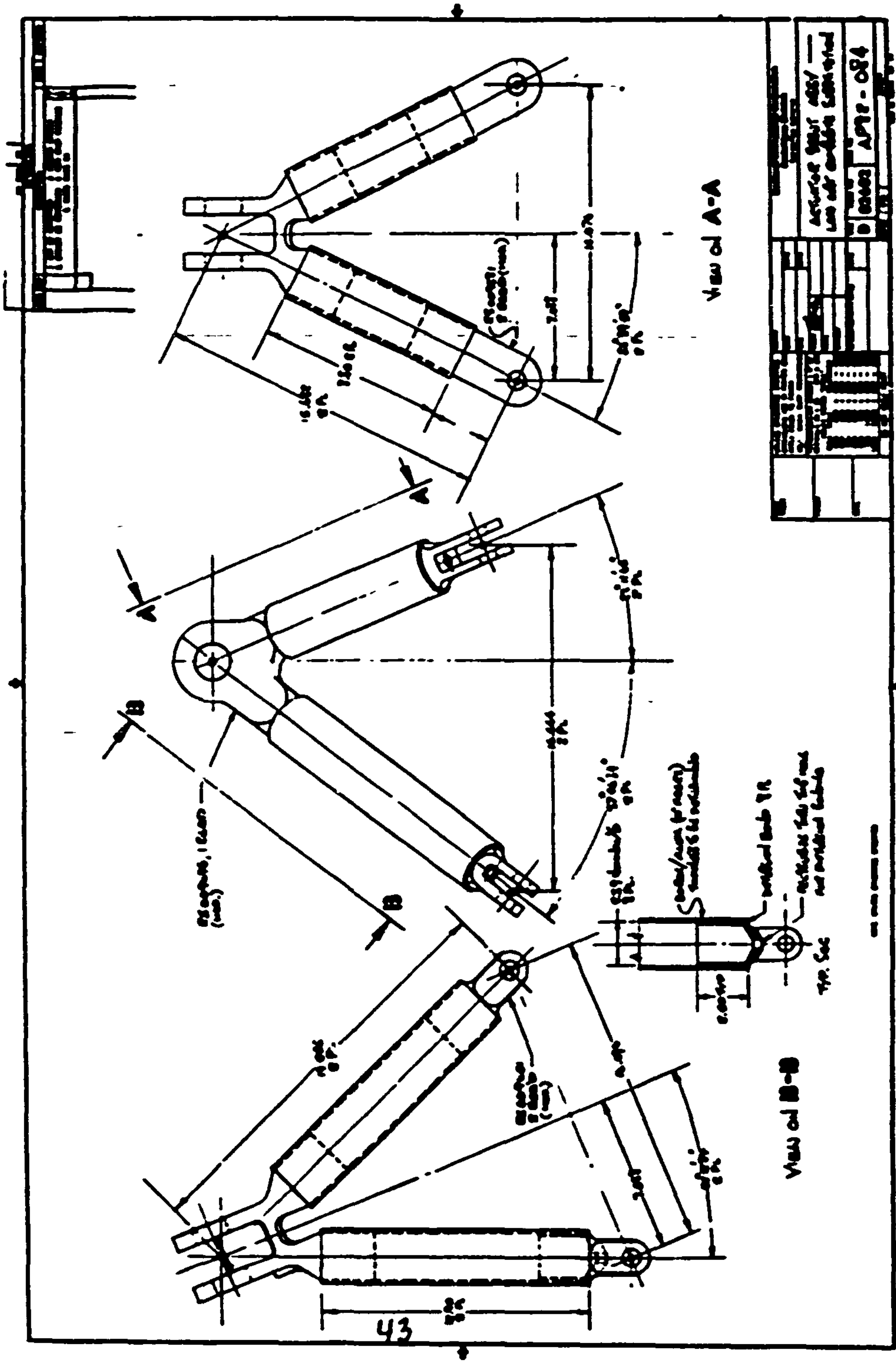

Figure 9. Actuator Strut Assembly

existing assembly on the Space Shuttle main engine (SSME), and provides support for the moving ends of the gimbaling control actuators. Table 11 summarizes two concepts and identifies the technology needs.

Boron/aluminum composite tubing is used to replace the existing titanium tubing. Unlike the low-pressure ducting, the B/Al composite tubing in the AP82-084 strut assembly is not subjected to internal pressure, enabling the fibers to be oriented parallel to the tube axis and avoiding the fabrication difficulties inherent in B/Al pressure tubing. The B/Al tubes are diffusion-bonded to the titanium clevises at a pressure and temperature of 10 ksi and 1000 F, respectively. The B/Al substitution results in a weight reduction of approximately 8 pounds over the existing weight of 45 pounds for the titanium weldment.

Slight additional weight savings could be achieved by substituting silicon carbide/aluminum (SiC/Al) composite for the titanium clevises. Thirty percent by volume of silicon carbide particulates in 6061 aluminum has isotropic properties, but less than half the strength of titanium. Therefore, the physical proportions of the clevises would have to be increased proportionately.

From the four valves used to control propellant flow, the main fuel valve (MFV) was selected as the candidate for composite material application. The MFV (Fig. 10) of the SSME operates in a hydrogen environment at an internal pressure of 6000 psi. In a LOX/CH_4 engine, the MFV will contain methane at about 4000 psi. Valve subcomponents such as the housing, shaft, couplings, and end-caps (Fig. 11 through 13) are candidates for discontinuous SiC/Al composite application.

Engine Systems

Low-Pressure Cryogenic Ducting. A study was made of the possibility of using composite material substitutions for elements of the low-pressure fuel and oxidizer ducting on the SSME. This would closely approximate the ducting requirements for the baseline earth-to-orbit engine (Fig. 14 and 15).

TABLE 11. COMPOSITE STRUT ACTUATOR

COMPONENT	COMPOSITES	WEIGHT SAVING	FABRICATION	TECHNOLOGY NEEDS	RANKING
ACTUATOR STRUT	TUBE	40%	EB WELD AT SEAM LONGITUDINALLY	Al-Al DIFFUSION BONDING OR BRAZING	LOWER STRENGTH Al CAN BE WELDED
Ti-6AL-4V (PRESENT)	A CIRCULAR CYLINDRICAL SHELL				
CONCEPT 2	B/Al (2024T4) PLIES 60% 0° 40% ± 45°				
	CLEVIS SiC WHISKER PARTICULATE/6061-T6	~5%	EXTRUSION		
CONCEPT 1	TUBE A CIRCULAR CYLINDRICAL SHELL	40%	DIFFUSION BOND	STATE OF THE ART	
	CLEVIS - Ti6-4				

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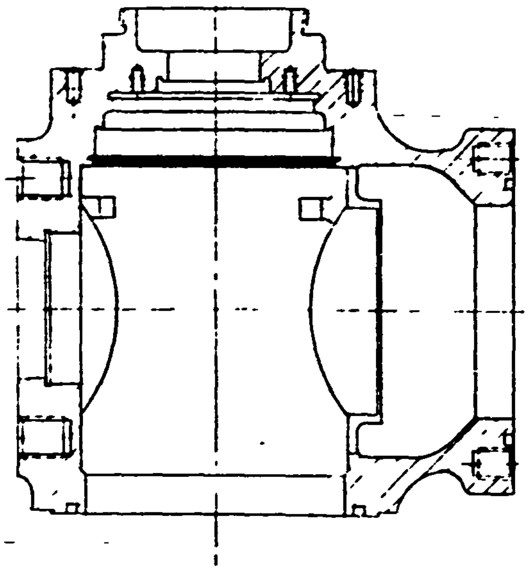

VALVE	EXISTING WGT. (LBS)	COMPOSITE WGT. (LBS)	Δ WGT.
MAIN PROPELLANT			
• HSG - FUEL	32.69	26	6.69
PREBURNER			
• HSG - FUEL	19.07	15	4.07

Figure 10. Main Fuel Valve Housing Assembly

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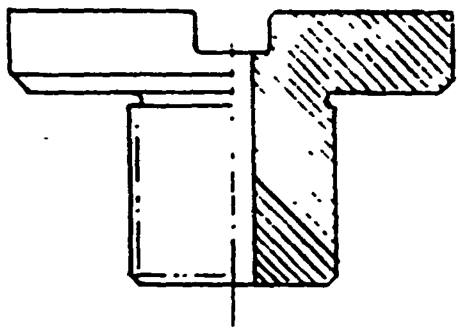
PART NAME	EXIST WGT (LBS)	COMPOSITE WGT (LBS)	ΔWGT
MAIN PROPELLANT			
• COUP. - FUEL (LOWER)	1.46	1.2	.26
• COUP FUEL (INTERMEDIATE)	0.79	.63	.16
• PREBURNER COUP.			
• COUP. - FUEL	.50	.40	.1



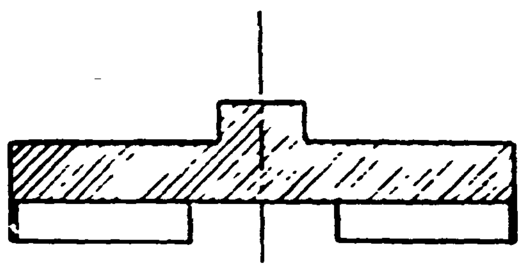


Figure 11. Main Valve Coupling Assembly

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VALVE	EXISTING WGT. (LBS)	COMPOSITE WGT. (LBS)	Δ WGT.
MAIN PROPELLANT			
• SHAFT - FUEL	11.0	8.8	2.2
PREBURNER			
• SHAFT - FUEL	3.32	2.66	.66

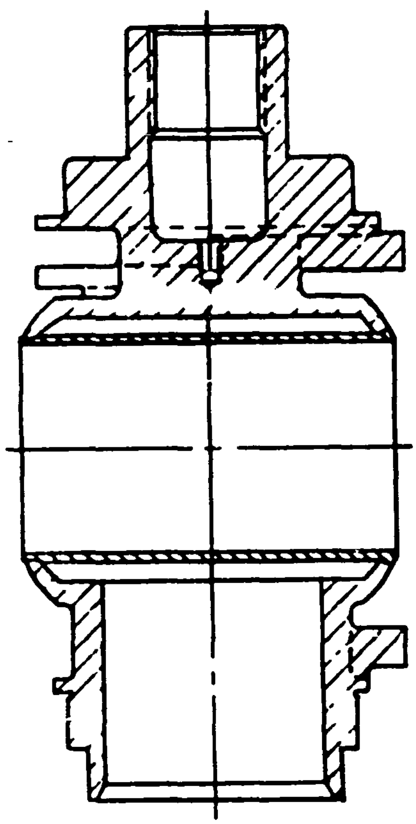

Figure 12. Main Valve Shaft Assembly

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VALVE	EXISTING WGT. (LBS)	COMPOSITE WGT. (LBS)	Δ WGT.
MAIN PROPELLANT			
• COUPLING - FUEL	1.59	1.27	.32
PREBURNER			
• COUPLING - FUEL	.50	.40	.1

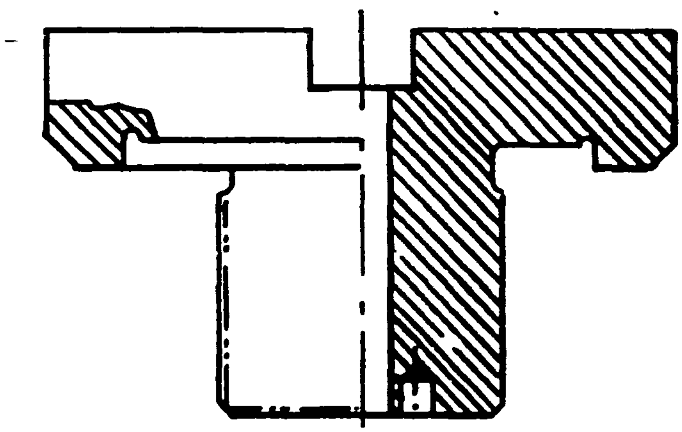

Figure 13. Main Valve Upper Coupling

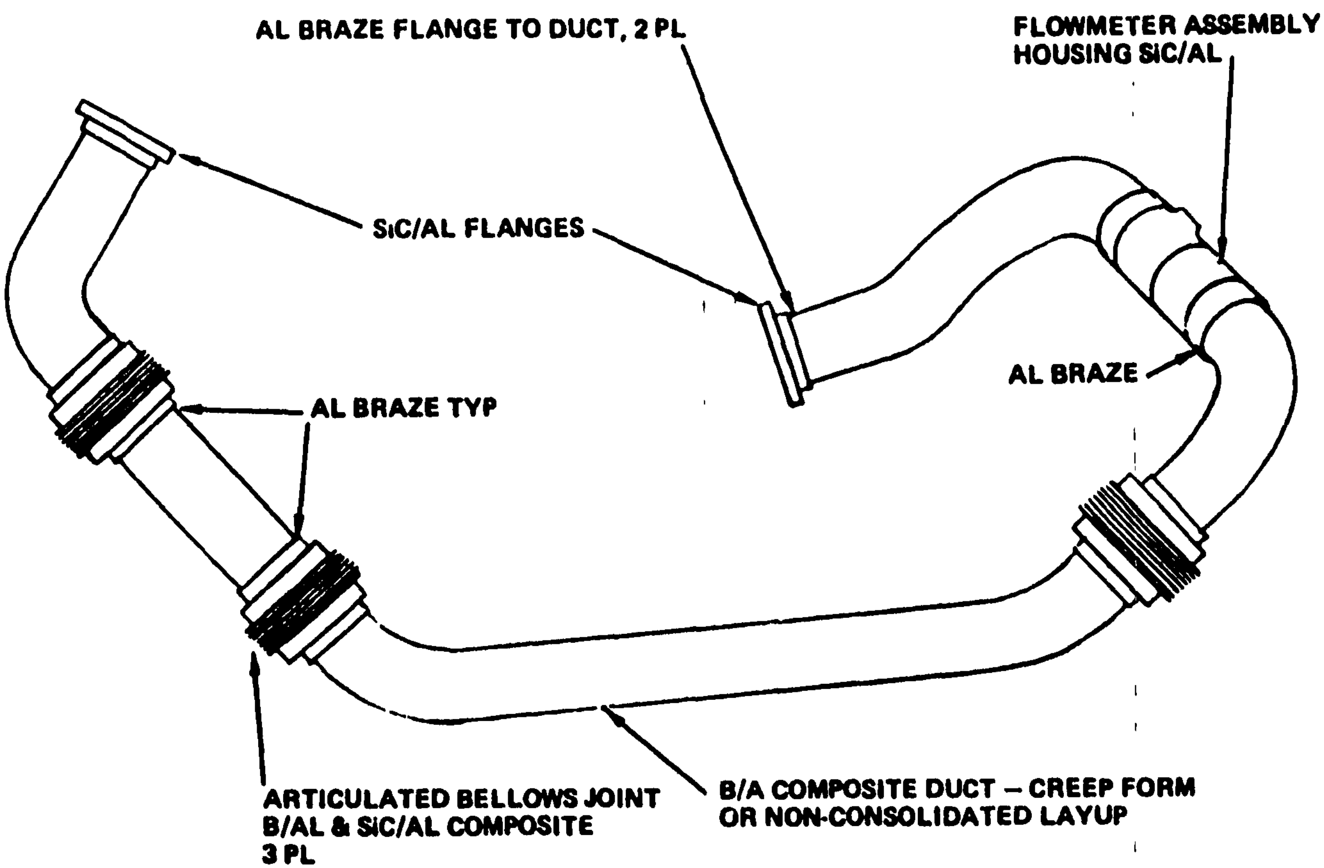

Figure 14. Low-Pressure Fuel Duct

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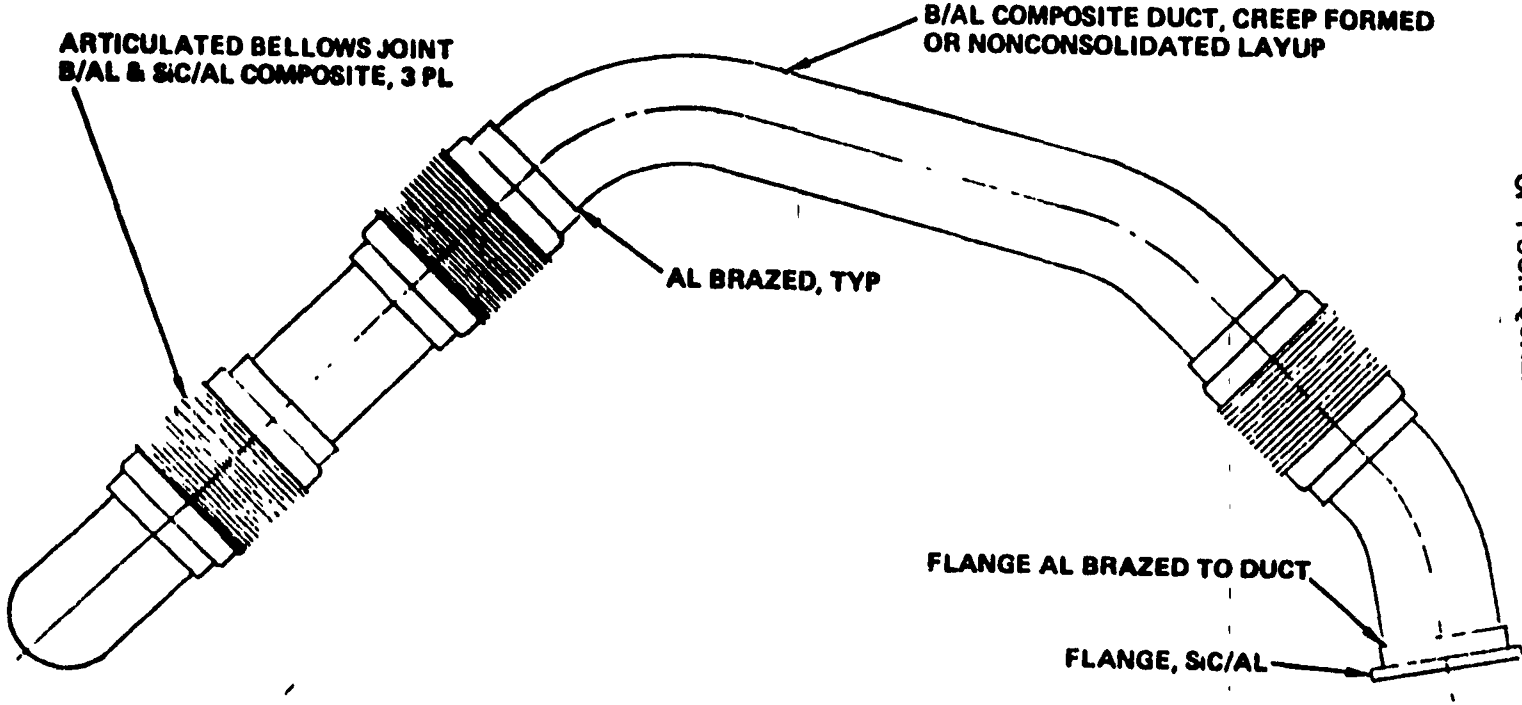

Figure 15. Low-Pressure Oxidizer Duct

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The subject ducts serve a dual purpose in that they transfer cryogenic propellants from the low- to the high-pressure fuel/oxidizer pumps and accommodate the engine gimbaling motion.

The latter function is accomplished by flexible bellows joints presently constructed out of Inconel 718 (Fig. 16). These joints make up almost 50% of the total duct weight. Weldability and ductility of existing metal matrix composites preclude their use for the Inconel 718 bellows. The internal linkage joint (Fig. 17) could be fabricated from SiC/Al composite. Joining the Inconel 718 bellows to the SiC/Al linkage joint requires diffusion bonding of transition sleeves to the linkage joint elements, and welding or brazing the ends to the bellows. Present weight of the low-pressure fuel (LPF) and low-pressure oxidizer (LPO) bellows joints are 12 and 25 pounds, respectively. Replacing the Inconel 718 internal linkage with equivalent SiC/Al composite would result in a 3- and 7-pound weight savings per bellow joint, respectively. With three bellows joints per duct, the potential saving is 30 pounds.

Present tubing material is Inconel 718. Boron/aluminum metal matrix composite is a suitable substitute. As with the bellows joints, diffusion-bonded transition sleeves are required to transmit the axial shear load from the composite ducting to the bellows joints and flanges.

Filament orientation in B/Al composite tubing, other than 0°, i.e., parallel to the tube axis, is limited by the nature of the fabrication process. Boron/aluminum is made by diffusion-bonding multiple layers of aluminum foil and boron fibers. In the case of B/Al tubing, the layers are assembled inside a tube and diffusion-bonded by internal pressure, and is illustrated schematically in Fig. 18. This results in compressing the layers against the fixed outer diameter of the tool. If any of the fiber layers are oriented transverse to the tube axis, they are subjected to extreme hoop stresses as they try to increase in length in response to the high internal pressure, thus resulting in tensile failure of the fibers. The problem can be alleviated to some extent by orientating the fibers at an intermediate helix angle. In any event, current fabrication methods limit the effectiveness of B/Al pressure tubing.

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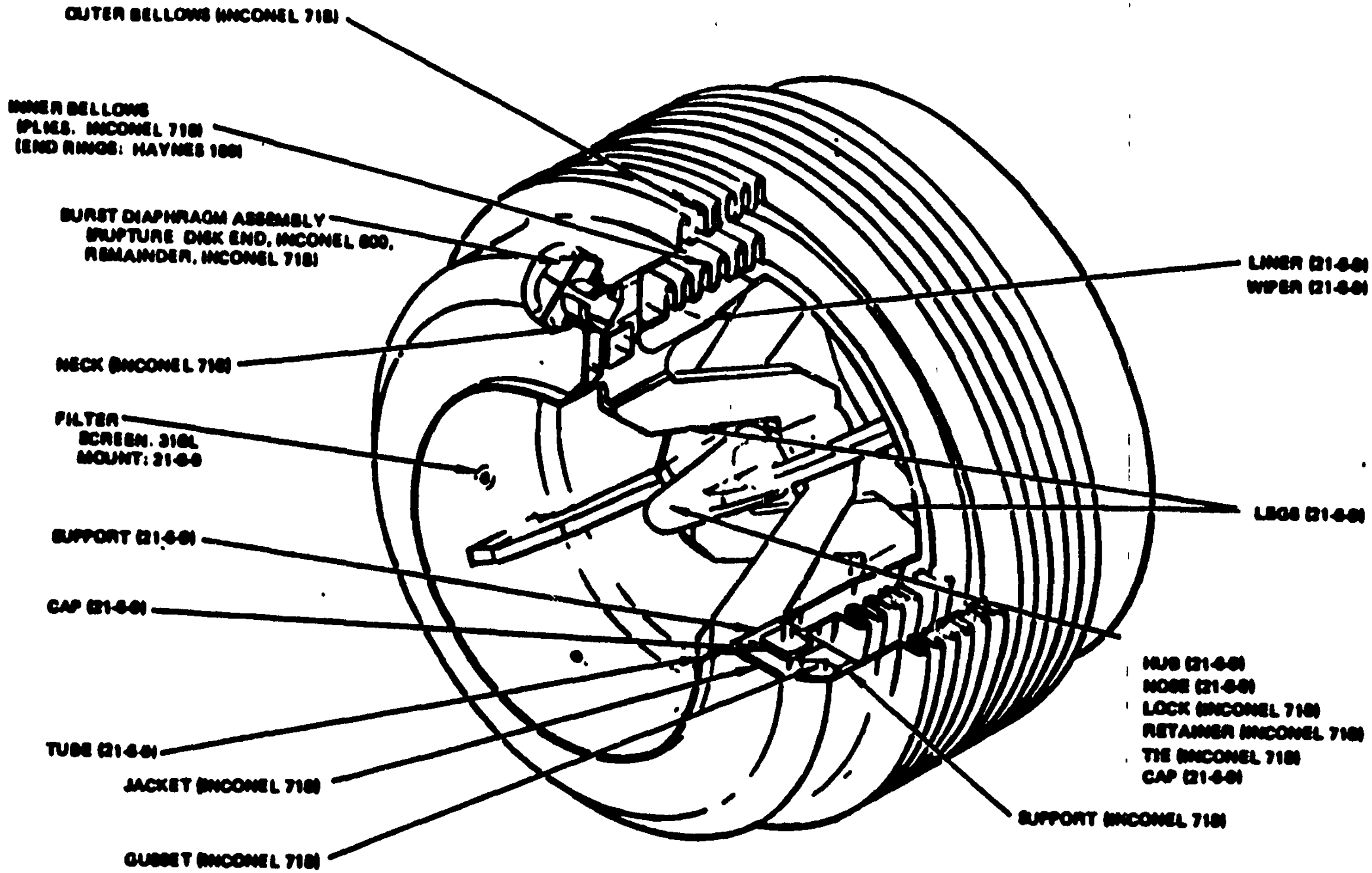

NOTE. DRY FILM LUBRICANT PER RA0112-086, TYPE I, CLASS 3 IS APPLIED TO THE FOLLOWING SLIDING SURFACES. WIPER/LINER, TIE/HUB, HUB/HUB

Figure 16. Flexible Bellows Joint

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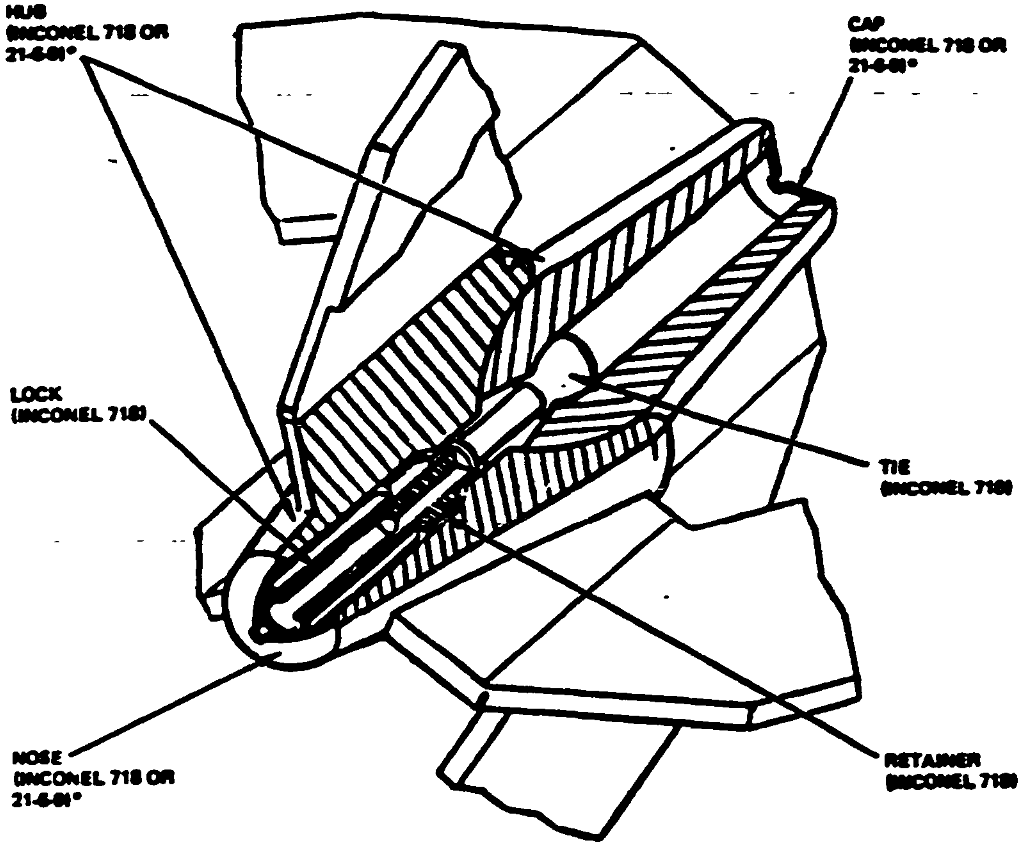

Figure 17. Internal Linkage Joint

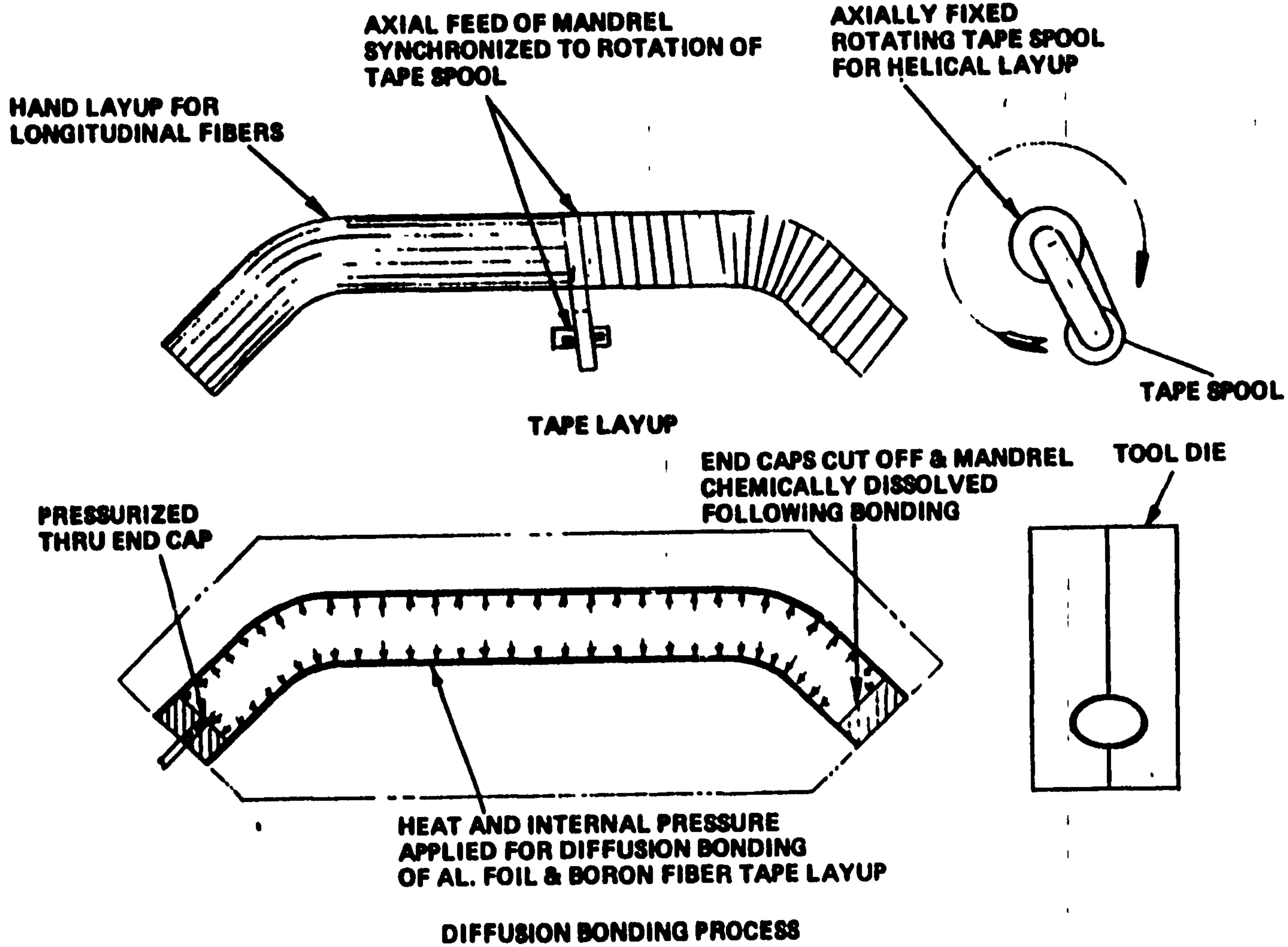

Figure 18. B/Al Duct Fabrication

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Discussion with the manufacturer, Amercon, indicates that this problem can be alleviated almost completely by placing the circumferentially wrapped fiber layers adjacent to the tool surface. This restricts the radial movement of fibers, thus reducing circumferential elongation.

Present weight of the Inconel 718 LPF and LPO tubing is 32 and 38 pounds, respectively. Equivalent-strength B/Al tubing for the fuel duct will be approximately 12 pounds, and approximately 15 pounds for the oxidizer duct.

The combined potential weight saving for the baseline earth-to-orbit engine LPF and LPO ducting through the selective substitution of metal matrix composites is 57 pounds.

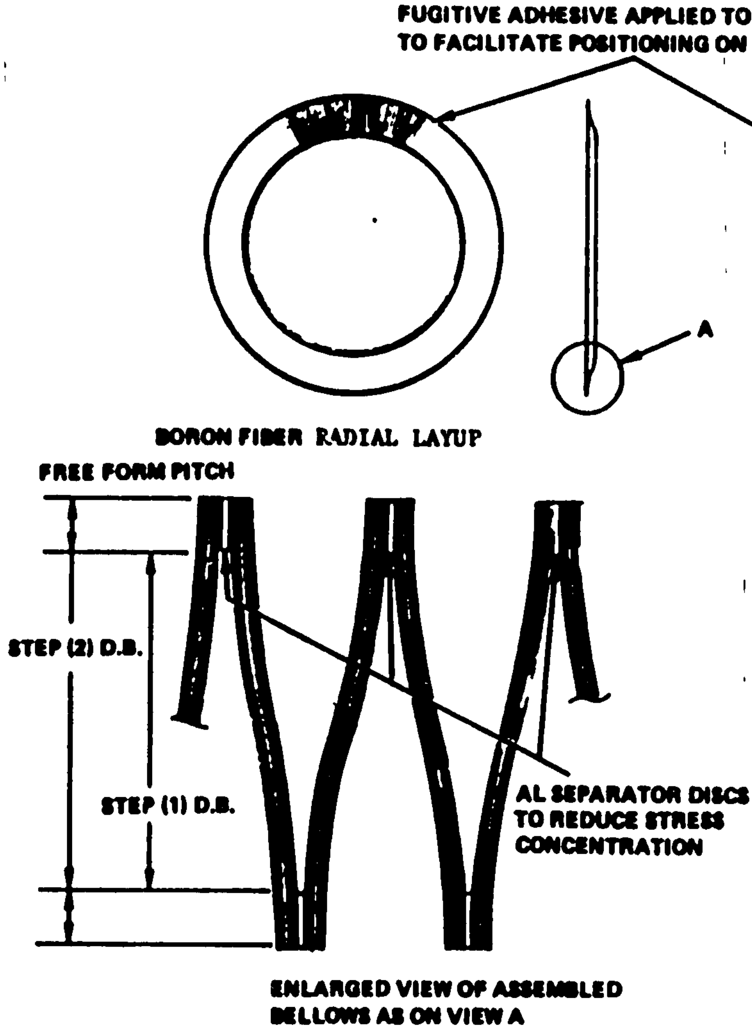
The foregoing metal matrix composite substitution is predicated on developments in diffusion bonding, particularly aluminum to super alloys and improved fabrication methods for B/Al composite pressure tubing.

A listing of the mechanical properties of B/Al and SiC/Al composites is shown in Table 7.

The earth-to-orbit baseline engine low-pressure propellant ducting must accommodate the gimbaling motion of the engine as well as thermal expansion. This is accomplished by the use of three bellows joints in each duct assembly as illustrated in Fig. 14 and 15.

Since these bellows joints represent almost 50% of the propellant duct assembly weight, a considerable amount of effort has been devoted to designing a metal matrix composite bellows. Fabrication of the B/Al bellows is illustrated in Fig. 19. The assembly drawing of the B/Al bellows joints is shown in Fig. 20. An alternate design incorporating SiC/Al composite is shown in Fig. 21.

<u>Graphite/Epoxy (Gr/Ep) Composite Wound Low Pressure Oxidizer and Fuel Ducting</u>. An alternate Gr/Ep low-pressure propellant ducting has been investigated in place of the previous B/Al metal matrix ducting. The Gr/Ep composite is applied over



- PRECONSOLIDATED DISCS MADE UP OF MULTIPLE LAYERS OF ALUMINUM FOIL INTERSPERSED WITH RADIAL AND CIRCUMFERENTIAL BORON FIBER
- INDIVIDUAL DISCS PARTIALLY DIFFUSION BONDED WITH INSIDE AND OUTSIDE EDGES LEFT FREE
- DISCS STACKED UP AND POSITIONED WITH SPLIT COLLET TOOLING
- BELLOWS ASSEMBLY SEALED INSIDE AN EVACUATED STAINLESS STEEL RETORT AND DIFFUSION BONDED
- BELLOWS REMOVED FROM RETORT AND TOOLING FOR INSPECTION

Figure 19. B/Al Bellows Fabrication

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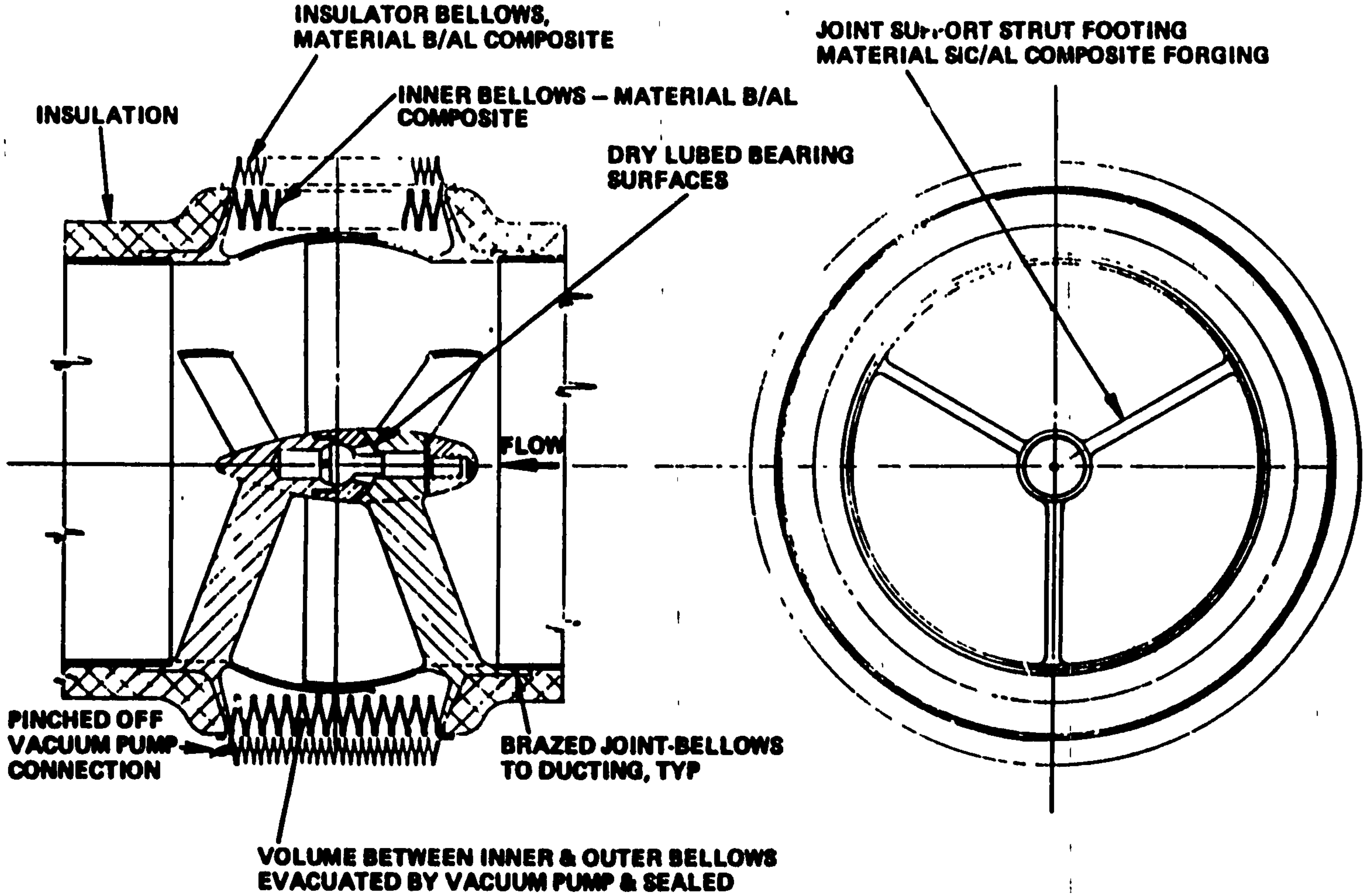

Figure 20. Articulated Bellows Joint

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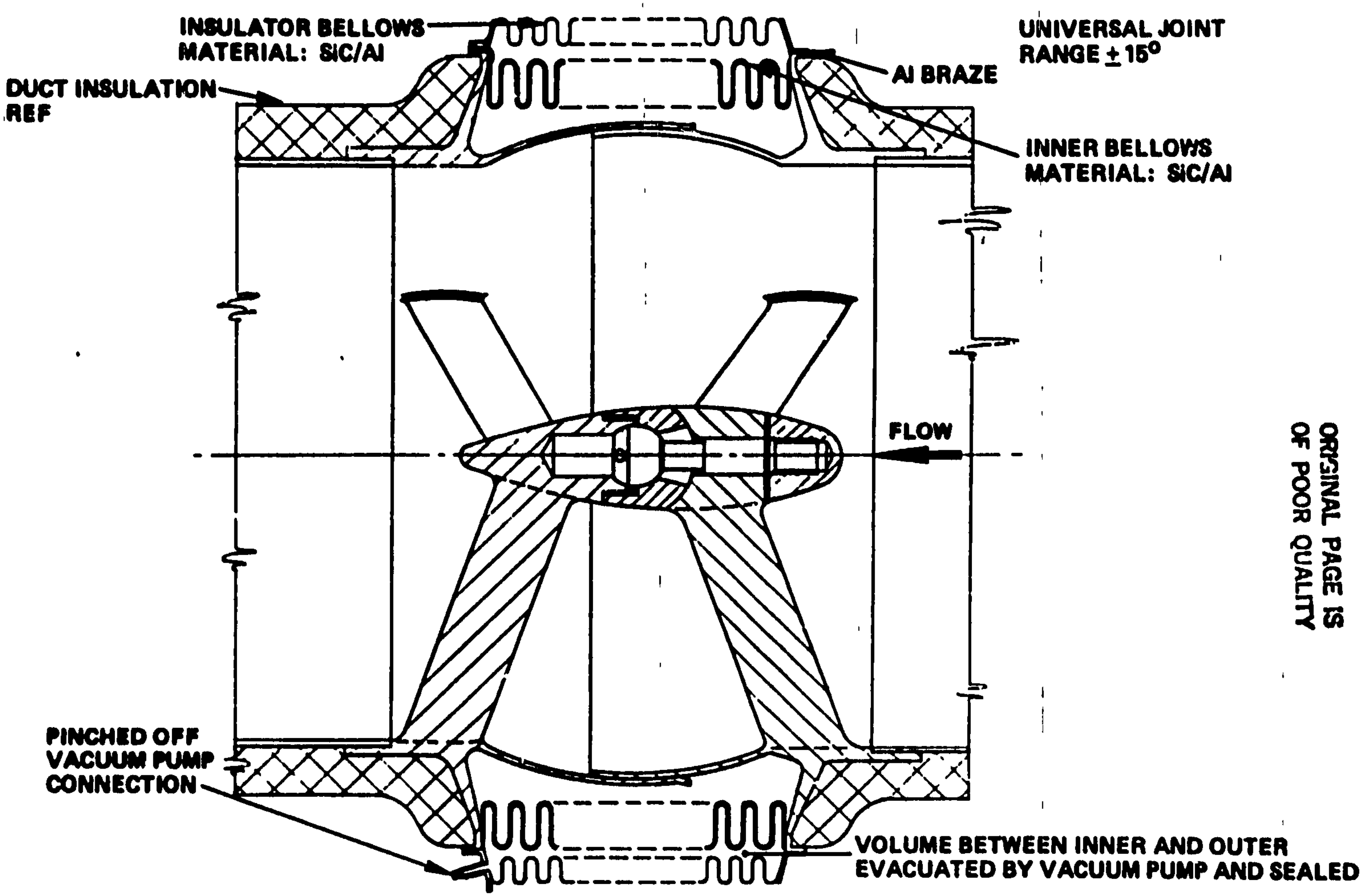

Figure 21. Articulated Bellows Joint Superplastic Forming-SiC/Al

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a 0.020-inch-thick 6061 Al welded sleeve. The filament is applied longitudinally in prepreg tape (0° orientation), and the outer layers are wound circumferentially (90° orientation).

The Gr/Ep overwraps a thickened aluminum convoluted ferrule at the end flanges and bellows joints for axial and hoop load reaction.

The possibility of separation of the Gr/Ep from the aluminum liner due to thermal cycling is a potential problem, particularly for the liquid hydrogen ducting.

Figure 22 illustrates the basic details of the duct configuration.

Graphite Epoxy Nozzle Jacket

Considerable weight savings can be achieved on the earth-to-orbit engine nozzle by incorporating a 16-layer (0.20-inch thick), Gr/Ep jacket over a REGEN tube bundle and light gauge Inconel 718 sheath. The Gr/Ep is applied in 13 prepreg gores with 0° fiber orientation. The outer three layers are wound circumferentially (90° orientation) to react hoop loading.

To facilitate application of the Gr/Ep jacket, the coolant feed ducts to the tube bundle are welded to tube stubs after applying and curing the jacket.

Figure 23 illustrates the general construction of the nozzle, and Table 12 shows the potential weight savings through substituting Gr/Ep composite for the more conventional metal jacket and hat bands. Note that the insulation weight requirements are also reduced through Gr/Ep composite substitution due to its inherent insulation properties.

Technology Needed for the Component Application

In this study, there are many technology areas identified for component application. Those in need of technology development can be divided into two categories; i.e., the generic and the specific.

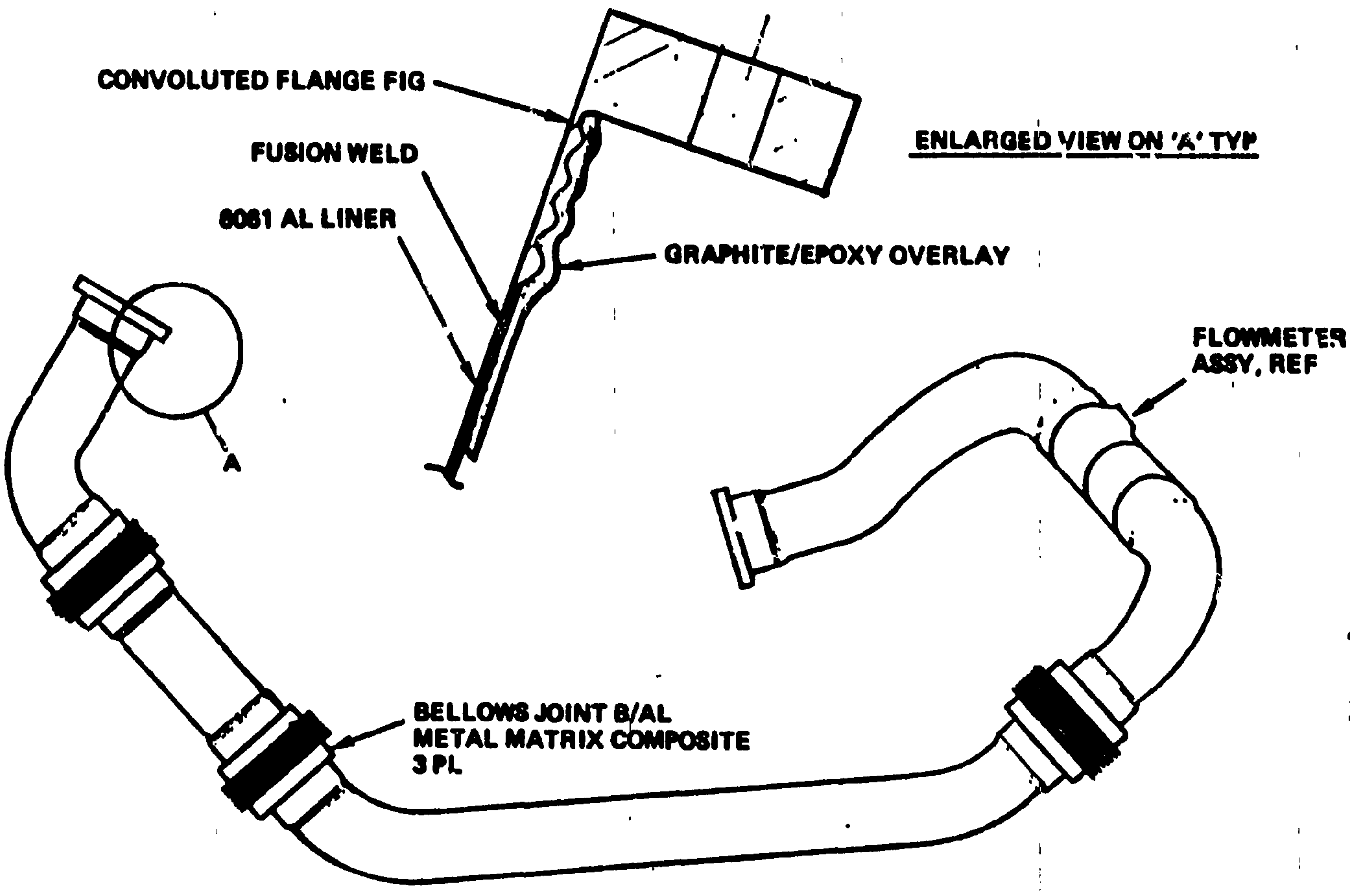

Figure 22. Gr/Ep Composite Wrapped Low-Pressure Propellant Duct

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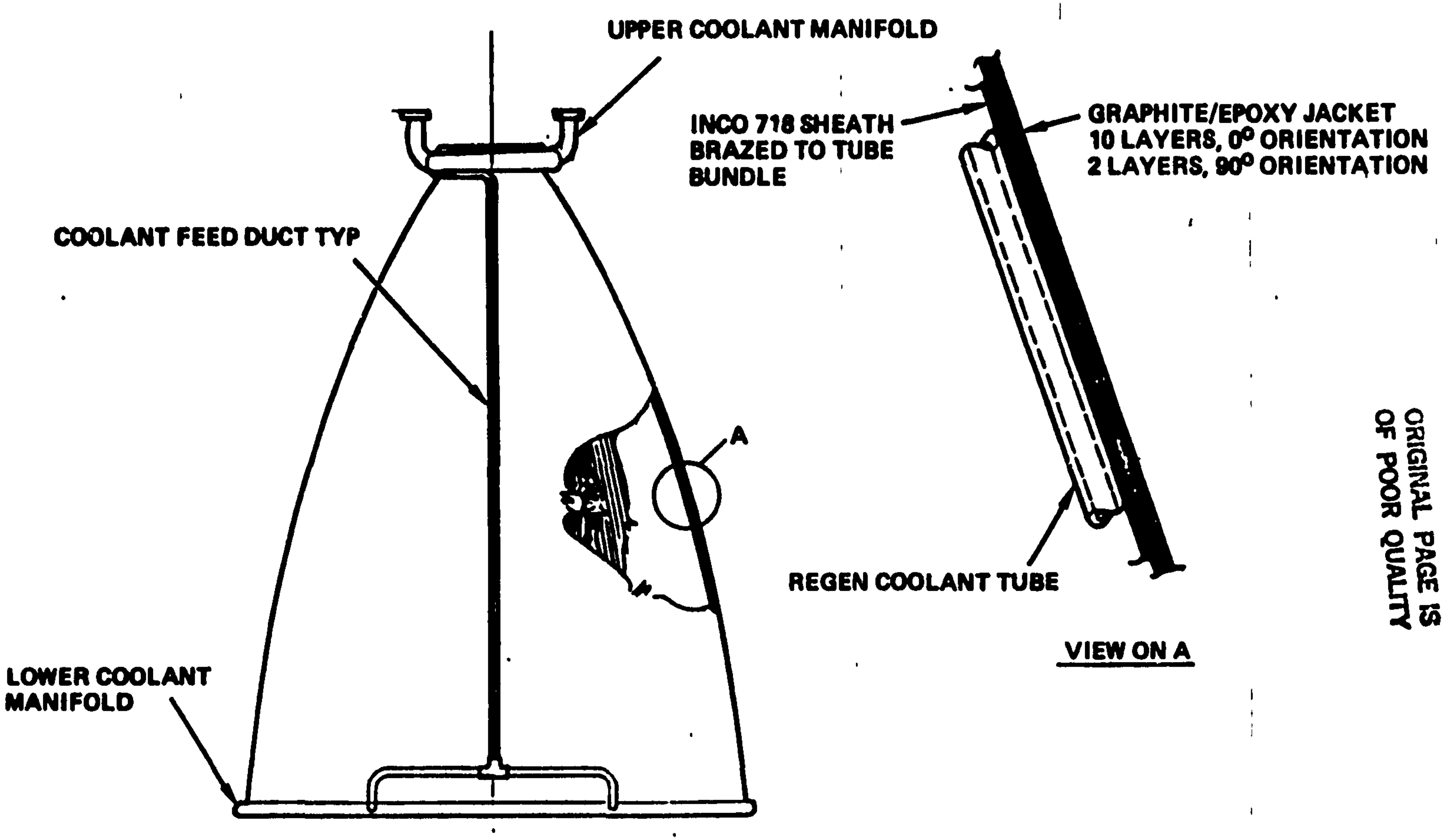

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Figure 23. Gr/Ep Composite Jacket

TABLE 12. EARTH-TO-ORBIT BASELINE ENGINE NOZZLE

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METAL DESIGN	WEIGHT POUNDS
1. TUBE BUNDLE	
• COOLANT TUBES	288.3
• PLATING TUBES	50.2
• BRAZE	62.5
2. AFT FUEL MANIFOLD	120
5. MIXER SEPARATOR VALVE	51.7
6. FORWARD OUTLET	156.3
7. INLET DIFFUSER AND SUPPORT	49.3
*8. BANDS	124.3
*9. RINGS	174.8
*10. HAT BANDS	192.9
11. DRAIN LINES	70.6
12. TRANSFER DUCTING	122
13. CHAMBER BYPASS DUCT	17.2
14. INSULATION	165.7
TOTAL	1645.8
COMPOSITE DESIGN (REPLACES BOXED ITEMS ONLY):	
SHEATH (INCONEL 718)	261.5
GRAPHITE EPOXY JACKET	77.7
INSULATION	64.7
TOTAL	403.9
BOXED ITEMS TOTAL	657.7
COMPOSITE DESIGN TOTAL	403.9
NET WEIGHT SAVING	253.8

Generic.

Cryogenic Properties. Because many engine components are exposed to cryogenic temperatures during operation, it is necessary to characterize the MMC materials' cryogenic, physical and mechanical properties. The aluminum alloys become stronger and show high ductility at cryogenic temperature; it remains to be seen whether aluminum MMC materials exhibit similar behavior.

Compatibility With Propellants. Compatibility tests should be run on MMC materials exposed to liquid rocket engine propellants. The environmental effect of propellants on the mechanical properties of the MMC materials should also be studied.

Thermal Cycle Fatigue Resistance. Thermal cycling of liquid rocket engine components will be a major challenge to MMC material's performance because of the large thermal expansion differentials between the matrix materials and the reinforcements.

Low Cycle Fatigue. The current baseline liquid rocket engines use ductile materials. It is foreseeable that the design properties and guidelines of MMC could be different from the current materials.

Whisker Orientation, Aspect Ratio Control. This is specifically for the SiC whisker-reinforced aluminum alloys. Currently, there is very limited data for this type of study.

Specific. There are specific technology areas to be developed in the components selected and conceptually designed. These include the following.

Anisotropic Properties of Whisker-Reinforced MMC Material. It is desirable to determine the shear strength of the whisker-reinforced aluminum in the plane in which most of the whiskers lie after extrusion. No need for this study is required if a particulate composite such as CT-90 is used.

Diffusion-Bonding Tooling Design. Assuming one can diffusion-bond the aluminum MMC to dissimilar metals (such as Inconel), it is suspected that the diffusion-bonding could require very high pressure (greater than 10 ksi) at elevated temperatures. Aluminum alloy would flow readily under this condition. The diffusion-bonding design guidelines established for titanium alloy low-pressure diffusion could be totally invalid, and special tooling and design guidelines should be established.

Creep Forming of B/Al Alloys. This is very important for the B/Al ducting design so that the B/Al tube could be bent properly.

TASK IV - CRITICALITY RANKING

In Table 13, a summary of criticality ranking of technology needs are assembled. Three material systems are included: continuous fiber metal matrix composite (MMC), discontinuous MMC, and polymer matrix composite. The technology needs for these materials are different, as indicated from Table 13. There are a number of steps involved in developing this table.

First, a number for the relative figure of merit of weight savings is assigned to each of the materials systems, and these numbers are marked as Column A as shown in the table.

Second, a number for the relative figure of merit of improved reliability, improved maintenance, cost reduction, wider application, and improved performance are assigned as shown in the first row.

Third, a number for the relative figure of merit of program cost and probability of failure are assigned. These numbers are opposite the previous figure of merits, and a negative sign is assigned.

After assigning these numbers, we start assigning values for the technology needs to each of the figures of merit. For example, the technology of fiber matrix compatibility improvement has highest impact on the reliability of the composite; a value of 10 is assigned. Therefore, the weighted figure of merit of this specific technology need in the consideration of improving reliability is 80 (or 8 x 10.

Following the example mentioned above, a total technology need's weighted figure of merit is calculated. For example, this value (B) for the transition piece is computed by:

5 x [Improved Reliability, 8] + 10 x [Improved Maintenance, 6] +
7 x [Cost Reduction, 5] + 8 x [Wider Application, 7] +
6 x [Improved Performance, 5] + 6 x [Program Cost, -6]
+2 x [Probability of Failure, - 10] = 165.

TABLE 13. CRITICALITY RANKING

MATERIALS SYSTEMS	A MERIT OF WEIGHT SAVINGS	TECHNOLOGY NEEDS	IMPROVED RELIABILITY (8)	IMPROVED MAINTAIN. (6)	COST REDUCT. (5)	WIDER APPLIC. (7)	IMPROVED PERFORM. (5)	PROG. COST −(6)	PROB. OF FAILURE −(10)	B TOTAL	AXB	RANKING
CONTINUOUS FIBER MMC	10	1. TRANSITION PIECE	5	10	7	8	6	6	2	165	1650	2
		2. + 45°, 90° CON-SOLIDATION	0	0	0	10	8	6	3	44	440	12
		3. FIBER/MATRIX COM-PATIBILITY IMPROVE-MENT	10	3	4	10	10	10	5	128	1280	6
		4. FRACTURE ANALYSIS	6	7	3	10	8	8	5	117	1170	8
		5. THERMAL CYCLE + MECHANICAL LOADING	5	2	0	5	3	3	4	34	340	13
DISCONTINUOUS MMC	8	6. NET SHAPE FORGING	4	5	10	10	9	2	2	195	1560	3
		7. FUSION WELDING	8	10	6	8	8	6	5	164	1312	4
		8. FRACTURE ANALYSIS	10	9	8	9	10	9	7	163	1304	5
		9. DESIGN ALLOWABLES	6	5	5	6	5	10	2	90	720	11
		10. WHISKERS ORIEN-TATION CONTROL	2	1	2	1	0	5	3	-21	0	15
POLYMER MATRIX COMPOSITE	8	11. VACUUM OUTGASSING	9	7	0	5	5	9	9	30	240	14
		12. CRYOGENIC CRAZING	7	9	0	9	6	8	3	125	1000	9
		13. DESIGN ALLOWABLES	6	5	9	4	10	2	2	148	1784	7
		14. MANUFACTURING AUTOMATION	10	8	10	10	9	10	1	223	1784	1
		15. MOISTURE ABSORPTIONS	8	10	0	8	4	7	5	108	864	10

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Finally, Column B is multiplied by Column A to yield a score for criticality ranking.

The criticality ranking list in Table 13 is one approach to identifying technology needs. The polymer matrix manufacturing automation technology is rated number one. This means that the pursuit of this technology program should result in the highest return for composite materials application to liquid rocket engines. The recent tremendous advancement in this area through the effort of the composite materials industry should help to build an engineering prototype composite component ready to be tested soon in an engine system.

In conjunction with the criticality ranking of technology needs for composite materials, the weight saving potential of composite materials is valued on the specific strength and specific modulus of the system. In Fig. 24, a plot of various materials systems positioned in a specific strength and specific modulus is shown. This figure is refined to reflect the relative weight saving potentials borne out from the conceptual design work we have performed. It can be seen that a position for the Gr/Ep was established in this figure. Another position is also created for the particulate SiC-reinforced X7090 aluminum alloys.

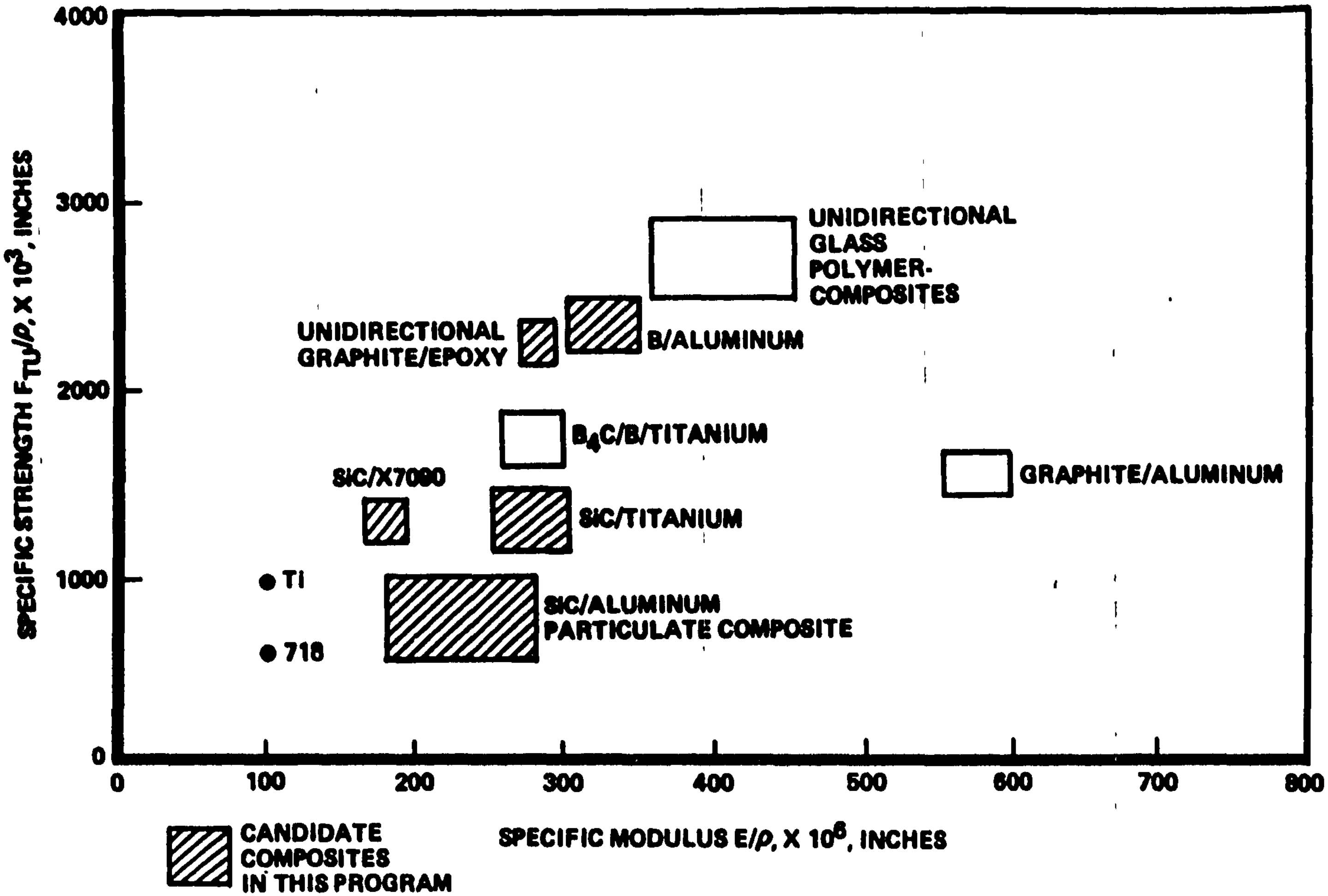

Figure 24. Alloy Comparisons

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TASK V - FOLLOW-ON TASKS

During this evaluation, our experience with the selected baseline engines has provided valuable component design and fabrication background in establishing component requirements and design configurations for composite material applications. It should be realized that component designs intended for composite material applications may be quite different from existing designs developed for conventional metallic fabrication. Both near- and far-term technology requirements were considered in this task. The required technology target date for the specified technology readiness date of 1987 for orbit-to-orbit engines and 1991 for earth-to-orbit engines is dictated by the demonstration level of technology readiness that is selected from Fig. 25. It is assumed that the level of readiness, as interpreted in the Composite Material Application for Liquid Rocket Engines Program, would be through the Conceptual Design Tested (level 3) demonstration phase. This selected level will dictate the component technology selected for this task effort.

A summary of the Rocketdyne recommended follow-on tasks is illustrated in Table 14. The numbers in the technology needs column are identified in the Criticality Ranking Chart (Table 13).

In the ranking analysis, the emphasis for the selection of follow-on parts among all the previously reviewed components is based on producibility, applicability, and cost effectiveness. The last item affects both the critical value of schedule and probability of success within the allocated funding. It is well recognized that the application of composites to liquid rocket engines is a relatively new program, and engine components differ significantly in geometry, loadings, and responses. Consequently, our selections must comply with the fundamental rules of ranking characteristics reported earlier. The candidates are the main fuel valve (MFV), low-pressure propellant ducting, gimbal bearing, high-pressure fuel pump shaft sleeves, shaft, and nozzle extensions. In view of cost effectiveness and producibility, the high-pressure fuel pump is removed from the final consideration for the follow-on task. Three components can be fabricated from a SiC/Al billet and/or SiC/Al sheet, and the nozzle extension

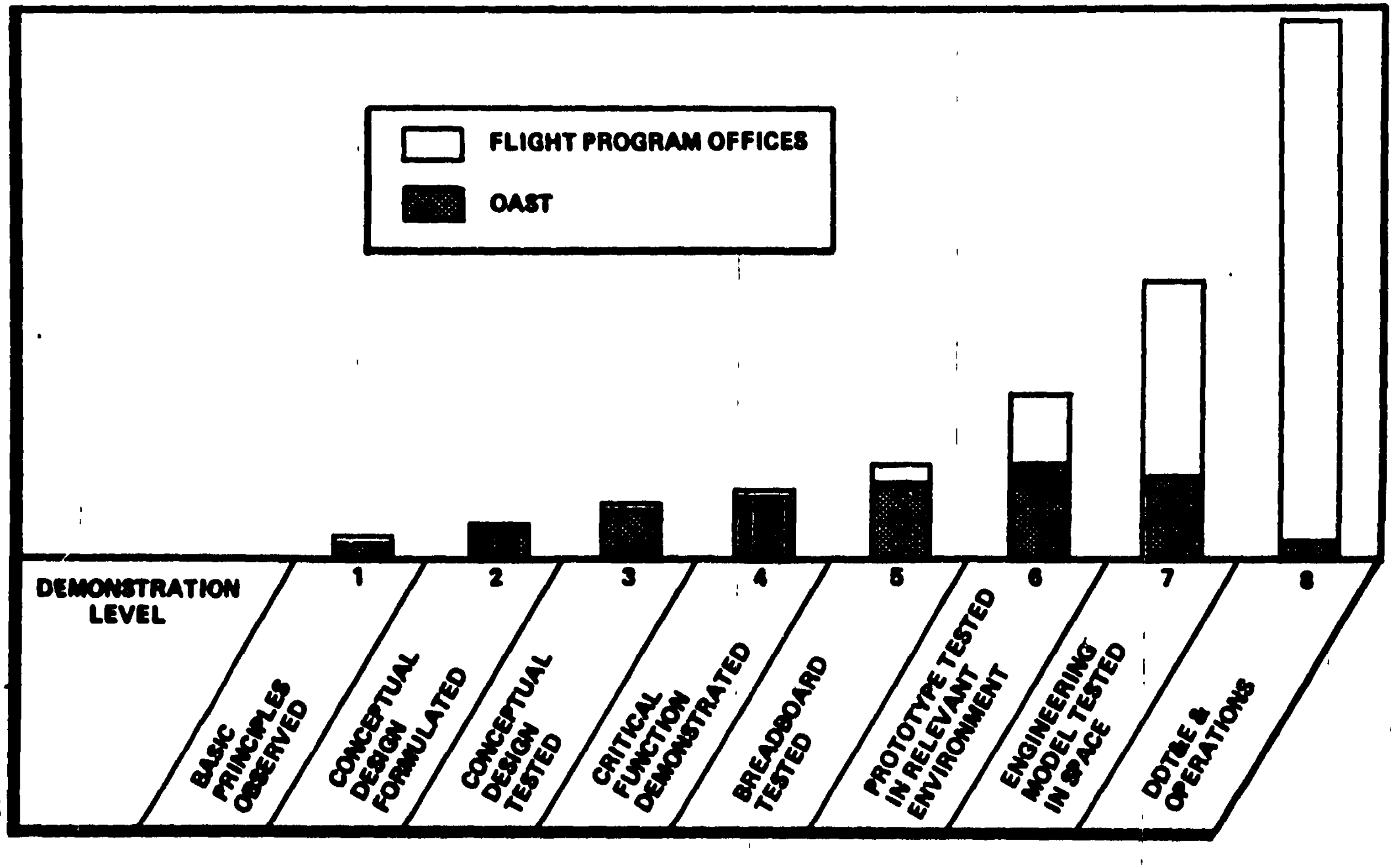

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Figure 25. Technology Readiness

TABLE 14. ROCKETDYNE RECOMMENDED FOLLOW-ON TASKS

COMPONENT	TECHNOLOGY NEEDS	PROGRAM DURATION
1. LOW PRESSURE PROPELLANT DUCTING	1, 6, 7, 8, 9, 11, 12, 14, & 15	18 TO 24 MOS
DUCTING	6061 Al LINER WITH GR/EP	
JOINTS & FLANGES	DISCONTINUOUS SiC/Al MMC	
BELLOWS	DISCONTINUOUS SiC/Al MMC	
2. HIGH PRESSURE FUEL PUMP	6, 9 & 10	12 MOS
SHAFT SLEEVES	SiC/Al, DISCONTINUOUS	
3. GIMBAL BEARINGS ASSEMBLY	6, 8 & 9 SiC/Al, DISCONTINUOUS	12 MOS
4. MAIN FUEL VALVE	6, 7, 8, 9 & 10	18 MOS
HOUSING	SiC/Al, DISCONTINUOUS	
SHAFT	SiC/Al, DISCONTINUOUS	
COUPLING	SiC/Al, DISCONTINUOUS	
5. HIGH PRESSURE FUEL PUMP	2, 3, 4 & 5	24 TO 30 MOS
SHAFT	SiC/TITANIUM, CONTINUOUS	
6. REGEN COOLED NOZZLE	11, 12, 13, 14, 15 & HIGH TEMP INSULATION	24 TO 30 MOS
STRUCTURAL JACKET	GR/EP	
7. COMBUSTION CHAMBER	11, 12, 13, 14, 15 & HIGH TEMP INSULATION	24 TO 30 MOS
STRUCTURE JACKET	GR/EP	
8. ACTUATOR STRUT	1 & 2 B/Al	12 MOS
9. NOZZLE EXTENSION	1, 2, 3, 4, 5 AND CARBON-CARBON	12 MOS

*NUMBERS – REFERENCE CRITICALITY RANKING

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can be fabricated from a carbon-carbon composite. The design of the main valve, ducting, and gimbal bearing is given in the following sections. A summary of the results is provided in Table 15, and associated methodology is given in Appendix B.

It is a well-known fact that the structural system in an optimum study must integrate the optimized material systems as illustrated in Fig. 26 to handle the structural system responses from either external excitations and/or interactions. It is clearly seen that the SiC/Al composite is a logical choice for the three components selected by a ranking process. However, fatigue and creep effects are not considered in the comparison because of insufficient fatigue and creep data on SiC/Al composite. As observed in Table 15, the weight reduction is a minimum when the existing part is highly stressed with a high-strength material of relatively low density such as the titanium gimbal bearing. On the other hand, the weight reduction can be dramatically attractive when the part is moderately stressed with a high-strength material of relatively high density such as the MFV of Inconel 718. In short, the bounds of weight reduction is from 11% for the gimbal bearing to 40% for the MFV of Inconel 718. It is to be noted that this upper limit of 40% weight reduction will be reduced to 29% when the valve considers both titanium and Inconel 718. The translation of this weight reduction into the structural system efficiency in a restricted study is the impact of the system optimization, and one of the prime objectives to be pursued in the follow-on tasks.

<u>The Selection of Components for Follow-on Tasks</u>

The components listed have been selected on the basis of the benefits, particularly weight reduction, to be gained from the application of composite materials as stressed in Task II, and to the extent to which such application requires addressing numerous technology needs identified in Task III and given high criticality ranking in Task IV.

Table 15 is a summary of component composite materials application, and the technology needs and program duration associated with them. From the criteria

TABLE 15. FOLLOW-ON COMPONENTS SUMMARY

COMPONENTS	DESIGN AND PRODUCIBILITY	PRESENT MATERIALS	WEIGHT, POUNDS	COMPOSITES	WEIGHT, POUNDS	WEIGHT REDUCTION, %	FABRICATION TECHNIQUE
GIMBAL BEARING	SEAT	TI-6AL-6V-2SN	46.1	SIC/7090 BILLET	41.0	11	MACHINING OF A SIC/AL BILLET
	BODY	TI-6AL-6V-2SN	42.1	SIC/7090 BILLET	37.0	11	
	SHAFT	TI-6AL-6V-2SN	6.2	SIC/7090 BILLET	5.0	11	
MAIN FUEL VALVE	HOUSING	TI-5AL-2.5SN INCO 718	30.4 54.5	SIC/7090 BILLET	22.8 33.0	25 40	MACHINING OF A SIC/AL BILLET
	SHAFT AND BALL	INCO 718	11.0	SIC/7090 BILLET	6.7	40	
	CAP	TI-5AL-215SN INCO 718	6.8 12.4	SIC/7090 BILLET	5.1 7.5	25 40	
	COUPLING	LOW-CARBON STEEL	7.69	SIC/7090 BILLET	3.5	40	
BELLOW & DUCTING	BELLOW	INCO 718	--	SIC/7475-T6 SHEET	--	--	HOT PRESS OF SHEET
	WITH FLEXI-JOINT	INCO 718	12.6	SIC/7090	8.2	37	DIFFUSION BONDING OF JOINTS AND WELDS
	DUCT	21-6-9 CRES	15/INCH	6061 LINER, GRAPHITE FIBER	11/INCH	28	FILAMENT WINDING
NOZZLE	EXTENSION	A-286 CRES	82.7	CARBON-CARBON	55.0	33	FILAMENT WEAVING

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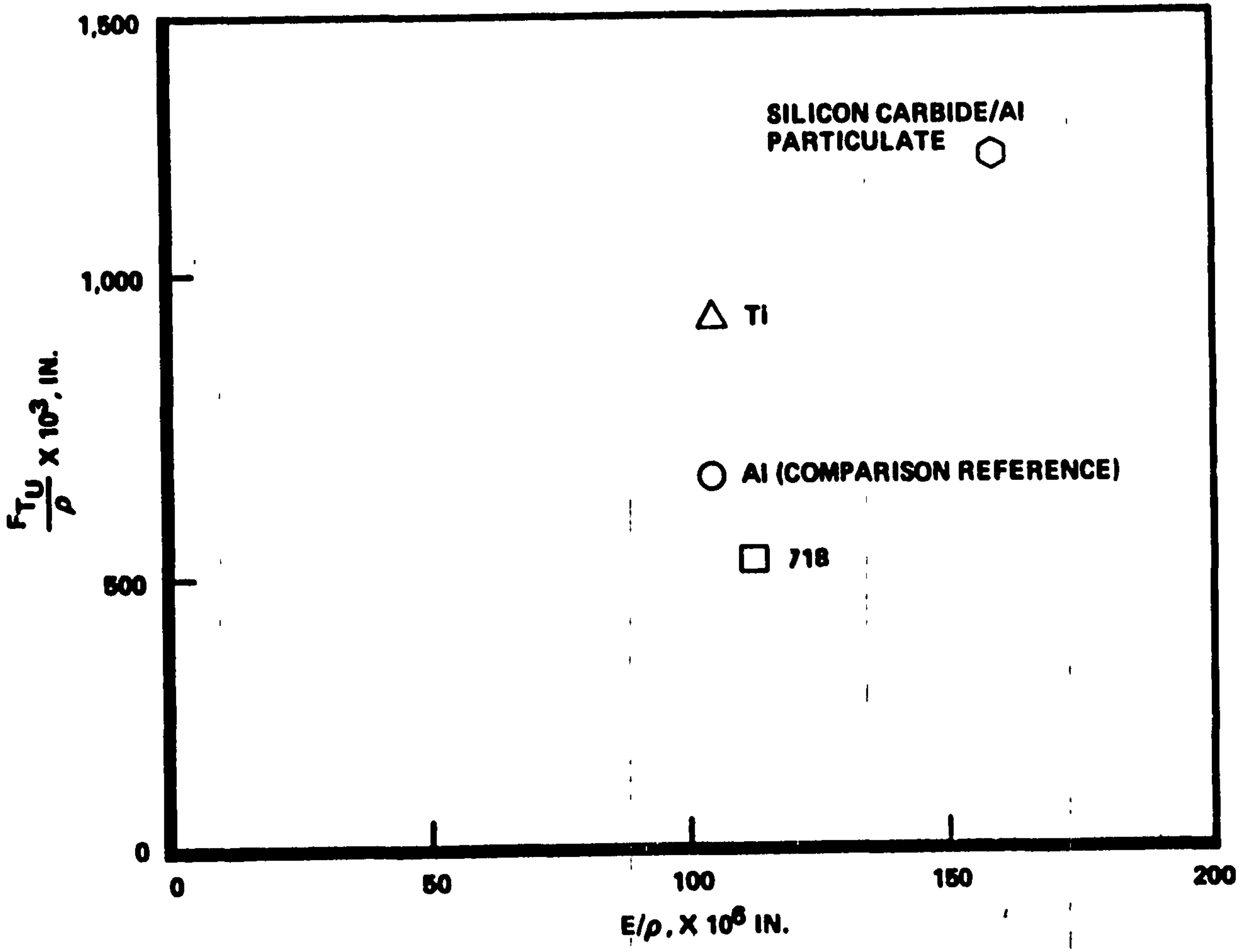

Figure 26. Comparison of Follow-on Material Properties

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previously stated, one can select the components for composite material application follow-on tasks. Five items are identified below.

1. The low-pressure propellant ducting with a total score of 10,434
2. The regenerative-cooled nozzle structural jacket, with a total score of 5072
3. The MFV with a total score of 4896
4. The nozzle extensions with a total score of 4880
5. A gimbal bearing with a total score of 3584

The number one choice is the low-pressure propellant ductings, joints, and flanges. This covers a wide variety of composite application technology for liquid rocket engines, and includes both MMC and PMC materials.

The next three number choices have similar score ratings. However, the MFV should se selected as the second choice, because the application of discontinuous metal matrix composites have emerged rapidly in recent years. The MFV fabrication would be the first of this type of component. Whereas, polymer matrix composite technology is relatively mature, most of the current activity is concentrated on manufacturing automation.

The gimbal bearing (Fig. 27) was selected as the third choice, and it is a highly stressed component of Ti-6Al-6V-25N with minimum factors of safety at several regions such as the body frame, clevis of seat, and the retainer cap of the block and shaft. Compatibility is not a problem with either fuel or oxidizer. The use of SiC/7090 particulate in a billet form can be cost effective in fabricating this part. Dimensional stability of the material is an important requirement, because the gimbal bearing is sensitive to variations in stiffness under operating conditions. A modified bearing geometry is shown in the text for a SiC/Al composite. Using the same factor of safety basis, a weight reduction is still possible. However, an 11% weight savings did not warrant its selection for a follow-on task. In Table 15, a list of the top four choices for follow-on tasks

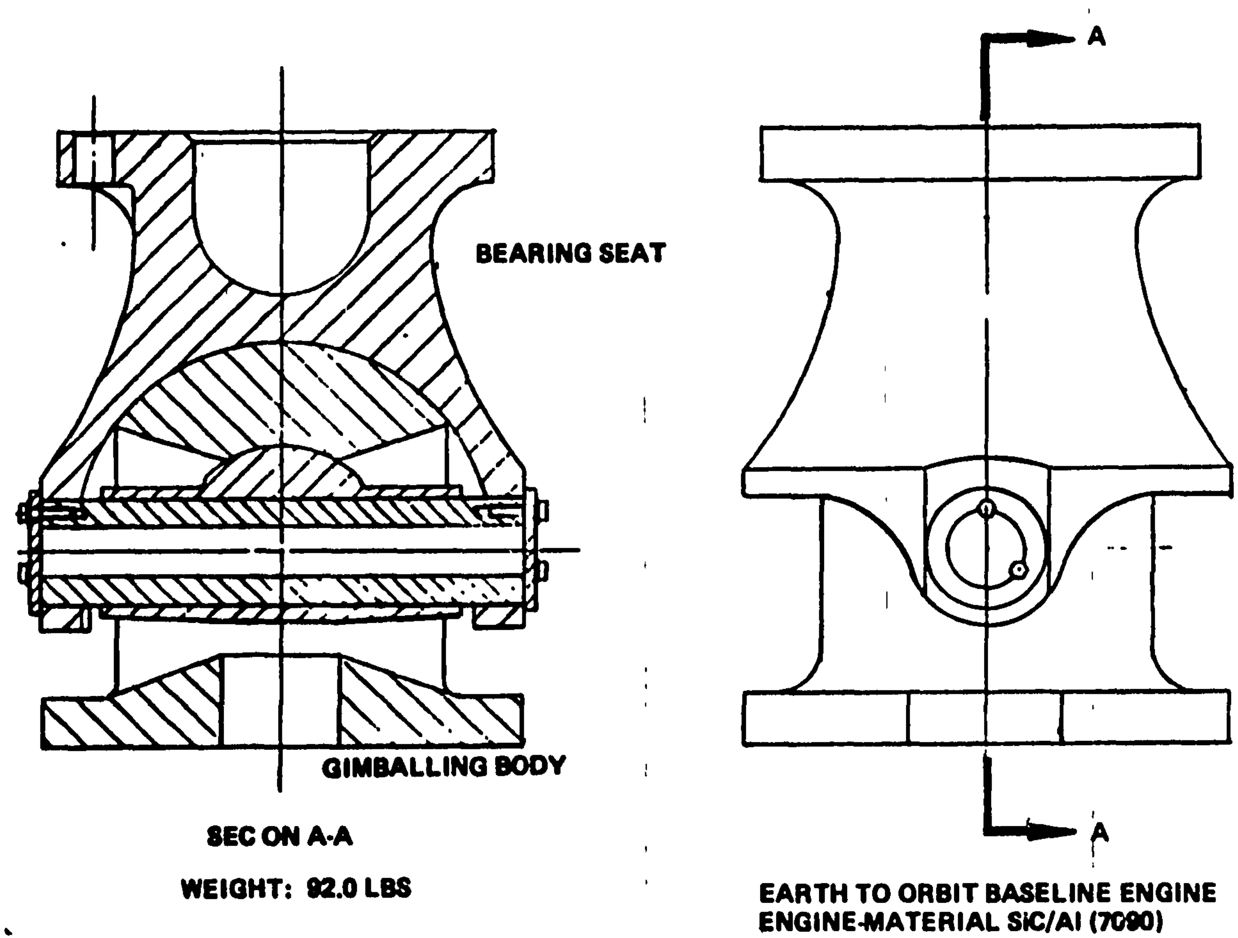

Figure 27. Gimbal Bearing Assembly

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is presented. The detailed technical approaches, cost, and schedules of three follow-on tasks for composite materials application will be discussed in the subsequent sections.

Composite Materials Application for Low-Pressure Propellant Ducts

The low-pressure propellant duct is shown in Fig. 28. It is made up of three components; articulated bellow joints, ducting, and flanges. Composite materials will be used in all components. The technical approach and discussion follow.

Technical Approach

There are several design concepts each of which are described as follows:

1. A metal matrix B/Al composite with the original articulated bellow joints and flanges
2. A metal ducting overwrapped with polymer matrix composite
3. A metal matrix composite materials bellow joints and flanges

The ducting could be made from a single-ply, discontinuous metal matrix composite by superplastic forming Inconel 718 material or by a metal liner overwrapped with polymer matrix composite materials. The articulated bellow joints could be assembled together by a diffusion bonding process or by brazing. The flange-to-ducting joints could be fabricated by diffusion bonding or brazing.

In the low-pressure ductings, the overwrap polymer matrix composite would have a marginal weight reduction over a single-ply design because there is a minimum metal liner thickness required. In the single-ply ducting design, both Inconel 718 materials and SiC/Al alloys were considered. In the Inconel 718 materials application, dissimilar metal joining at the flanges and the bellow joints are encountered. In the SiC/Al design, only aluminum-to-aluminum alloy joining is required.

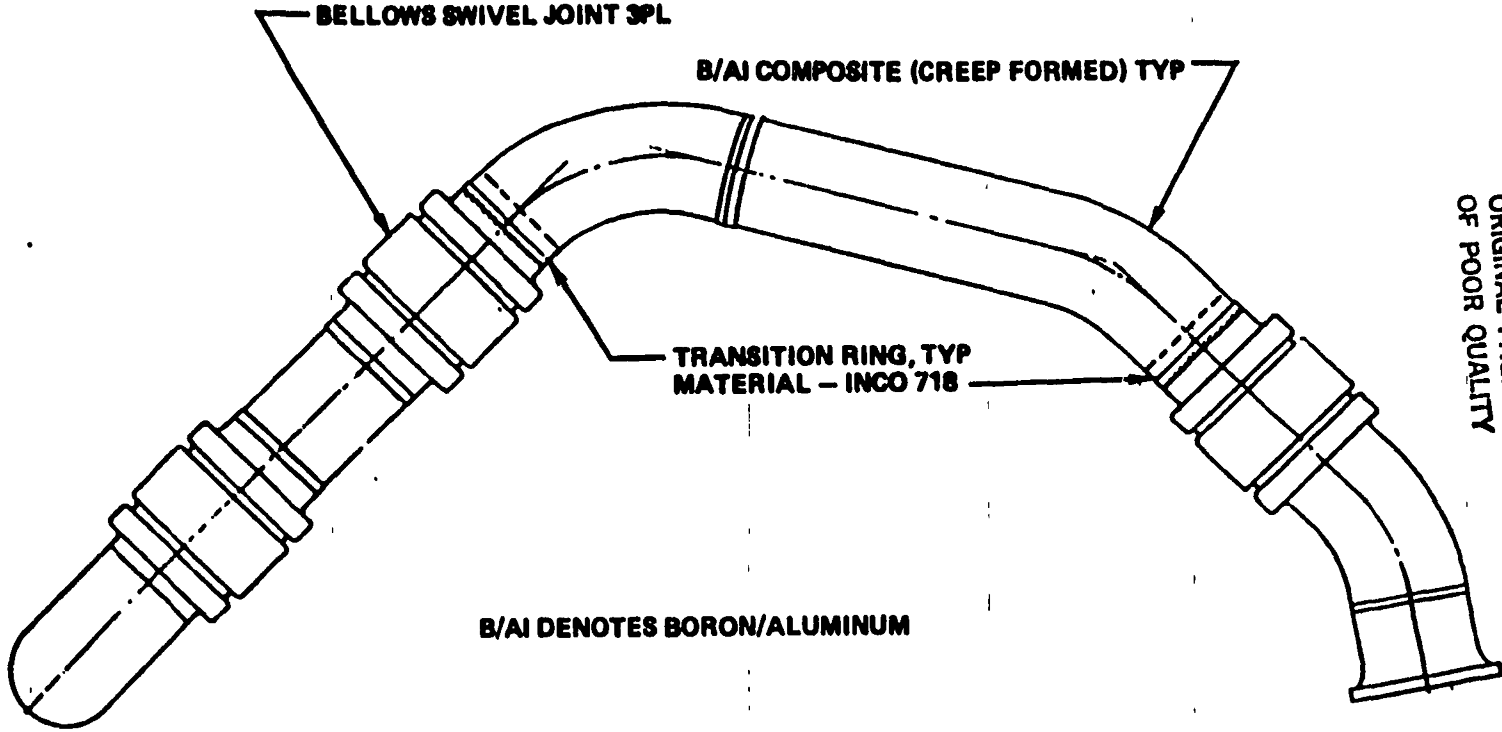

Figure 28. Low Pressure Oxidizer Duct

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The weight savings for each of the above designs are significant. The final selection of the design would be based on structural criteria and ease of fabrication. Each of the designs involves a different type of technology and has the potential for failure. In the first phase of a follow-on task, the technology program for each of the design concepts would be developed and evaluated. The final selection would be approved by NASA.

Structural Considerations of Low-Pressure Ducting and Bellows Joints

The study of ducting and bellows has been reported in the previous sections. The addition of an axially constrained flex-joint completes the ducting system. The function of such a joint is to prevent the excessive strain of an associated bellow. In operation, the bellows are relatively highly stressed, possibly in the strain-hardening state. To maintain the flexibility of a flexiline, the longitudinal load, pressure induced, must be transferred from one end of a bellow to the other by way of a flexijoint. Except for the stresses near the welds, the joints are moderately loaded. Therefore, the use of SiC/Al is feasible. Diffusion bonding is to be utilized for joining the bellow and the legs of the flexijoint. As stated previously, the bellow can be hot-pressed with a die; a weight reduction of 40% is expected in this case.

Environmental Effects on the Gr/Ep Composite Materials

In the application of polymer matrix composite materials, one of the major concerns is moisture absorption of a PMC material. The moisture absorption of PMC materials is a diffusion-controlled process. In other words, at a given temperature, it takes a certain amount of time for the PMC to be saturated with moisture. Typically, the glass transition temperature decreases as a function of equilibrium moisture concentration. It is also reported that, in the presence of external loads, the moisture initial absorption rate and effective diffusivity would increase to degrade the PMC properties.

Two distinct phenomena have to be considered when the effect of moisture on FRP characteristics is studied. One is the "instantaneous" influence of the mere presence of water within the multiphase composite material where it plays the role of a fourth phase, in addition to fiber, matrix, and interface. The presence of water during the mechanical test has an effect mainly on strength and viscoelastic behavior of the material, which is expected to be reversible and to disappear on thorough drying.

The second phenomenon is chemical in nature and manifests itself by long-term, irreversible degradation of FRP properties. To demonstrate this effect, two different commercial epoxy resin matrix formulations, a "medium-temperature" system and a "high temperature" system, were tested in tension after immersion in hot water. Dried specimens of the medium-temperature resin were stronger than their wet counterparts. The reverse was the case with specimens based on the high-temperature resin.

In the follow-on task, the resin moisture absorption and its potential as a dry-out treatment will be considered. A proper resin system will be selected to satisfy the liquid rocket engine operating environment.

Joining of Inconel 718-SiC/Al Ducting and Bellows Assemblies by Brazing

Brazing offers two distinct advantages over diffusion bonding for fabricating this type of hardware. First, the lower pressures required for brazing would permit the design of simpler tooling, and the required loads could be applied with gas-inflated pressure bags reacting against rigid tooling. Secondly, since joining must occur at relatively low temperatures (approximately 1000 F) processing time would be reduced by brazing. The parts need to be heated only long enough to reach an appropriate uniform temperature and to allow sufficient time for braze alloy distribution within the joint. With diffusion bonding, the hardware must be held at temperatures long enough for adequate diffusion to occur for formation of a true metallurgical bond. Another advantage of brazing over diffusion bonding is that brazing does not require plastic deformation and, therefore, makes the basic design easier.

To develop a successful brazing technique, several areas must be addressed. These include:

1. Selection of a braze alloy compatible with the alloys to be joined, the expected service environment, and the braze temperature limitations imposed by the hardware. Typically, two or three braze alloys will be selected for each of the braze coupon samples. The braze quality will be evaluated initially by metallographic examination.

2. Evaluation of requirements for surface preparation prior to brazing (e.g., nickel plating)

3. Evaluation of effects of differential thermal expansion during brazing

4. Tooling requirements

5. Development of an inspection technique such as ultrasonic inspection or radiographic inspection

These questions could be answered by a limited development program. All questions except items 3 and 4 could be investigated through braze tests with simple, flat coupon specimens. Investigation of items 3 and 4 would require specimens which simulate actual hardware geometry.

<u>The Materials and Producibility of Articulated Bellows Joints</u>

The convoluted bellows would be made from a superplastic SiC/Al (7475) composite material. To minimize fatigue damage, the bellows would be laminated. The cost saving by forming the bellows superplastically could be very significant.

The evacuated structural collar would be made of SiC/6061 Al composite to facilitate closeout welding. The SiC/6061 Al composite materials are the only fusion-weldable aluminum composite materials available.

In the tripod joints, the legs will be made out of a SiC/X7090 aluminum alloy. This material has the highest strength among all the aluminum composite materials. High strength is utilized to minimize the thickness of the legs to avoid disturbing the fuel flow. The bellows, the evacuated structural collar, the ducting, and the tripod legs will be assembled together by a diffusion-bonding process. After the diffusion is complete, a vacuum will be attained in the collar to provide insulation. A primary feature of this fabrication method is that minimal handling is required; consequently, the quality is expected to be consistent.

The Materials and Producibility of Ducting

Several ideas have been conceived to obtain a lightweight tubular ducting using composite materials. These include (1) a metal liner overwrapped with polymer matrix composite materials, and (2) a discontinuous SiC metal matrix composite.

In the first design concept, the major technology issue is to provide a curved thin metal liner (as thin as 0.010 inch). Based on an industry survey, the current state-of-the-art technology minimum thickness limitation is about 0.050 inch. Thinner metal liners create serious handling problems. This was one of the most serious problems encountered by a Martin Marietta program in lightweight composite feedlines for cryogenic space vehicles. In the low-pressure ducting (e.g., 700 psi for low-pressure oxidizer ductings), the 0.050 inch thick Inconel 718 material is thick enough to meet the structural criteria. Overwrapping in this case would not be required. The deletion of glass/epoxy overwrap significantly improves the overall cost savings.

In the second concept, a lightweight, high-strength SiC/Al composite would be used. This could be superplastically formed. It is conceivable that using the superplastic composite materials, a curved, thin ducting (0.030-inch thickness) could be fabricated.

This concept, as previously reported using a B/Al composite, is not considered in view of the apparent advantages of alternative approaches. The B/Al concept is complicated and very costly.

Regardless of what materials are used for the propellant ducting, sound and practical joints to the flange and articulated bellow joints must be provided. Diffusion bonding, brazing, and fusion welding would be considered. Dissimilar metal joints investigated by Martin Marietta, using explosive bonding and co-extrusion would be evaluated.

Superplastic Deformation of SiC/Al and Inconel 718 Materials

The superplasticity of a material is characterized by mechanical properties where, at certain temperatures (typically around 0.5 to 0.6 of the melting temperature) and certain pressures, the material possesses a perfectly plastic (no elastic springback) deformation with elongation greater than 300%. The deformation constituent equations are:

$\sigma = K \dot{\varepsilon}^n$ (1) or $\dot{\varepsilon} = K' \sigma^n$

K, K' are materials constants

σ = Stress

$\dot{\varepsilon}$ = Strain rate

m = Strain rate exponent

n = Stress exponent

Where, typically, m is equal to about 0.5 for superplastic materials.

For a liquid, the m value is equal to 1. The high value of m illustrates the ability of the materials to avoid "necking down" of the structural part. For example, in the equation above, when a necking occurs, the localized stress (σ) at that point would increase. The low value of n (superplastic materials) would prevent the rapid increase of the $\dot{\varepsilon}$ (strain rate) at that location and, therefore, provide a uniform deformation throughout the part. These characteristics are particularly useful for a blow-forming process where a uniform low gas pressure (typically 500 psi) is applied to blow a sheet material into a final shape, as illustrated in Fig. 29.

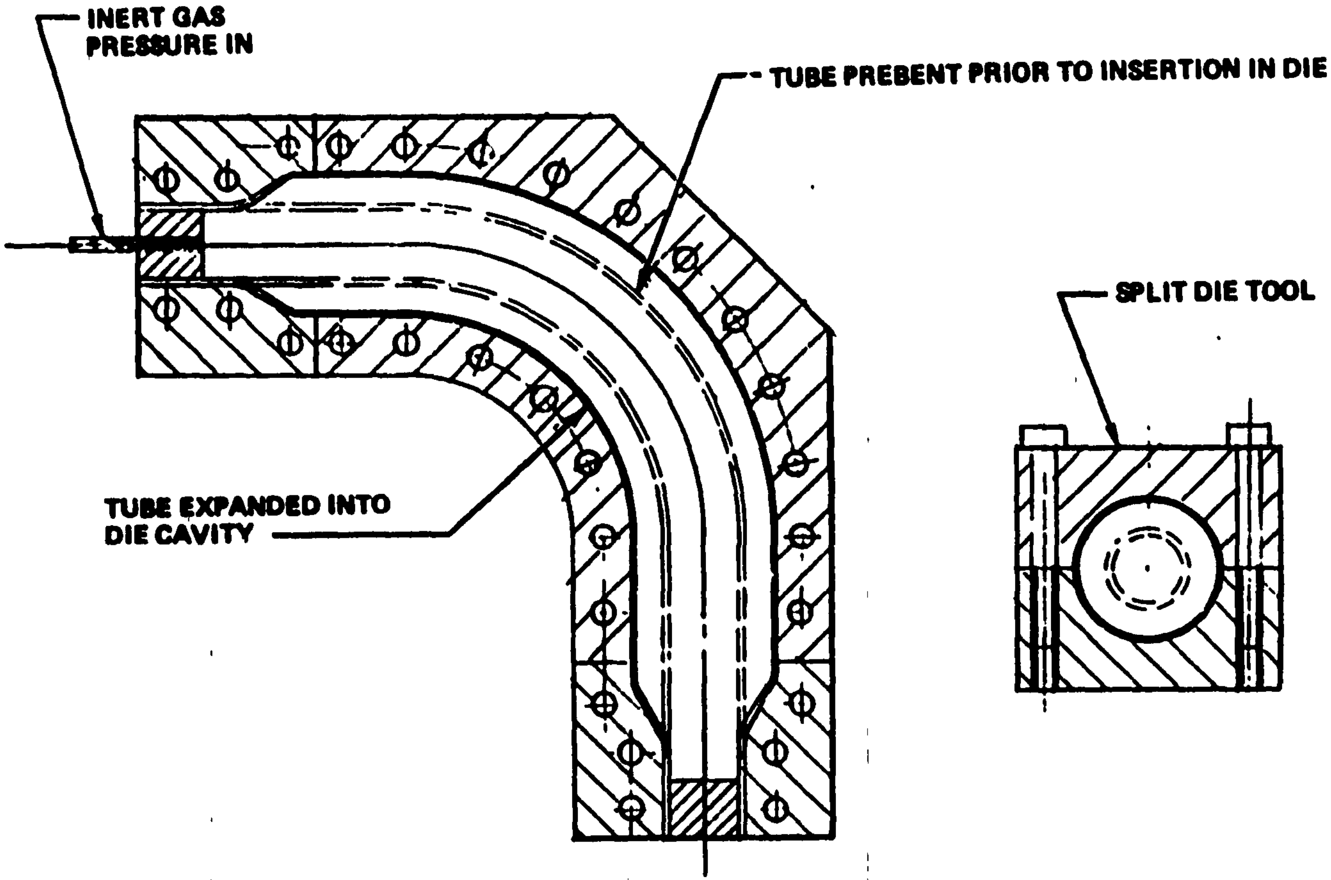

Figure 29. Superplastic Forming of Duct Elbow

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Rockwell International is the technical leader in the area of superplastic forming and diffusion bonding. Currently, there are many superplastically formed Ti-6V-4Al parts in the B-1 structure. Rockwell also has a proprietary position in the SiC/Al composite and Inconel 718 alloys. This expertise could be channeled into the follow-on tasks of both the ductings and the convoluted bellows.

A superplastically formed Inconel 718 test piece is shown in Fig. 30.

Design Description

Recent work at the Rockwell Science Center has demonstrated the superplasticity of SiC/Al. This characteristic, combined with diffusion bonding, opens the door for unique fabrication techniques in the manufacture of propellant duct assemblies.

The following design description covers the fabrication of a subscale duct, bellows, and flange assembly and could be used to meet one of the follow-on task requirements of the composite material application program. The assembly is illustrated in Fig. 31.

The materials used in the duct assembly cover the current range of SiC/Al composites. The duct and bellows are fabricated out of SiC/Al with a 7475 Al matrix. It is consolidated by spraying SiC powder on superplastic 7475 Al foil and stacking multiple sheets. The stack is hot-press-forged in vacuum and extruded or rolled into seamless tubing. The tubing to be used for the duct is bent to contour prior to insertion in a split die. Heat and pressure are applied to superplastically expand the tubing to its final shape (see Fig. 29). The bellows are made from similar seamless tubing. To improve the fatigue strength of the bellows, two plies and two forming cycles are used. The outer surface of the inner bellows is flame-coated with an inhibitor spray to preclude diffusion bonding of the two plies. The bellows construction and tooling die are illustrated in Fig. 32.

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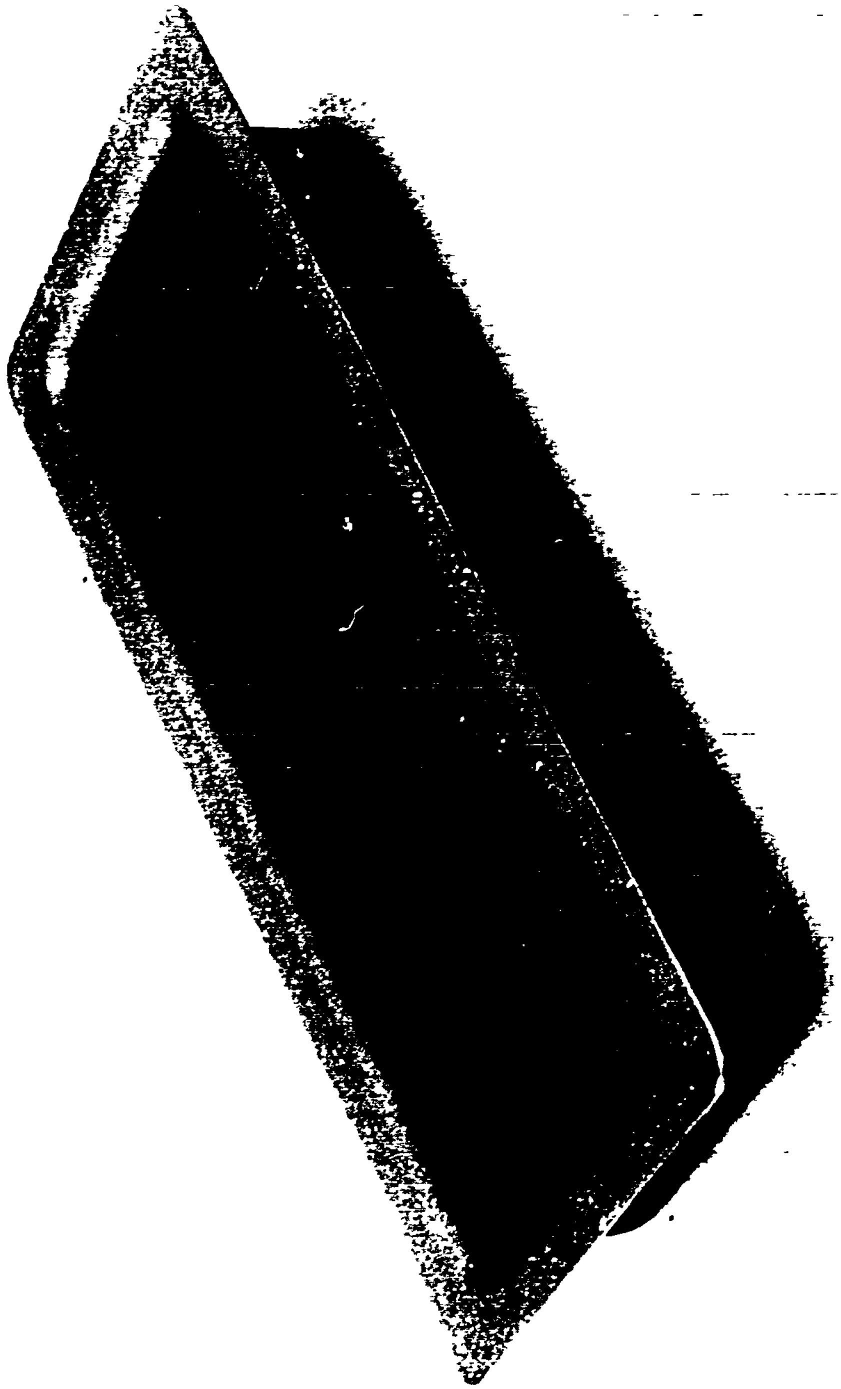

Figure 30. Superplastic-Formed Inconel 718

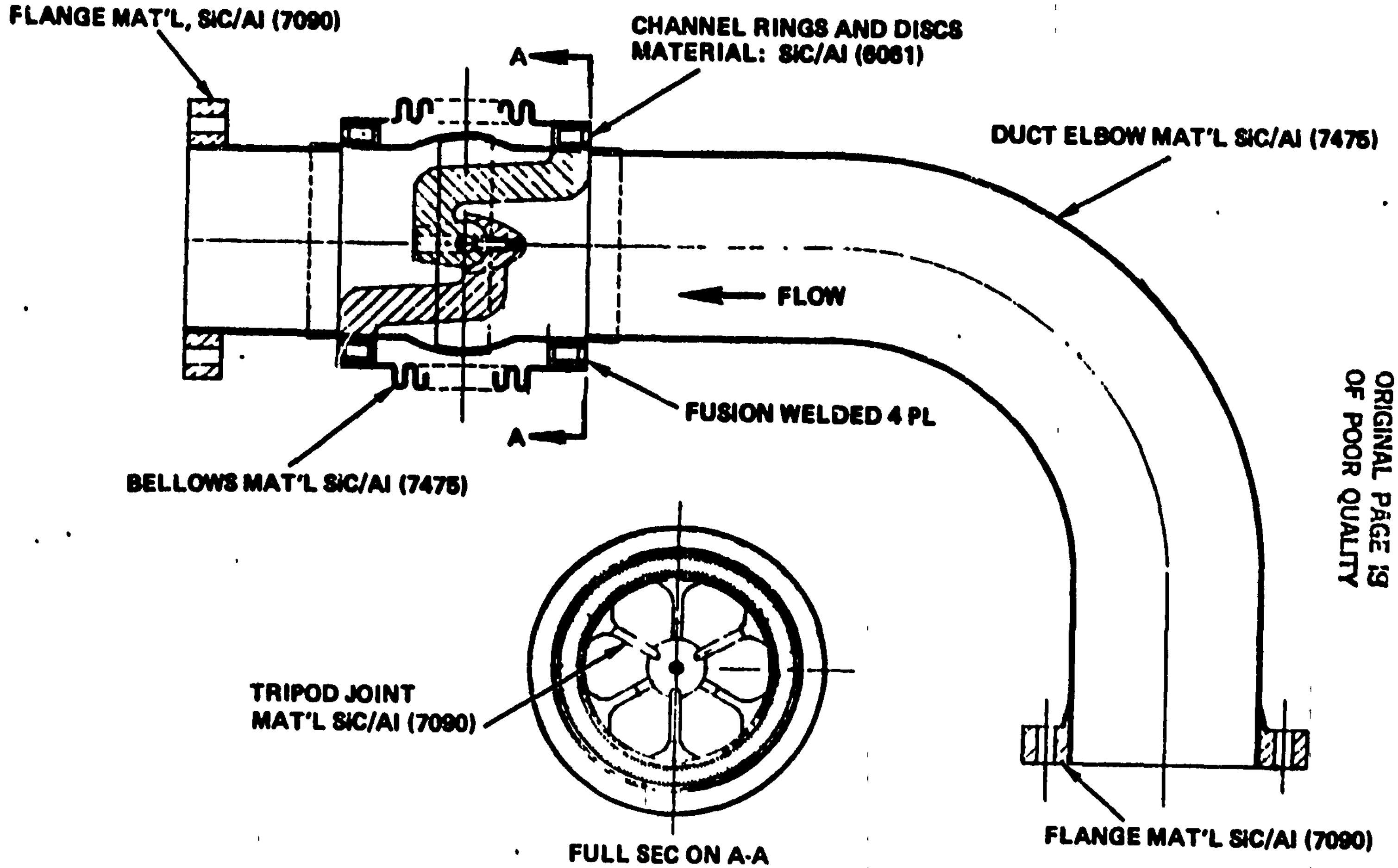

Figure 31. Composite Test Unit

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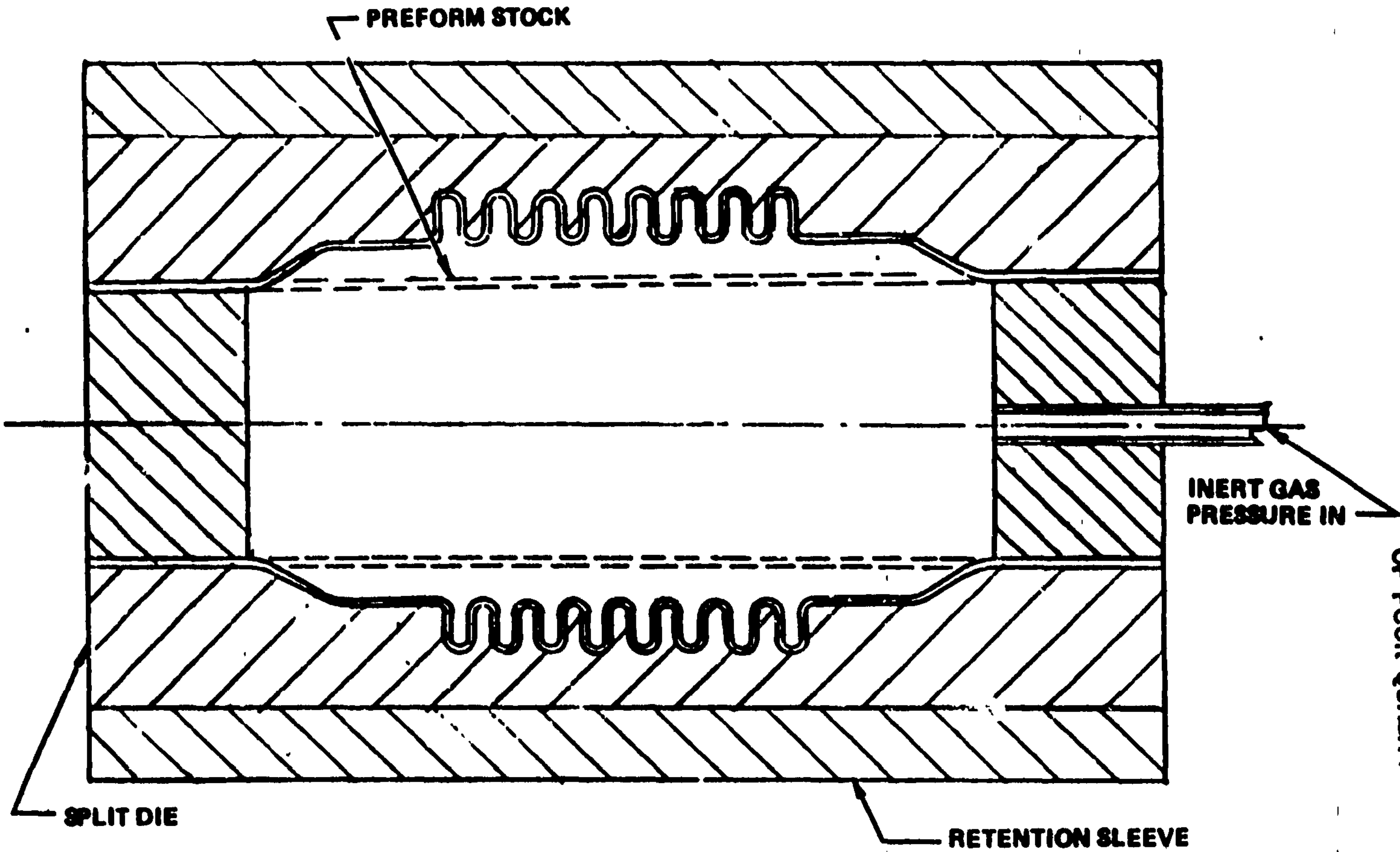

Figure 32. Superplastically Formed Bellows

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The tripod swivel joint constrains the bellows assembly axially and is made from SiC/Al with a 7090 Al matrix. This is a DWA material and is currently the highest strength SiC/Al composite. In the interests of economy, the tripod would be forged to net shape with a minimum of final machining. The tripod is similar in design to the bellows joint successfully used on the SSME.

Two channel rings support the bellows and, when the open sides are welded with closure disks, provide structural stiffness against axial loading and closed toroidal cavities that can be evacuated for improved insulation against cryogenic propellant boiloff. These are machined out of SiC/Al with a 6061 Al matrix. This is relatively low-strength SiC/Al, but it can be welded.

The flanges are machined out of SiC/Al with a 7090 Al matrix. These are diffusion bonded to both ends of the duct, and provide a mounting support for the test fixture.

The final assembly of the duct and bellows test unit is carried out by bolting the various split die modules into two units, inserting the duct and bellows components into the cavity, and closing the die. Heat and pressure can now be applied to diffusion bond the assembly into an integrated whole. Following removal and inspection of the bonded assembly, the two closure disks are fusion-welded to the channel rings as illustrated in Fig. 31.

Typical illustrations of two cryogenic bellows are shown in Fig. 33 and 34. Figure 33 is a LOX bellows joint with a single bellows. Figure 34 has two bellows with the space between the bellows evacuated to insulate the joint against the more severe boiloff problem of liquid hydrogen. Both joints are constructed entirely out of SiC/Al and have great weight and cost saving potential over similar components fabricated from Inconel 718 and stainless steel.

- Composite Materials Application for Main Fuel Valves (MFV)

This component is one of the prime subassemblies in any engine system. It is subjected to a cryogenic fuel with relatively low pressurization. The housing

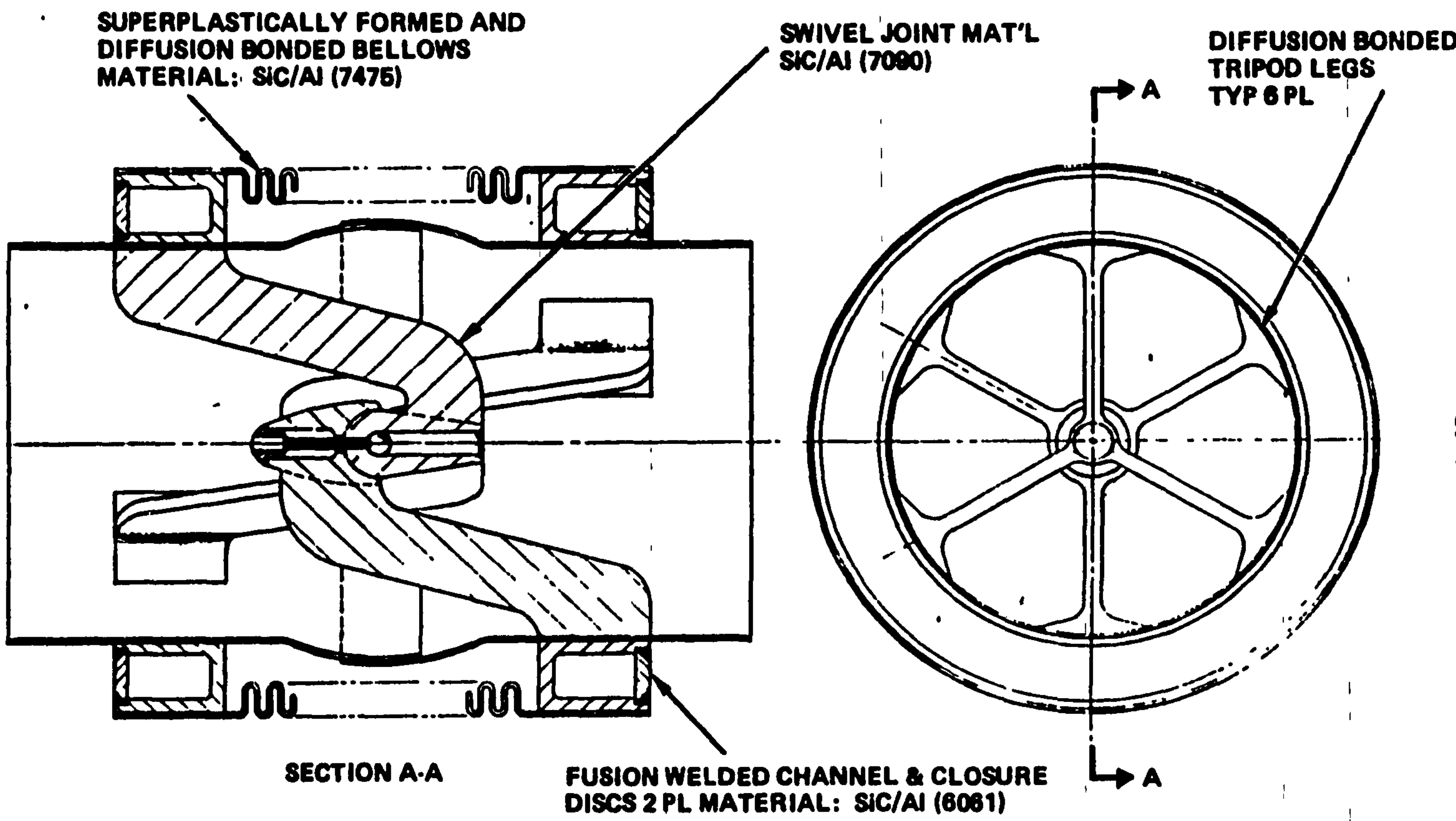

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Figure 33. Articulated Bellows Joint (Liquid Oxygen)

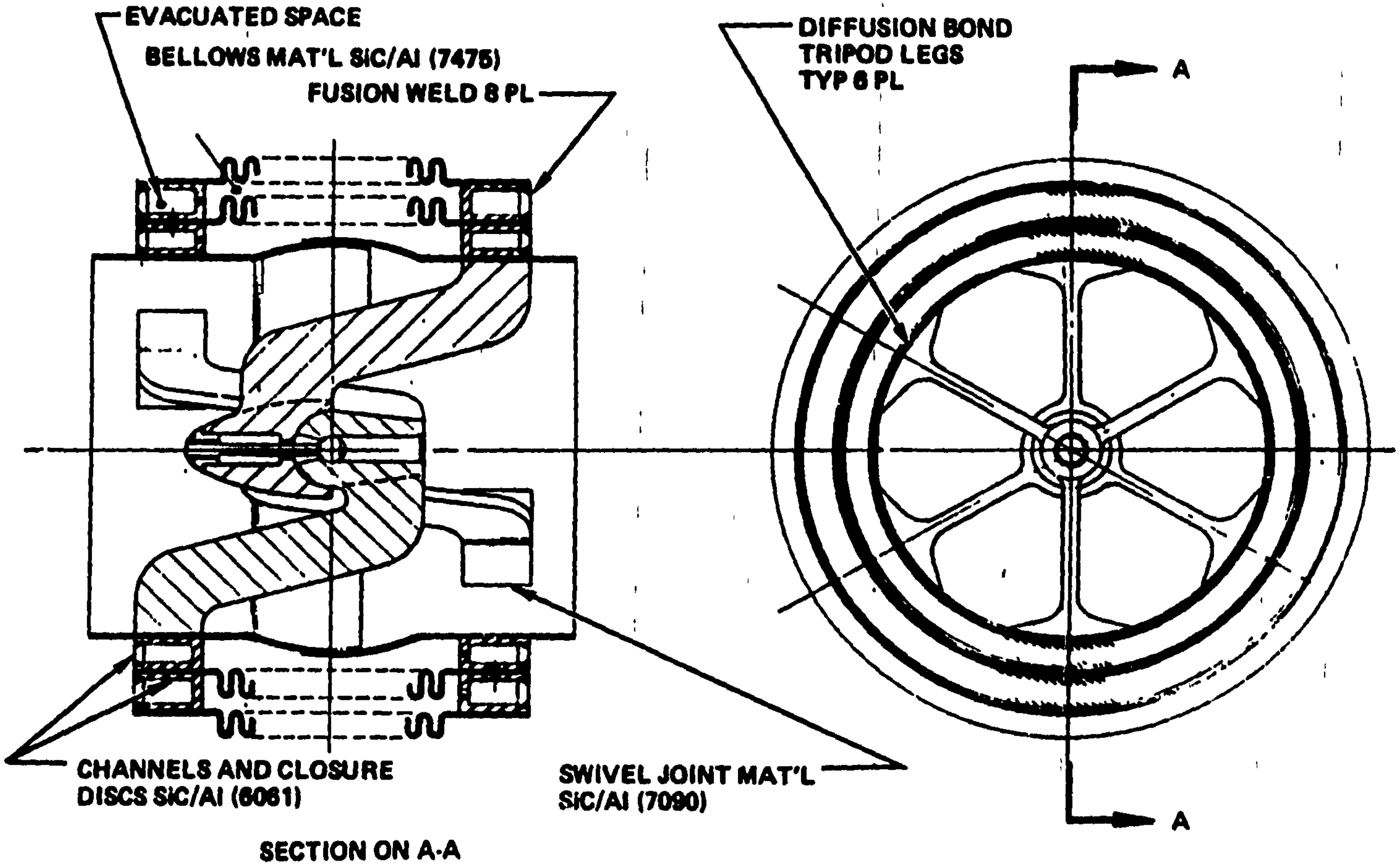

Figure 34. Articulated Bellows Joint (Liquid Hydrogen)

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and cap are made of Ti-SAl-259N, but the alternatives are Inconel 718. The shaft and ball are Inconel 718. The coupler is of low-carbon steel. Structurally, they are treated either as a thick cylindrical shell or an irregular spherical shell with the flange as plates. The primary stresses are pressure induced, while the thermal influence tends to counteract against the internal pressurization. For conservatism, the secondary thermal stresses are neglected. However, in the fatigue investigation, the cyclic effect of both temperature and pressure is noted. Except at the wall outlet of the body, the parts are moderately stressed. Consequently, the existing design is adequate with the substitution of SiC/7090 Al composite. This composite is a billet of particulate reinforcement in the matrix. It can be conveniently considered as grossly isotropic. Local increases of wall thickness at the outlet of the housing by about 20% is all the necessary geometrical modification required to make the new design structurally acceptable. The availability of SiC/Al billets makes the fabrication possible within a relatively short time period. Details on the weight reduction realized are given in the summary table (Table 9).

Technical Discussion and Approaches

The SSME MFV (a 2.500-inch-diameter ball valve) represents a typical valve application for evaluating composites for high-performance cryogenic valves. Detail parts considered for fabrication from composites will include the valve housing, shaft, end cap, and valve-to-actuator coupling. The current designs use titanium alloy for the housing and end cap and Inconel 718 for the shaft and coupling. In the evaluation, the thermal and structural characteristics would be of major concern.

The housing, shaft, and end cap would be redesigned, using composite materials. The parts will be analyzed structurally using finite-element analysis and considering pressure, external, thermal, and vibration loads. Special attention would be focused on critical areas of high local stress caused by stress concentration. Data from previous pressure tests on a strain-gaged housing would be utilized to optimize the housing analysis. Parts would be fabricated to be used in conjunction with existing detail parts to build a valve assembly. Pressure tests would be run on the housing and end cap using stress coat and strain gages to evaluate the stress distribution and optimize the designs. A major design goal is to redesign the three parts in such a way that they can be integrated into an existing SSME valve design without impacting engine interfaces. One anticipated problem area is threaded inserts for the engine duct bolts; current design uses high-strength bolts. Tests would be conducted on inserts installed in composite materials to ensure that they meet the current requirements. Splines in the shaft and coupling also may be a problem, and the design would be evaluated both analytically and by test to ensure their structural and life capabilities. A major goal is to design the composite parts so that they are physically interchangeable with the current details. This permits the composite to be assembled with existing parts to complete a valve assembly for test.

Thermal

Composite materials have different thermal contraction coefficients than the existing parts. Because the design is for service in liquid hydrogen, significant changes in hardware dimensions and fits occur during chilldown from ambient to cryogenic temperature. Particularly, critical elements are the 440C shaft bearings on the shaft and in the housing, the dynamic shaft seals, and the guides for the ball seal lifting mechanism. Rocket engine valves and lines used for liquid hydrogen are insulated to prevent liquid air condensation on their outer surfaces. The current housing is insulated with foam, which is protected with a nickel-plate shell. A method of insulating composite parts and providing a protective shell over the insulation would be developed.

General

General design problems which may occur with composite materials would be evaluated during the design phase, and analyzed and tested as required. Tests would be run to determine the wear characteristics of the shaft and ball and their associated seals when used in high-pressure (high seal load) applications.

Even slight wear generates particles which cause seals to leak. Static seals also may create problems because of the high unit load on the metal-to-metal seal contact area. Plastic deformation of the seal contact area may create leak paths on a second seal installation. Mechanical wear is not expected to be a problem because of the relatively low contact velocities and contact loads and low cycle life requirement. A life endurance test would be run to verify the capability of the composites to meet the wear and life requirements.

The primary stresses are pressure induced, while the thermal influence tends to counteract against the internal pressurization. For conservatism, the secondary thermal stresses are neglected. However, in the fatigue investigation, the cyclic effect of both temperature and pressure is noted. Except at the outlet wall of the body, the parts are moderately stressed. Consequently, the existing design is adequate with the substitution of SiC/7090 Al composite. This composite is a billet with particulate reinforcement in the matrix. It can be conveniently considered as grossly isotropic. A local increase of about 20% in wall thickness at the outlet of the housing is all the necessary geometrical modification required to make the new design structurally acceptable. The availability of SiC/Al billet makes the fabrication possible within a relatively short time. Details on weight reduction are given in the summary.

Design Considerations

1. Thermal

   a. Bearing installation - consider coefficient of thermal contraction effect on bearing fits

   b. Coefficient of thermal contraction effect on bellows and cam follower loads for ball seal

   c. Contraction effect on shaft to housing - clearance small enough for seal support

   d. Shaft thrust spring - load reduction due to thermal coefficient.

   e. Method of applying insulation - will materials take plasma spray and plating?

f. Guide fits with temperature

g. Housing chill time versus titanium.

2. Structural - Housing and Shaft

a. Ductility problems due to local high stresses or stress concentration

b. Thermal stresses at joints with dissimilar materials

c. Combined loads - thermal, pressure, and mechanical

d. Housing strength - adding material may not increase strength sufficiently

e. Insert installation - thread requirements and material

f. Load capacity of shaft splines and coupling slider bearings

g. Capacity of cam to take cam follower bearing Hertz stress

h. Bearing load on shaft - will it need wider race?

i. Structural tests with stress coat, strain gages, etc., required.

3. General

a. Wear characteristics of material with dynamic seals with high pressure and high unit-load shaft seals and ball seal

b. Static seal - will material take high unit loads of sealing land without plastic deformation?

c. Several locations have small diameter screws - do they create special problems?

d. Grooves for bearing retainers - is thin lip a problem?

e. Will sealing surfaces be more easily damaged in assembly, handling, cleaning, etc.?

f. SSME valves have high velocity - is there more potential of cavitation damage with this material?

The Fabrication of the SiC/Al Main Fuel Valve

The candidate materials for the MFV are particulate SiC-reinforced alloys. These materials have isotropic properties and can be fabricated by the conventional forming techniques such as forging, extrusion, and secondary machining. The main feature of these materials, which differ from the conventional homogenous materials, are (1) they have low ductility (currently 3 to 5% ductility is obtainable), and (2) the mechanical properties, including the strength and ductility, are improved with hot working. This hot working apparently improves the distribution of SiC particles to promote better mechanical properties. These two features have imposed special constraints in the design of the MFV.

Rocketdyne has expertise in engine designs dealing with both features of the particulate SiC/Al composite materials. For example, Rocketdyne has been designing engine components using beryllium alloys in RS-27, MX and some 250-pound-thrust class small engines. The alloys are considered very brittle and have only 2% to 4% elongation.

On the hot-working related mechanical properties of materials, Rocketdyne has used thermal mechanical processed (TMP) alloys for liquid rocket engine components. This includes Incoloy 903 for high-pressure turbopump components, and Waspaloy for the turbine shaft and disk, in which the finish forging operations (the final 40% - 50% reduction) are performed at temperatures below the gamma prime solvus. Upon subsequent heat treatment, only part of the residual strain (from low-temperature deformation) is relieved, and the strengthening due to retained strain and precipitation hardening are synergistic.

The material cost of SiC/Al is also a concern. Generally speaking, the material costs about $200/lb. It is highly desirable to utilize net shape forging technology to make parts. This feature of minimizing machining and maximizing mechanical properties poses a major challenge to an application of all alloy materials encountered today. One of the subtasks of the MFV composite application will be devoted to the forging and machining tradeoff analysis.

The Effect of Thermal Mechanical Processing on the Mechanical Properties of SiC Composite Materials

It was shown that hot working (rolling, forging) improved the strain to failure for particulate SiC-reinforced aluminum composite materials. For example, a 30% hot rolling (1000 F) has caused a 25V/O SiC/CT-90 (or SiC/X7090) significant increase in both strength (from 90 to 115 ksi) and ductility (1% to 2%). The effect of hot working is more pronounced on the heat-treated materials. This could be due to two reasons: (1) hot working improves bonding between the metal matrix and the particles, and (2) hot working breaks up the segregated structure and improves the alloy homogeneity.

From extensive studies it was found that the mechanical properties of SiC/X7090 aluminum is most sensitive to a thermal mechanical process. There are appreciable data available that indicate the practicability of translating the basic material's response to hot working into complex forging shapes.

In whisker SiC-reinforced aluminum alloy, however, hot working has an interesting effect on the mechanical properties of the materials. Hot working causes the whisker to orient toward the rolling direction and creates properties anisotropy. Also, hot working tends to break up the whisker, and this complicates the properties control of the materials.

Composite Materials Application for Nozzle Extensions

The state-of-the-art design of the typical orbit-to-orbit nozzle uses a regeneratively cooled section from the throat to the intermediate expansion ratio and a tubular dump-cooled extension to the nozzle exit. Full regenerative cooling is undesirable because of the high expansion ratio required to obtain optimum performance in the orbital environment. Alternatives to the tubular dump-cooled concept have arisen due to the cost and complexity of the tubular design. These alternatives have centered on radiation-cooled concepts using refractory metals or carbon-carbon composites. A comparison of the three primary nozzle extension concepts is shown in Table 16.

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TABLE 16. COMPARISON OF NOZZLE EXTENSION DESIGNS
FOR A 15K ORBIT-TO-ORBIT ENGINE

CONCEPT	WEIGHT, LBM	COOLANT REQUIREMENT, LBM/SEC	LIFE CYCLES	LIFE TIME, HOURS
TUBE WALL DUMP COOLED	83	0.36	300	10
COLUMBIUM REFRACTORY COOLED ATTACHMENT	95	0.1	COATING DEPENDENT	
CARBON-CARBON COMPOSITE COOLED ATTACHMENT	56	0.1	UNDEFINED	

It can be seen that the carbon-carbon design offers significant cost and weight advantages over the other two concepts. Both the carbon-carbon and columbium nozzles have a lower cooling requirement over the dump-cooled design. They also share a critical need for protection against oxidation. Recent experience with deterioration of the disilicide coating on the Space Shuttle RCS has shown that the columbium design is thermal cycle limited. The life potential of the carbon-carbon nozzle is not well defined, yet it remains attractive due to its weight and cost advantages.

Schedule and Cost Estimated on Follow-on Tasks

Based on the technical discussion described previously, the schedule and cost estimate of three follow-on tasks - (1) the low-pressure propellant ducting, (2) the MFV, and (3) the nozzle extension - are provided in Fig. 35 through 37.

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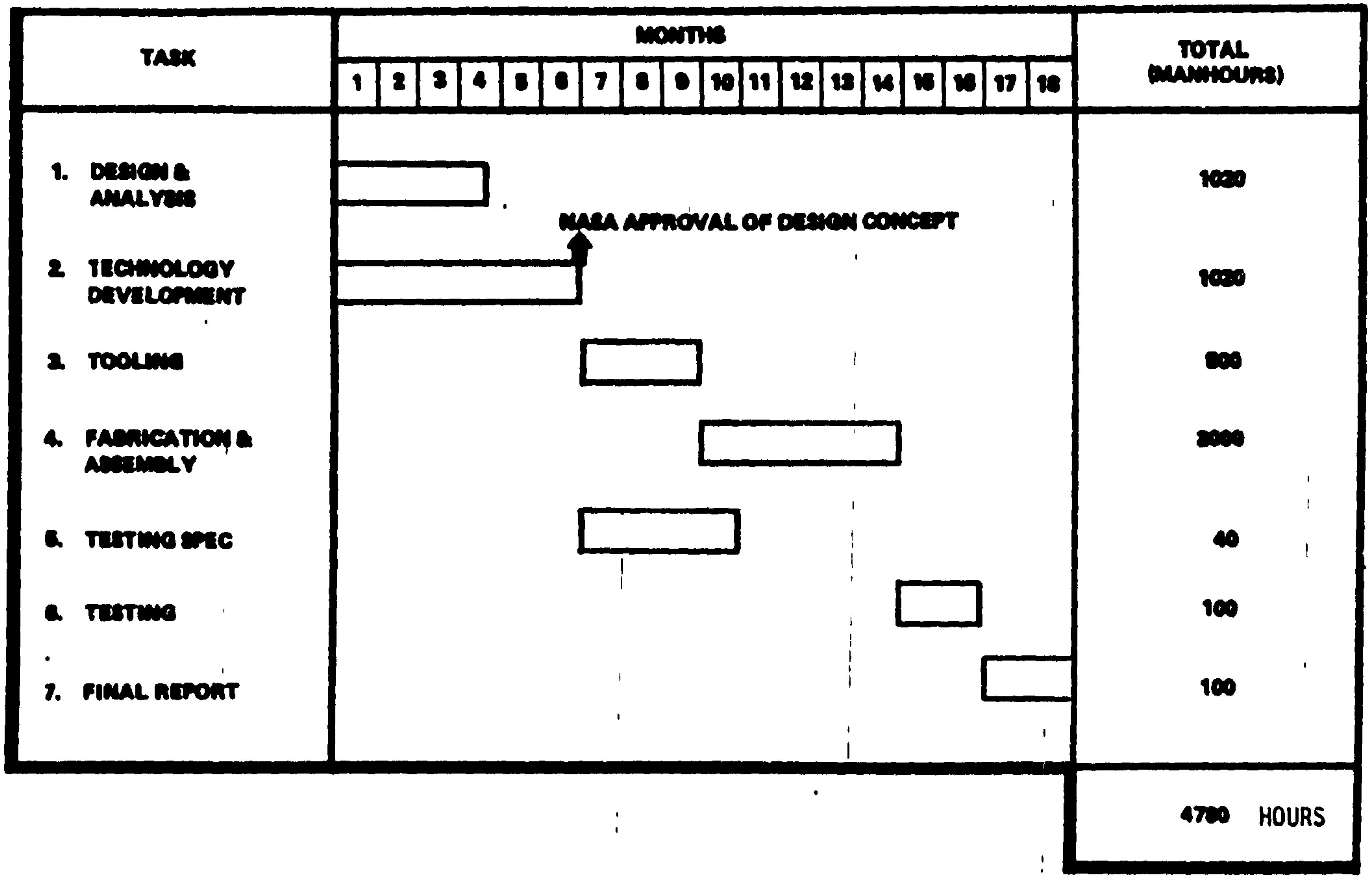

Figure 35. Low-Pressure Oxidizer Duct

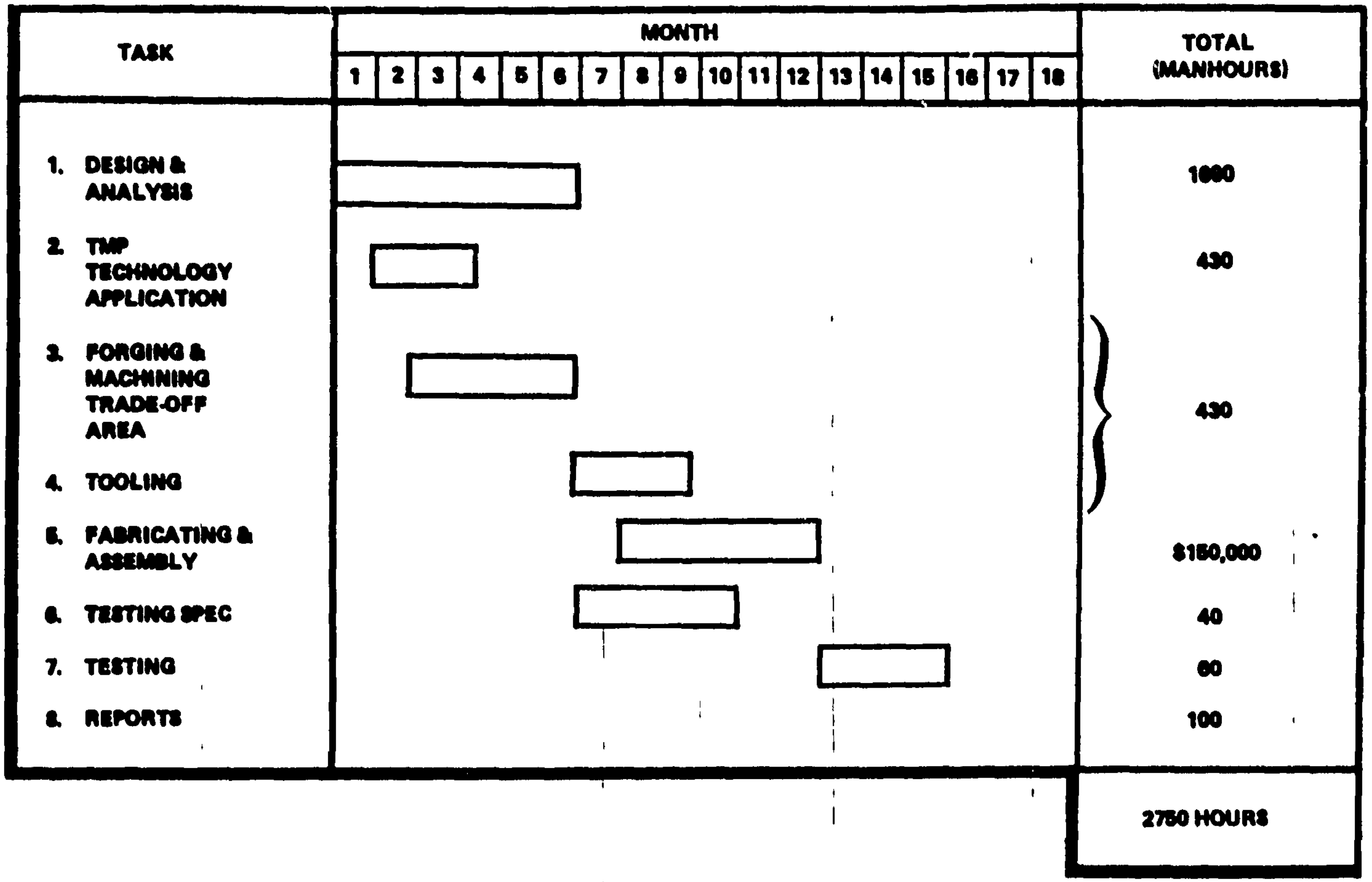

Figure 36. Main Fuel Valve Schedule

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TASK	TOTAL MAN-HRS
Carbon-Carbon/Coating System Evaluation	200
Test Nozzle Procurement	$60K
Best Concept (2 units)	
Unprotected (2 units)	
Refurbish Injectors (2 units)	200
Fab Combustors (2 units)	200
Activate Test Facility	450
Hot Fire Test	1000
Report	150
TOTAL - Basic Program	2200
Alt. Concept Procurement	$30K
Alt. Concept Test	500
TOTAL - With Alt.Concept	2700

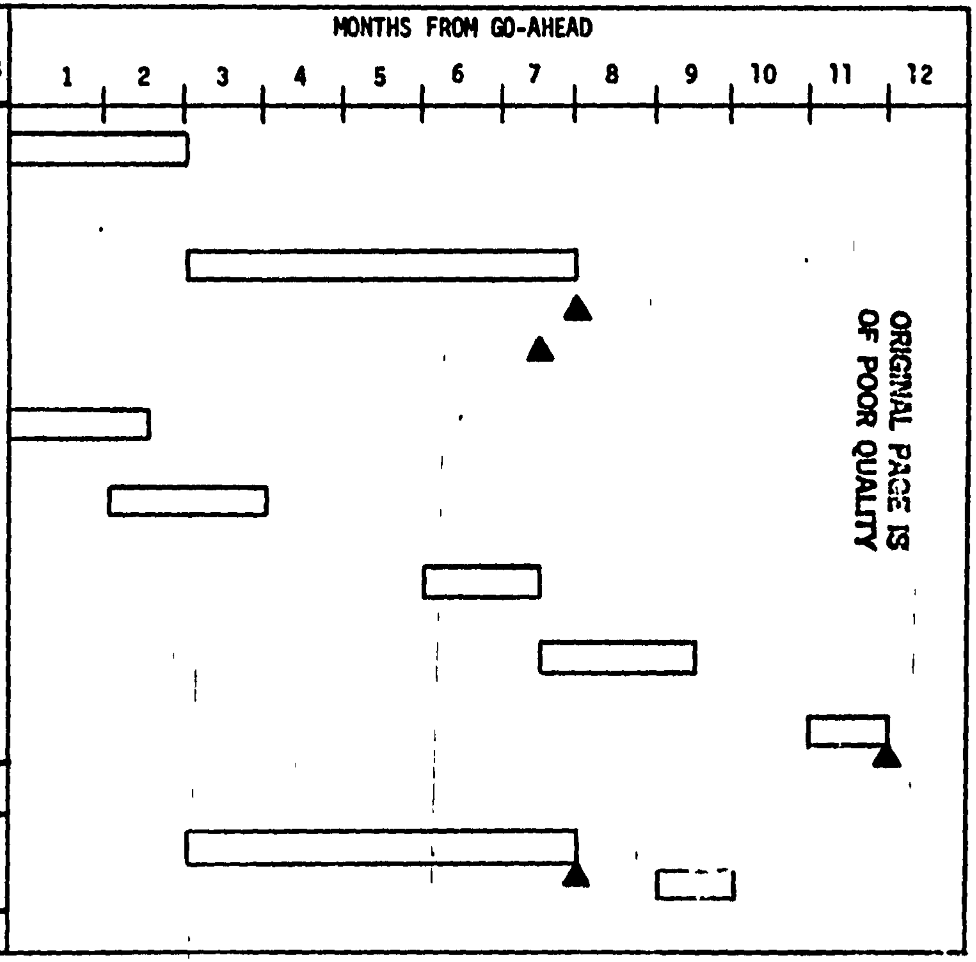

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Figure 37. Carbon Carbon Nozzle Schedule

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Low-Pressure Propellant Ducts

In this follow-on effort, the various design concepts of the propellant ducts described in the previous section will be designed in detail and analyzed for structural integrity; this includes a composite materials bellows joint, ducting, and flange. A subscale, low-pressure propellant duct (3-inch diameter) would be designed with the final configuration including a curved section of the ducting, a bellows joint, and a flange.

The identified technology needs would be developed, including (1) the physical and mechanical properties of the composite materials, and the establishment of the design allowables for the cryogenic application, (2) superplastic forming of SiC/Al bellows, (3) diffusion bonding of different pairs of materials, (4) brazing of different pairs of materials, (5) nondestructive inspection of different joining methods, and (6) investigation of polymer matrix composite manufacturing automation potential. The technology development will be in conjunction with on-going industry activity to minimize cost. Upon completion of this effort, approval for the final ducting design would be obtained from NASA-MSFC.

The final assembly resulting from this effort is a subscale version of a low-pressure propellant duct. To evaluate this assembly test, specifications would be generated so that all design requirements are met and testing will be carried out by the test facility presently performing the qualification tests of propellant ducts.

Main Fuel Valve

In this follow-on effort, a full-scale MFV housing, shaft, couplings, and end caps would be designed and fabricated using a SiC/Al composite material. Specific composite materials would be selected first, based on the criteria of material reproducibility, weight reduction potential, and wider applicability. The materials properties of interest, in response to thermal mechanical processing, would be investigated.

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In view of the high cost of the SiC-reinforced aluminum alloy, machining of the components would be minimized, net shape forgings, however, could be very costly, particularly when small quantities are involved. A trade-off analysis would be performed to minimize fabrication cost. A fabrication procedure would be provided to optimize the materials properties and fabrication cost. The final assembly would result in a complete MFV, which could be integrated into noncomposite parts and be available for testing.

The testing specifications would be provided to ensure that all design requirements are met, and testing would be performed to demonstrate the feasibility of this MFV.

Nozzle Extensions

A test program is needed to evaluate the potential of carbon-carbon composites for liquid rocket engine nozzle application. Specifically, this program will address the two technology issues concerning carbon-carbon nozzles: protective coatings and thin wall fabrication. Long-term variations are needed for protected carbon-carbon. Methods of surface coating, surface conversion, or infiltration must also be investigated for the preferred SiC coating. Even though Rocketdyne has built thin wall carbon-carbon liners, there is limited carbon-carbon thin wall fabrication experience. Durability, handling methods, and fabrication need to be demonstrated.

This follow-on program will conduct a reduced-scale nozzle design and test which simulates orbit-to-orbit nozzle design and environmental problems. Candidate carbon-carbon/coating systems will first be identified and evaluated. Design and procurement of the most promising concepts will follow. A hot-fire evaluation tesc will then be conducted using the existing high-altitude facility at the North American Aircraft Operations plant in Los Angeles.

The carbon-carbon/coating system candidates will be identified by conducting a survey of available data and suppliers. The candidates will be evaluated based on their suitability for orbit-to-orbit rocket engines using LOX/LH_2 propellants operating at a mixture ratio of 6:1 and a chamber pressure of 1500 psia. The

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assumed carbon-carbon nozzle will extend from an expansion ratio of 225:1 to the exit at 625:1.

The most promising candidate will be selected for fabrication of the two test nozzles. The evaulation may indicate that a second candidate is also attractive because of some advantage over the leading choice. For example, the second candidate may have significantly lower cost yet a higher erosion rate. In this event, two additional test nozzles will be constructed, using the second material system. Two unprotected carbon-carbon nozzles will be fabricated to provide a control as to the effectiveness of the coatings tested.

The test nozzles will be designed for integration with a thruster which has been previously tested at the same high-altitude facility to be used for this program. This thruster uses LOX/LH_2 propellants at a mixture ratio of 6:1. Figure 38 illustrates how the nozzle gas properties of a low chamber pressure thruster duplicate those of the high chamber pressure baseline orbit-to-orbit engine. Existing injectors will be used, but new combustors will be constructed to permit replacement of the test nozzles.

The number of potential suppliers will be maximized so that the test nozzles may be competitively procured. The selection criteria will include supplier history, likelihood of success, cost, and schedule.

The existing high-altitude test facility is more than adequate for this program. The test rig is intact, with only facility and instrumentation checkout required. The propellant capacities provide long total duration, up to 15 minutes, at a mixture ratio of 6. Each nozzle will be tested for a number of burns to correspond to the total burn time per mission. This will provide a typical single mission exposure for an orbit-to-orbit liquid rocket engine.

A program schedule is shown in Fig. 37. Direct benefits derived from this program include the following data concerning carbon-carbon nozzles:

- Thin-wall fabrication
- Thin-wall protection

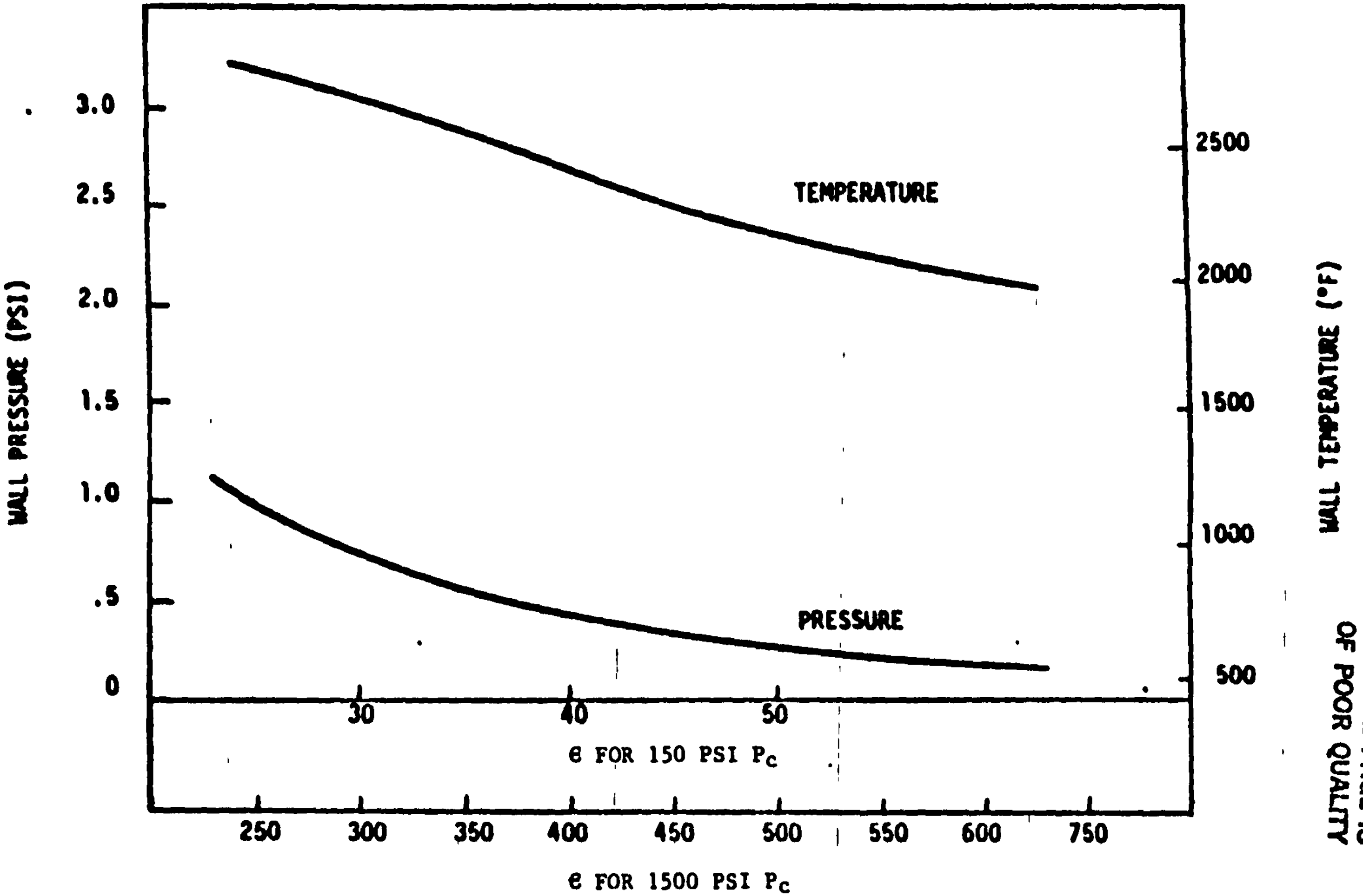

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Figure 38. Thruster Nozzle Gas Properties

- Sensitivity to thermal cycling
- Erosion rate during hot fire
- Handling problems

This follow-on program will provide a low-cost means of providing this much needed data, which should significantly aid in the development of carbon-carbon high expansion ratio nozzles. In addition, the test facilities, test nozzle design, and test program permit program expansion or follow-ons to test other radiation-cooled nozzle materials.

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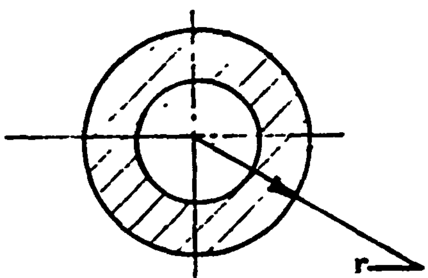
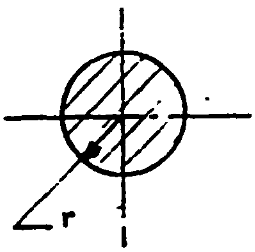
APPENDIX A

PREDICTION OF COMPOSITE PROJECTIONS

Prediction of composites properties can be (1) by the interpolation of existing data, and (2) by the continuum mechanics approach. The latter consists of solving a boundary value problem for a circular cylindrical shell. The stress field for a solid cylinder is for the fiber, while that for a hollow cylinder is for the idealized model of matrix.



MATRIX MODEL



FIBER MODEL

The well known equation(Ref. A-1) is

$$\frac{d^4\phi}{dr^4} + \frac{2d^3\phi}{rdr^3} - \frac{1d^2\phi}{r^2dr^2} + \frac{1d\phi}{r^3dr} = 0$$

The stress function, ϕ is,

$$\phi = ALnr + Br^2Lnr + Cr + D$$

where

$$\alpha r = \frac{1\partial\phi}{r\partial r}$$

$$\alpha r = \frac{\partial^2\phi}{\partial r^2}$$

For the composite properties along the fiber, an axial force is applied to generate α_{xx}. With appropriate generalized Hooke's law, ε_r ε_o and ε_x can be obtained. With the associated boundary conditions including the interface of fiber in matrix, the terms of stress and strain can be evaluated. In a conservative system, the strain energy of the composite is the sum of the strain energy

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Ref. A-1 Elasticity, McGraw-Hill, 1951, P. 58, J.N. Goodier and S. Timoshenko of fiber and matrix. The result leads the composite property as a function for both fiber and matrix properties and the volumetric ratio of fiber in the composite or $E_c=f(E_f, E_m, \nu_f, \nu_m)$ volume ratio of fiber. For other cases, the load is applied accordingly similar to the derived results in an experiment.

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APPENDIX B

METHODOLOGY

The components investigated in this study are treated as shells and plates of (Ref. B-1) gross isotropic and local anisotropic, and (Ref. B-2) gross anisotropic and local isotropic. Standard equilibrium equations are used in the analysis but the governing equations in terms of displacement functions are different because of the variation in the generalized Hooke's Law. Furthermore, the local strain incompatibility between the matrix and its associated reinforcement leads to either debonding of reinforcement and/or interlaminar dislocation of plies. The non-uniform boundary stress also contributes to the stress concentration near the interface. The intensity factor can be located within or beyond the boundary, depending upon the relative strain rate hardening of composites (Ref. B-1). The components of SiC/Al (silicon carbide particulate or whisker in aluminum matrix), such as the main fuel valve, gimbal bearing, and pump housing, are considered gross isotropic, and applicable equations are discussed below.

PRIMARY STRESSES

The circumferential stress in a thick circular cylinder under internal pressure can be calculated by (Ref. B-2)

$$\alpha_\theta = p\left(\frac{b^2 + a^2}{b^2 - a^2}\right) \qquad \text{(A-1)}$$

where p = Internal Pressure
b,a = External and Internal Radii
α_θ = Hoop (circumferential) stress

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Because of end constraints, an axial stress is to be considered in addition to the thrust, or

$$\alpha_{x_1} = p \frac{a^2}{b^2-a^2} \quad , \quad \alpha_{x_2} = \frac{F}{A}$$

where α_{x_1} = Axial Stress by Pressure
α_{x_2} = Axial Stress by Thrust
F = Thrust
A = Cylinder Cross-Sectional Area
$\alpha_r = p$ Represents the radial stress as expected.

It is to be noted that the triaxial stresses can be represented by an effective stress, an invariantive parameter of the state of stress, or (Ref. B-3)

$$\alpha_{EFF} = \frac{\sqrt{2}}{2} \left[(\alpha_1 - \alpha_2)^2 + (\alpha_2 - \alpha_3)^2 + (\alpha_3 - \alpha_1)^2 \right]^{1/2} \qquad \text{(A-2)}$$

<u>Primary Stress, Circular Plate</u>

For a plate with simply supported edge subject to a uniformly distributed pressure, the maximum bending moment is (Ref. B-4)

$$M = \frac{\sqrt{3} + \nu}{16} p(b^2 - a^2) \qquad \text{(A-3)}$$

SECONDARY STRESSES

The thermal stresses in a circular cylinder subject to radial gradient are given by (Ref. B-2)

$$\sigma_r = \left(\frac{\alpha E}{1-\nu} \frac{1}{r^2} \frac{r^2-a^2}{b^2-a^2} \int_a^b Trdr - \int_a^r Trdr \right) \qquad \text{(A-4)}$$

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$$\sigma_\theta = \left(\frac{\alpha E}{1-\nu}\frac{1}{r^2}\;\frac{r^2+a^2}{b^2-a^2}\int_a^b Trdr + \int_a^r Trdr - Tr^2\right) \tag{A-5}$$

$$\sigma_x = \left(\frac{\alpha E}{1-\nu}\;\frac{2}{b^2-a^2}\int_a^b Trdr - T\right) \tag{A-6}$$

where α = Coefficient of Expansion

E = Elasticity Modulus

r = Space Variable in the Radial Direction

T = Temperature Function

ν = Poisson's Ratio

When the thermal gradient is along the longitudinal axis of the cylinder, while the temperature is constant through the thickness of the wall, the governing equation is (Ref. B-3)

$$\frac{d^4W}{dX^4} + r\beta^4 W = -\frac{Eh\alpha}{Da}F(x) \tag{A-7}$$

which would be identical to an equilibrium equation for a cylinder subject to an internal pressure, if $\frac{Eh\alpha}{a}F(x)$ is equated to p.

F(x) in this case is the thermal gradient in the axial (x) direction. Consequently, in a liner elastic range, the shell solutions are applicable such as

$$\sigma_\theta = \frac{pa}{h} = \left(\frac{a}{h}\right)\left[\frac{E\alpha hF(x)}{a}\right] = E\alpha F(x) \tag{A-8}$$

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DISCONTINUITY STRESSES

Geometrical discontinuity leads to the effect of compatibility forces, Mo and Qo, to satisfy the continuity of sections. The moment is given by (Ref. B-3)

$$M_x = M_o\phi(\beta x) - Q_o \frac{\rho(\beta x)}{\beta} \tag{A-9}$$

where $\beta^4 = 3(1-\nu^2)/a^2h^2$

$\phi(\beta x) = e^{-\beta x}(\cos\beta x + \sin\beta x)$

$\rho(\beta x) = e^{-\beta x}\sin\beta x$

$M_o = p/2\beta^2,\ Q_o = -p/\beta$

As stated previously, the same methodology is also suitable for thermal loads.

STRAIN

When the thermal gradient is relatively steep, the resulting thermoelastic stress is expected to be beyond the range of the linear elasticity. Consequently, thermo-plasticity is to be considered. By making use of Hooke's law, the total strain in each axis can be estimated.

For example in the circumferential direction (Ref. B-2)

$$\epsilon_\theta = \frac{1}{E}\,[\sigma_\theta - \nu\,(\sigma_r + \sigma_z)] + \alpha T \tag{A-10}$$

Similarly, ϵ_r, and ϵ_z can be written. Where ϵ = strain, total.

They can be conveniently defined as effective strain (Ref. B-4)

$$\epsilon_{EFF} = \frac{\sqrt{2}}{3}\left[(\epsilon_1-\epsilon_2)^2 + (\epsilon_2-\epsilon_3)^2 + (\epsilon_3-\epsilon_1)^2\right]^{1/2} \tag{A-11}$$

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ε_{EFF} is kept within the yield strain. Equations A-2 and A-11 are examples for principal stresses and strains only. Ref. B-4 provides more details for cases other than the principal forces and displacements. The true stress is then read off stress-strain curves.

SPECIAL TOPICS

Stability solutions are not to be repeated here as they are available in literature in Ref. B-5 through B-9 dealing with both static and dynamic conditions for either circular cylinder or cones subject to various external loads.

GROSS ANISOTROPIC CASE

One of the many approaches in the derivation of a system of equations of motion or of equilibrium is to consider the Newtonian formulation. With the aid of virtual work, a set of governing equations can be obtained in accordance with D'Alembert's principle. The resulting equations are given below (Ref. B-10).

By summing up the forces in the y-direction on the deformed shell, the first equation of motion is

$$\frac{\partial N\phi}{a\partial\phi} + \frac{\partial Nx\phi}{\partial x} = Ph\,\frac{\partial^2 v}{\partial t^2} - Py$$

Similarly, in the x-direction,

$$\frac{\partial Nx}{\partial x} + \frac{\partial Nx\phi}{a\partial\phi} = Ph\,\frac{\partial^2 U}{\partial t^2} - Px$$

in the z-direction

$$\frac{\partial \theta x}{\partial x} + \frac{\partial Q\phi}{a\partial\phi} + N_x\,\frac{\partial^2 W}{\partial x^2} + N_\phi\left(\frac{1}{a} + \frac{\partial^2 W}{a^2\partial\phi^2}\right) + 2N_{x\phi}\,\frac{\partial^2 W}{a^2\phi\partial x} = Ph\,\frac{\partial^2 W}{\partial t^2} - P_z$$

When summing up moments in the y-direction

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$$\frac{\partial M_x}{\partial x} - \frac{\partial M_x\phi}{a\partial\phi} - Q_x = \frac{Ph^3}{12}\frac{\partial^2\theta}{\partial t^2}$$

in the x-direction,

$$\frac{\partial M\phi}{a\partial\phi} - \frac{\partial M\phi x}{\partial x} - Q_\phi = \frac{Ph^3}{12}\frac{\partial^2\psi}{\partial t^2}$$

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a	Radius
E	Modulus of elasticity
G	Shear modulus
h	Shell thickness
I	Mass moment of inertia
i	Index
L	Length
M	Moment
m	Mass, number of waves
N	Force, a large integer
n	Number of waves
P	Pressure
Q	Transverse shear
R	Radius
t	Time
u,v,w	Displacement in x,y,z direction respectively
X	Force
x	Displacement
x,y,z	System of coordinates
α	$m \pi/2$
β	$n \pi/a$
υ	Poisson's ratio
ρ	Mass density
ϕ	Angle
θ,ψ	Rotation in x-z and y-z plane, respectively
$\cdot$	Differentiation with respect to time

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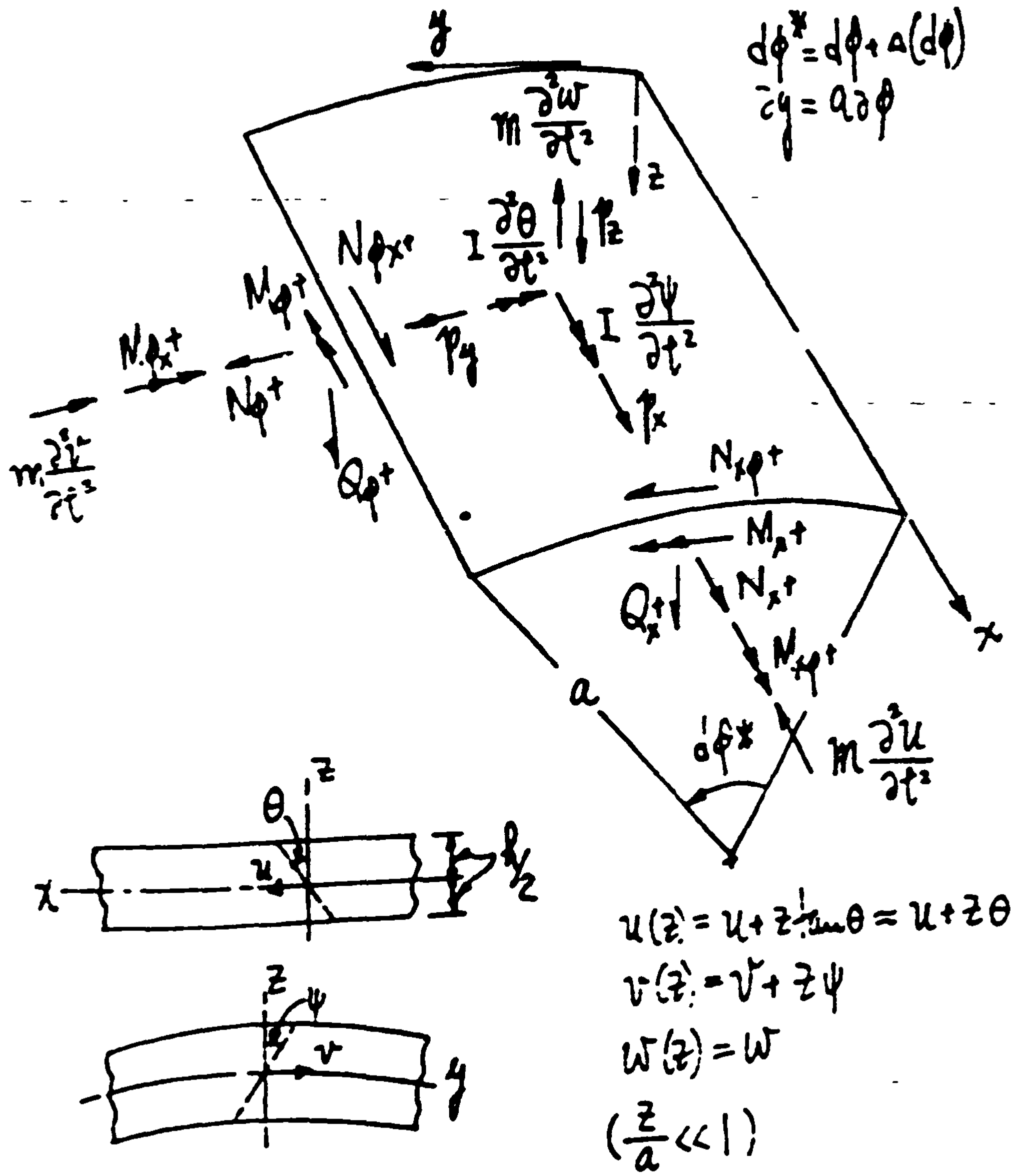

Shell Geometry and Loading

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Ref. B-11 gives the applicable, generated Hooke's Law, as follows:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = \begin{Bmatrix} \alpha_x \Delta T \\ \alpha_y \Delta T \\ \alpha_z \Delta T \\ 0 \\ 0 \\ 0 \end{Bmatrix} + \begin{bmatrix} \frac{1}{E_x} & -\frac{\upsilon_{xy}}{E_y} & -\frac{\upsilon_{xz}}{E_z} & 0 & 0 & 0 \\ -\frac{\upsilon_{yx}}{E_x} & \frac{1}{E_y} & -\frac{\upsilon_{yz}}{E_z} & 0 & 0 & 0 \\ -\frac{\upsilon_{zx}}{E_x} & -\frac{\upsilon_{zy}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{xy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \end{Bmatrix}$$

where

ε_i = longitudinal strain

γ_i = shear strain

α_i = coefficient of thermal expansion

E_i = tensile modulus

G_{ij} = shear modulus

υ_{ij} = Posson ratio

σ_i = normal stress

τ_{ij} = shear stress

In a macro-micromechanics analysis, the force displacement relations remain to be the result of combining the strain-displacement, and the stress-strain relations. Then, the governing equations in a selected displacement function with orthotropic material properties can be analyzed in a similar fashion, as those in the gross isotropic case. Reference B-12 and B-13 illustrate the analysis of multiple layer designs. Reference B-14 further outlines the engineering approach for the design of composites.

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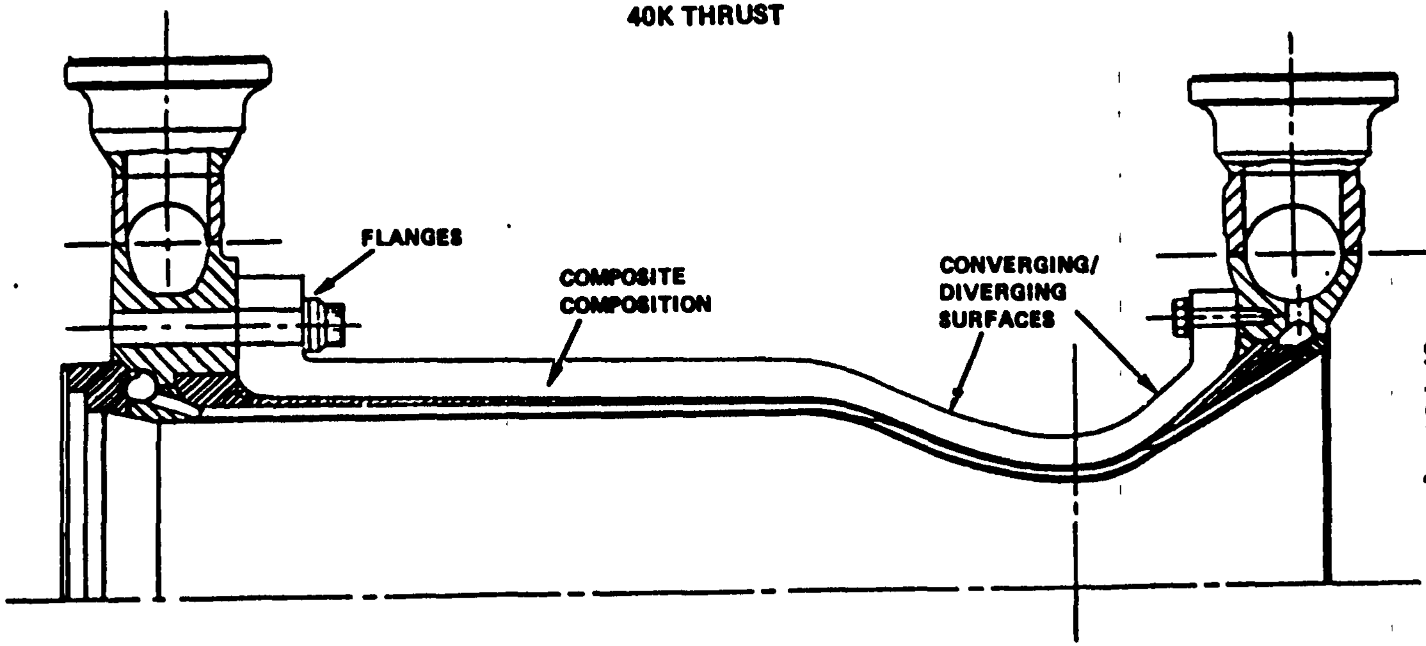
APPENDIX C

COMBUSTION CHAMBER STRUCTURAL JACKET STUDY

A combustion chamber structural jacket was selected as the subject for a design and fabrication demonstration program under Rocketdyne IR&D funding, after due consideration of the state-of-art with respect to available materials and fabrication techniques of composites. This study investigated the potential weight savings that could be achieved on a 40K LOX/H_2 regeneratively cooled thrust chamber with the use of composite materials. Preliminary emphasis was directed toward this hardware because it would provide a direct comparison between existing metallic parts and a composite substitute. Using a copper alloy liner fabricated from a previous design, a graphite/epoxy structural jacket was designed and fabricated as illustrated in Fig. C-1 and C-2. The resultant hardware has been successfully proof-tested and is now available for hot-firing demonstrations. Having completed this study, the fabrication processes and manufacturing experience is now readily available. This demonstrated improvement is applicable to present state-of-the-art thrust chambers.



- OPERATING PRESSURE 3000 PSIA
- PROOF PRESSURE FACTOR 1.2

Figure C-1. Subscale Structural Jacket

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Figure C-2. Graphite-Epoxy Structural Jacket

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APPENDIX D

EVALUATION OF METAL MATRIX COMPOSITE (MMC) MATERIALS

PHYSICAL AND MECHANICAL PROPERTIES

In general, a comprehensive set of property data for a material is generated only after there is a widespread application of it. MMC materials, except B/Al, are new and, therefore, their property data are fairly limited. However, there has seen a certain amount of fundamental work carried out in the last two decades regarding strengthening mechanisms and interfacing reactions, such that the general behavior of some MMC material systems can be characterized. Such information is very useful for materials selection and properties prediction. In this section, we will discuss four aluminum matrix MMC materials; SiC particulate, SiC whisker, SiC continuous fiber, and boron fiber reinforcement.

Most of the physical properties of composites such as the thermal expansion coefficient, density, thermal conductivity, and modulus of elasticity follow the rule of mixtures when the reinforcement is discontinuous fiber reinforced MMC material also follows the rules of mixtures. Property values for transverse or cross-ply are difficult to predict and require individual measurement. The wide range of physical properties obtainable through proper selection of the volume fraction provides a great deal of freedom for the designer. For example, the high thermal expansion coefficient of an aluminum alloy could be reduced by a SiC or graphite second phase. This would minimize macroscopic expansion of the body, although microscopic strains within the body would increase.

The impact of reinforcement on a material's mechanical properties results in an increase in specific strength and modulus, as shown in Fig. D-1. In this figure, the longitudinal properties of composite materials are listed and high values of UtS/ρ and E/ρ are observed. Discontinuous SiC reinforced aluminum has isotropic characteristics with high specific values of E/ρ but only a moderate increase in UtS/ρ.

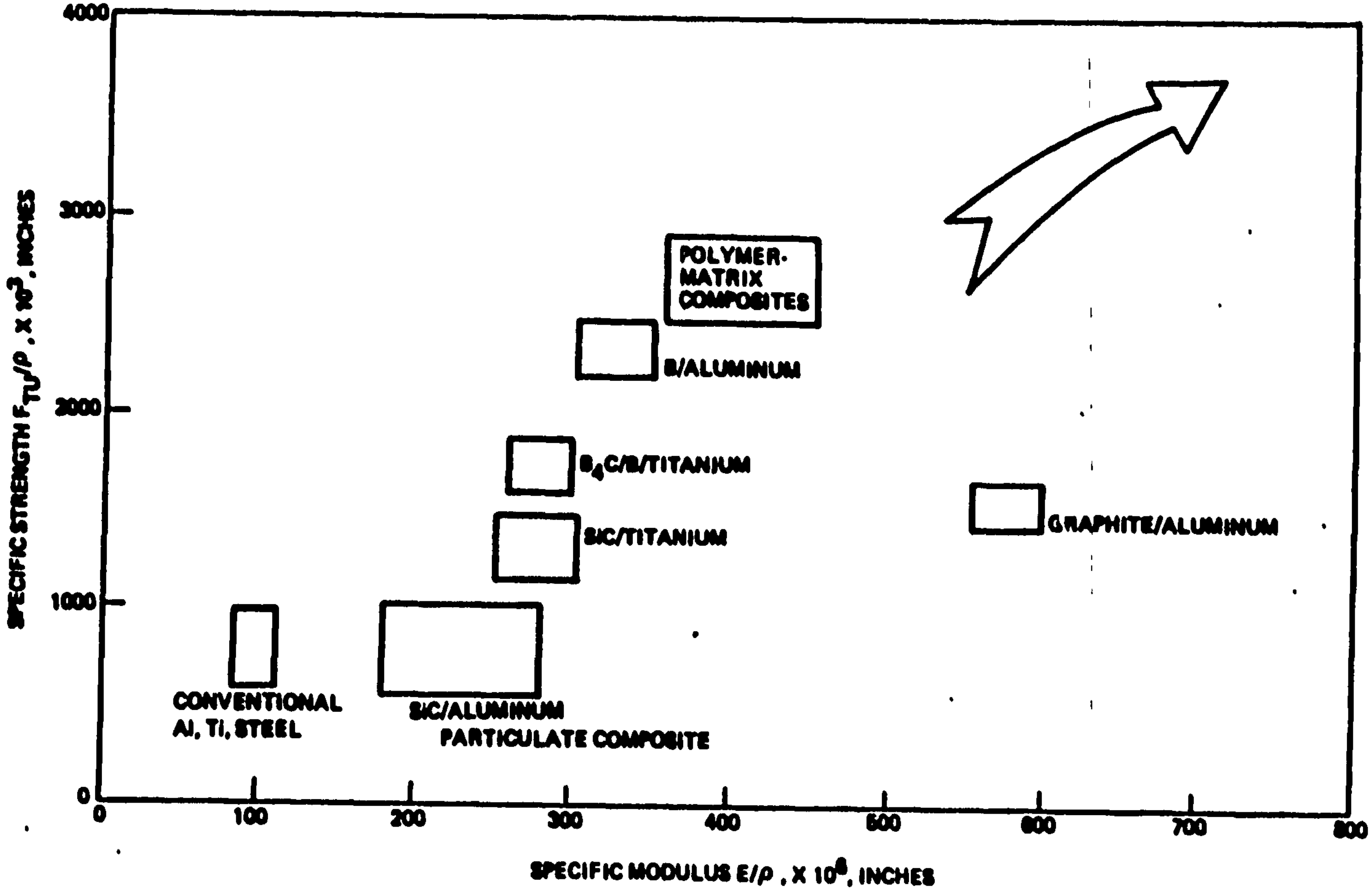

Figure D-1. Comparison of Strength, Stiffness, and Weight Considerations for Composites and Conventional Metallic Alloys

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Mechanical properties data of a representative B/Al continuous composite are shown in Table D-1. The fiber volume fraction is 46%, which for practical purposes, is also a realistically obtainable volume fraction. It can be seen that the mechanical properties are greatly influenced by the fiber orientation. In comparison to polymer matrix composite materials, the matrix strength of B/Al is much higher and it is advantageous in applications where matrix strength is required to transfer loads. A typical example is the Space Shuttle Orbiter mid-fuselage tubular truss members, where B/Al composite can transfer the loads to the clevis more effectively than the polymer matrix composite.

In Fig. D-2 the mechanical properties of a SiC whisker-reinforced 2024 aluminum alloy are shown. It can be seen that while it is desirable to increase the strength and modulus of the composite materials by increasing the volume fraction of the SiC whisker, the ductility of the composite materials is reduced. With the current state-of-the-art technology, it seems that limiting the whisker volume fraction to a 20% level would result in an optimum combination of mechanical properties. Because preparation of the whisker-reinforced aluminum requires further hot working to homogenize the microstructure, the whiskers in the final product tend to orient toward the hot working direction and also degrade in fiber aspect ratio, as shown in Fig. D-3. The property value shown in Fig. D-3 represents only the whisker orientation direction properties, and it is reported that the transverse properties are either comparable or only slightly higher than those of the matrix material.

In Fig. D-4 the stress strain curve of some SiC particulate-reinforced aluminum alloys is shown. The CT90 is a new material, utilizing Alcoa's new P/M RSR X7090 alloys as the matrix material. This high strength material has pushed the discontinuous MMC UtS/ρ ratio nearly to the 1000 scale.

Properties of a 48 V/O SiC continuous fiber-reinforced aluminum composite are shown in Table D-2. With proper coatings on the SiC fibers, their high temperature stability is much better than that of boron fibers, as shown in Fig. D-5.

In general, the MMC materials exhibit excellent compressive strength; for example, the B/Al and the SiC whisker aluminum alloy all booked a comprehensive

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TABLE D-1. TYPICAL CHARACTERISTICS

45 v/o FIBER REINFORCED 6061 ALUMINUM COMPOSITES

Property \ Reinforcement type & Direction	5.6 mil BORON Uniaxial (0°)	5.7 mil BSC Uniaxial (0°)	5.6 mil BORON ±45°	5.6 mil BORON 50% 0°, 50% ±45°
ULTIMATE STRENGTHS				
Tension (L)	210 ksi	155 ksi	36 ksi	95 ksi
Tension (T)	25 ksi	18 ksi	36 ksi	27 ksi
Shear	23 ksi		90 ksi	50 ksi
Compression (L)	600 ksi		70 ksi	250 ksi
MODULUS				
E (L)	31 Msi	31 Msi	19 Msi	26 Msi
E (T)	20 Msi	20 Msi	19 Msi	20 Msi
G (L-T)	7 Msi	7 Msi	11 Msi	9 Msi
ENDURANCE LIMIT (10^6 CYCLES)	140 ksi			
POISSON'S RATIO				
ν (L-T)	0.25	0.25	0.40	0.33
ν (T-L)	0.15	0.15		
CTE, 10^{-6}/Deg.				
α (L)	3.2/°F		5.6/°F	3.5/°F
α (T)	10.5/°F		5.6/°F	8.6/°F

(L) - Longitudinal, 0°, Direction. (T) - Transverse, 90°, Direction.
Transverse Tension and Shear Strengths Can Be Increased By Thermal Treatment.

Boron Fiber Diameter is 5.6 mils (0.142 mm). Composite Density is 0.095 lb/in³ (2.63 g/cm³)
BSC Fiber Diameter is 5.7 mils (0.145 mm). Composite Density is 0.097 lb/in³ (2.68 g/cm³)
Monolayer Thickness is 7.35 mils (0.187 mm)

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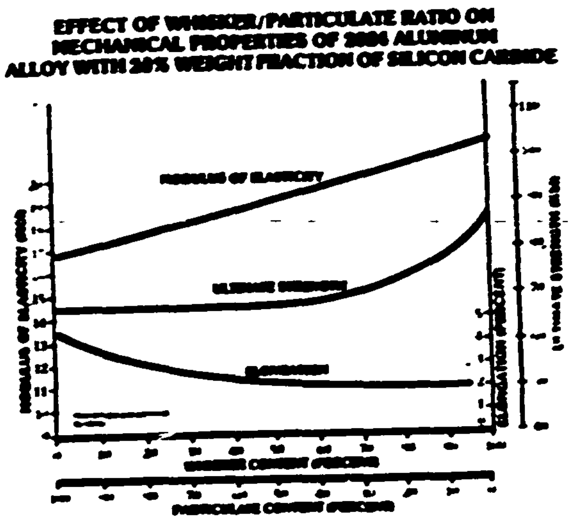

Figure D-2. The Mechanical Properties of SiC/2024 As A Function of the Percentage SiC Volume Fraction

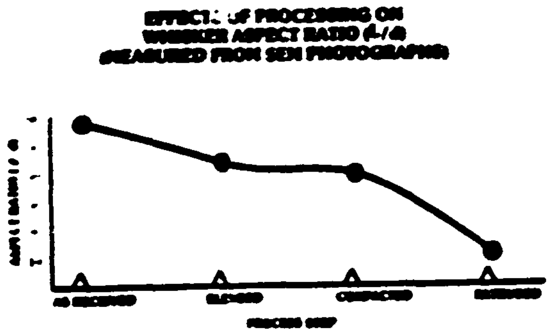

Figure D-3. The Aspect Ratio Reduction As A Function of Process Steps

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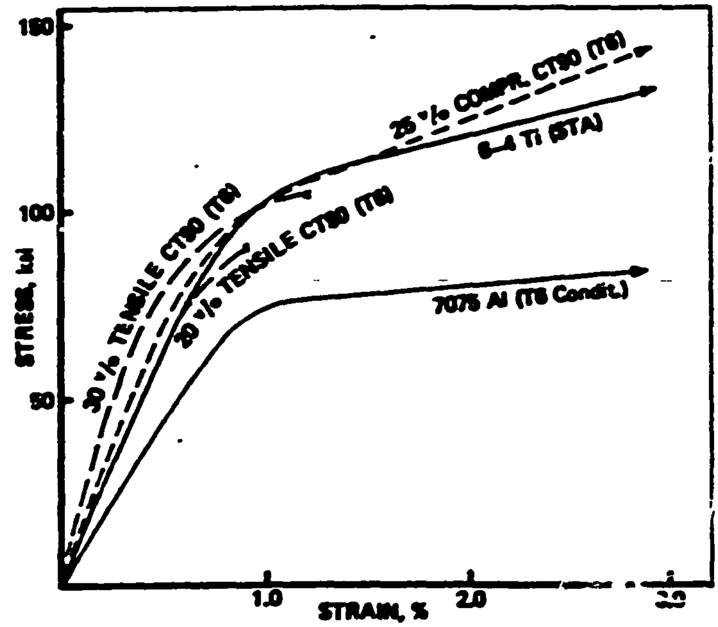

Figure D-4. The Stress-Strain Curve For Some SiC Particulate Reinforced Composite Materials

TABLE D-2. HOT MOLDED SCS IN 6061/713 BI-ALLOY MATRIX
1110-1120°F/20 MINUTES/800 PSI (48 V/O)

SPECIMEN NO.	σ_{11} KSI	ϵ_{11}%	E_{11} MSI	SPEC. NO	σ_{22} KSI	ϵ_{22}%	E_{22} MSI
[illegible]-1	245	1.0	31.2	NM #1	14.1	.116	20.[illegible]
-2	272	1.04	31.8	NM #2	12.4	.102	18.5
-3	272	1.03	29.8	NM #3	13.4	.119	13.8
-4	270	1.06	28.5				
-5	254	1.0	28.4				

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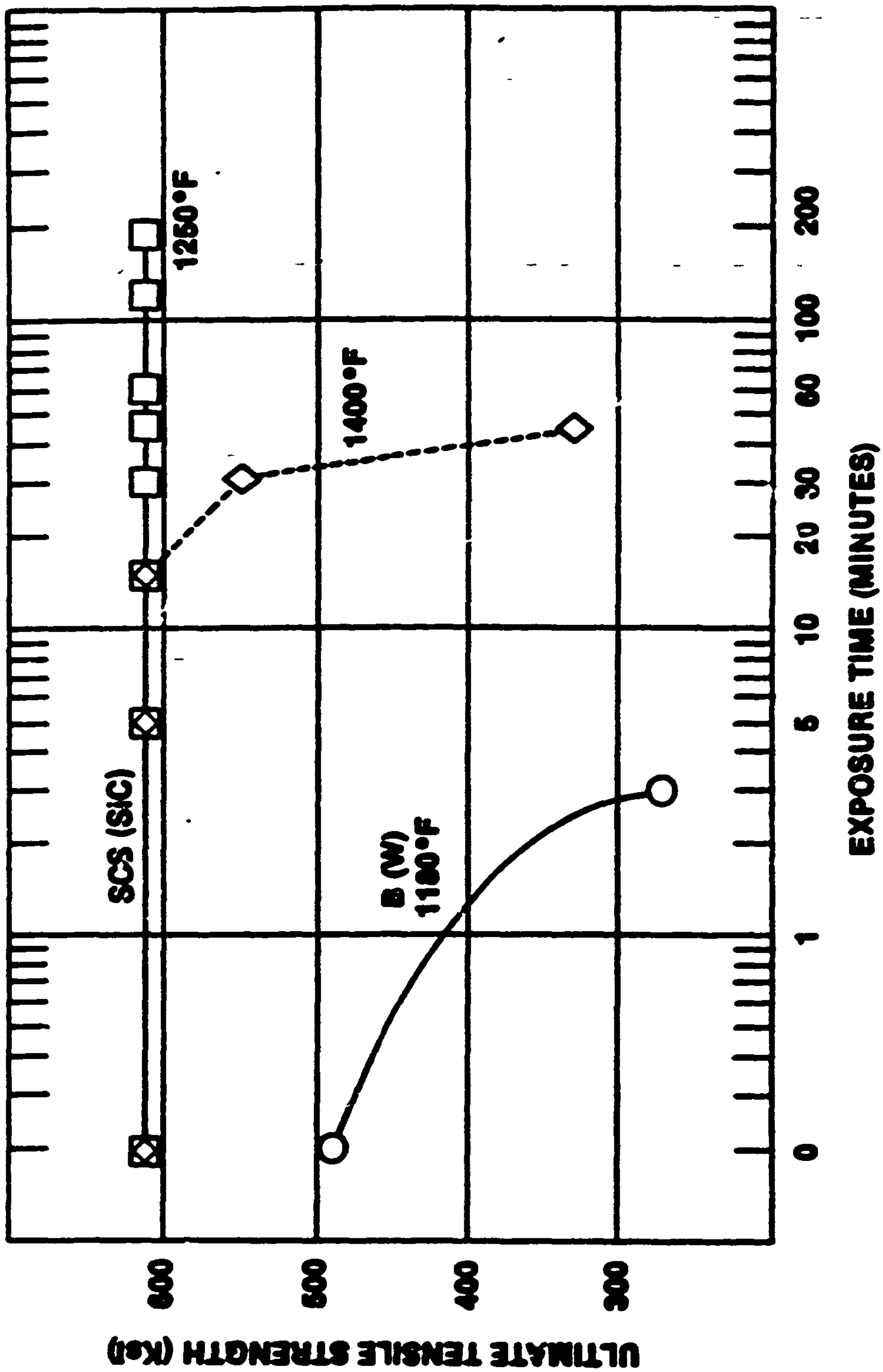

Figure D-5. Strength of SiC and W Fibers

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strength of 600 Ksi. MMC bearing strength is expected to be very high, and this unique property should be utilized as much as possible. Another advantage of MMC materials is their high-cycle fatigue resistance, as shown in Fig. D-6.

Fabricability of MMC Materials

Diffusion Bonding. Procedures have been well established to produce B/Al panels by diffusion-bonding processes; aluminum sheet and arrayed boron fiber are stacked up and hot pressed to consolidate in a vacuum.

Hot Creep Forming. Final shape of a flat sheet could be formed in a specially designed die by a slow, hot, low-pressure press. There is data on the creep forming of continuous fiber aluminum matrix composites into stiffener shapes, such as Z's. Creep forming of tubing or flanges have, as yet, not been demonstrated.

Liquid Metal Infiltration. This is the technique limited primarily to the continuous fiber/matrix system where the fiber's strength does not degrade. This includes the SiC fiber and Al_2O_3 FP fiber reinforced aluminum alloys. This process involves vacuum or positive pressure casting. Fabricated fiber preforms are inserted in the mold and molten aluminum is introduced for infiltration into the fiber preform to form the composite shape. The major problem encountered in this technique is the wetability and the retention of fiber spacing. The fiber wetting problem has been solved by modifying the surface of the SiC fiber to include a higher content of silicon. The concern for retention of fiber spacing and placement during infiltration of the metal can be approached by a hybridization of SiC fiber with other fibers interwoven to form a fabric.

Vacuum Hot Pressing. A vacuum hot pressing process is used to manufacture silicon carbide whisker/particulate reinforced aluminum composite materials. The first step of this process is to verify the quality of the aluminum powder and ceramic reinforcement to be used in the process. The next step is to mix the aluminum powder and reinforcement into a homogeneous mixture, which is then heated, evacuated, and pressed in a hydraulic press such that liquid base compaction and consolidation takes place.

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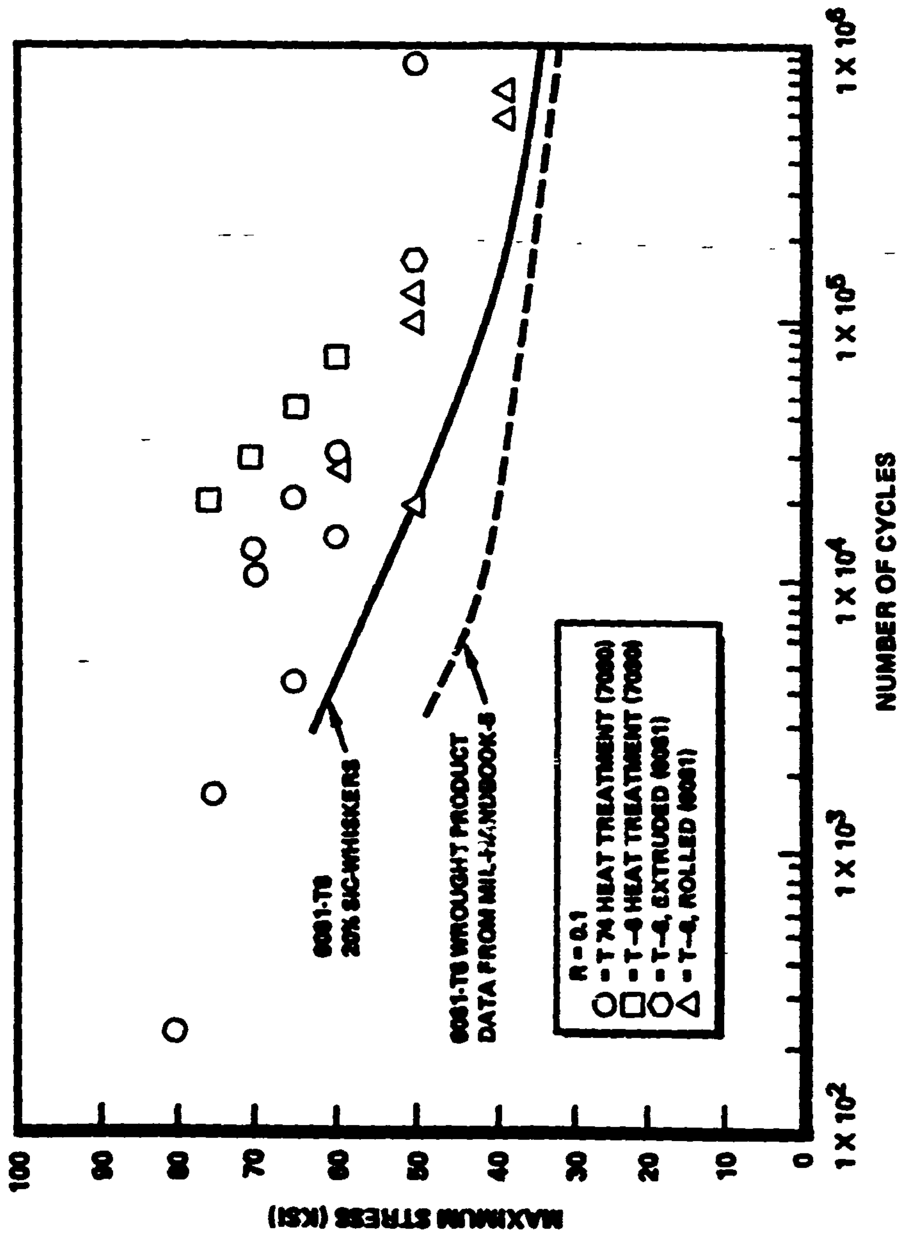

Figure D-6. Fatigue Data

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Extrusion and Forging.

Extrusions are applicable to either particulate or whisker-reinforced composites. For liquid rocket engine component applications, where thick gage sections are involved, extruded MMC materials are available. In discontinuous MMC materials, hot extrusion is a step that promotes better homogenized microstructure and consequently improves mechanical properties. Forgings produced from whisker or particulate MMC materials require establishing new forging parameters in order to obtain optimum flow characteristics. Again, hot forging is a step to improve mechanical properties of hot pressed whisker or particulate composite materials.

Secondary Fabrication. Sawing, routing, drilling, reaming, and EDM have been investigated by Rockwell's B-1 division, and satisfactory operation can be achieved with some modification of procedures.

Joining.

Joining of the MMC materials is probably the most challenging aspect in the consideration of its application to liquid rocket engine components. The most common engineering joint is the fusion weld joint. Two potential technology problems are associated with fusion welding of MMC materials: the sluggishness of the base materials, and the strength difference between weldment and base materials. There is an additional problem associated with discontinuous SiC reinforcement. During the powder mixing process, the aluminum would capture a certain amount of moisture, and upon heating, hydrogen gas evolves which causes blistering type defects in the base materials. It is reported that elevated temperature out-gasing could be performed to eliminate this problem. One industrial supplier, however, indicated that they did not have this problem, and they indicated that they are developing a proprietary filler material to eliminate the strength difference problem.

Other welding techniques which have been demonstrated successfully include inertia welding and diffusion welding. The diffusion welding was demonstrated in a B/Al to Ti-6V-4Al tapered lap joint used in the Space Shuttle mid-fuselage truss tubular members. The diffusion bonding of MMC materials to Ti alloys is

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considered promising because of the Ti alloys. Diffusion bonding of MMC materials to dissimilar metals could be used as a transition piece for fusion, EB, or laser welding. Diffusion bonding of aluminum to aluminum is generally considered very difficult because of surface oxide formation. Currently Rockwell is working on a program to demonstrate the feasibility of vacuum diffusion of aluminum alloys. Other types of bonding methods, such as brazing and adhesive bonding, are available for joints where high bond strength is not required.

Joints. The poor weldability of high strength aluminum limits the joining capability. Therefore, metal matrix composites suffer from having the strength of joints limited to that of the matrix material, which is considerably less than that of the reinforcing fibers. This problem requires an increased area of brazing contact or beefed up weld to ensure adequate fiber load transfer. Transitional methods illustrated in Fig. D-7 and D-8 may provide some remedy to this difficulty.

Hybrid. Hybrid composites combine composite materials with titanium, nickel, or aluminum foil, and may be used for ducting, struts, and similar members. This permits tailoring the composite structure to meet specific strength and thermal requirements and omit material where not required for added weight saving. Typical examples of hybrid construction are illustrated in Fig. D-9 through D-11.

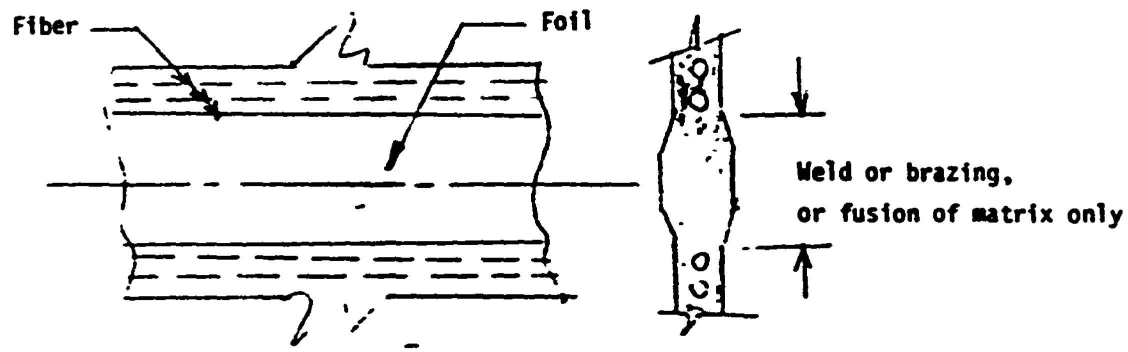

Figure D-7. Joint Parallel to Fiber Orientation

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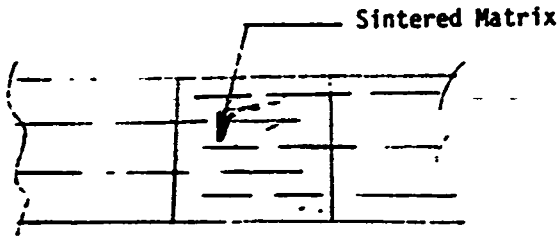

Figure D-8. Joint with Sintered Matrix with Extended Reinforced Fibers

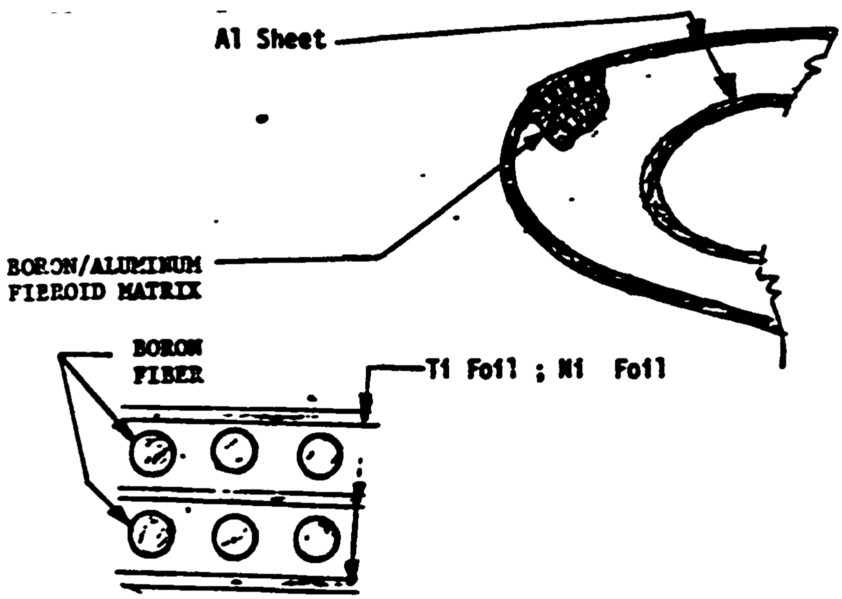

Figure D-9. Improvement on Thermal Requirement

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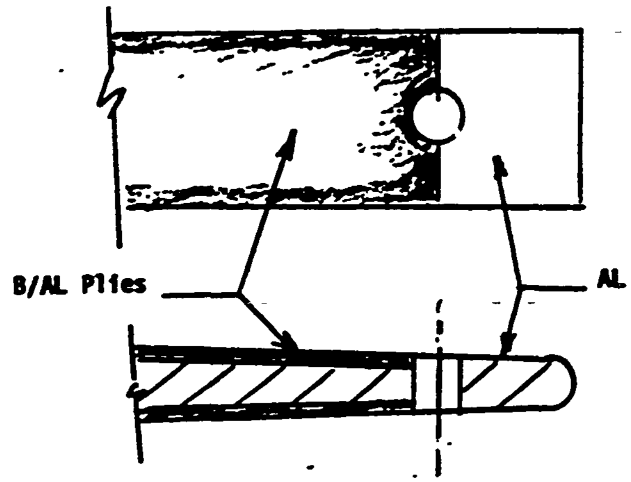

Figure D-10. Mechanical Attachment by Transition

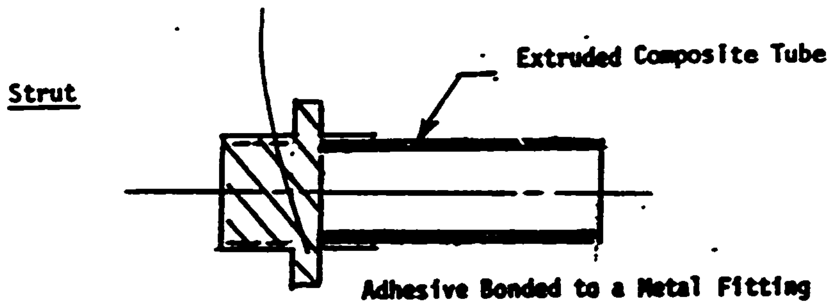

Figure D-11. Strut Bonding

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