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CONCEPTUAL DESIGN STUDY OF ADVANCED ACOUSTIC-COMPOSITE NACELLES

BY

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16. Abstract

Conceptual studies were conducted to assess the impact of incorporating advanced technologies in the nacelles of a current wide-bodied transport and an advanced technology transport. The studies evaluated the improvements possible in the areas of fuel consumption, flyover noise levels, airplane weight, manufacturing costs, and airplane operating costs. Short and long-duct nacelles were evaluated. The study considered use of composite structures for acoustic duct linings in the fan inlet and exhaust ducts as well as for other nacelle components. For the wide-bodied transport, the use of a long-duct nacelle with an internal mixer nozzle in the primary exhaust showed significant improvement in installed specific fuel consumption and airplane direct operating costs compared to the current short-duct nacelle. The long-duct mixed-flow nacelle is expected to achieve significant reductions in jet noise during takeoff and in turbo-machinery noise during landing approach. Recommendations were made of the technology development needed to achieve the potential fuel conservation and noise reduction benefits, identified in the study.

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FOREWORD

The conceptual design study described in this report was conducted for the Aeronautical Systems Division at the NASA Langley Research Center in Hampton, Virginia, under Contract NAS1-13356. Richard C. Dingeldein was the NASA Program Manager and Harry T. Norton, Jr., was Project Engineer.

The Douglas Aircraft Company, division of the McDonnell Douglas Corporation in Long Beach, California, was the prime contractor for the study with Kenneth E. Nordstrom the Douglas Program Manager. The Aircraft Engine Group of the General Electric Company in Evendale, Ohio, provided technical assistance to Douglas under subcontract. Donald F. Sargisson was the General Electric Technical Program Manager.

Messrs. Nordstrom and Sargisson were assisted by various technical specialists in conducting the studies reported here. Major contributions from the following personnel are gratefully acknowledged.

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6. Propulsion System Integration, Evaluation and Technology Requirements	R. T. Kawai	

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CONCEPTUAL DESIGN STUDY OF ADVANCED ACOUSTIC-COMPOSITE NACELLES

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1.0 SUMMARY

This report presents the results of a program for the "Conceptual Design Study of Advanced Acoustic-Composite Nacelles." This program had as its objectives (1) the evaluation of advanced nacelle concepts which provided lower fuel consumption and reduced community noise levels through new or unique installation arrangements, (2) the assessment of the effects of applying advanced acoustic composite materials to the nacelle concepts which were developed, and (3) the delineation of the technology development program needed to implement application of these advanced nacelle concepts. The concepts included integration of nacelle acoustic treatment and structure, advanced acoustic duct linings, and a long-duct nacelle with an internal forced mixer. The assessment included estimates of the potential weight and production costs of individual components compared to equivalent metal structures and an estimate of the potential payoffs based on airplane direct operating costs. Each of the nacelle concepts, with the effects of applying composites included, was evaluated from the standpoints of community noise levels and installed performance compared to a current production nacelle. The potential payoffs were shown in terms of reduction in airplane direct operating cost (DOC), and community noise levels and in terms of airplane fuel savings. The technology development required to realize the potential weight, cost, noise and fuel saving benefits was then identified.

Two separate and distinct time periods were considered for this investigation. The first assumed nominally a 1980 time frame for certification of a new version of a current wide body transport (WBT) which could incorporate an advanced acoustic composite nacelle. The second assumed nominally a 1985 time frame (or later) for certification of an advanced technology transport (ATT)

*General Electric Company, Evendale, Ohio

which would be an all new airplane, including appropriate application of advanced acoustic composites to the nacelle. For the WBT, most of composite nacelle component designs were based on replacement of existing components and entailed a minimum amount of redesign. For the ATT, all new designs were evolved which could take better advantage of the characteristics and properties of advanced composites. The levels of technology employed assumed that those concepts which had already attained some proof-of-concept through existing or recent research programs, or for which technology was nearly in-hand, would be available for the WBT airplane. For the ATT airplane, it was assumed that more-advanced concepts as well as some material improvements would be available.

This program developed composite component designs for a number of applicable nacelle parts. The cost and weight of each detail part was determined and its effect on the total nacelle weight and cost to the aircraft manufacturer was ascertained. The benefits of nacelle composites and/or the new nacelle concepts were determined by calculating the effects of nacelle weight, cost and performance changes on the base aircraft characteristics. From these changes it was possible to assess noise levels and fuel consumption, the prime parameters of interest, as a function of nacelle weight and cost. The nacelle cost analysis was accomplished through standard business and aircraft pricing plans. The input to this analysis consisted of shop and tooling costs. Development costs were addressed separately. For the DOC analyses, payload, range and takeoff gross weight were held constant and fuel consumption and airplane empty weight were changed as required to reflect the effects of the new nacelles. Direct operating costs were calculated using the 1967 ATA formula modified by Douglas to reflect more realistic airplane economics.

The results of these investigations indicated that advanced acoustic composites offer significant potential weight and cost savings and will result in reduced fuel consumption and noise when applied to nacelles. Specifically, the study results showed that a long-duct, mixed-flow nacelle incorporating advanced composites would reduce the cruise specific fuel consumption (SFC) 3.4% and airplane empty weight 657 kg (1449 lb) on a typical wide body transport. If evaluated as a direct change on an existing airplane, i.e., not taking credit for airframe re-sizing as is done on a new or derivative aircraft, the composite long duct nacelle reduced the fuel burned on a 9890 km (5340 n mi) mission by 4.75%. The reduction was due to the combination of improved cruise SFC and the lower cruise thrust required as a result of the reduced weight of fuel and airplane empty weight. If applied to new or derivative aircraft, the benefits from this advanced nacelle technology would be expected to be larger due to airplane sizing effects.

Concurrent with the fuel consumption reduction, the 90 EPNdB noise contour was reduced 35% and the takeoff noise was reduced 4 EPNdB.

For the public to benefit from the potential fuel saving offered by the composite, long-duct, mixed-flow nacelle, an integrated technology development program is recommended, starting with base technology development for specific nacelle requirements, followed by experimental flight demonstrations and concluding with an in-service evaluation.

The experimental flight demonstration is required to substantiate that the combination of the relatively small, individual performance benefits from the long duct nacelle drag improvements, internal mixer propulsive efficiency improvements and advanced composite weight reductions will, in fact, result in the relatively large overall benefit identified in this study. Independent programs are not likely to make the total benefits visible. The flight demonstration is also necessary to substantiate the predicted in-flight noise reduction.

Commercial airline service evaluation is required to substantiate the durability and maintainability of weight- and cost-effective advanced composite nacelle components. Composites are not likely to have broad acceptance in nacelles without such a service evaluation because of the severe environment that the nacelle represents and the fact that other programs currently in progress on advanced composites do not encompass the nacelle requirements. In addition, resistance to incorporation of composites in nacelles will exist until their durability and maintainability are sufficiently demonstrated to assure that reduced cost of ownership will result from their use.

The recommended program offers a high probability of achieving real fuel savings, noise reduction and improved airline economics. Since the use of advanced acoustic-composites could be applied to newly produced versions of current wide body transports, it is estimated that the early and widespread use of this technology could result in fuel savings exceeding $1 billion. This observation can be easily appreciated when it is recognized that a newly produced transport can be expected to have an operational life of at least 15 years. Also, the current wide body transports and their derivatives are expected to provide the bulk of the commercial airline service in the 1980s.

2.0 INTRODUCTION

Historically, significant advances in air transportation have developed from improvements in the propulsion system, in basic structural materials, and in basic aerodynamics. Examples of past propulsion-system improvements include the replacement of piston engines by turbojet engines, turbojet engines by low-bypass-ratio turbofan engines, and most recently, the replacement of low-bypass-ratio turbofans by modern high-bypass-ratio turbofans. Early material improvements included the replacement of wood-frame and fabric structures by stressed-skin metallic structures. Aerodynamic advancements, particularly for increasing flight speeds, have resulted from the pioneering efforts of Whitcomb and others at NASA Langley, especially in the development of the supercritical airfoil. Presently, no all new advanced propulsion concepts appear to promise the large step improvements that have occurred in the past, although the present national concern for energy conservation has resulted in a resurgence of interest in turboprops. While advanced technology turboprops warrant re-investigation, the probability of their introduction into major commercial operations in the 1980s is remote. This conclusion is clear from the fact that it has taken 17 years for the development of the present commercial airline transportation system using turbofan engines after the technology was in hand. In January 1975, there were more than 2400 jet-powered transports comprising most of the U.S. airline fleet. A major replacement or widespread use of new aircraft is required for any new development to have a large impact.

In the aerodynamics area, the supercritical wing technology can be expected to be used in the next new transport. However, as pointed out in References 1 through 3, other additional advances are also required to make a new transport economically practical and hence possible.

More recently, the replacement of metal by advanced composite structures has been identified in a number of studies and experimental programs as a potentially significant advance.

The purpose of the investigation described in this report was to determine the payoffs from the application of advanced technology, including advanced composite materials, to the nacelles of high-bypass-ratio turbofan engines. This investigation encompassed the areas of aerodynamics, propulsion system integration, acoustics, structures and materials with the aim of identifying the potential gains in performance and potential reductions in fuel consumption and community noise levels. The use of advanced composite materials was found to be a key ingredient in making practical the advanced nacelle configurations which are expected to provide significant improvements in airplane performance with reductions in fuel consumption and community noise levels.

The airplanes included in this conceptual study were a current wide-bodied transport (WBT) and an advanced technology transport (ATT) configured to meet mission and aerodynamic characteristic requirements specified by NASA. During the course of the study, it became apparent that major benefits could accrue on new production or derivatives of current WBT aircraft. Since the timing for an ATT is at best doubtful, the activities applicable to WBT received considerably more emphasis than those applicable to the ATT.

All current WBT engine installations use short fan ducts. These short duct installations were selected by the airframe manufacturers based on trade studies which evaluated performance, weight, noise and cost. Several factors justified a re-assessment of the installation configuration.

The development of a worldwide fuel shortage has increased the cost of fuel over the cost at the time of the production short-duct nacelle design. Costs are expected to rise even further due to inflation, increasing oil value as reserves diminish, and, for domestic use, a decreasing percentage of price-controlled "old" fuel. In the meantime, development of high tensile strength and high modulus fibers has resulted in the ability to reduce airplane component weights about 40% when these fibers are stabilized in a resin matrix. Reference 4 summarizes how this advanced composite material technology has advanced to where practical usage is now possible. Concurrently, material prices, particularly for graphite, have decreased due to increased commercial production, especially for golf clubs and skis. Recent programs at Douglas and at other companies have also identified that sacrificing a part of the potential weight savings to simplify fabrication can reduce manufacturing costs.

This advanced acoustic composite nacelle study thus provided the opportunity to exercise the use of advanced composites, as Dr. Lovelace points out in Reference 4, ". . . across the interfaces of materials, structures, aerodynamics, and others." Prior to this study for NASA, Douglas and General Electric had evaluated use of a metal long-duct, mixed-flow nacelle. The reduction in fuel consumption achieved by the mixed flow nacelle was counterbalanced by the increase in weight and attendant operating costs, and it was concluded that an airplane economic improvement did not result. Consequently, the metal long duct mixed flow configuration did not look attractive at that time.

With the introduction of composites in the NASA study, and additional design refinements, the prospects for improved airplane performance changed considerably because the use of advanced composites showed promise in several areas relative to metal:

(1) Reduced weight
(2) Reduced manufacturing costs from simpler constructions
(3) Reduced initial development costs from simpler tooling
(4) Integration of acoustic treatment with the nacelle structure.

Recent advances in structural material systems that provided the incentive for this study included development and use of fibers of graphite and Kevlar. These light-weight, high-strength fibers are used with resin systems to produce structural components with higher strength-to-weight ratios than metal. Different choices of constructions were selected to fit the particular requirements of various components.

Advanced composite material systems have been, or are undergoing technology development and testing for various airplane components including flaps and rudders. For the McDonnell Douglas F-15 airplanes, the U.S. Air Force has sponsored development of a complete wing made from advanced-composite structures by the McDonnell Aircraft Company in St. Louis, Missouri. Application of advanced-composite structures to transport nacelle components represents unique engineering challenges because of the environmental conditions (high acoustic loading, high temperatures, high vibration levels, and exposure to various fluids and solvents); because of the use of acoustically absorptive structures having porous surfaces exposed to the airflow in the inlet and exhaust ducts, and because of the requirements for routine access to, and maintenance of, various engine-mounted systems, and normal removal and replacement of nacelle components.

In addition to performance improvement, fuel savings, weight reduction and nacelle component cost reduction possibilities, reduction of airport-community noise is also of national concern. The studies therefore emphasized fuel consumption reduction and also noise reduction.

Previous studies of methods to reduce community noise levels, especially at locations below or to the side of the takeoff flight path where the noise levels are controlled by jet noise, inevitably resulted in performance and cost penalties for existing aircraft designs. Consideration of long-duct installations provides the possibility of reducing jet noise. This low frequency noise is not as readily absorbed by the atmosphere as is the higher frequency turbomachinery noise and reduction of jet noise by use of a mixed flow nozzle would be of great benefit at long distances from aircraft, where most of the poeple who are annoyed by aircraft noise reside.

The specific objectives of this study were then to:

1. Identify engine installation conceptual designs that reduce fuel consumption and reduce noise levels through the use of advanced technology;

2. Determine the research and technology requirements needed to be able to achieve the fuel savings and noise reductions; and

3. Recommend an overall technology development plan with emphasis on maximizing fuel savings.

The balance of this report is divided into nine main sections. Section 3 describes the tasks that were performed and Section 4 presents the study groundrules, a definition of the reference WBT and ATT airplanes, and a description of the methods used to assess changes in flyover noise, airplane performance, manufacturing costs, and airplane economics. Sections 5 and 6 describe the nacelle configurations that were developed for the WBT and ATT airplanes while Sections 7 and 8 present the results of the evaluation of the various nacelle configurations. Sections 9 and 10 discuss the recommended research and technology programs needed to implement application of advanced acoustic-composite structures to the nacelles of future WBT and ATT airplanes. Section 11 presents some concluding remarks.

SYMBOLS

A_i	Area based on inlet lip diameter, m^2 (ft^2)
A_0	Free stream capture area, m^2 (ft^2)
A_{max}	Maximum nacelle area, m^2 (ft^2)
A_8	Core nozzle exit area, m^2 (ft^2)
A_{28}	Fan nozzle exit area, m^2 (ft^2)
AL	Aluminum (Figure 28)
ALT	Alternate (Figure 8)
ATA	Air Transport Association
ATT	Advanced Technology Transport
BLK	Block (Figure 8)

SYMBOLS (Continued)

BSC	Borsic (Figure 28)
$C_{D_{\pi p}}$	Nacelle pressure drag coefficient
D_p	Pressure drag, N (lb)
D_{eq}	Diameter based on mixing plane total area, m (ft)
DOC	Direct Operating Cost (Figure 8)$/ASkm ($/ASNM)
EPNL	Effective Perceived Noise Level, EPNdB
F_N	Net Thrust, N (lb)
F_p	Partially mixed thrust, N (lb)
F_u	Unmixed thrust, N (lb)
F_m	Fully mixed thrust, N (lb)
FLT	Flight (Figure 8)
HMG	High Modulus Graphite (Figure 28)
HTG	High Tensile Strength Graphite (Figure 28)
IOC	Indirect Operating Cost (Figure 8) $/ASkm ($/ASNM)
K4	Mixing Effectiveness (Figure 25) percent
L	Nacelle length or mixing chamber length, m (ft)
$(L/D)_{eq}$	Nacelle equivalent length to diameter ratio
LRC	Long Range Cruise (Figure 8)
M	Mach number
M_{CR}	Mach number at cruise (Figure 6)
MDOF	Multiple Degree of Freedom
MLGW	Maximum Landing Gross Weight, kg (lb)
MTOGW	Maximum Takeoff Gross Weight, kg (lb)
$N/\sqrt{\theta}_{t2}$	Corrected fan speed, RPM
NPN	Non-Propulsive Noise
OEW	Operating Empty Weight, kg (lb) (also OWE)
P	Static pressure or mixer perimeter, N/m^2 (lb/in^2) or m (ft)
P_T	Total Pressure, N/m^2 (lb/in^2)
PNLT	Tone-Corrected Perceived Noise Level, PNdB
q_o	Free stream dynamic pressure, N/m^2 (lb/in^2)
RES	Reserve (Figure 8)
SDOF	Single Degree of Freedom

SYMBOLS (Continued)

SFC	Specific Fuel Consumption, kg/hr/N (lb/hr/lb)
T_{T_C}	Core stream total temperature, °K (°R)
T_{T_F}	Fan stream total temperature, °K (°R)
TOGW	Takeoff Gross Weight, kg (lb)
V	Airspeed, (Figures 8 & 9) m/sec (Knots)
V/O	Fiber Volume Fraction, (Figure 28) percent
WBT	Wide Body Transport
$W\sqrt{\theta_{t2}}/\delta_{am}$	Corrected engine mass flow, kg/sec (lb/sec)
β	Bypass Ratio
α_F	Flap Deflection Angle, Degrees
θ	Temperature Ratio
δ	Pressure Ratio

3.0 STUDY DESCRIPTION

The study was conducted during the time period of July 1974 through June 1975. The overall system analyses were conducted by Douglas Aircraft with major contributions to propulsion system performance and noise analyses and research and technology ground test program costs for the WBT from General Electric. General Electric conducted most of the ATT propulsion system conceptual design studies. Six basic tasks were conducted following the schedule shown on Figure 1.

TASK I - The initial task was composed of conceptual design studies to identify promising advanced technology configurations. Cost versus benefit analyses were conducted to identify beneficial technology requirements. The first task was completed with recommendations for the configuration(s) upon which to conduct preliminary design and recommendations for limited tests.

TASK II - The second task was to conduct preliminary design of configuration(s) that showed promise.

TASK I. CONCEPTUAL DESIGN STUDIES ON WBT AND ATT

TASK II. PRELIMINARY DESIGN OF WBT INSTALLATION

TASK IV. LIMITED TESTS

TASK V. IDENTIFY TECHNOLOGY REQUIREMENTS FOR WBT

TASK VI. IDENTIFY TECHNOLOGY REQUIREMENTS FOR ATT

TASK VII. RECOMMENDED OVERALL RESEARCH AND TECHNOLOGY PROGRAM

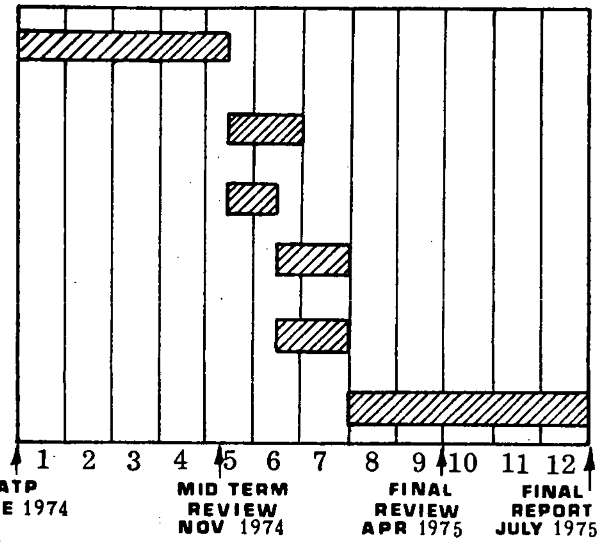


FIGURE 1. PROGRAM TASKS AND SCHEDULE

TASK III - After TASK I, the possible benefit to major U.S. airlines of significant fuel savings by technology advancement for WBT installations resulted in concentration of activities on WBT aircraft and preliminary design on the ATT nacelle was terminated. Increased emphasis was placed on TASK II, V and VII in lieu of TASK III.

TASK IV - Limited tests were conducted in specific areas where an improved understanding was necessary in order to plan a technology development program. The specific areas identified were fire resistance of composites using a polymeric matrix and acceptable techniques for perforating resin-impregnated graphite surfaces.

TASK V - The technology developments required to achieve the potential benefits on WBT aircraft were assessed. An overall program was identified and recommended to the NASA.

TASK VI - This task identified and recommended areas for further research and technology on ATT propulsion systems.

TASK VII - Research and technology plans for the program recommended in TASK V were developed. These plans included schedules and rough order of magnitude costs.

4.0 STUDY APPROACH

The basic approach followed for this study consisted of: 1) definition of the study baseline WBT and ATT aircraft and engines; 2) conceptual design studies of alternate WBT and ATT engine installation arrangements utilizing advanced technology concepts; 3) development of advanced acoustic composite WBT and ATT nacelle component designs to a level of detail sufficient for weight and cost estimating; 4) evaluation of installation performance, noise and weight characteristics; 5) assessment of costs and benefits; 6) selection of configurations for preliminary design and program planning activities; 7) definition of research and technology needs; 8) evaluation of alternative technology development approaches, and 9) recommendation of an overall technology program plan.

4.1 Study Ground Rules

The basic study ground rules were to identify relatively near-term technologies for the WBT portion of the study and more-advanced technologies for the ATT. Specific ground rules were emphasis on low-cost design concepts for the composite constructions rather than absolute minimum weight; minimum fuel consumption rather than minimum noise; and realistic flight requirements for both the nacelle concepts and the composite structural designs. Consistent with the study timing, only currently available fibers and resin systems were evaluated for the wide body transport while more-advanced fibers and resins were evaluated for the ATT. The purpose of the ground rules was to identify technologies that might be actually utilized in future-production commercial transports. Technology utilization requires that judgment be used in the conceptual designs so that a proper balance will exist between benefits to the airframe and engine manufacturer, the airline operators, and the general public. Airlines will resist use of a quieter installation if it results in excessive deterioration of economic performance. Even reduction of fuel consumption will not be attractive if the higher initial cost of new advanced-technology hardware is excessive. The real challenge is formulation of a research and technology program that will result in fuel savings in actual practice by properly balancing between fuel saving, weight, cost, and noise reduction benefits.

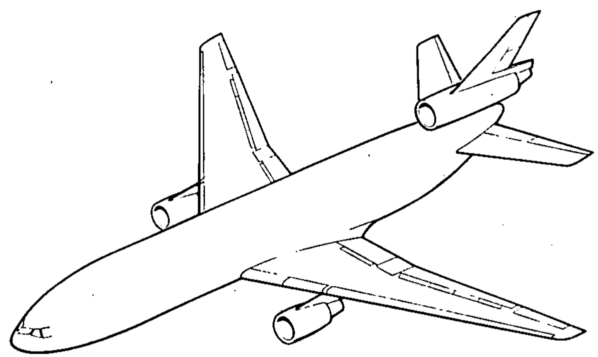
4.2 Baseline WBT and ATT Airplanes

4.2.1 WBT Baseline - The study baseline WBT characteristics are shown in Figure 2. The airplane is a trijet carrying 270 passengers in mixed class. The design range for the airplane is 10,000 km (5,400 n mi). The choice of a trijet presented the opportunity to address tne unique aircraft-system problems associated with both wing- and tail-engine installations. In addition, because the CF6-50 engine series also powers other current two- and four-engine wide-bodied airplanes, the benefits of reductions in fuel consumption and community noise will be available for several current wide-bodied jet transports.

The payload range curve for the study baseline WBT is shown in Figure 3. The flight profile uses a step climb, consistent with normal navigation restrictions. The shaded area shows where a major portion of longer range flights are flown. These 5185 km (2800 n mi) to 7223 (3900 n mi) flights are representative of average in-service stage lengths and were the basis for the fuel savings analyses.

The CF6-50 engine characteristics and cycle parameters are shown in Figure 4. The engine is a high bypass ratio turbofan with a takeoff thrust of 222.5 kN (50,000 lb).

The engine powers the DC-10-30, the A-300, and the 747-300 airline airplanes and with the Military designation F103, it powers the Air Force Airborne Command Post version of the 747. It is expected to power stretched versions of the DC-10 with an additional possible application being a 4-engine cargo derivative of the DC-10. Continued new production is expected through 1980.



MTOGW, kg (lb)	256,284	(565,000)
MLGW, kg (lb)	190,966	(421,000)
Design Range, km (n mi)	10,000	(5400)
(3) GE CF6-50 Engines		
270 Passengers		

Characteristics

Fuselage Length, m (ft)	52.0	(170.5)
Wing Span, m (ft)	47.3	(155.3)
Tail Height, m (ft)	17.5	(57.5)
Fuselage Diameter, m (in)	6.0	(237)
Wing Area, sq m (sq ft)	329.8	(3550)
Wing Sweep, degrees	35	
Aspect Ratio	6.8	
Horiz. Tail Area, sq m (sq ft)	124.3	(1338)
Horiz. Tail Span, m (ft)	21.7	(71.2)
Horiz. Tail Sweep, degrees	35	
Vert. Tail Area, sq m (sq ft)	56.2	(605)
Vert. Tail Sweep, degrees	40	

FIGURE 2. STUDY WIDE BODY TRANSPORT BASELINE AIRCRAFT CHARACTERISTICS

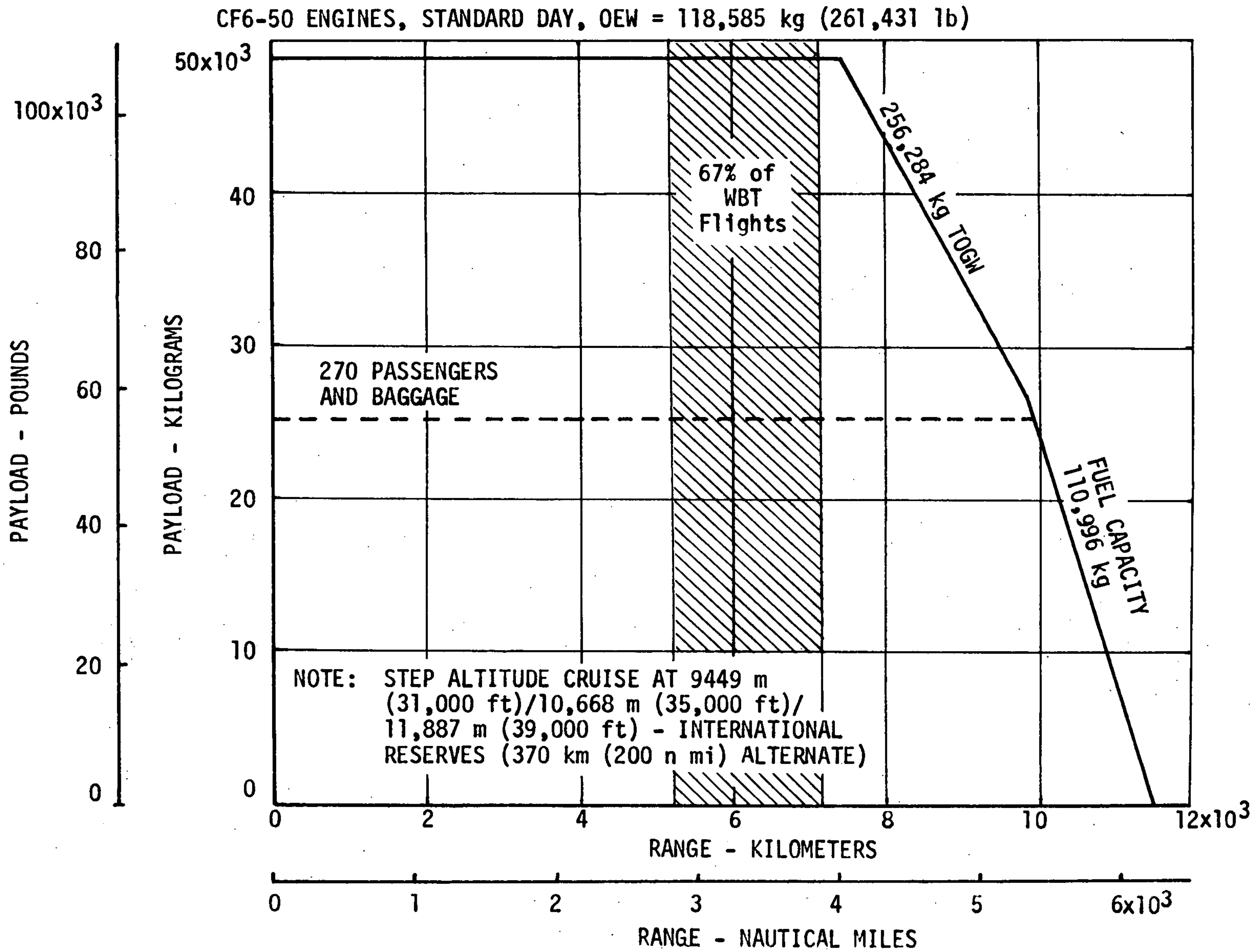
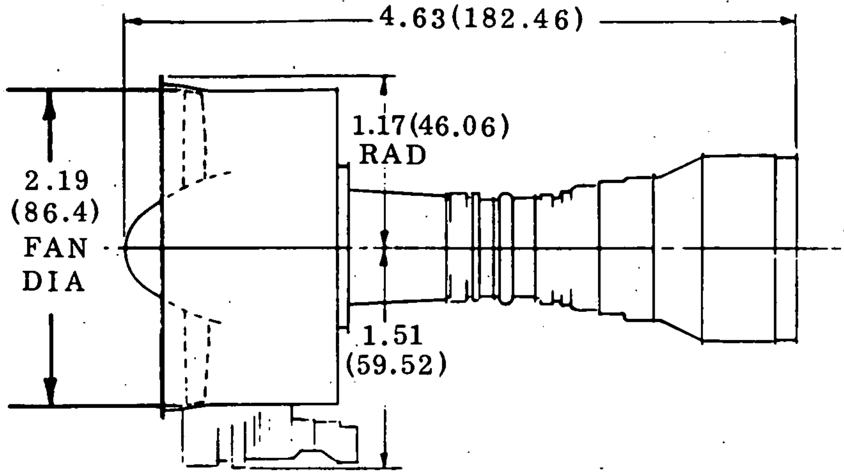


FIGURE 3. STUDY WBT BASELINE PAYLOAD RANGE FOR MACH 0.82 CRUISE



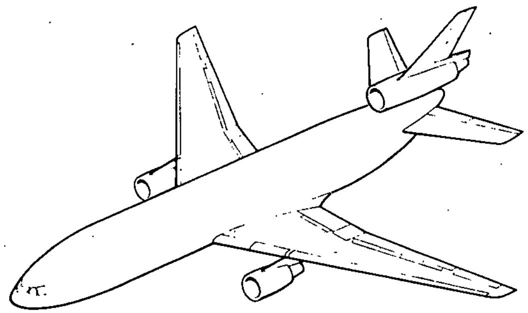
Bypass Ratio	4.18
Takeoff Thrust	222.5 kN (50,000 lb)
Engine Weight	3829 kg (8440 lb)
Cruise SFC at M = 0.85 at 10,668 m (35,000 ft)	0.6765

NOTE: "Dimensions in Meters (Inches)"

FIGURE 4. STUDY WBT BASELINE ENGINE CHARACTERISTICS

4.2.2 <u>ATT Baseline</u> - The ATT is a smaller and shorter range airplane than the WBT, carrying 200 passengers. The ATT baseline airplane characteristics are shown in Figure 5. These characteristics were developed to meet NASA specifications.

The payload/range curve for the ATT is shown in Figure 6. The design range was specified as 5556 km (3000 n mi) with a design payload of 18,598 kg (41,000 lb) at a design cruise Mach number of 0.90. The ATT engine and cycle parameters are shown in Figure 7. The ATT study engine, designated ATT No. 4, was derived from the results of previous ATT propulsion-system studies conducted by G.E. and reported in reference 5. The ATT No. 4 engine is rated at 133.5 kN (30,000 lb) static takeoff thrust and makes extensive use of composite technology for all components to which the properties of advanced composite materials can be properly applied. The ATT No. 4 engine also incorporates the concept of an integrated engine/nacelle combination to provide an aerodynamically and structurally more efficient installed propulsion system.



MTOGW, kg (lb)	129,836	(286.235)
MLGW, kg (lb)	110,225	(243,000)
Design Range, km (n mi)	5556	(3000)

(3) GE ATT No. 4 Engines

200 Passengers

Characteristics

Fuselage Length, m (ft)	47.9	(157.1)
Wing Span, m (ft)	40.3	(132.2)
Tail Height, m (ft)	15.7	(51.5)
Fuselage Diameter, m (in)	5.5	(218)
Wing Area, sq m (sq ft)	213.7	(2300)
Wing Sweep, degrees	36.5	
Aspect Ratio	7.6	
Horiz. Tail Area, sq m (sq ft)	61.9	(666)
Horiz. Tail Span, m (ft)	17.1	(56)
Horiz. Tail Sweep, degrees	36.5	
Vert. Tail Area, sq m (sq ft)	40.9	(440)
Vert. Tail Sweep, degrees	41.5	

FIGURE 5. STUDY ADVANCED TECHNOLOGY TRANSPORT BASELINE AIRCRAFT CHARACTERISTICS

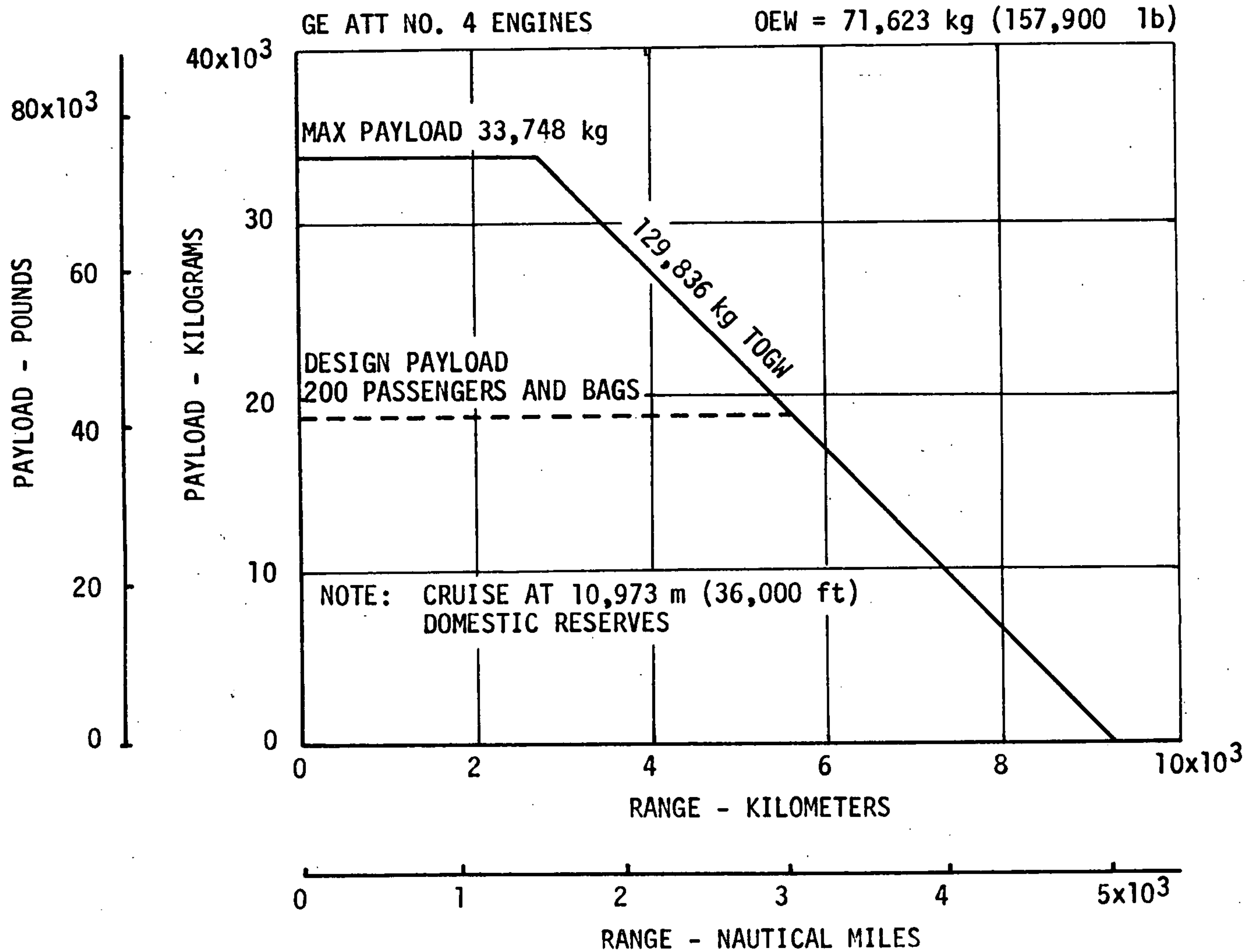
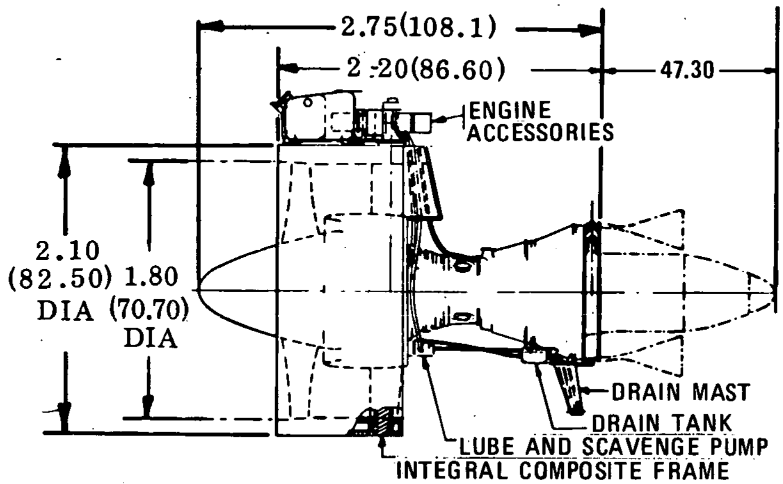


FIGURE 6. STUDY ATT BASELINE PAYLOAD RANGE FOR MACH 0.90 CRUISE



Bypass Ratio	7.52
Takeoff Thrust	133.5 kN (30,000 lb)
Engine Weight	1930 kg (4195 lb)
Cruise SFC at M = 0.85 at 10,668 m (35,000 ft)	0.638

NOTE: "Dimensions in Meters (Inches)"

FIGURE 7. STUDY ATT BASELINE ENGINE CHARACTERISTICS

4.3 Method for Analyzing Results

4.3.1 Performance - The internal and external performance of each of the study configurations was estimated by making detailed evaluations of engine installation component losses. An existing computer cycle deck was used to obtain the engine thermodynamic data for calculating nozzle performance.

Internal performance was estimated by General Electric and independently checked by Douglas. Nozzle performance was calculated using the fan and primary engine flow conditions, i.e., pressures, temperatures and air flow rates with the nacelle geometry being evalauted to calculate pressure drops and flow mixing. External drag changes estimated were for differences in skin friction.

Airplane performance and fuel consumption were calculated using an existing Douglas computer program that accurately simulates flight performance. Changes in weight and specific fuel consumption were accounted for as inputs to the basic program. The effect of various changes was determined by comparing airplane performance with the modified weights and SFC's to the base airplane performance for identical missions and flight profiles.

Sample printouts from the performance computer program are shown in Figures 8 and 9. Figure 8 shows a printout for the base airplane flying a 9893 km (5342 n mi) mission with a three step cruise profile at 9449, 10668 and 11887 m (31,000, 35,000 and 39,000 ft). Figure 9 shows a similar printout for the base airplane flying the same mission with the long-duct nacelle.

4.3.2 Weights - Weight estimates for the WBT study nacelle configurations were made from drawings of appropriate nacelle composite components developed in this study. These are dimensioned scale drawings that include specification of the advanced composite constructions. Reference 6 was the basic source of design data used for graphite/epoxy. These data were supplemented by design allowable strength data from Douglas tests. Strength data for Kevlar were from Reference 7. The basis for use of composite materials for application to areas subject to impact exposure was from Reference 8.

For the ATT nacelle, General Electric provided estimates of the major engine and nacelle component weights and costs for use in the ATT direct operating cost (DOC) analyses.

4.3.3 Noise - Changes in aircraft noise were determined by logarithmically adding the noise produced by the engine noise component contributions with the non-propulsive sources of noise (boundary layer, wakes, etc.). For the WBT aircraft, the component noise levels for the current acoustical treatment in the nacelles were estimated on the basis of an analytical method developed from static engine noise data and verified by comparisons with the results of actual flyover noise measurements at takeoff and approach power settings.

BASE CASE

***** TO *****

REFERENCE NO. 1 CASE NO. 1 FLIGHT NO. 0 PROFILE NO. 25 DATE 03/27/75 TIME 15.46.28

NOMINAL DISTANCE 5342	MAX TAKEOFF WT	555000	SEATS	270	ALTERNATE DESTINATION	
ADJUSTED DISTANCE 5342	MAX LANDING WT	408000	MAX PAYLOAD	55350	DISTANCE TO ALTERNATE	200
WINDS	OPERATOR'S EMPTY WT	261431	MAX FUEL	244700	ALTERNATE MAX LANDING WT	408000

	INITIAL WEIGHT	LIMIT WEIGHT	TEMP (STD+)	FINAL ALTITUDE	PROCEDURE	WIND COMPONENT	SEGMENT TIME	TOTAL TIME	SEGMENT DIST	TOTAL DIST	SEGMENT FUEL	TOTAL FUEL
RAMP	555981			0	GND MAN		0.100	0.100	0.0	0.0	981	981
TAKEOFF	555000	555000		1500	AIR MAN		0.067	0.167	0.0	0.0	2100	3081
CLIMB	552900		0.0	31000	320 IAS	0.0	0.351	0.518	144.9	144.9	12623	15704
CRUISE	540277	589513	0.0	31000	.82 M	0.0	4.041	4.559	1945.1	2090.0	82146	97850
CLIMB	458131		0.0	35000	320 IAS	0.0	0.065	4.624	30.6	2120.6	1586	99436
CRUISE	456545	496101	0.0	35000	.82 M	0.0	4.763	9.387	2252.2	4372.8	79540	178976
CLIMB	377005		0.0	39000	320 IAS	0.0	0.063	9.450	29.6	4402.4	1302	180278
CRUISE	375703	410236	0.0	39000	.82 M	0.0	1.747	11.197	822.1	5224.5	25392	205670
DESCENT	350311		0.0	1500	320 IAS	0.0	0.318	11.515	117.5	5342.0	1527	207197
APPROACH	348784			0	AIR MAN		0.067	11.582	0.0	5342.0	1440	208637
LANDING	347344	408000		0	GND MAN		0.067	11.649	0.0	5342.0	340	208977
RAMP	347004			0				11.649		5342.0		208977
RESERVE FUEL												
% FLT TIME	348784	0	0.0	39000	LRC		1.148				15642	15642
FLT TO ALT	331362				TABLE 52	0.0			0.0		14937	30579
ZERO FUEL	316766	316781										

BLK TIME	11.65	TAXI-OUT WT	555981	BLK FUEL	208977	PASSENGERS	269	REVENUE	143700	DOC $/MILE	3.54
FLT TIME	11.48	TAKEOFF WT	555000	RES FUEL	30579	CARGO WT	0	DOC	18893	DOC ¢/PAS MI	1.31
V BLK	458	LANDING WT	347344	TOTAL FUEL	239215	TOTAL PAYLOAD	55335	IOC	18893	DOC ¢/TON MI	12.78
V CR	476	TAXI-IN WT	347004					PROFIT	105914	% BREAKEVEN	26.20

WEIGHT (POUNDS) DISTANCE (NAUTICAL MILES) SPEED (KNOTS) TIME (HOURS)

FIGURE 8. SAMPLE COMPUTER PRINTOUT FOR BASELINE AIRCRAFT MISSION RANGE OF 9893 KILOMETERS (5342 NMI)

CONFIG II ,3-26-75

***** TO *****

REFERENCE NO. 1 CASE NO. 1 FLIGHT NO. 0 PROFILE NO. 25 DATE 03/27/75 TIME 15.43.43

NOMINAL DISTANCE 5342	MAX TAKEOFF WT	555000	SEATS	270	ALTERNATE DESTINATION	
ADJUSTED DISTANCE 5342	MAX LANDING WT	408000	MAX PAYLOAD	55350	DISTANCE TO ALTERNATE	200
WINDS	OPERATOR'S EMPTY WT	259983	MAX FUEL	244700	ALTERNATE MAX LANDING WT	408000

	INITIAL WEIGHT	LIMIT WEIGHT	TEMP (STD+)	FINAL ALTITUDE	PROCEDURE	WIND COMPONENT	SEGMENT TIME	TOTAL TIME	SEGMENT DIST	TOTAL DIST	SEGMENT FUEL	TOTAL FUEL
RAMP	543445			0	GND MAN		0.100	0.100	0.0	0.0	981	981
TAKEOFF	542464	555000		1500	AIR MAN		0.067	0.167	0.0	0.0	2100	3081
CLIMB	540364		0.0	31000	320 IAS	0.0	0.333	0.500	136.5	136.5	11591	14672
CRUISE	528773	589513	0.0	31000	.82 M	0.0	3.638	4.137	1750.8	1687.3	70702	85374
CLIMB	458071		0.0	35000	320 IAS	0.0	0.064	4.202	30.5	1917.9	1526	86900
CRUISE	456545	496101	0.0	35000	.82 M	0.0	4.935	9.137	2333.4	4251.3	79588	166488
CLIMB	376957		0.0	39000	320 IAS	0.0	0.063	9.200	29.5	4280.8	1254	167742
CRUISE	375703	410236	0.0	39000	.82 M	0.0	2.006	11.206	944.0	5224.8	28056	195798
DESCENT	347647		0.0	1500	320 IAS	0.0	0.317	11.523	117.2	5342.0	1471	197269
APPROACH	346176			0	AIR MAN		0.067	11.590	0.0	5342.0	1440	198709
LANDING	344736	408000		0	GND MAN		0.067	11.657	0.0	5342.0	340	199049
RAMP	344396			0				11.657		5342.0		199049
RESERVE FUEL												
% FLT TIME	346176	0	0.0	39000	LRC		1.149				15018	15018
FLT TO ALT	329378				TABLE 52	0.0			0.0		14386	29404
ZERO FUEL	315333	315333										

BLK TIME 11.66	TAXI-OUT WT	543445	BLK FUEL	199049	PASSENGERS	270	REVENUE 144234	DOC $/MILE	3.47
FLT TIME 11.49	TAKEOFF WT	542464	RES FUEL	29404	CARGO WT	0	DOC 18515	DOC ¢/PAS MI	1.28
V BLK 458	LANDING WT	344736	TOTAL FUEL	228112	TOTAL PAYLOAD	55350	IOC 18515	DOC ¢/TON MI	12.52
V CR 475	TAXI-IN WT	344396					PROFIT 107204	% BREAKEVEN	25.67

WEIGHT (POUNDS) DISTANCE (NAUTICAL MILES) SPEED (KNOTS) TIME (HOURS)

FIGURE 9. SAMPLE COMPUTER PRINTOUT FOR BASELINE AIRCRAFT WITH LONG DUCT NACELLE AND MISSION RANGE OF 9893 KILOMETERS (5342 NMI)

Table 1 lists values of engine and airplane parameters used in determining the noise of the baseline WBT airplane. The parameters are for the maximum takeoff and landing gross weights. The approach conditions included both the maximum 50-degree flap deflection and the normal 35-degree flap deflection. These two flap settings were included in the evaluation of the nacelle treatment for the WBT because the maximum flap deflection is required as part of the federal aircraft noise-certification requirements while the 35-degree flap setting is the approach flap setting most widely used in service. In addition, the relative strengths of the fan noise from the inlet and fan discharge ducts and the turbine noise are quite different at the 2820-rpm fan speed required for a maximum-flap landing and the 2463-rpm fan speed required for a normal-flap landing. Thus, it was considered worthwhile to evaluate the changes in approach noise at the two flap settings for the WBT. The ATT engine and airplane parameters for noise calculations are shown on Table 2. For the ATT, the approach noise evaluations were conducted only for the maximum-flap condition.

The basic ATT engine installation was a long-duct mixed-flow design with an internal mixer nozzle for the primary flow. The component noise levels, for the baseline installation with no acoustical treatment, were estimated by General Electric from previous component noise data correlations for static engines. The static estimates were then projected to the specified flight conditions (see Table 2), accounting for doppler frequency shifts and the effect of forward motion on turbomachinery and jet noise.

The effects of modifying the engine nacelles to incorporate composite acoustical treatment (plus, in the case of WBT, of changing from a separate-flow to a mixed-flow nacelle) were estimated on the basis of the results of previous tests and analyses for each affected component noise source. While the available test results obviously could not have been for the identical linings proposed in this study, since these advanced linings have not yet been developed, the linings for which data were available were considered representative of the proposed advanced linings, at least with regard to the acoustical characteristics. Thus, there was a relatively high level of confidence in the noise reduction estimates,

TABLE 1. - WBT AIRCRAFT AND ENGINE† PARAMETERS FOR MTOGW AND MLGW*

PARAMETER#	PARAMETER VALUES FOR		
	TAKEOFF	APPROACH MAX FLAPS	APPROACH ALT. FLAPS
Net Thrust per Engine, F_n/δ_{am}, percent	100	40	30
Referred Fan Speed, $N_1/\sqrt{\Theta_{t2}}$, rpm	3748	2820	2463
Relative Fan Blade Tip Mach No., $M_{t, rel}$	1.46	1.05	0.91
Fan Pressure Ratio, FPR	1.68	1.32	1.24
Average Inlet Mach No. at Fan, M_{in}	0.59	0.37	0.32
Referred Inlet Airflow, $W_a\sqrt{\Theta_{t2}}/\delta_{am}$, kg/s	704	489	432
Bypass Ratio, BPR	4.16	5.07	5.34
Tailpipe Pressure, P_{t7}, N/m^2	170,537	121,491	115,079
Tailpipe Temperature, T_{t7}, °K	833	695	664
Primary Jet Velocity, $V_{j,p}$, m/s	500	275	230
Fan Jet Velocity, $V_{j,f}$, m/s	331	240	214
Mixed-Flow Jet Velocity∇, V_j, m/sec	360	245	215
Airspeed, V_a, m/s	102	83	86
Aircraft Mach No., M_a	0.30	0.24	0.25
Flap Deflection Angle, deg	10	50	35
Aircraft Flight Path Angle, deg	6	-3	-3
Fuselage Angle of Attack, deg	12	6	7
Height∆ Above Ground, m	331	113	113

† 38 fan blades, fan exit area 1.49 sq m, primary exit area 0.55 sq m.

For operations from a sea-level runway, no wind, surface air temperature 25°C (77°F), surface relative humidity 70 percent, slats extended, engine bleeds off during takeoff and on during approach, no thrust reduction during climbout.

* Weights for a payload for a 100-percent load factor (270 passengers) and bags, no lounges, and upper-galley configuration, and appropriate international fuel reserves. Total payload of 24,950 kg (55,000 lb).

∇ Applies to long-duct mixed-flow nacelles only.

∆ Height below flight path for FAR 36 measuring points.

TABLE 2. - ATT AIRCRAFT AND ENGINE[†] PARAMETERS FOR MTOGW AND MLGW[*]

PARAMETER[#]	PARAMETER VALUES FOR	
	TAKEOFF	APPROACH MAX FLAPS
Net Thrust per Engine, F_n/δ_{am}, percent	100	36
Referred Fan Speed, $N_1/\sqrt{\Theta_{t2}}$, rpm	4822	3305
Relative Fan Blade Tip Mach No., $M_{t,\ rel}$	1.48	1.01
Fan Pressure Ratio, FPR	1.60	1.21
Average Inlet Mach No. at Fan, M_{in}	0.59	0.40
Referred Inlet Airflow, $W_a\sqrt{\Theta_{t2}}/\delta_{am}$, kg/s	417	282
Bypass Ratio, BPR	7.52	9.63
Tailpipe Pressure, P_{t7}, N/m^2	155,273	122,544
Tailpipe Temperature, T_{t7}, °K	428	364
Mixed-Flow Jet Velocity, V_j, m/s	337	204
Airspeed, V_a, m/s	87	74
Aircraft Mach No., M_a	0.25	0.21
Flap Deflection Angle, deg	25	50
Aircraft Flight Path Angle, deg	7	-3
Fuselage Angle of Attack, deg	10	10
Height Above Ground, m [Δ]	549	113

† 30 fan blades, mixed-flow exit area 1.34 sq m.

For operations from a sea-level runway, no wind, surface air temperature 25°C (77°F), surface relative humidity 70 percent, slats extended, engine bleeds off during takeoff and on during approach, no thrust reduction during climbout.

* Weights for a payload for a 100-percent load factor (200 passengers) and bags, no lounges, and upper-galley configuration, and appropriate domestic fuel reserves. Total payload of 18,598 kg (41,000 lb).

Δ Height below flight path for FAR 36 measuring points.

both for the WBT with its modifications to the current nacelle treatment and for the ATT where treated surfaces replaced hardwall surfaces.

Two different criteria were used to obtain numerical ratings of the noise-reduction benefits. These criteria were (a) changes in effective perceived noise level (EPNL) at the takeoff and approach locations of Part 36 of the Federal Aviation Regulations (FAR 36) for aircraft noise certification, and (b) changes in the area enclosed by the 90-EPNdB contour for operations at maximum takeoff and at maximum landing gross weights (MTOGW and MLGW). Changes in the FAR 36 noise levels were chosen because certified noise levels are widely used to compare the noise of different aircraft. Changes in the area enclosed by the 90-EPNdB contour were chosen because these changes should be representative of changes in the total community noise exposure for the majority of people exposed to takeoff and approach noise.

Changes in FAR 36 sideline noise levels were not included since the takeoffs were assumed to follow the procedures currently used by all wide-body transports, wherein thrust reduction is not used during the climbout. Thus, changes in noise at the takeoff point should be nearly the same in the maximum EPNL on the 465 m (0.25 n mi) sideline and separate calculations of changes in sideline noise levels were not necessary.

For the WBT airplane, changes in noise levels at the FAR Part 36 locations and conditions were determined relative to the EPNLs certified by the FAA as a result of the aircraft noise-certification-demonstration tests for the baseline airplane. The certification tests, and other flyover noise tests conducted during the flight-development program, provided information, for various engine power settings, on the variation of noise with distance between the airplane and the location of an observer on the ground. These noise/distance power-setting curves, when coupled with takeoff and approach flight profiles were used for calculating equal-noise-level contours around an airport.

4.3.4 Manufacturing Cost - Drawings of the advanced composite components were prepared in accordance with a format developed in a previous study contract (Ref. 9). This format dictated that certain minimum information appear on the drawing, but not to the level of detail normally required of full production drawings. The use of this format allowed the composite component drawings to be used for both weight and manufacturing cost estimating.

A manufacturing cost estimating drawing was prepared by engineering using inputs from manufacturing, planning and process as well as the technical requirements of the specific component in question, and a weight estimate was completed. The drawing was then input to a cost analysis information flow system, described in detail in Section 7.4. This flow system, shown in Figure 10, involved an iterative process in which the various disciplines participate in each of the steps. The Douglas manufacturing research and development group assessed the drawing from the standpoint of probable production environment and facilities required. The planning and tooling groups developed the operational sequences required to fabricate and assemble the part which in turn defined specific tooling needs and established quality-control procedures.

The planning efforts also included initiation of a bid work sheet (sample shown in Figure 11) for each component to document the manufacturing operations in sequence. This work sheet enabled the manufacturing group to estimate labor manhours for setup, fabrication and assembly at each step. Final manhour data were processed by the cost analysis group and combined with material and purchased parts costs, and with appropriate shop allocation factors and learning curves.

The final result of these cost analyses was an estimate of the total cost to produce the component in question based on predetermined assumptions for length of production run, number of manufacturing releases, number of components per release, and production rate. Estimates were also made for comparable conventional metal baseline components.

The cost information derived by this approach is typical of trade studies made during an actual hardware design phase and is more realistic than a parametric analysis. The estimates reflected the cost, in a production environment, of the various processes used to produce the components and

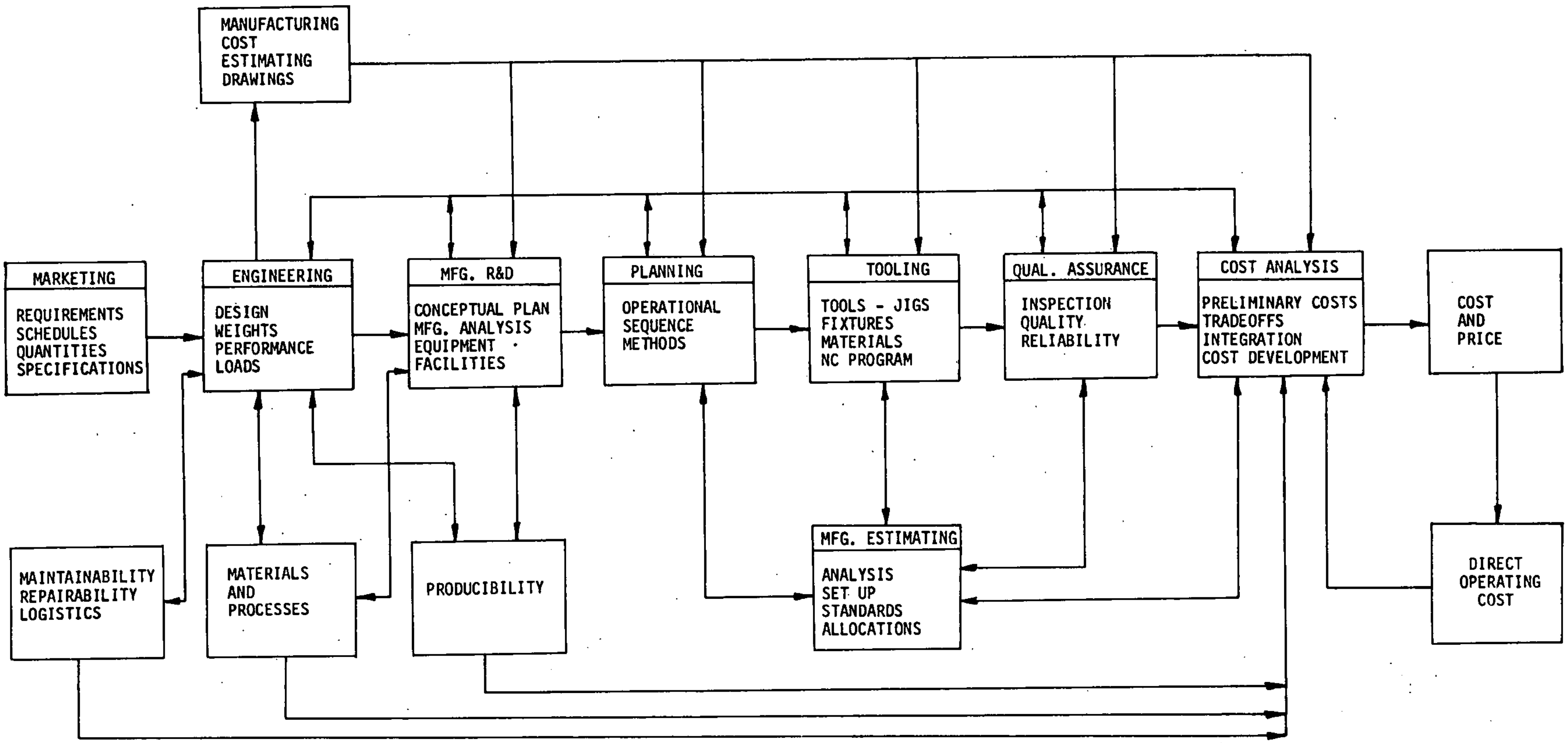


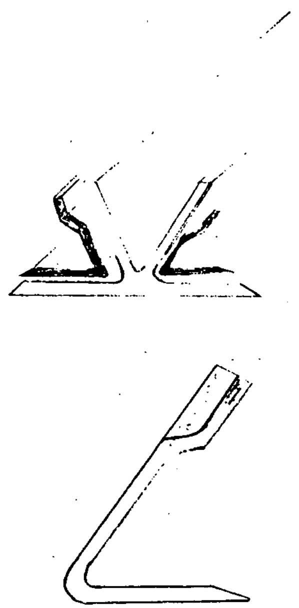
FIGURE 10. COST ANALYSIS INFORMATION FLOW SYSTEM

BID WORK SHEET

MAT'L: GRAPHITE/EPOXY	TOTAL NO.REQ.	PART NO: UNASSIGNED	CHG. LET.
SIZE:		PART NAME: CORNER ANGLE - FOR "K" & "T" SECTIONS	
SPEC:		NEXT ASSEM: TO RETAIN HONEYCOMB & SKIN SANDWICH	
		END ITEM:	

PL/	
Q.C.	
MAT'L.	
PROC.	
TOOL EST.	
MFG. EST.	

PART ILLUSTRATION: 1.406



NO.	OPERATION	TOOL	EQUIPMENT	DEPT.	UNIT COST SET-UP	UNIT COST FAB.	UNIT COST ASSEM.	TOOL COST DES.	TOOL COST FAB.
1	SET UP PULTRUSION				8.0	-			
	MACHINE WITH CONTROL	PULTRUSION MACHINE							
	TAPE AND GRAPHITE								
	FEED SPOOLS								
2	SET UP FEED SPOOLS	PULTRUSION MACHINE			4.0				
	FOR 120° ANGLE SECTION								
	PULTRUSION OPERATION								
	FIBER ORIENTATION	%	10 OF PLIES	WIDTH TAPE					
	$\pm 45^{\circ}$	60	16	5.0					
	0°	30	6						
	90°	10	2						
3	FEED ALL TAPES				-	114			
	(PREPREG OR WET LAYUP)	PULTRUSION MACHINE							
	THRU ANGLE SECTION DIE								
	AND PULTRUDE AT THE RATE								
	OF 4 FT. PER MINUTE								
4	CURE TO ADVANCE	PULTRUSION MACHINE			-	-			
	B-STAGE IN PULTRUDER								

UNIT COST SUMMARY		
SET-UP	12.0	HRS
FAB.	5.812	HRS
ASSEM.		HRS
MAT'L.	$	
CYCLE		DAYS

FIGURE 11. SAMPLE MANUFACTURING COST ANALYSIS BID WORK SHEET

the mix of materials which will be used. This latter point was particularly important in considering the cost of advanced composite components, which can vary widely on a per pound basis among the various forms (tape, broadgoods, chopped fiber castings, integrally woven, etc.).

4.3.5 Operating Economics - The results of the performance and weight analyses were combined with the manufacturing cost estimates to provide inputs to airplane direct operating cost (DOC)analyses, for each of the WBT nacelle configurations and the single ATT configuration. The outputs from the various analyses included changes in block fuel usage, revised airplane empty weights and revised airframe costs, all of which make up part of the 1967 ATA DOC formula. This formula, as modified and updated by Douglas, and modeled by a Douglas Advanced Design computer program was used for this study. The output of the DOC study of the WBT configurations included comparative DOC's at various aircraft mission ranges as well as comparisions of DOC distribution by element for a range of fuel prices.

Sensitivity studies were also conducted as part of the DOC analysis, using the existing DOC computer program, for the WBT nacelle configurations. These sensitivity studies investigated the impact on DOC of changes in fuel consumption, airframe maintenance and airplane price over appropriate ranges determined from other areas of the study. For example, the largest fuel consumption change considered likely to result from this study was about 4%; therefore, DOC sensitivity to ±4% changes in fuel consumption was investigated.

5.0 WBT NACELLE CONFIGURATIONS

As noted previously, the primary objective of the WBT studies was to establish engine installation conceptual designs which offered the potential for fuel savings and noise reduction and then to assess those concepts for their impact on other parameters such as weight, cost and airplane performance. With those objectives in mind, the results of a previous Douglas and General Electric study were used as the starting point of this contract. That previous study showed that a thermal mixing long duct nacelle offered attractive fuel savings, if the weight increase relative to the current short duct nacelle could be minimized. Also, to ensure that the study included adequate technical breadth, both lower noise and lower SFC versions of the reference airplane short duct nacelle were also investigated.

5.1 WBT Acoustical Studies

5.1.1 Requirements for Lower Community Noise Levels - For any given level of noise, the number of people annoyed by the sound of the selected reference WBT airplane (and indeed for any current jet transport) is probably greater for most takeoff operations than for most landing operations because the area enclosed by the takeoff noise contour is substantially larger than the area enclosed by the landing noise contour, especially for maximum weight operations. Thus, the WBT study gave the highest priority to reduction in takeoff noise and second priority to reduction in landing noise.

5.1.2 Baseline WBT Component Noise Levels - In order to visualize the needs for component noise reduction, Figure 12 shows predicted values for the peak levels of tone-corrected perceived noise level (PNLT) for the five principal sources of engine noise and for the combined sources of non-propulsive noise (NPN). The PNLT values in Figure 12 were calculated for MTOGW and MLGW operations using the conditions of Table 1 for the Part 36 locations of 6.48 km (3.5 n mi) from brake release for takeoff and 1.85 km (1.0 n mi) from threshold for landing. The columns on the right in Figure 12 show the certified EPNLs for the takeoff and approach locations. The Part 36 Appendix C noise level requirements for takeoff and approach at the 256,284 kg (565,000 lb) MTOGW are indicated by the arrows labeled FAR 36. The takeoff noise levels are for a full-thrust climbout. The baseline WBT meets the Part 36 requirements.

At the takeoff point, Figure 12 shows that the total perceived noisiness of the flyover noise signal is clearly dominated by the jet noise which is generated downstream of the nozzle exit. Other engine noise sources generated within the engine (turbomachinery noise from the inlet, fan-exhaust, and turbine-exhaust ducts, and low-frequency core-engine noise

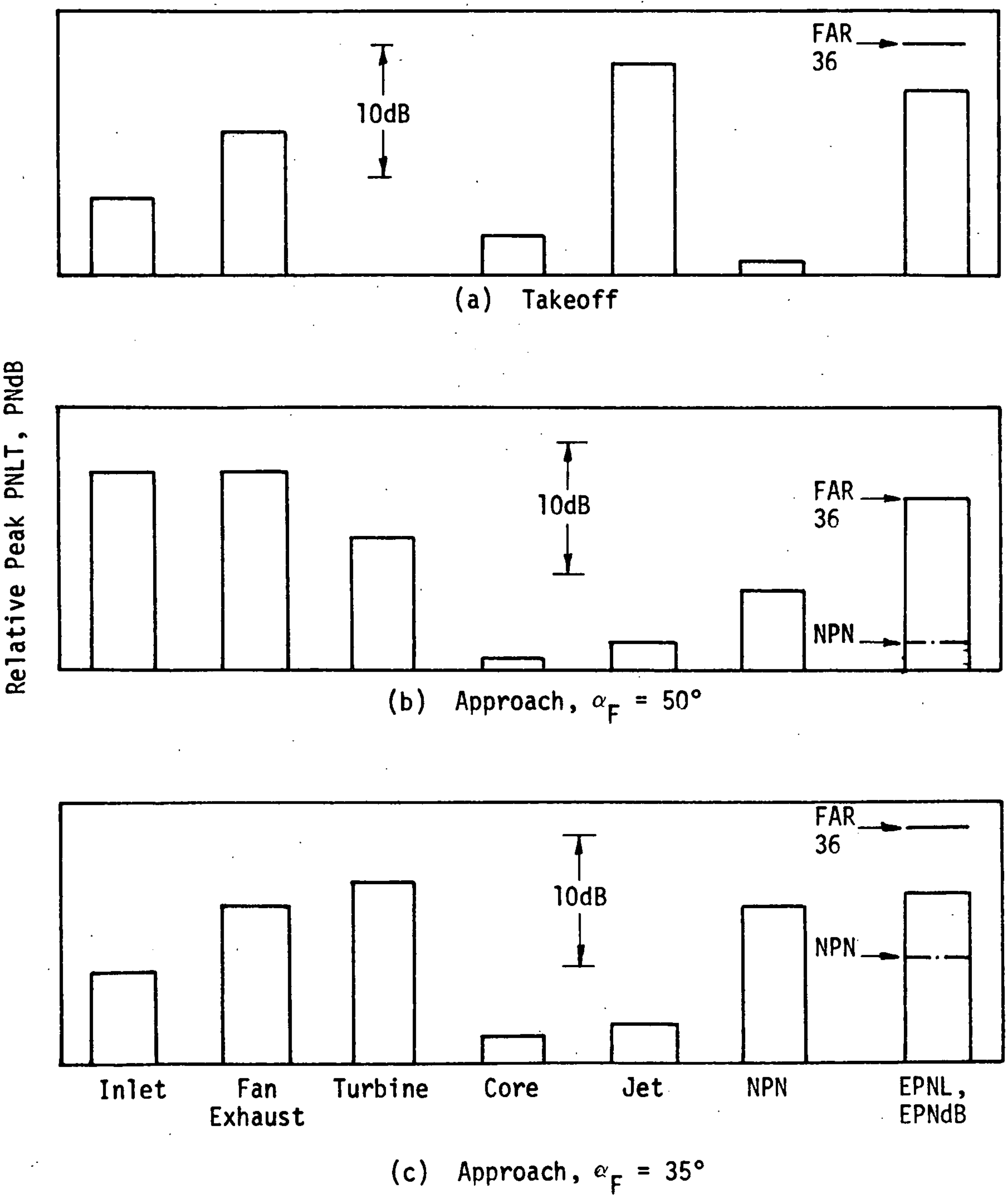


FIGURE 12. BASELINE WBT COMPONENT NOISE LEVELS AT MTOGW AND MLGW FOR FAR PART 36 MEASUREMENT LOCATIONS

from the primary exhaust nozzle) do not contribute significantly to the perceived noisiness of the jet-noise source. Nonpropulsive noise is insignificant at the takeoff power setting.

At approach with maximum flaps, Figure 12 indicates that fan noise from the inlet and fan-exhaust ducts is most important, with high-frequency turbine noise being the next-most-important source. The level of core noise is below the level of the jet and NPN noise sources. As a consequence, there was no need to consider incorporating any acoustical treatment to reduce low-frequency core noise since the level of jet and nonpropulsive noise would not be changed by any nacelle modifications considered in this study.

With the normal flap deflection, Figure 12 indicates that while the turbomachinery noise sources are still dominant, the relative level of the NPN source is higher than for the maximum flap conditions because of the higher airspeed associated with flying down the 3-degree glideslope at the same weight but with less drag, see Table 1. Note that for the normal flap condition, the noise from the turbine stages is dominant; fan-exhaust is second; and inlet noise is third in importance.

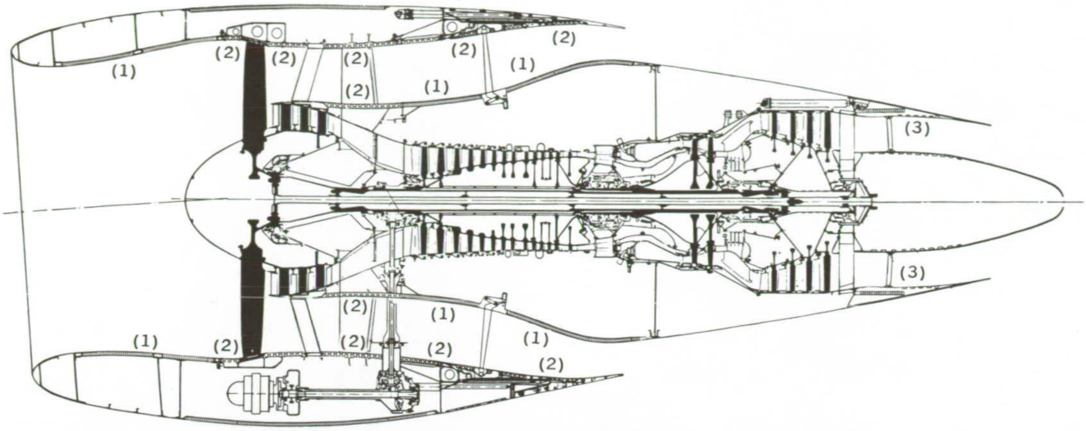
With the current Part 36 requirements and the component levels shown in Figure 12, any improvements to the acoustically absorptive linings in the nacelle would logically be designed to achieve the most reduction in landing noise for maximum flap deflections. Thus, in order of importance, modifications to the acoustical treatment now installed in the nacelles of the baseline WBT concentrated on reduction of (1) inlet noise, (2) fan-discharge noise, and (3) turbine noise. However, future certification requirements might be modified to permit demonstration of compliance using normal flaps, Reference 10. These new requirements could dictate a different emphasis, namely (1) turbine noise, (2) fan-discharge noise, and (3) inlet noise. For the purpose of this study, the maximum-flap conditions generated the design requirements for the acoustical treatment. The noise during takeoff would not be affected by changes in the duct linings.

5.1.3 Acoustical Features of Baseline Nacelles - In order to evaluate the noise-level changes resulting from incorporation of advanced acoustic-composite duct linings, it is necessary to have an understanding of the current acoustical treatment. Figure 13 shows the current nacelle treatment for the wing-engine installation. The tail-engine installation has the same treatment in the fan- and turbine-discharge ducts, but different inlet treatment in the long inlet duct. Nacelle lining changes considered for this study, therefore, considered the treatment in the fan- and turbine-discharge ducts for both wing and tail engines, but only inlet lining changes for the wing engines. The tail-engine inlet treatment was not changed because it was considered part of the airplane structure rather than an engine-nacelle component.

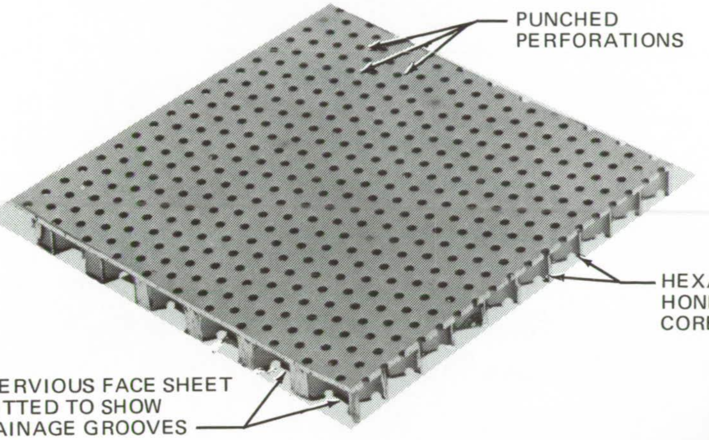
From Figure 13, it can be seen that the inner barrel of the inlet duct uses perforated aluminum sheet and aluminum honeycomb for most of the inlet duct treatment. This lining design is termed single-degree-of-freedom (SDOF). There is a 0.13-m (5-inch)-long segment of double-diamond (multiple-degree-of-freedom of MDOF) lining [item 2 in Figure 13 (b)] just forward of the fan rotor. These MDOF linings are a bonded fiberglass laminate construction. The fan-exhaust ducts use a combination of SDOF linings on the aft part of the inner wall and MDOF linings on the forward part of the inner wall and along the outer wall. The turbine-discharge ducts use SDOF high-temperature metal linings on the centerbody and nozzle wall with perforated steel face sheets and corrugated steel backing structure.

The baseline WBT nacelles have ratios of effective treatment length to effective duct passage height (L/H) of 1.0 for the inlet duct (using the duct radius as the measure of duct height), 2.8 for the fan-discharge ducts, and 1.4 for the turbine-discharge ducts.

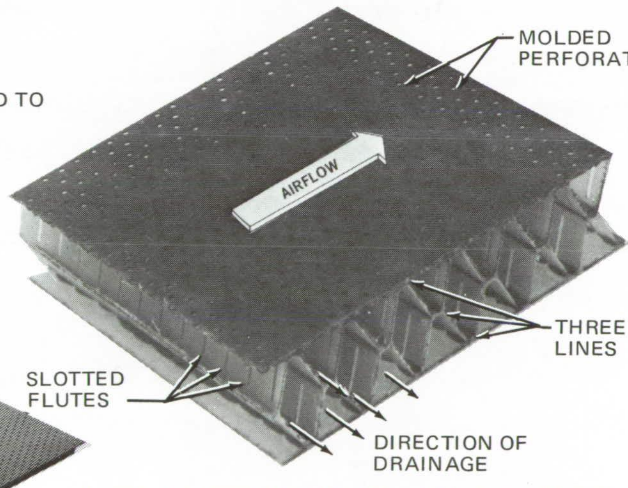
5.1.4 Noise Reduction Concepts - Various short- and long-duct nacelles were considered in the study as candidates for incorporating advanced acoustic-composite duct linings. The short-duct nacelles incorporated advanced duct linings to reduce turbomachinery noise. The long-duct nacelles incorporated advanced duct linings and an internal mixer. Only



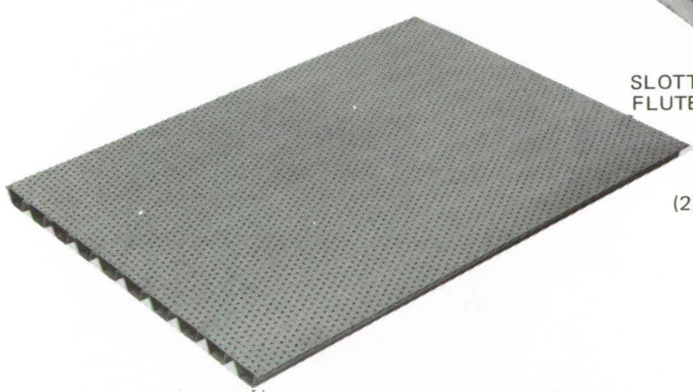
(a) LOCATIONS OF ACOUSTICAL TREATMENT [(1), (2) AND (3) REFER TO LININGS ILLUSTRATED BELOW]



(1) PERFORATED ALUMINUM SHEET BONDED TO ALUMINUM HONEYCOMB CORE



(2) PERFORATED FIBERGLASS LAMINATE BONDED TO SLOTTED FIBERGLASS LAMINATE DOUBLE-DIAMOND CORE



(3) PERFORATED STEEL SHEET BRAZED TO CORRUGATED STEEL CORE

(b) EXAMPLES OF ACOUSTICAL DUCT LININGS

FIGURE 13. ACOUSTICAL TREATMENT FOR BASELINE WBT WING ENGINE NACELLE

the long-duct mixed-flow nacelle offered the possibility of reducing jet noise during takeoff; the separate-flow short-duct nacelles were not expected to cause any change in the jet noise level from the baseline short-duct nacelle.

All the advanced acoustic-composite duct linings for the inlet and fan-discharge ducts would be designed to integrate their acoustical design requirements with the structural and environmental design requirements. This integrated approach was adopted to maximize the efficiency of the installations and minimize the penalties.

5.1.4.1 Jet Noise - Over the past 20-year period a very large number of model-scale and full-scale static tests have been conducted to study a variety of jet-noise-suppression devices for turbojet and turbofan engines. Several designs have been flight tested, often with disappointing results, i.e., less noise reduction and more performance loss than predicted on the basis of the static tests. For turbofan engines, investigators in recent years have been studying a variety of mixer designs for the primary nozzle in long-duct mixed-flow arrangements. These mixers have included free mixers (round nozzles) as well as forced mixers of the type envisioned for nacelle configuration II.

The results of static model-scale tests have been inconclusive and no reproducible trends have been deduced. Based on the results of past experience with turbojets and low-bypass-ratio turbofans, it is clear that the effects of forward motion must be realistically simulated in order to provide a reasonable probability of reliably estimating the in-flight jet noise suppression.

For the long-duct nacelle, it is expected that the differences in the flow fields around the baseline short-duct nacelle and the mixed-flow long-duct nacelle will change the noise-generation process such that the long-duct will produce noticeably less jet noise at takeoff power than the short-duct nacelle. Figure 14 shows the results of the analyses that support this belief. The plot in Figure 14 shows the difference between perceived noise levels projected to a 305-m level-flight flyover from

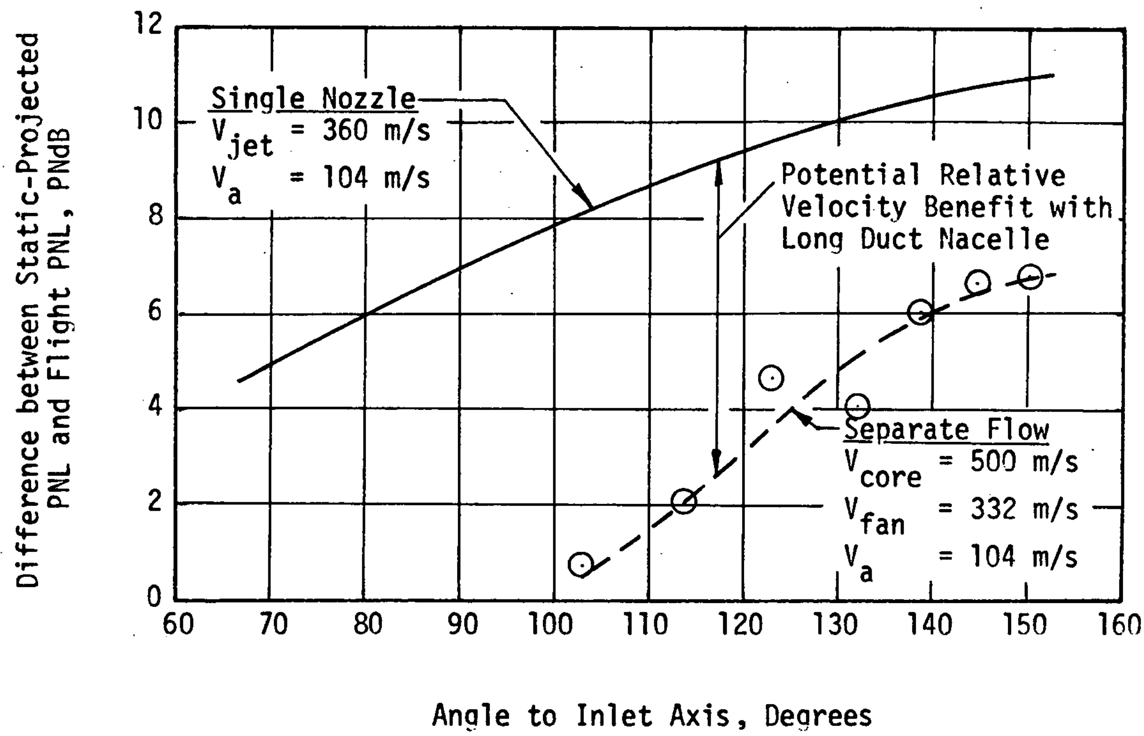


FIGURE 14. EFFECT OF FORWARD MOTION ON JET NOISE FROM SEPARATE FLOW TURBOFAN EXHAUST JETS AND FROM THE EXHAUST OF A SINGLE CONICAL NOZZLE. PNLs CALCULATED FOR A LEVEL FLIGHT FLYOVER AT 305m (1000 ft)

static measurements and actual flight data. The bottom dashed-line is drawn through data points for a separate-flow nozzle system on an airplane powered by high-bypass-ratio turbofans. The upper solid line is an average trend line obtained from several simulated and actual static-to-flight comparisons from model-scale and full-scale tests for round conical nozzles. The vertical distance between the two curves is a measure of the flight (relative-velocity) effect on the jet noise produced by a mixed-flow long-duct nacelle compared with the jet noise produced by the exhaust from a separate-flow short-duct nacelle.

Note that the difference between the two curves in Figure 14 is on the order of 5 to 6 PNdB in the aft quandrant at angles between 120 and 150 degrees. For the internal forced-mixer nozzle on nacelle configuration II, it was not certain what degree of mixing will be achieved between the fan and primary streams. The full 5 to 6 PNdB was therefore termed a "potential relative-velocity benefit" in Figure 14. In assessing the actual noise-reduction capability for nacelle configuration II, it was considered prudent to assume that the mixing would not be complete and that less than the full noise-reduction potential could be realized.

5.1.4.2 Inlet Noise - For inlet-radiated fan noise, the best choice for an advanced duct lining appeared to be a lining that would have the acoustical characteristics of compressed open-cell polyurethane foam, but without the weight or environmental problems that currently prevent use of this type of product in engine nacelles. Phased treatment [step changes in lining acoustical impedance in the axial or circumferential directions] was also considered but the available experimental evidence indicated that a bulk absorber such as compressed open-cell polyurethane foam would achieve greater noise reduction than a phased, or multisection, treatment.

Figure 15 shows the results of scale-model fan rig and full-scale CF6 tests conducted by GE that corroborate the advantage of a bulk absorber lining over an SDOF lining of the type currently used in the WBT inlet. At the 2820-rpm fan speed used for the maximum-flap landing, the bulk absorber provided about 2 PNdB additional noise reduction for the same

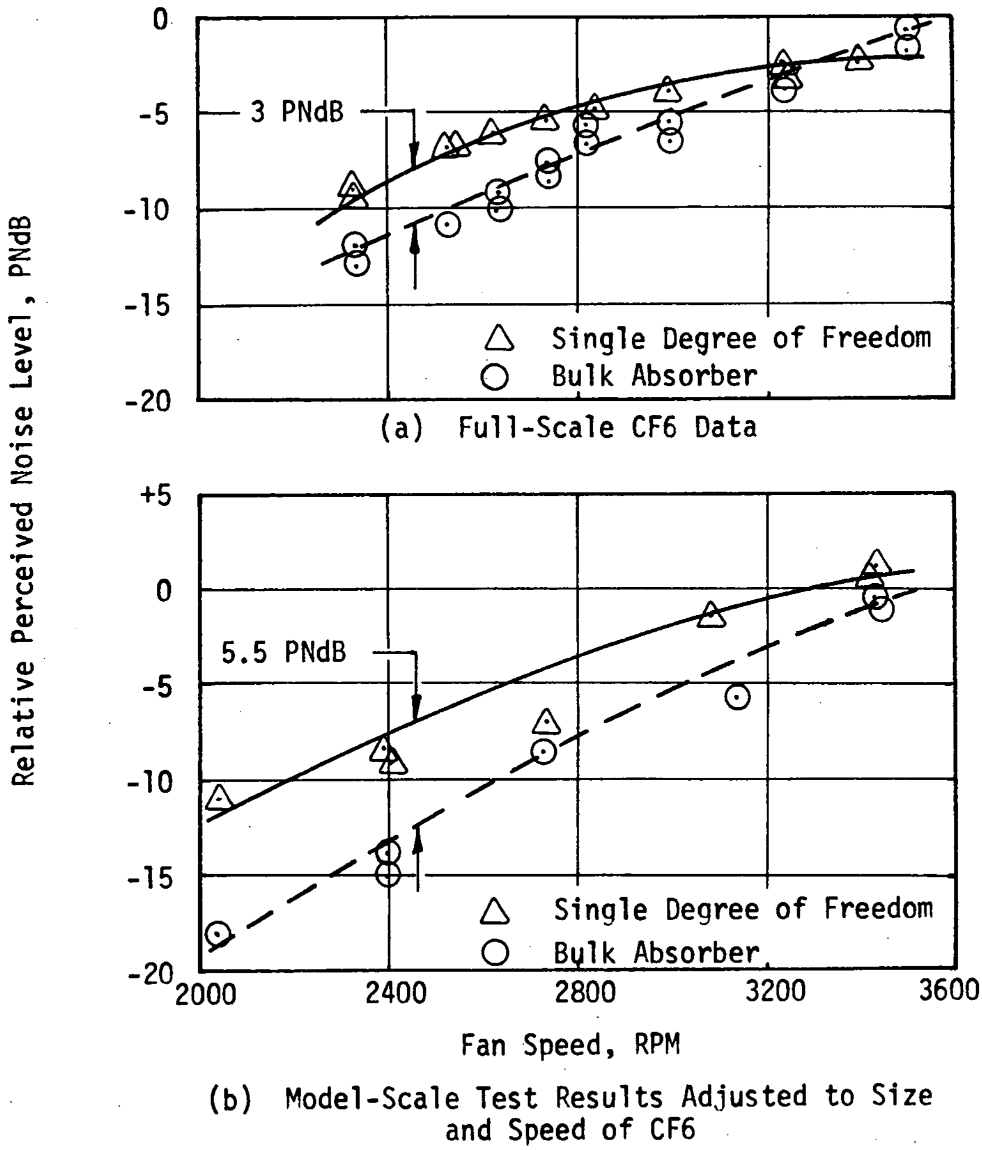


FIGURE 15. INLET NOISE LEVELS WITH SDOF AND BULK ABSORBER DUCT LININGS: L/H 1.0; STATIC CONDITIONS; 61-M (200 FT) SIDELINE AT 60 DEGREES FROM INLET AXIS

L/H value of 1.0 as for the inlet on the baseline WBT. Larger benefits were observed at lower fan speeds.

5.1.4.3 Fan Discharge Noise - For noise radiated from the fan-discharge ducts, there were several candidate noise-reduction concepts. The first was straightening of the fan outlet guide vanes. As can be seen from Figure 13 (a), the root of the fan OGVs is closer to the fan blades than the tip. Straightening these fan OGVs to increase the blade-to-vane root distance (preserving the blade-to-vane tip distance) was estimated to be worth 1 PNdB of noise reduction at approach and takeoff power settings. Thus, straightened fan OGVs were considered as part of the nacelle modification for each candidate nacelle.

For the short-duct study nacelles, all treated surfaces in the fan-discharge ducts used a broadband type of lining design (probably similar in concept to the current double-diamond MDOF design), but made from advanced fibers such as graphite or the DuPont Kevlar organic fiber. It was estimated that an additional 2.8 sq m (30 sq ft) of treated area could be provided on the outer wall of the fan duct to increase the L/H value from 2.8 to 3.3 for the same aerodynamic flow paths. The porous core structures for these broadband linings could use an integrally woven or a locked-core construction method as explained in more detail in Section 5.8. Two of the three study short ducts had only these advanced linings and the additional treated area on the outer duct wall. The third short-duct study nacelle (IC) considered the impact on fan noise of installing a 0.61-m (24-inch) -long acoustically treated circumferential splitter in the fan-discharge ducts giving an L/H of 4.8 compared to the no-splitter value of 3.3 for configurations IA and IB.

For the study long duct, the effective L/H value in the fan exhaust duct was 10.0 with treatment tuned to have maximum fan noise attenuation at the 2820-rpm condition and with the straightened fan OGVs. With this much treatment area potentially available, the most-appropriate lining design was a simple perforated face sheet, made from advanced fibers, bonded to a composite, but impervious, honeycomb core, with appropriate provisions for drainage. Because of the high levels of inlet and turbine noise, the additional noise reduction that would be obtained from the more-expensive and heavier MDOF linings was not needed and the SDOF linings were adequate. The basic acoustic design philosophy was to not overly suppress the noise from any one source so that the resulting nacelle design would have an overall acoustical balance in the amount of nacelle treatment selected.

5.1.4.4 Turbine Noise - For turbine noise reduction, essentially all of the nozzle wall was treated, and additional treatment was installed on the wall of the centerbody. Moreover, the current corrugated-core design, Figure 13 (b-3), was changed to a honeycomb-core design to gain additional treated area since the corrugations block almost half the holes in the perforated face sheet. With the aerodynamic lines of the current turbine-discharge duct and with retention of the turbine thrust reversers, the effective turbine L/H value for configuration IA and IC was increased to 1.8 from 1.4 for the baseline WBT. For configuration IB without the turbine thrust reversers but with the shortened primary nozzle, the effective turbine L/H value was also 1.8.

The mixer nozzle for the long-duct nacelle, described in Section 5.5, was designed without acoustic treatment to reduce turbine noise because of the weight, cost, and performance penalties associated with an acoustically treated mixer nozzle. Turbine treatment was incorporated only on the wall of the centerbody and the wall of the mixed-flow nozzle downstream of the exit plane of the mixer nozzle. The effective L/H value for the perforated-steel/honeycomb turbine treatment on the centerbody and outer nozzle wall was estimated to be 1.8.

Because of the importance of turbine noise in the total landing-noise signature, it would be advantageous to conduct additional studies in the next phase of the program to evaluate installation of additional turbine treatment. Further, the effect of the lobed mixer-nozzle on turbine noise generation within the common-flow nozzle was unknown and needs to be determined by flight testing. These additional studies would use the results of the mixer-nozzle configuration studies as the basis for developing practical turbine-treatment duct-lining designs. Judging from the conclusions that are now available, it would be impractical to consider treating the walls of the lobes of the mixer nozzle or installing treated circumferential or radial splitters within the lobes. The only practical configuration appears to be one that incorporates an acoustically treated "spool piece" (two concentric cylinders) between the turbine-discharge flange and the entrance to the mixer nozzle.

5.2 WBT Study Short Duct Nacelles

As shown in Figure 16, four basic short duct, separate flow nacelles were evaluated. Configuration 1 was the baseline nacelle as installed in current production airplanes. Configuration 1A reflected the incorporation of composites within the baseline aerodynamic contours to reduce weight. Configuration 1B represented an improvement to the performance and reliability of the basic separate-flow system by a shortening of the core nozzle and deletion of the core reverser. Configuration 1C was identical to 1A except for the addition of acoustic splitters in the fan duct. All of the short duct nacelles have identical nose cowl aerodynamic parameters and most of the flow path lines and aerodynamic contours are also the same.

The baseline, Configuration 1, is shown in detail in Figure 17. The major nacelle components are identified and, as can be seen, the existing nacelle incorporates substantial areas of acoustic treatment, although only portions are of current technology composite construction. The nose cowl has a bonded aluminum honeycomb inner barrel for the acoustic treatment with about 6.41 sq m (69 sq ft) of effective area. The inner and outer walls of the fan discharge duct also incorporate acoustic treatment, some of it non-structural fiberglass composite. The inner flow path is bonded aluminum honeycomb for the most part and the outer flow path contains a number of bolt-in panels made of fiberglass and using the GE double-diamond concept. The acoustic treatment in the primary exhaust nozzle uses a stainless steel perforated face over a corrugated core with a total effective area of about 1.95 sq m (21 sq ft). In total, there is about 23.2 sq m (250 sq ft) of acoustic treatment in each CF6-50 wing engine.

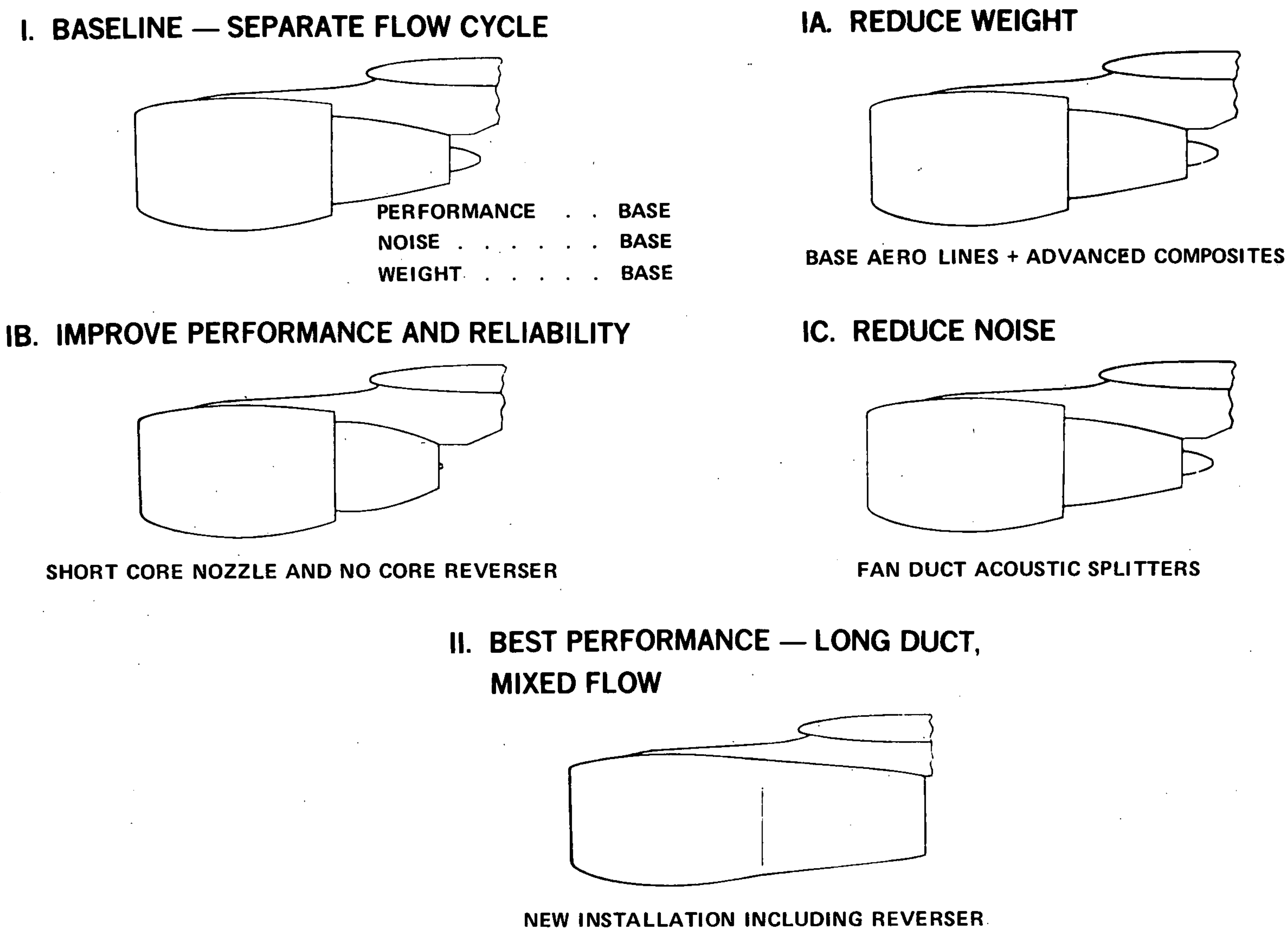


FIGURE 16. WIDE BODY TRANSPORT STUDY NACELLE CONFIGURATIONS

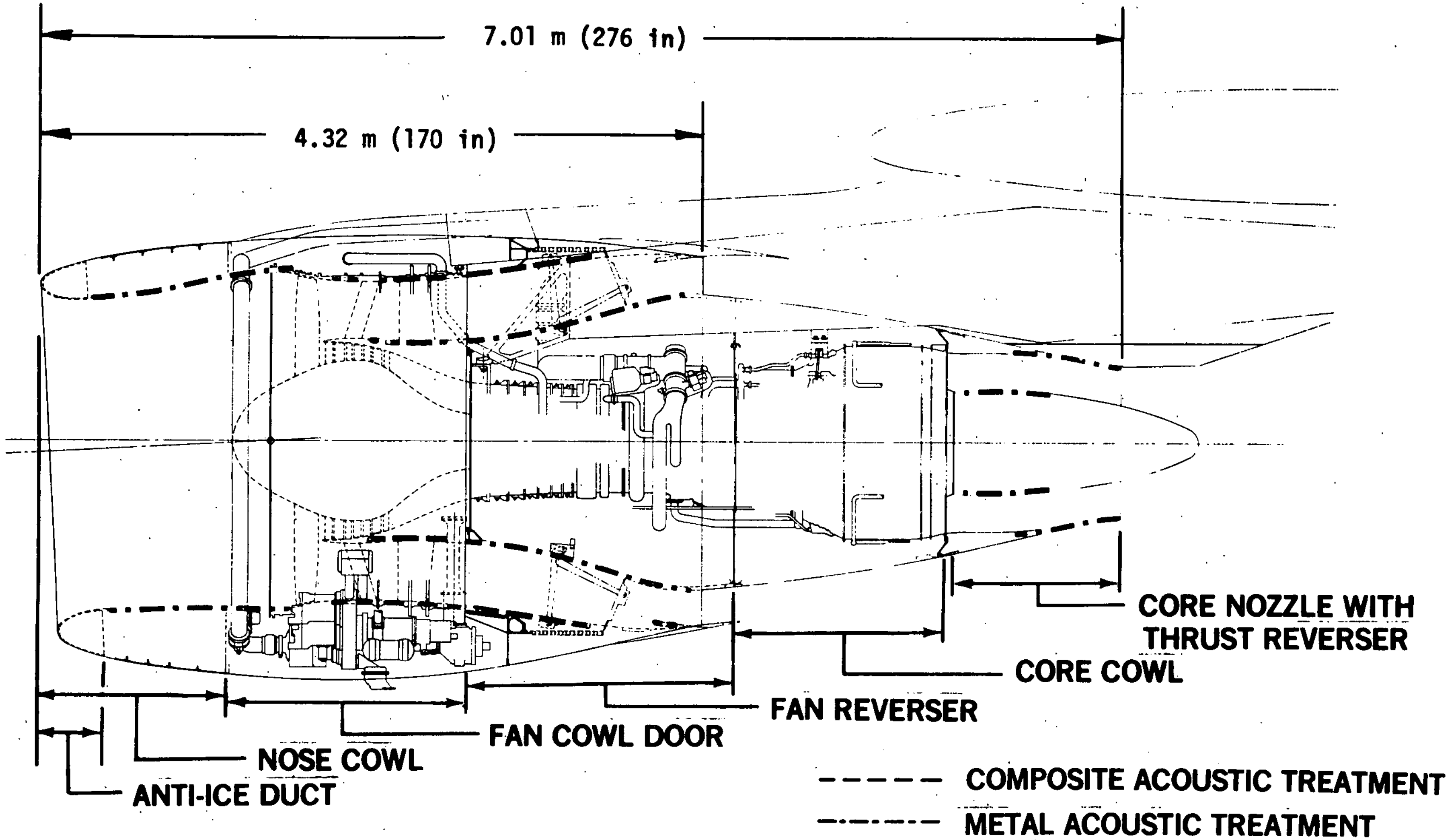


FIGURE 17. STUDY WBT NACELLE CONFIGURATION I - BASELINE SHORT DUCT INSTALLATION

The addition of advanced composites to the basic nacelle is shown in Configuration 1A (Figure 18). The inner and outer barrels of the nose cowl were constructed of advanced composites. In addition, the fan cowl access doors, which in Configuration 1 were of bonded aluminum honeycomb, were changed to an advanced composite construction. The inner wall of the reverser also incorporated advanced composites as did the outer wall components and a portion of the internal structure of the reverser itself. The aft core cowl reflected the use of advanced composites with high-temperature-capability resins and fibers. All of the acoustic treatment in the turbine area would be revised but would remain metal, since this is a high temperature area out of the realm of application for advanced composites. It was estimated that with the incorporation of advanced composites as shown in Configuration 1A, approximately 488 kg (1077 lb) of weight could be saved per airplane. No inherent aerodynamic improvement was anticipated so there was no effect on fuel consumption except that which was attributable to the reduced weight.

Figure 19 shows nacelle configuration 1B, which represented the best performance short-duct installation considered practical. It was basically the same as Configuration 1A except that the aerodynamic flow paths aft of the fan nozzle exit were revised and shortened and resulted in somewhat steeper boattail angles. It was also expected that the deletion of the turbine thrust reverser would permit the application of some additional, improved turbine acoustical treatment, all of which would be metallic. Considerable weight savings were realized by deleting the turbine reverser and the weight reduction for Configuration 1B was estimated to be 959 kg (2118 lb) per airplane. In combination with the aerodynamic improvements, an installed fuel consumption improvement of about 1.74% could be realized.

Figure 20 shows the separate flow configuration in which Configuration 1A had an acoustically-treated splitter added downstream of the fan to reduce fan discharge noise. This design provided more surface area of acoustically treated components and also increased the ratio of effective treatment length to effective passage height for better noise absorption. However, installation weight was increased and the net benefit of the weight savings

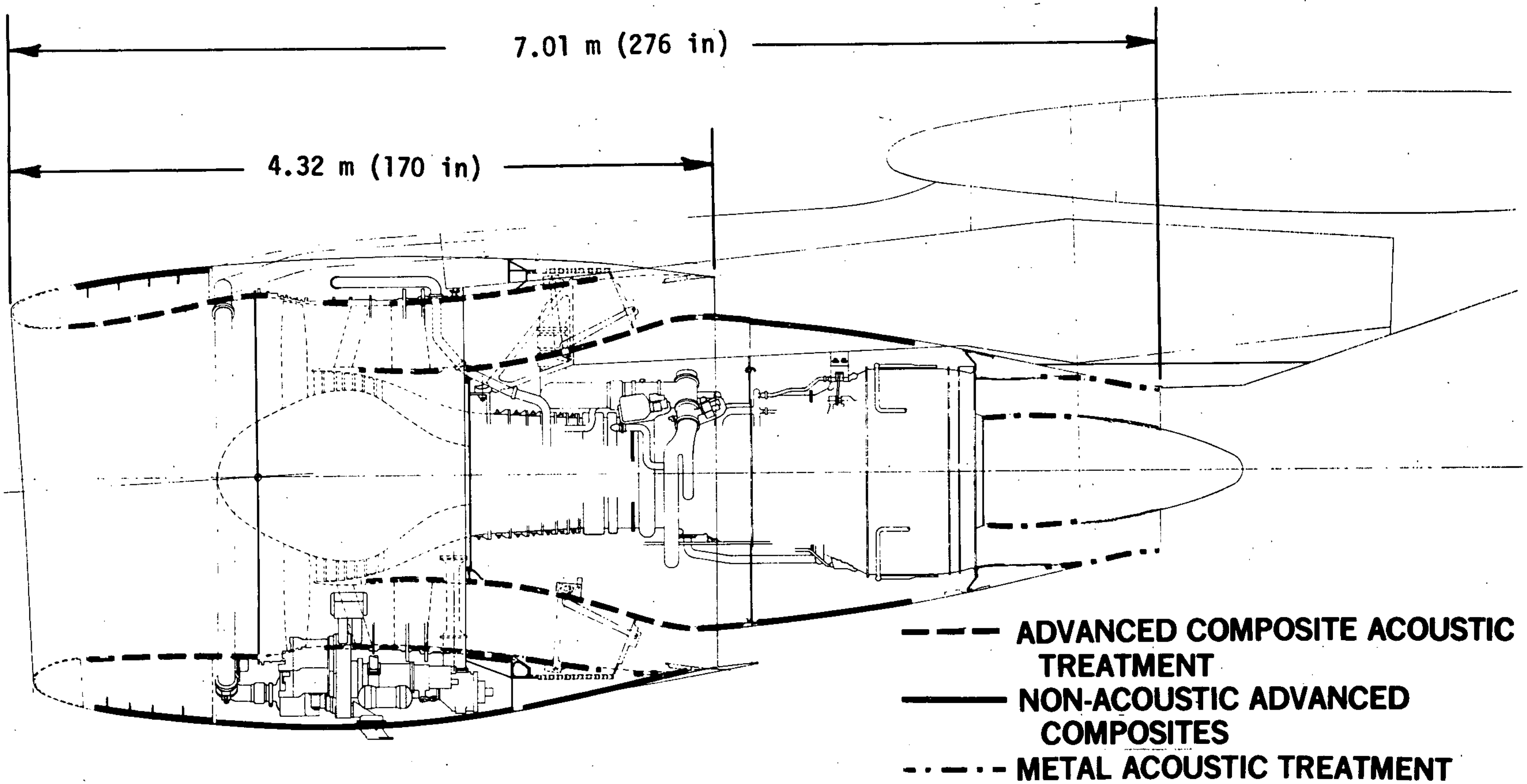


FIGURE 18. STUDY WBT NACELLE CONFIGURATION IA - SHORT DUCT WITH COMPOSITES

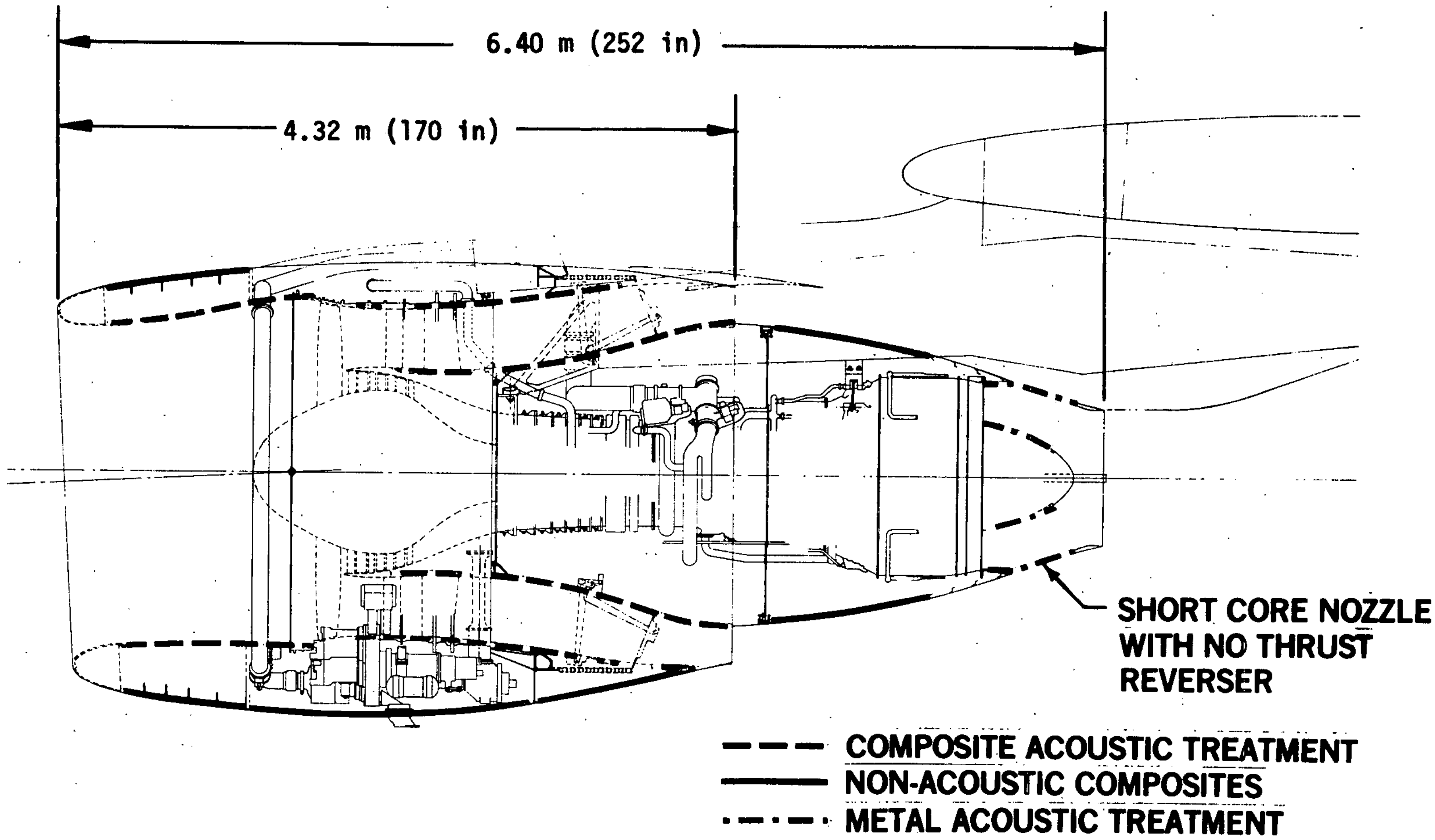


FIGURE 19. STUDY WBT NACELLE CONFIGURATION IB - SHORT DUCT WITH COMPOSITES SHORT EXHAUST NOZZLE AND NO TURBINE REVERSER

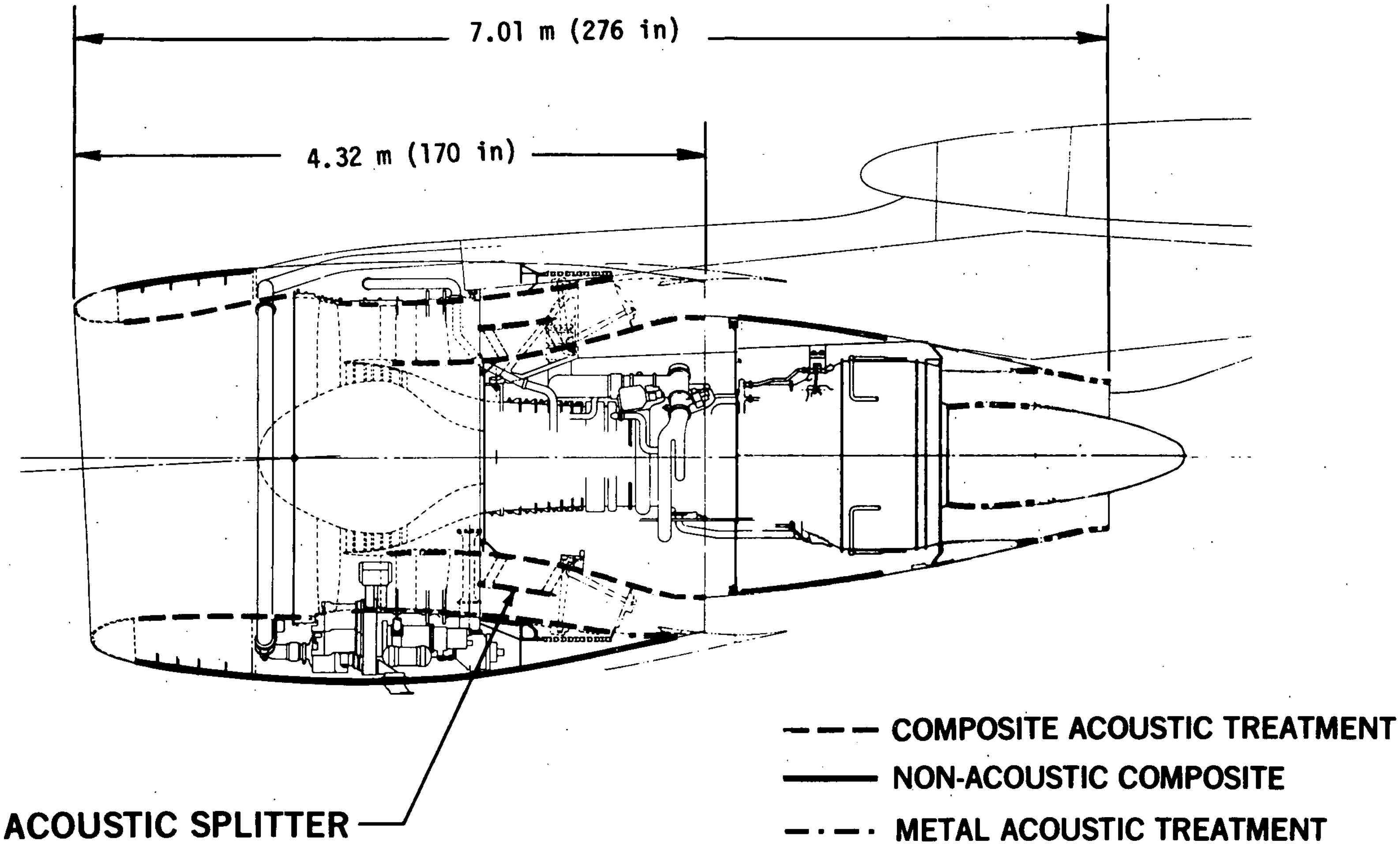


FIGURE 20. STUDY WBT NACELLE CONFIGURATION IC - SHORT DUCT WITH COMPOSITES AND FAN DUCT ACOUSTIC SPLITTER

from advanced composites was 281 kg (621 lb) instead of 488 kg (1077 lb). Since SFC suffered due to higher fan duct pressure drop and higher scrubbing drag over the splitters, the result was essentially no net aircraft fuel consumption improvement with configuration 1C.

5.3 WBT Study Long Duct Nacelle

Referring again to Figure 16, an additional nacelle was studied. This was a long duct configuration which took advantage of the inherent performance improvement available from the addition of a thermal mixer to the basic CF6-50C engine cycle. Configuration II, as shown in Figure 21, represented the aerodynamically ideal configuration from the standpoint of obtaining the best performance benefits from the long-duct, mixed-flow system. It had large fan discharge passages to keep the duct Mach numbers down in order to minimize pressure losses and the generation of flow noise over the treated surfaces. The forward portion was essentially the same as all the short duct configurations, with the inlet and fan cowl doors identical to those on the short duct configurations. A major change was made in the reverser area of the fan where a new reverser concept was incorporated to reduce pressure losses below those of the existing fan reverser and employing advanced composites to reduce weight. The long-duct mixed-flow concept is particularly suited to being configured without a turbine reverser because the over-expansion of the exhaust from the turbine nozzle that occurs when the fan flow is prevented by the fan reverser from entering the mixing zone, effectively spoils the core engine thrust.

The long-duct configuration offered a large increase in the area available for installation of acoustical treatment to reduce fan discharge noise. As a result of this large treated area, fan discharge noise did not dominate the flyover noise levels of the WBT with long-duct nacelles. However, possible changes to the turbine acoustic treatment for this configuration and the overall effect of the mixer on turbine noise are areas of uncertainty at this point. Therefore, for the long-duct configuration, inlet and turbine noise were approximately balanced for the approach condition. For the takeoff condition, jet noise was dominant, although the thermal mixer was estimated to be able to reduce the level of jet noise.

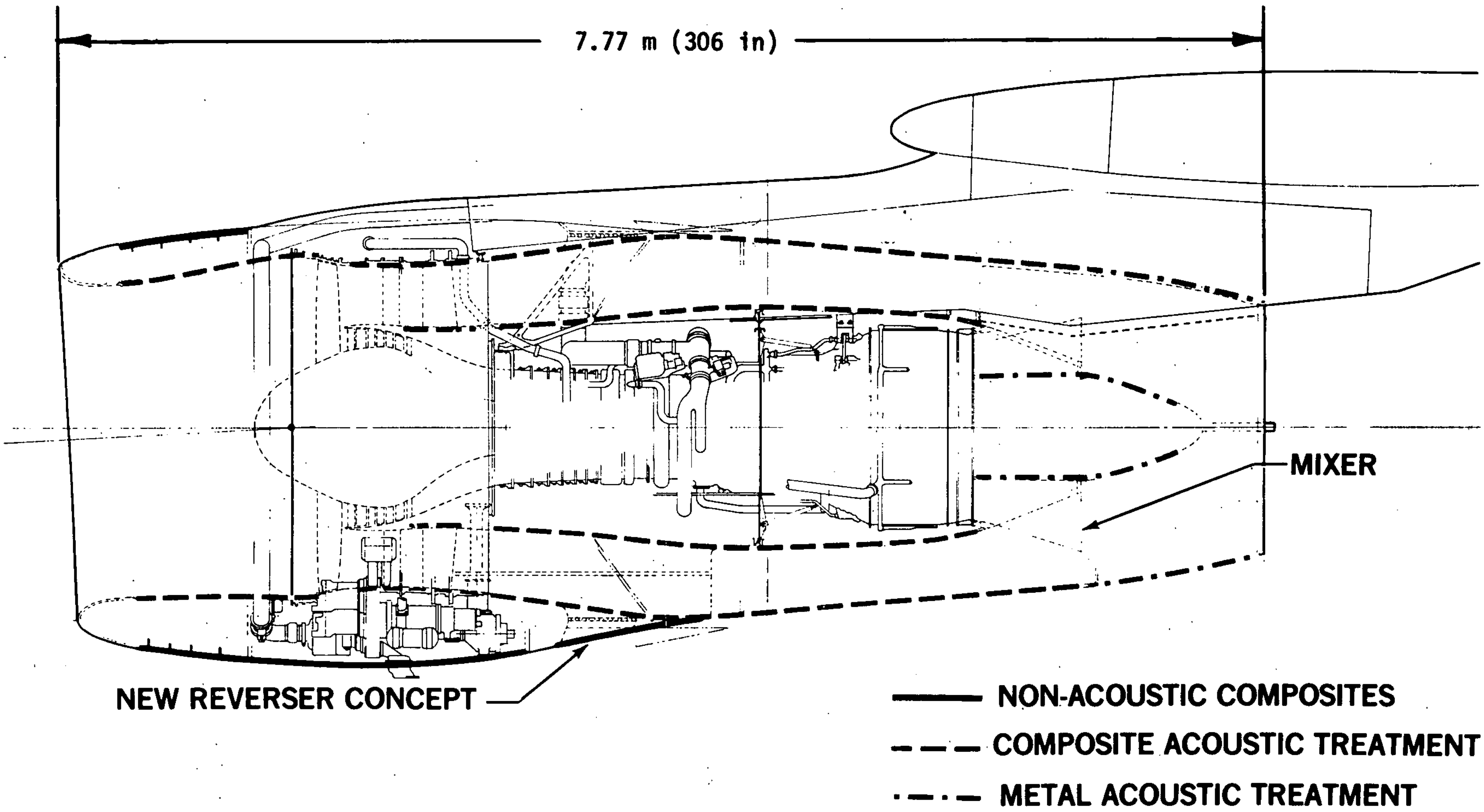


FIGURE 21. STUDY WBT NACELLE CONFIGURATION II - LONG-DUCT, MIXED-FLOW

Configuration II also offered fuel consumption improvement of approximately 4% due to the combination of the thermal mixer and the improved overall aerodynamics as illustrated in Figure 22, and the effects of the estimated 657 kg (1449 lb) per airplane weight reduction. The contribution of the forced thermal mixer is about 2-1/2% of the 4-1/4% total improvement. The mixer is described in detail in Section 5.5. The improved external aerodynamic performance of the long-duct resulted in part from elimination of the supersonic scrubbing drag at cruise, as shown in Figure 22. A more detailed analysis of internal and external performance is described in detail in Section 7.1.

The weight of the long-duct was determined from the estimates of the composite component weights. The individual nacelle components are described in Section 5.8 and detailed weight breakdowns for each component accompany the individual descriptions. Weight tabulations for the long-duct nacelle and each of the short-duct nacelles are given in Section 7.2.

5.4 Bulk Absorber Inlet Acoustic Treatment

As described in Sections 5.2 and 5.3, all WBT nacelles studied used identical aerodynamic parameters for the inlet. Much aerodynamic development work had been completed for this inlet configuration so inlet improvement efforts were limited to studies of better acoustic treatment concepts.

Both model scale and full scale CF6 inlets have been tested that incorporated what is generically called a "bulk" absorber. For these tests a reticulated matrix polyurethane foam was compressed to about one third of its free standing height for a total absorbent layer thickness of approximately one inch. The acoustical results from full scale testing confirmed the model test results which showed that the bulk absorber acoustic lining had distinctive advantages, because of its broader bandwidth of noise reduction.

5.5 Mixer Nozzle

As discussed in Section 5.3, the long-duct nacelle represented an attempt to take advantage of the theoretical propulsive efficiency improvement

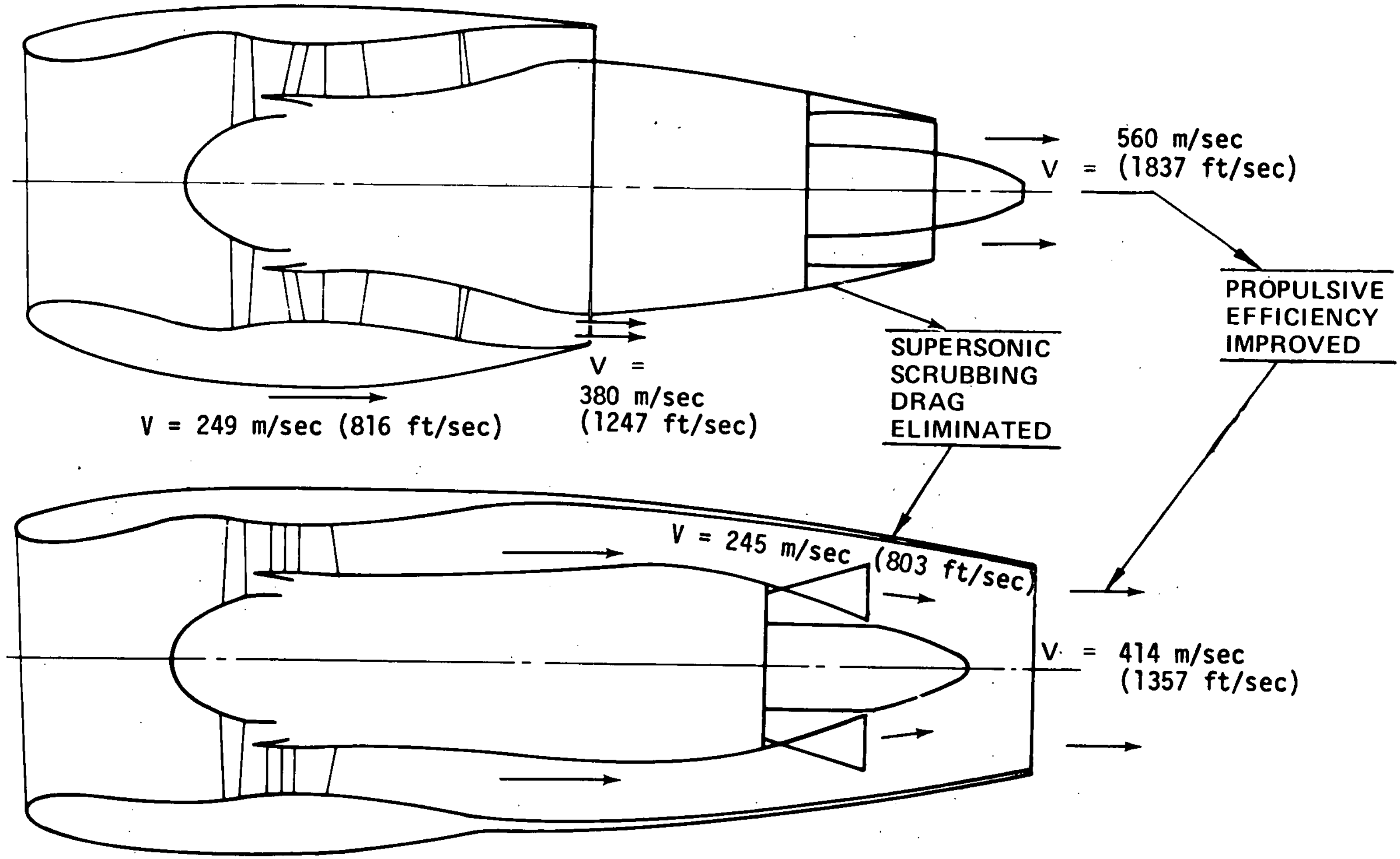


FIGURE 22. COMPARISON OF SHORT-DUCT AND LONG-DUCT NACELLE TYPICAL CRUISE AIRFLOW VELOCITIES

that results from a mixed-flow exhaust system (Ref. 11). For the CF6-50C engine cycle, that improvement has been found in other studies to be on the order of 2.5% in gross thrust. However, in any practical application, the mixing process becomes less than ideal because mixing effectiveness (K4, %), pressure losses, weight effects and installation drags must be accounted for. General Electric scale model tests and analytical studies have shown, however, that the goal of a 2.5% gross thrust improvement is practical for the CF6-50 cycle.

5.5.1 Mixer Aerodynamic Design - The mixer aerodynamic design that evolved during this study involved essentially the consideration of three interrelated items. First, the total mixing plane area was dependent on nacelle geometric constraints and on achieving acceptable mixing plane Mach numbers and static pressure balances. Second, the geometry of the mixer at the mixing plane (number of lobes, lobe angles, etc.) controls the percentage mixing effectiveness. This may be seen by typical geometry/ mixing effectiveness correlations, such as those shown in Figure 23. Third, the contour of the mixer wall, the axial length of the mixer and the volume of the mixing chamber and the mixer Mach numbers and boundary layer separation distributions all play a part in the system design. Since all three of the above items were interrelated, the mixer design process was iterative.

The CF6-50 mixer design was based primarily on scaling of a successful GE scale model mixer. Mixer wall contour and length were designed to be geometrically similar to the scale model rather than being based strictly on analytical considerations of boundary layer separation characteristics. Since the intent was to conceive a low risk design to demonstrate the value of a mixer on the CF6-50, the mixer must be considered non-optimum in comparison with purely analytical considerations.

Figure 24 shows mixer geometry nomenclature. Various combinations of the parameters shown were used to compare mixer designs and to correlate mixer geometry with performance. Figure 25 shows the correlation of mixing effectiveness (K4) with interface area function as suggested by Frost

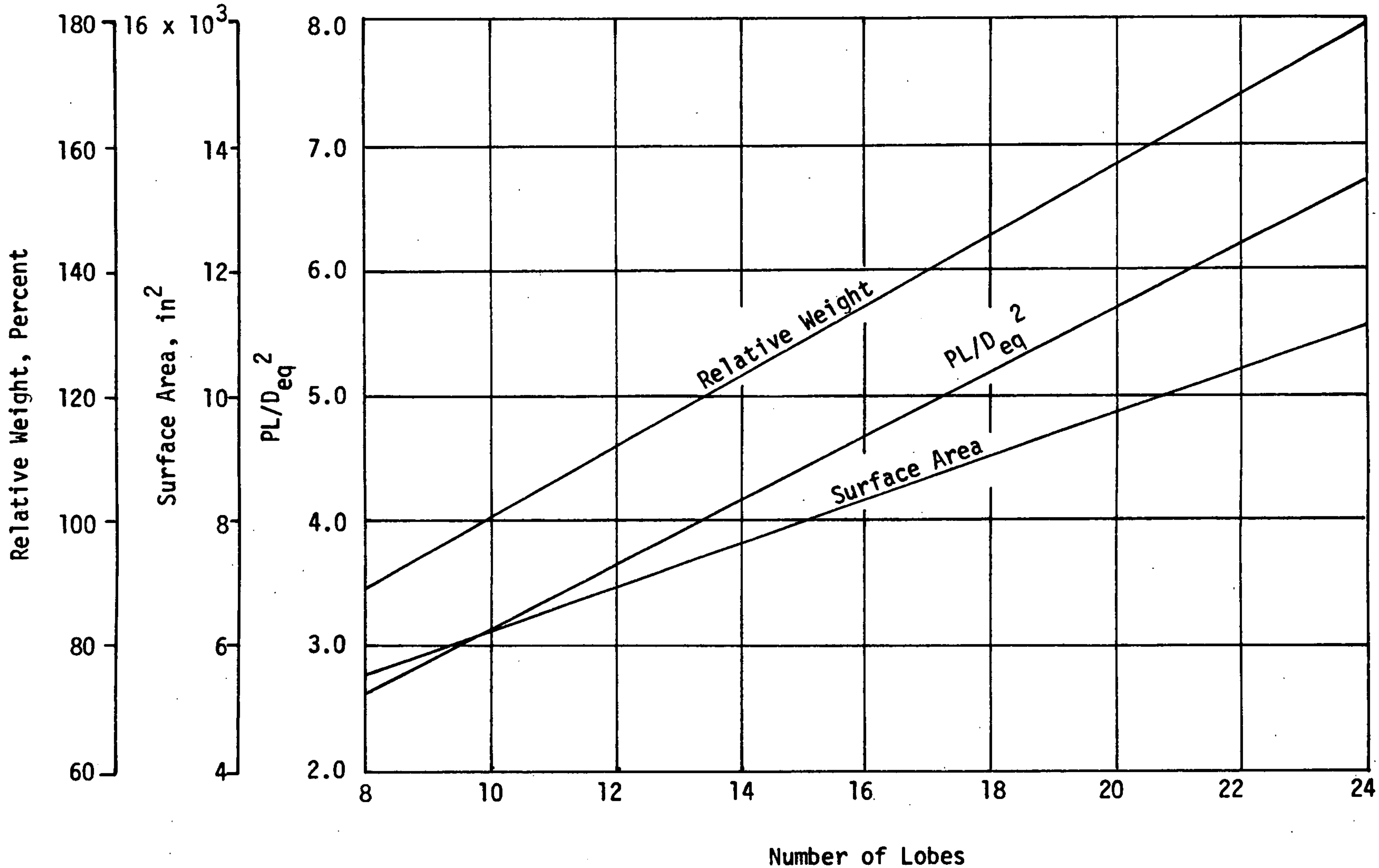
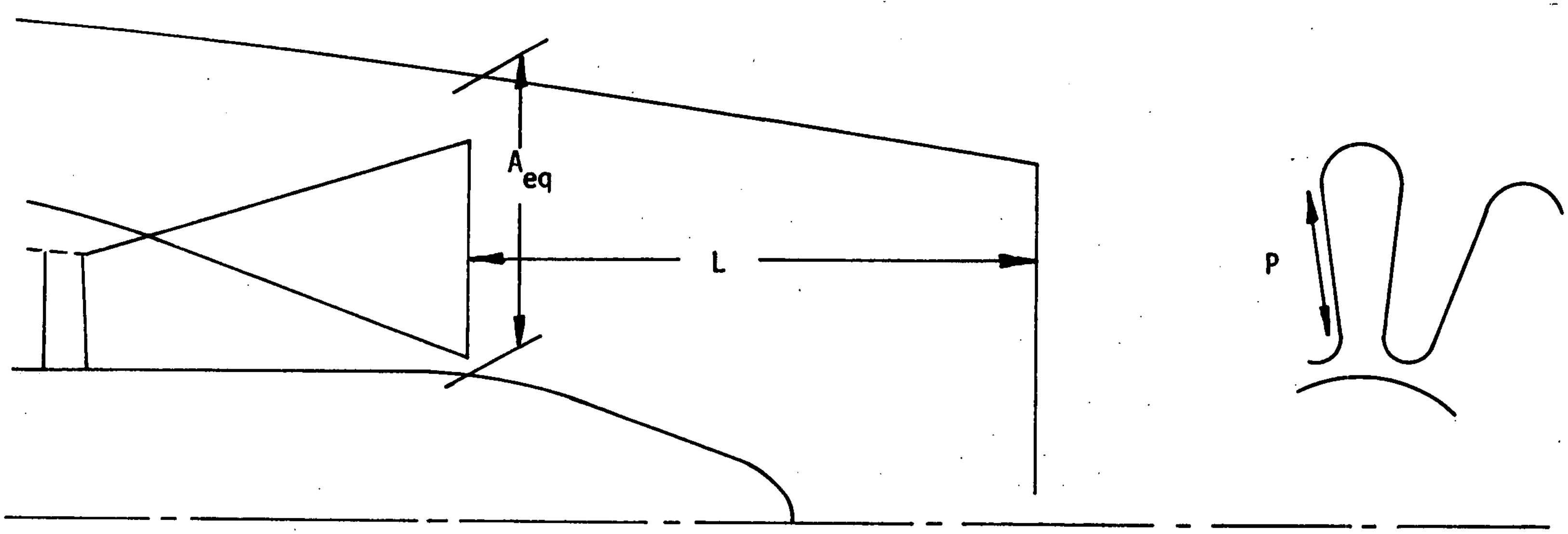


FIGURE 23. MIXER PARAMETERS VS. NUMBER OF LOBES

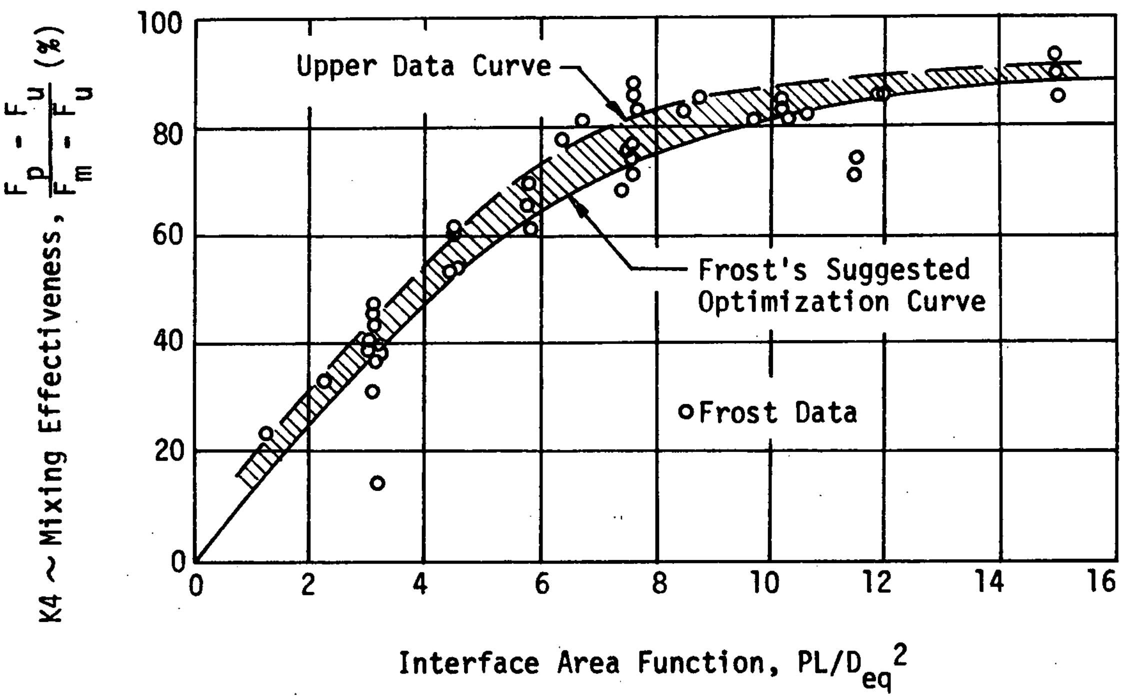


L = Mixing chamber length

P = Perimeter of mixer at mixing plane

$D_{eq} = \sqrt{(4/\pi)A_{eq}}$ = Equivalent diameter of mixing chamber at mixing plane

FIGURE 24. MIXER GEOMETRY NOMENCLATURE



F_p = Partially mixed thrust
F_u = Unmixed ideal thrust
F_m = Fully mixed ideal thrust
P = Perimeter of mixer at mixing plane
L = Mixing chamber length
D_{eq} = Equivalent diameter of mixing chamber at mixing plane

FIGURE 25. MIXING EFFECTIVENESS VS INTERFACE AREA FUNCTION

(Ref. 12). For the CF6-50 mixer, the design objective for mixing effectiveness was 65% or better.

5.5.2 Selected Mixer Configuration - The mixer configuration that evolved from this study is shown in Figure 26. Acoustic treatment was incorporated on the centerbody only. A chem-milled pattern was used on the stainless steel lobe sidewalls to reduce local wall thickness for weight reduction. The mixer would be supported from the plug at the bottom of each lobe by hinged links. Total weight of the mixer and centerbody was estimated to be 133 kg (293 lb). This mixer design was the shortest, lowest weight configuration investigated in this study which had a high probability of giving a 65% mixing effectiveness based on both Frost and model data. The chute angles chosen were consistent with the goal of a low risk design.

The effect of varying lobe number while holding all other geometric parameters (seen in side-view) constant was shown in Figure 23. Increasing lobe number increased PL/D_{eq}^2. This then increased theoretical mixing effectiveness, but had an adverse effect on weight and surface area. In Figure 27 these effects have been converted to SFC changes relative to a 17-lobe design. In keeping with the goal of obtaining a low risk design it was decided not to decrease the number of lobes from 17 since Frost's data showed this to have an adverse effect. Increasing the number of lobes presented mechanical, aerodynamic and weight problems and might not be beneficial in terms of improved SFC. A mixer with 17 lobes was therefore chosen for the long-duct nacelle.

5.6 WBT Candidate Composite Materials

The basic composite materials considered for the WBT were limited to those readily available and requiring little or no additional material development. The types of fibers and resins that were considered are shown in Figure 28 and Table 3 and consist primarily of graphite, DuPont Kevlar and fiberglass or hybrid combinations of these, and

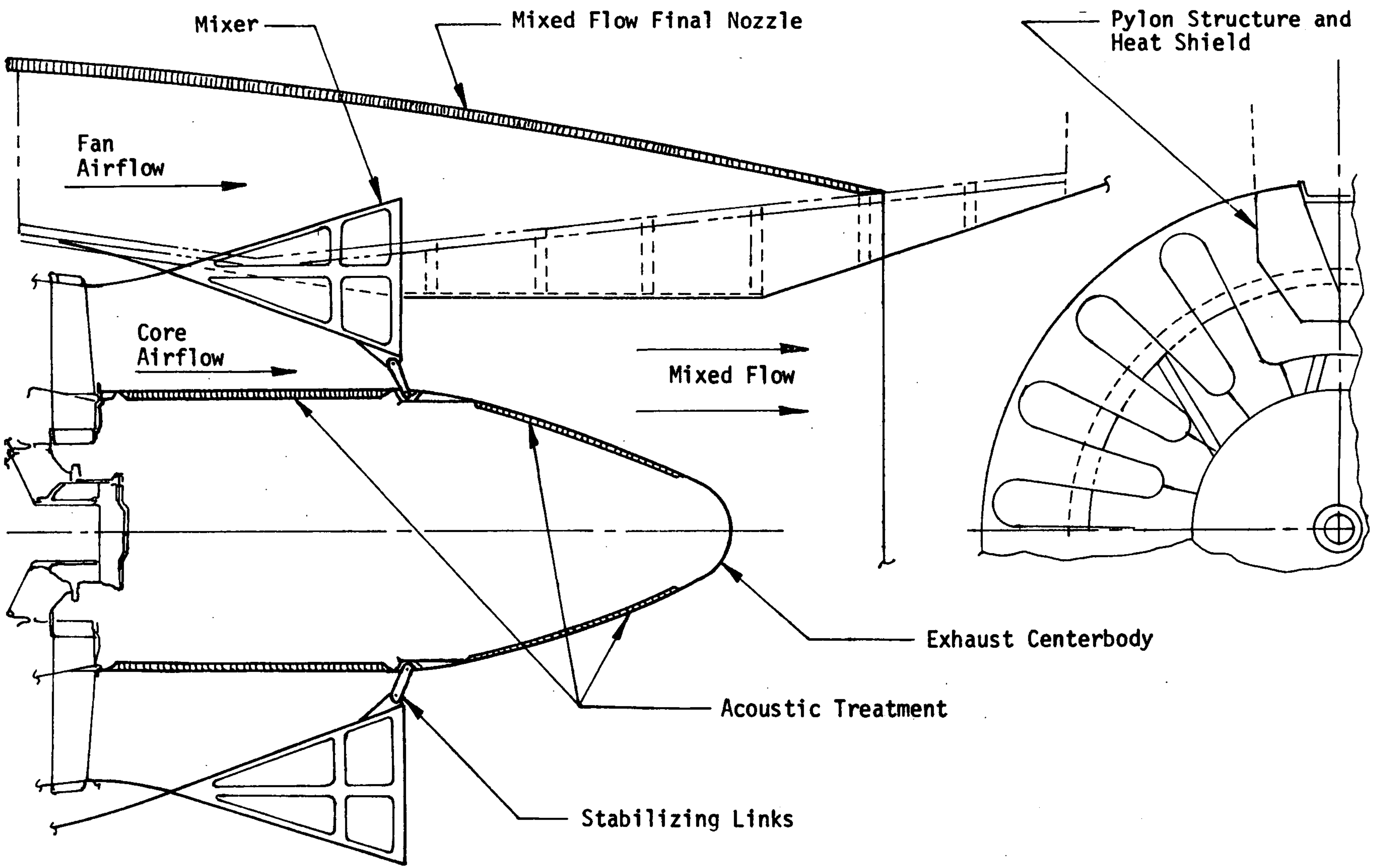


FIGURE 26. SELECTED MIXER CONFIGURATION FOR LONG-DUCT NACELLE

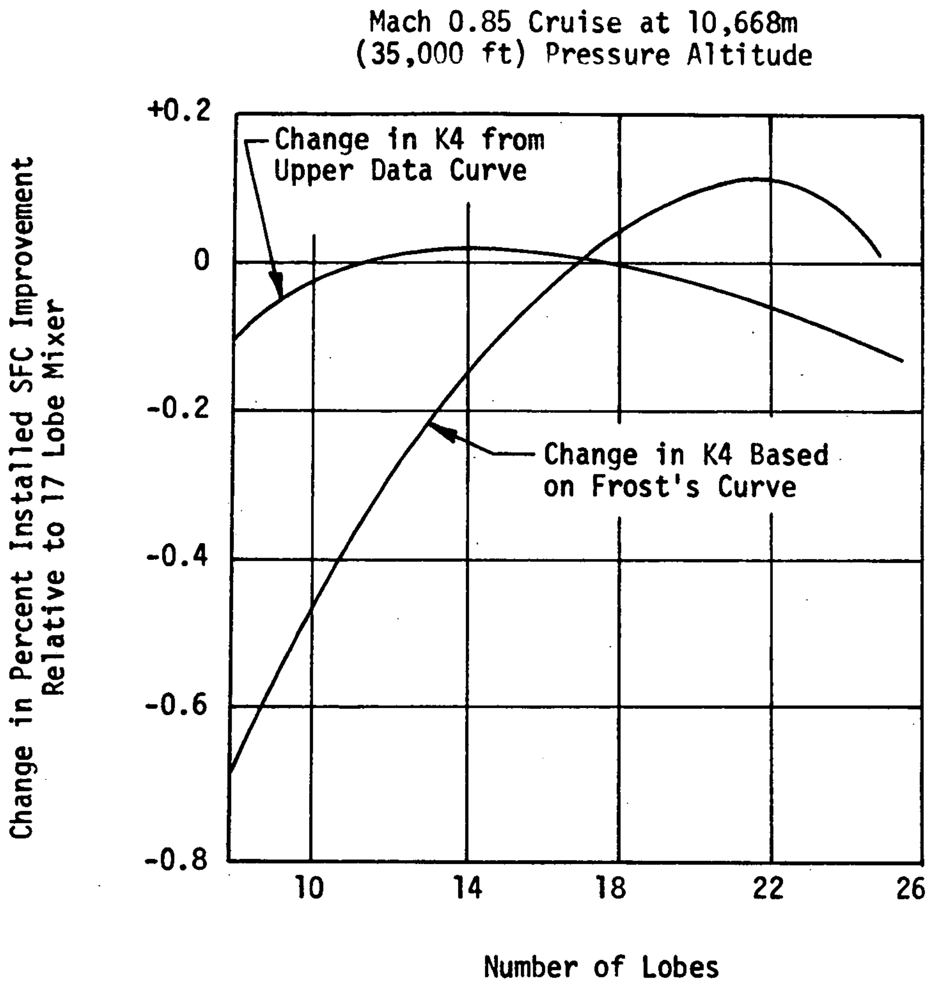


FIGURE 27. EFFECT OF NUMBER OF MIXER LOBES ON INSTALLED PERFORMANCE OF LONG-DUCT NACELLE

either epoxy or polyimide resin systems. Limitation of the WBT studies to just these materials was based on the desire to minimize material development risks consistent with a potential certification schedule, in the early 1980s.

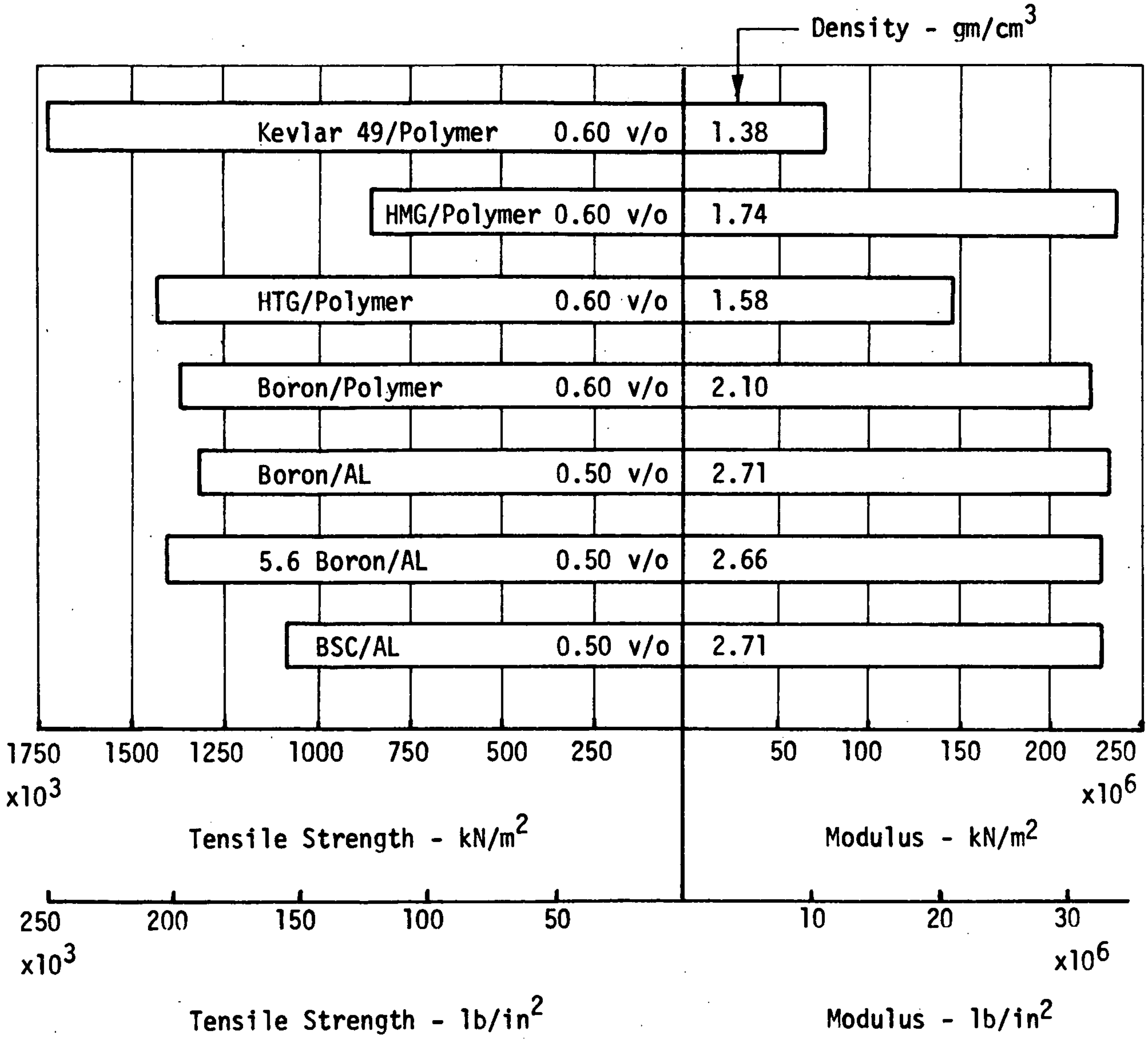


FIGURE 28. COMPARISON OF ADVANCED MATERIALS ABSOLUTE STRENGTH AND MODULUS

TABLE 3. - WIDE-BODY TRANSPORT ADVANCED MATERIALS

MATERIAL	USE	USEFUL MAXIMUM TEMPERATURE
RESINS:		
EPOXY	LOW-COST MATRIX	450°K (350°F) FOR 1000 HOURS 422°K (300°F) FOR 50,000 HOURS
POLYIMIDE	ACCEPTABLE COST MATRIX FOR SLIGHTLY ELEVATED TEMPERATURES THICKNESS LIMITED TO 1/2-IN. DUE TO OUTGASSING	533°K (500°F) FOR 20,000 HOURS 477°K (400°F) FOR UNLIMITED LIFE
FIBERS:		
GLASS	LOW-COST AND GOOD STRENGTH TO WEIGHT	700°K (800°F) FOR 1,000 HOURS 589°K (600°F) FOR 50,000 HOURS
GRAPHITE	HIGH STRENGTH AND STIFFNESS TO WEIGHT - LOW IMPACT	589°K (600°F) FOR 50,000 HOURS
KEVLAR 49	HIGH TENSILE STRENGTH. NOT RECOMMENDED FOR COMPRESSION. HIGH IMPACT STRENGTH	477°K (400°F) FOR 1,000 HOURS 422°K (300°F) FOR 50,000 HOURS

Hybrid combinations of existing materials, especially graphite and Kevlar, received special emphasis because of the potential of these types of material combinations to offer better than the average of each material's characteristics, and thus the potential for further weight and cost reduction. For example, based on data from Reference 8, in an application requiring the impact energy absorbing characteristics of Kevlar 49, while simultaneously requiring the compressive ultimate strengths of graphite, a hybrid of 25% Kevlar and 75% graphite provided a good combination of material properties (see Table 4). Since Kevlar is also less costly and lighter than graphite, the hybrid material provided the potential for lower cost and lighter-weight products.

TABLE 4. CHARACTERISTICS OF HYBRID UNIDIRECTIONAL COMPOSITES

	ULTIMATE TENSILE STRENGTH KN/m² (lb/in²)	ULTIMATE COMPRESSION STRENGTH kN/m² (lb/in²)	IMPACT STRENGTH Joule (ft-lb)
GRAPHITE/EPOXY	124,100 (180,000)	124,100 (180,000)	37.7 (27.8)
KEVLAR/EPOXY	137,900 (200,000)	27,580 (40,000)	123.9 (91.4)
HYBRID/EPOXY (75% GRAPHITE 25% KEVLAR)	127,500 (185,000	99,975 (145,000)	74.2 (54.7)
% INCREASE OF HYBRID RELATIVE TO GRAPHITE	+2.7	-20%	+96%

5.7 WBT Constructions

A wide variety of potential construction arrangements were investigated in some detail in the WBT studies, and to a lesser extent, in the ATT activities. These investigations involved five basic types of sandwich or laminate constructions, as shown in Figure 29, each with its own advantages and disadvantages and each most applicable to a given area of the nacelle or given nacelle function. In some cases, the construction was more amenable to certain materials than others. For instance, requirements such as fire containment dictated a sandwich type of construction and required protection of graphite from erosion and the retention of sufficient strength to carry pressure loads with some of the resin burned out. It should be emphasized that this study was not merely a parametric study of middle-of-the-panel designs but rather, a study of semi-detailed designs of a total part, including end fittings, closeouts, cutouts, etc. The decision on construction type and material application was based on the requirements of the particular part.

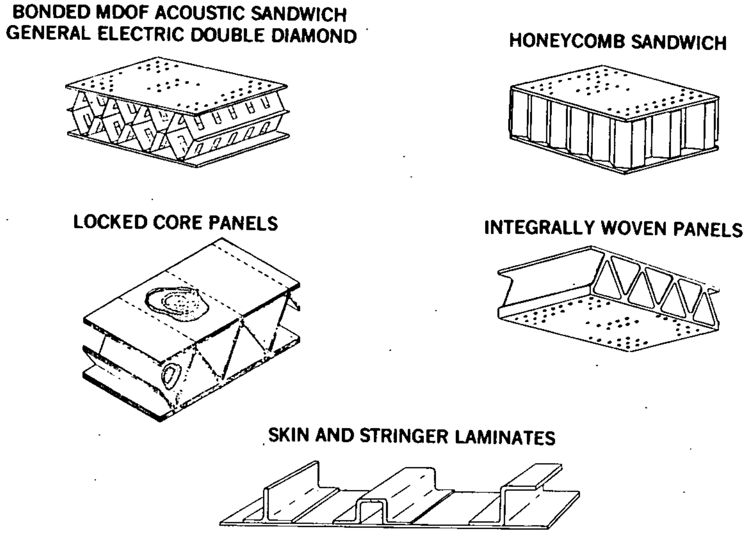


FIGURE 29. TYPICAL CONSTRUCTION ARRANGEMENTS EVALUATED

5.8 Composite Structure Designs - WBT

As noted earlier, the basic WBT nacelle concepts were formulated with the goal of maximizing commonality of parts to fullest extent. In that regard, the same nose cowl aerodynamic contours were used for all five nacelles, so that only one basic composite nose cowl design had to be generated. The same was true of the fan cowl door, although left and right hand parts are required. For the long duct nacelles, the aft fan ducts and core cowl doors used the same parts for the left and right hand sides. As a result only five basic drawings were required; one for the nose cowl; and one each for the fan cowl door, aft fan ducts, inner core cowl and fan reverser. To ensure complete coverage of all major nacelle components, one additional drawing of a metal final nozzle was developed. The all metal internal mixer design was evolved during this study from a concept that had been developed by GE as part of other related activities prior to the start of this contracted effort.

5.7.1 Composite WBT Nose Cowl - As shown in Figure 30, two basic composite nose cowls were designed in this study which differ only in the inner barrel arrangement. Configuration A, shown on sheet 2 in Section E-E, represented the more extensive use of composites, featuring a graphite attach ring with steel inserts co-cured with the multiple-degree-of-freedom acoustic inner barrel. The three-segment outer barrel consisted of seven plies of Kevlar 49 in a Style 285 weave and co-cured, 22-ply graphite stiffeners. This configuration was evolved from a strength/stiffness trade study summarized in Figure 31. The acoustic inner barrel structure on Configuration A was basically a hybrid graphite and Kevlar truss web design with a porous face of four or five plies of open-weave material containing 75% Thornel 300 graphite and 25% Kevlar 49 per ply impregnated by a controlled-flow polyimide resin. The core was comprised of two plies of the same material that could be either laid-up over mandrels and co-cured or fabricated by either the integral weaving or lock core techniques, depending on the outcome of more specific cost trade studies made at the time of final design. The back face was five plies of T-300 graphite/polyimide. The entire inner barrel would be made up of three segments which would be subsequently bonded or mechanically attached together to form the complete part. A hi-silica glass cloth, glass honeycomb fire barrier was employed in that area of the nose cowl inner barrel which projects into the nacelle fire zone. While there is some analytical and empirical basis for showing this type of fire shield design, it by no means represents a firm final design and a significant amount of technology development work in the area of fire burnthrough resistance remains to be done before a certifiable design is developed for these advanced acoustic-composite structures.

The co-cured graphite flange would be comprised of 28 to 72 plies oriented as required to distribute the high loads carried through this important joint. Steel inserts were used for the attach bolt holes and a rub-strip was employed at the interface with the attach flange on the engine.

The existing metal double-wall anti-ice inlet lip was retained in both nose cowl Configurations A and B, as shown in Sections A-A and E-E of Figure 30. To prevent exposure of the composites to possibly damaging high temperature air, a collector bulkhead was added and anti-ice discharge

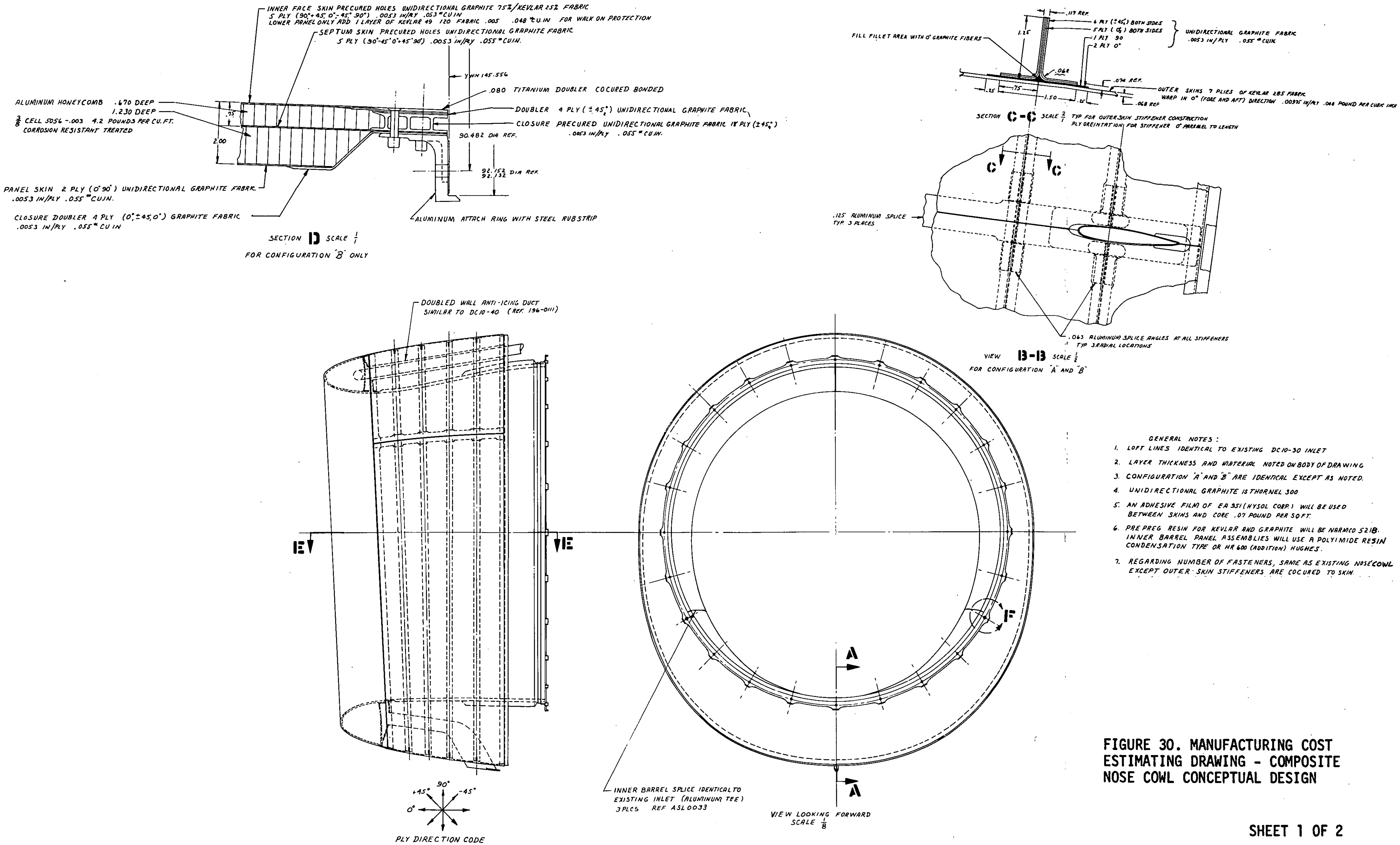
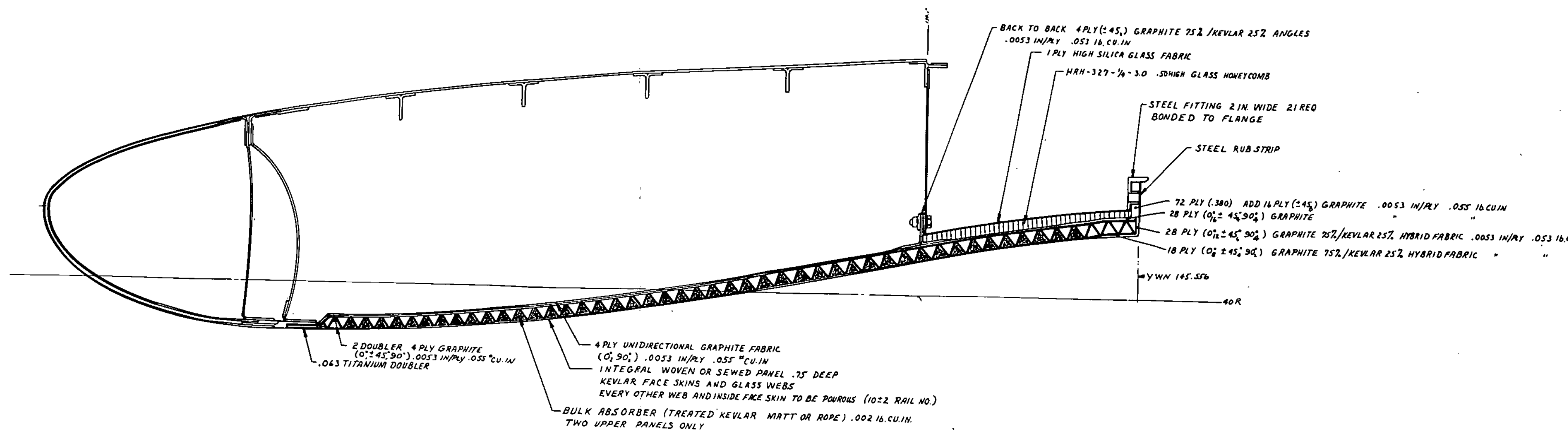
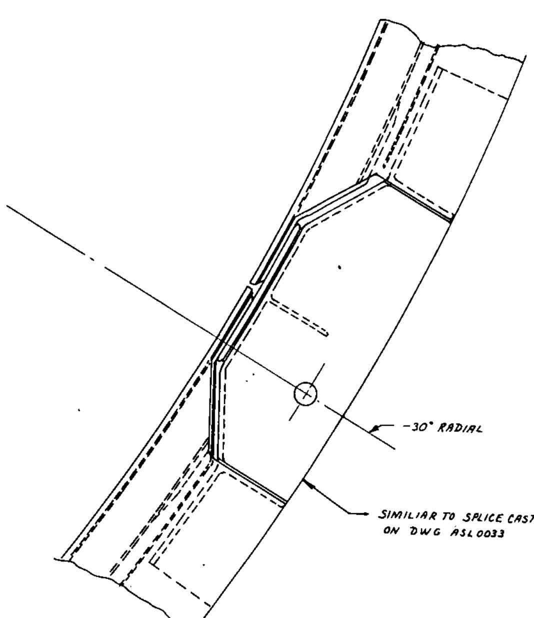


FIGURE 30. MANUFACTURING COST ESTIMATING DRAWING - COMPOSITE NOSE COWL CONCEPTUAL DESIGN

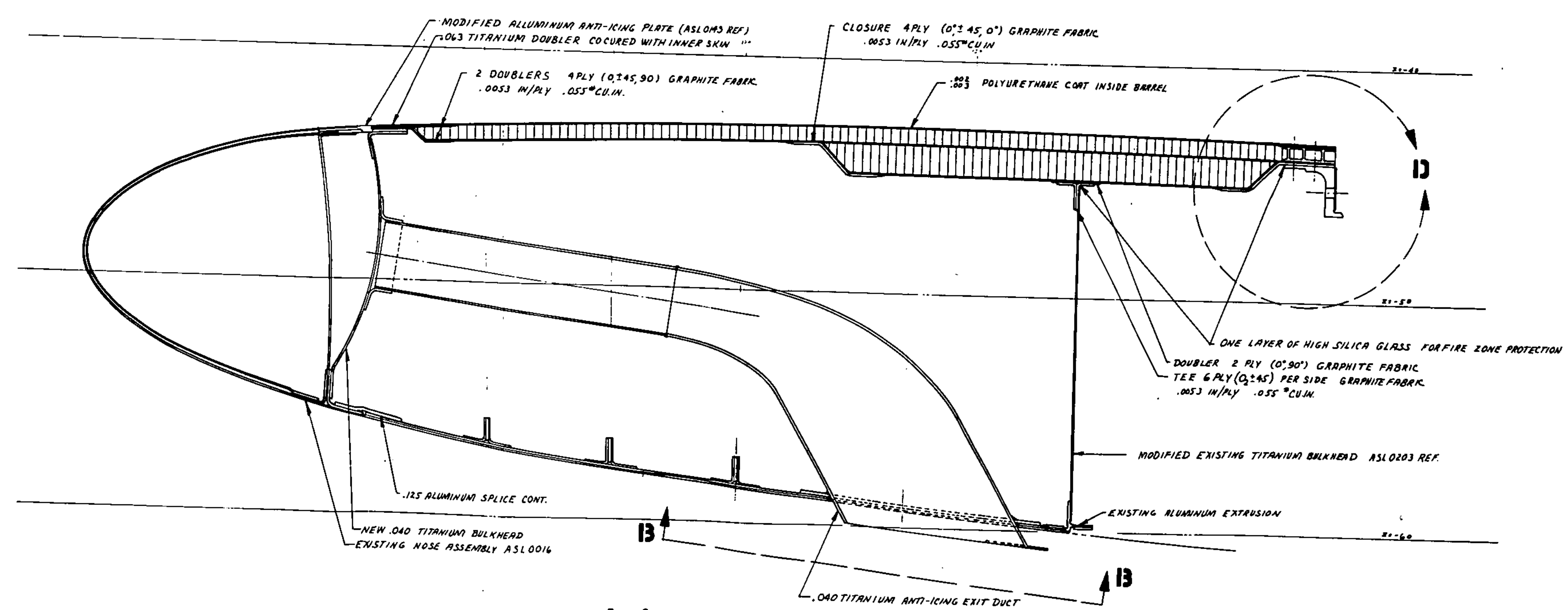
SHEET 1 OF 2



SECTION E-E SCALE 1/2
FOR CONFIGURATION "A" ONLY



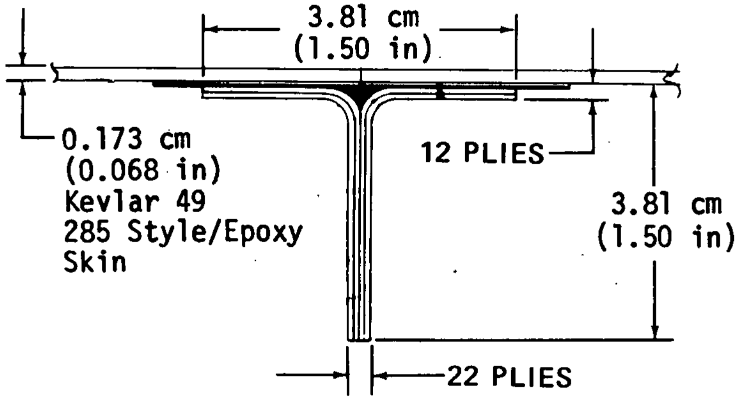
VIEW F SCALE 1/1
FOR CONFIGURATION "A" ONLY
TYPICAL FLANGE SPLICE



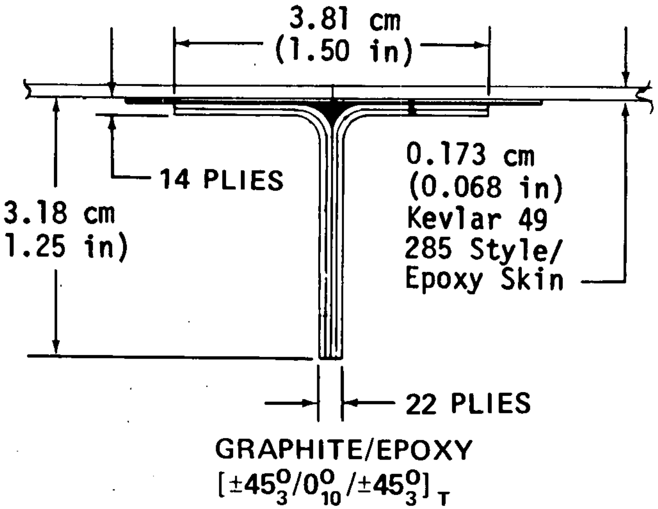
SECTION A-A SCALE 1/2
FOR CONFIGURATION "A" AND "B" EXCEPT
INNER BARREL CONSTRUCTION FOR "B" ONLY

FIGURE 30. MANUFACTURING COST ESTIMATING DRAWING - COMPOSITE NOSE COWL CONCEPTUAL DESIGN

SHEET 2 OF 2



CONFIGURATION X



CONFIGURATION Z

Structural Weight Comparison:

Configuration	$A_{(KEV/E)}$ cm^2 (in^2)	$A_{(G/E)}$ cm^2 (in^2)	$A_{(AL)}$ cm^2 (in^2)	Weight kg/cm (lb/in)	% Weight Saving
X (All Kevlar)	6.187 (0.959)	0	--	0.0085 (0.048)	21
Z (Kevlar Skin and G/E Stiffener)	3.181 (0.493)	1.605 (0.2487)	--	0.0067 (0.038)	37.5
Baseline (Aluminum)	--	--	3.923 (0.608)	0.0108 (0.0608)	--

FIGURE 31. EVALUATION OF COMPOSITE NOSE COWL OUTER BARREL STIFFENED SKIN CONFIGURATIONS

would be ducted overboard through a standoff, low-drag mast. The anti-ice supply air was routed to the leading edge section through a double-wall duct.

Configuration B differed from A primarily in the design of the acoustic inner barrel. The linings were considered to consist of perforated hybrid graphite/Kevlar facesheets bonded to aluminum honeycomb core. The facesheets would be either precured with perforated holes or co-cured with perforations or possibly co-cured and mechanically perforated after curing. The attach flange was also different, incorporating a continuous aluminum ring with steel shear fitting inserts. This flange arrangement would enhance electric current transfer in the event of a lightning strike on the inlet.

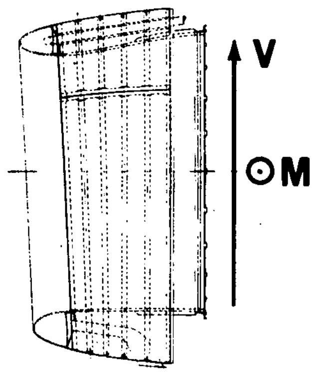
Configuration A was estimated to weigh 222 kg (491 lb) and B was estimated at 230 kg (507 lb). A tabulation of the weight breakdown for both configurations is shown in Table 5 along with the baseline metal design.

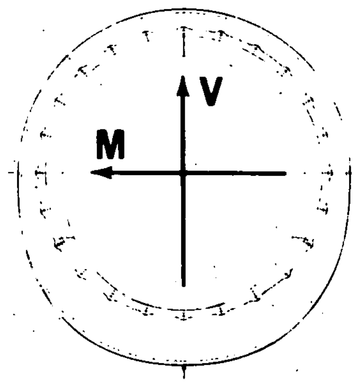
TABLE 5. - NOSE COWL WEIGHT BREAKDOWN

	CONFIG. A		BASELINE		CONFIG. B	
INNER BARREL	47.6	(105)	58.9	(130)	52.1	(115)
OUTER BARREL	32.2	(71)	51.2	(113)	32.2	(71)
NOSE LIP	79.7	(176)	79.7	(176)	79.7	(176)
FIRE SHIELD	1.4	(3)	5.0	(11)	1.4	(3)
BULKHEAD, AFT	23.6	(52)	23.6	(52)	23.6	(52)
BULKHEAD, FORWARD	17.7	(39)	17.7	(39)	17.7	(39)
ANTI-ICE EXHAUST DUCT	1.8	(4)	-	-	1.8	(4)
SHROUD	1.4	(3)	-	-	1.4	(3)
ENGINE ATTACH	17.2	(38)	35.3	(78)	19.9	(44)
TOTAL	222.4 kg	(491 lb)	271.3 kg	(599 lb)	220.7 kg	(507 lb)

Aside from the structural loads indicated in Figures 31 and 32, special design considerations included accommodation for handling and maintenance-related abuse to the skin panels of the lower inner barrel segment by providing an extra ply of Kevlar. The aluminum bonded honeycomb panels used in current inlets accommodate this abuse with a face sheet gauge thicker at the bottom than on the sides and top [.081cm (.032 in) thick vs .064 cm (.025 in)]. Another consideration was the use of unbalanced skin laminates shown in Configuration B of Figure 30, where five-ply skins provide a "balanced" panel using the center of the panel as the neutral plane. The result was a saving of three plies per skin and a significant weight and cost saving. This concept essentially indicated a co-cured fabrication process, since precured skins could be expected to be too badly warped to permit practicable fitup.

5.8.2 Fan Cowl Door - The fan cowl door shown in Figure 33 is basically a sandwich construction consisting of a two-ply outer skin of Kevlar 49, Style 285, a core of 49.65 kg/m^3 (3.1 lb/ft^3) aluminum honeycomb with a 0.476 cm (3/16th in) cell size, and an inner face of four plies of T300 graphite and one ply of high-silica glass cloth. The entire panel was envisioned as a co-cured sandwich using fire-retardant epoxy resin system. An aluminum door frame and latches and hinges identical to those used in the existing bonded aluminum honeycomb door were employed, both providing an adequate electric current path in the event of a lightning strike. The application of composite hinge and latch fittings represented an area of technology that was beyond the scope of this study. Since this door encloses the accessory area of the nacelle it must also function as a fire barrier. This requirement meant that the door be capable of withstanding a 15-minute exposure to a 1367°K (2000°F) flame without failure or penetration by the flame. The general requirements of nacelle fire protection and some of the tests that were conducted to ascertain the capability of advanced composites with non-metallic matrices to function as fire barriers are discussed in Section 5.11. As can be seen from the figure, the fan cowl door contains a large number of small servicing access doors and cooling inlet and exit cutouts. It also contains a pressure relief door which is set to relieve at a differential pressure of





V = 498,200 N (112,000 lb)

M = 384,000 Joule (283,300 ft-lb)

	Pressure N/m^2 (psi)	Temperature °K (°F)
Inner Barrel	53,780 (7.80)	450 (350)
Outer Barrel	10,340 (1.50)	394 (250)

	Tension N (lb)	Shear N (lb)
Max Attach Bolt Loads	35,140 (7,900)	16,115 (3,623)

FIGURE 32. SUMMARY OF NOSE COWL DESIGN LOADS

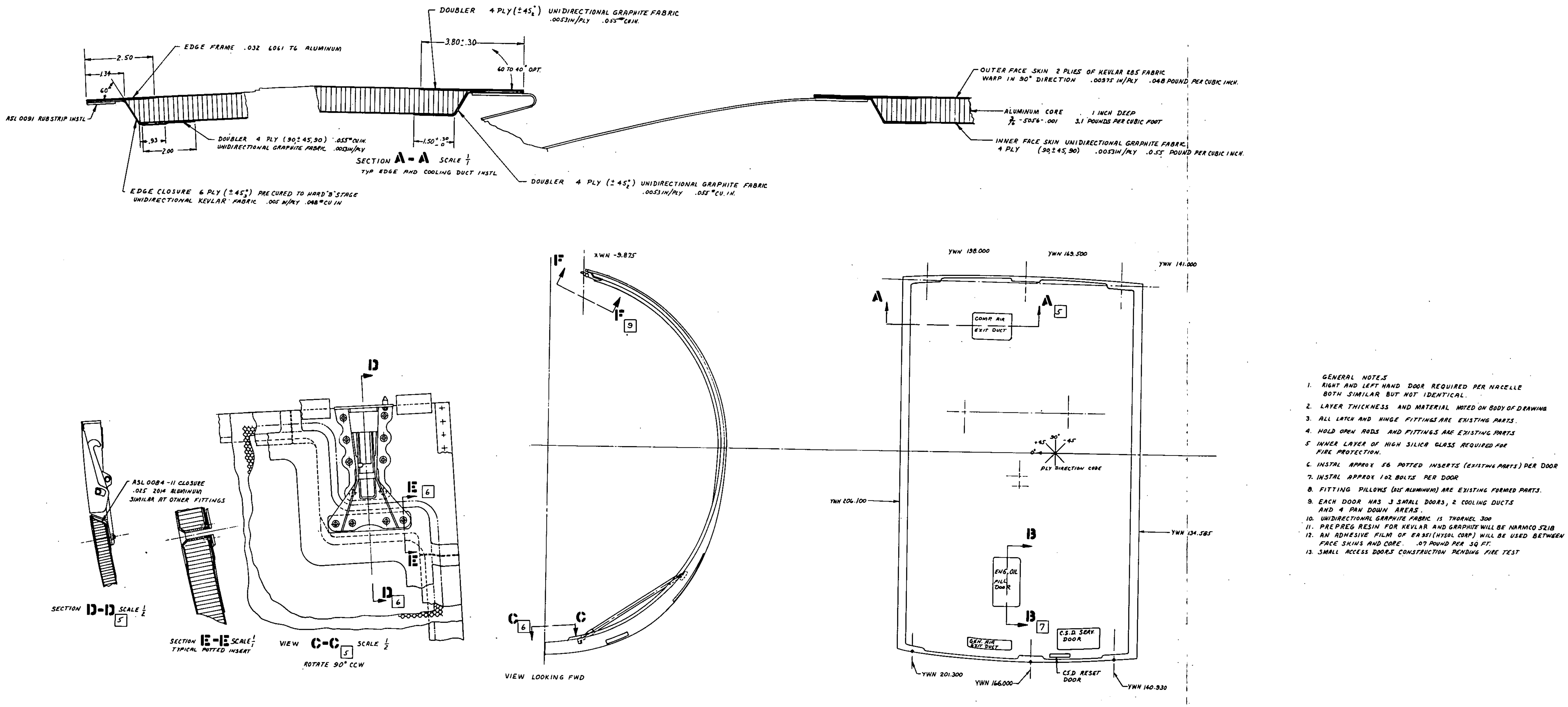


FIGURE 33. MANUFACTURING COST ESTIMATING DRAWING - COMPOSITE FAN COWL DOOR CONCEPTUAL DESIGN

SHEET 1 OF 2

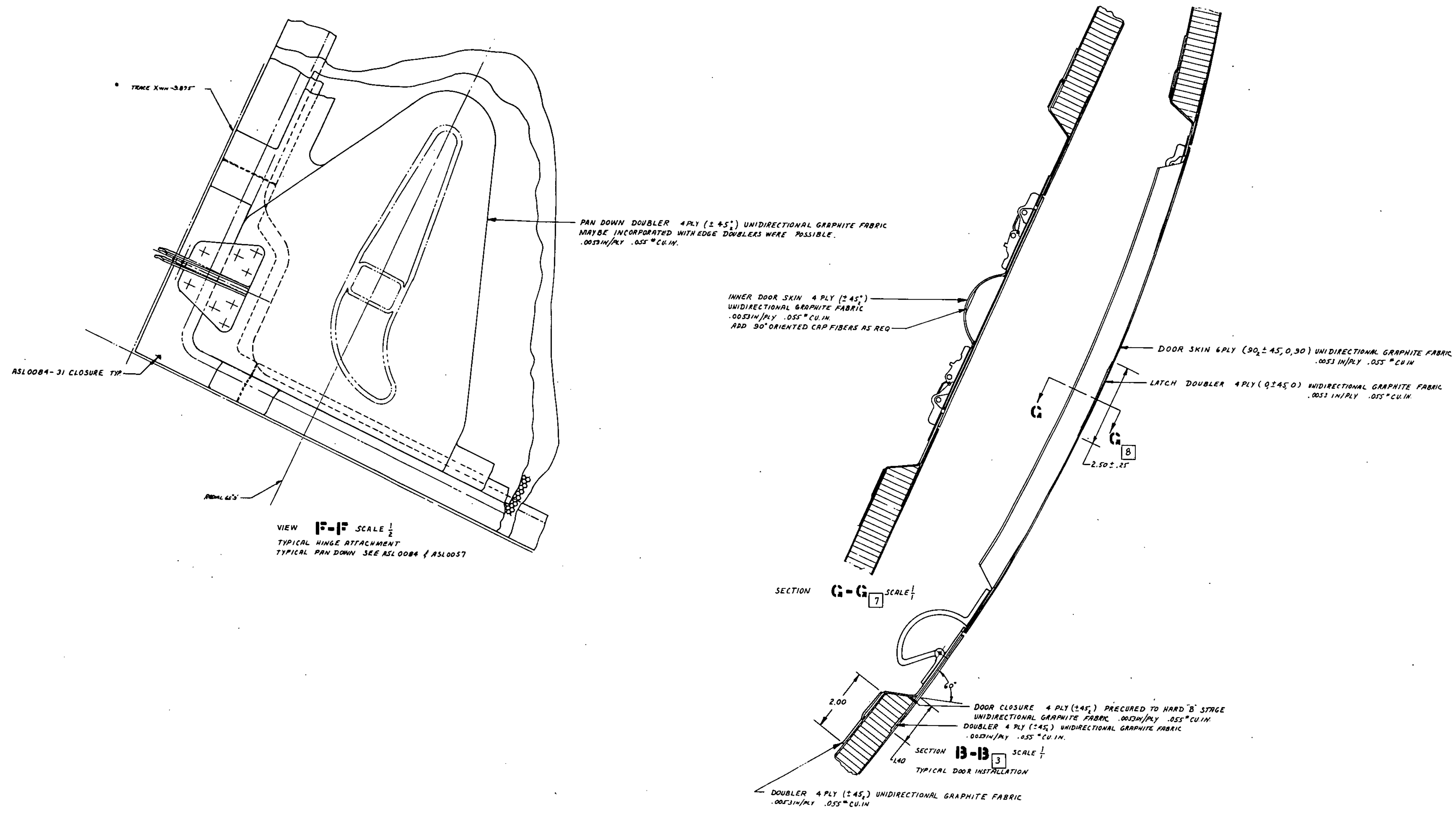


FIGURE 33. MANUFACTURING COST ESTIMATING DRAWING - COMPOSITE FAN COWL DOOR CONCEPTUAL DESIGN

SHEET 2 OF 2

approximately 13,790 N/m^2 (2 psi). The primary design load condition for the fan cowl door was a differential pressure of 41,369 N/m^2 (6 psi) in the event of a burst pneumatic duct.

Application of Kevlar 49 Style 285 fabric for the outer face was based on providing good impact characteristics required for this surface of the nacelle which is subject to damage when routine maintenance functions are performed. Two plies of this thick fabric were used to provide protection for the honeycomb core.

The total weight of a pair of composite fan cowl doors was estimated at 99 kg (218 lb). The weight breakdown given in Table 6 shows that a weight savings of approximately 36 kg (80 pounds) per nacelle, [109 kg (240 lb) per airplane for the 3-engine WBT] would be realized. The tail installation fan cowl doors differed slightly in external shape from the wing engine doors but otherwise were identical.

TABLE 6. - FAN COWL DOOR WEIGHT BREAKDOWN

	COMPOSITE		BASELINE	
DOOR PANEL	25.14	(55.50)	40.43	(89.25)
CLOSURES AND DOUBLERS	3.51	(7.75)	7.00	(15.45)
ACCESS DOORS	2.42	(5.35)	2.08	(4.60)
LANDINGS	2.27	(5.00)	2.22	(4.90)
SHIMS	.45	(1.00)	.45	(1.00)
OUTLETS	3.85	(8.50)	3.85	(8.50)
HINGES, LATCHES, ETC.	4.17	(9.20)	4.17	(9.20)
FIRESHIELD	3.94	(8.70)	3.67	(8.10)
ATTACHMENTS & HOLD OPEN RODS	3.62	(8.00)	3.62	(8.00)
	49.38 kg	(109.00 lb)	67.60 kg	(149.00 lb)

5.8.3 Composite Fan Reverser - Figure 34 shows a composite fan reverser concept that was developed during this study. The figure depicts an exploded view of the various major pieces and assemblies that make up the fan reverser assembly. In addition, two representative cross sections are shown to indicate the construction in two or three key areas of the reverser. This reverser assembly would consist primarily of honeycomb construction for the flow passage walls where acoustic treatment is required. The design concept includes hybrids of graphite, Kevlar, aluminum honeycomb core, and some application of high-silica glass on glass honeycomb core where fire protection is required.

In many cases, such as for example the blocker door, these advanced composites replace bonded fiberglass components used in current WBTs. The fan exhaust passage surfaces comprising the core cowl were envisioned as composite structures with integral acoustic treatment utilizing a honeycomb construction. As shown in Section A-A the high-silica glass cloth and glass honeycomb were used in areas where fireproofing is a requirement. The high temperature environment made the use of polyimide matrix appropriate for these parts. For the outer walls of the annular passage where the thermal environment is moderate, an epoxy matrix was suitable.

The fan reverser concept is the same bifurcated arrangement used in the current all-metal reversers. The weight breakdown of the reverser is shown in Table 7. The total weight was estimated to be 649 kg (1433 lb). It was estimated that an additional 63 kg (140 lb) could be saved by eliminating the bifurcations in favor of circular, hoop-tension duct systems.

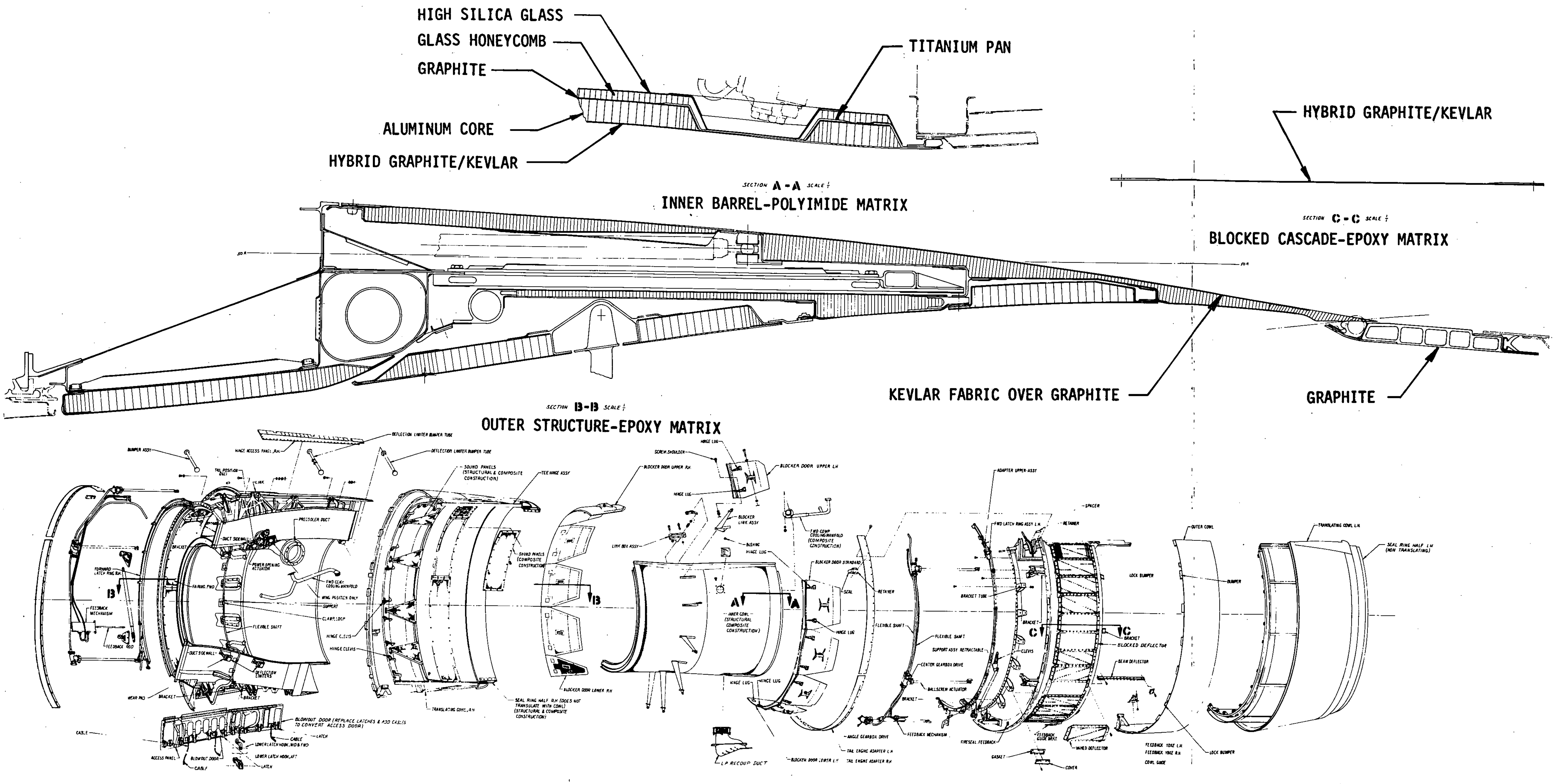


FIGURE 34. MANUFACTURING COST ESTIMATING DRAWING - COMPOSITE FAN THRUST REVERSER CONCEPTUAL DESIGN

TABLE 7. - FAN THRUST REVERSER WEIGHT BREAKDOWN

	NACELLE II		NACELLE IA & IB	
CONTROLS AND ACTUATION	56.63	(125)	71.12	(157)
INTERLOCK AND CONTROL KIT	13.59	(30)	17.21	(38)
TRANSLATING COWL	147.23	(325)	160.82	(355)
BIFURCATIONS (FIXED COWL)	303.51	(670)	339.75	(750)
DEFLECTOR ASSEMBLY	42.13	(93)	44.39	(98)
FORWARD LATCH	13.59	(30)	15.86	(35)
TOTAL	576.67 kg	(1273 lb)	649.15 kg	(1433 lb)

5.8.4 Core Cowl Door - Figure 35 shows the concept for the core cowl door for the long-duct mixed-flow nacelle. The door was of sandwich construction incorporating integral acoustic treatment on the outer flow path. The outer face skin was made from a hybrid of 75% graphite, and 25% Kevlar. The aluminum honeycomb core had a density of 67.27 kg/m^3 (4.2 lb/ft^3) and 0.95 cm (3/8-inch) cell size. The inner face skin would consist of four plies of uni-directional graphite fabric with a polyimide matrix. The assembly was backed with a standoff titanium heat shield to enable it to withstand the heat radiated from the engine case. A piano-hinge attachment and multiple latches were utilized to avoid concentration of loads in the composites. The thermal environment would dictate the use of a polyimide matrix resin system. Use of a polyimide resin would require additional fabrication process development for the face skins to insure that the cure temperatures for the selected polyimide would be compatible with the aluminum honeycomb core.

A pair of these doors was used in each nacelle and the weight of each pair was estimated at 62.52 kg (138 lb), as shown in the weight breakdown in Table 8.

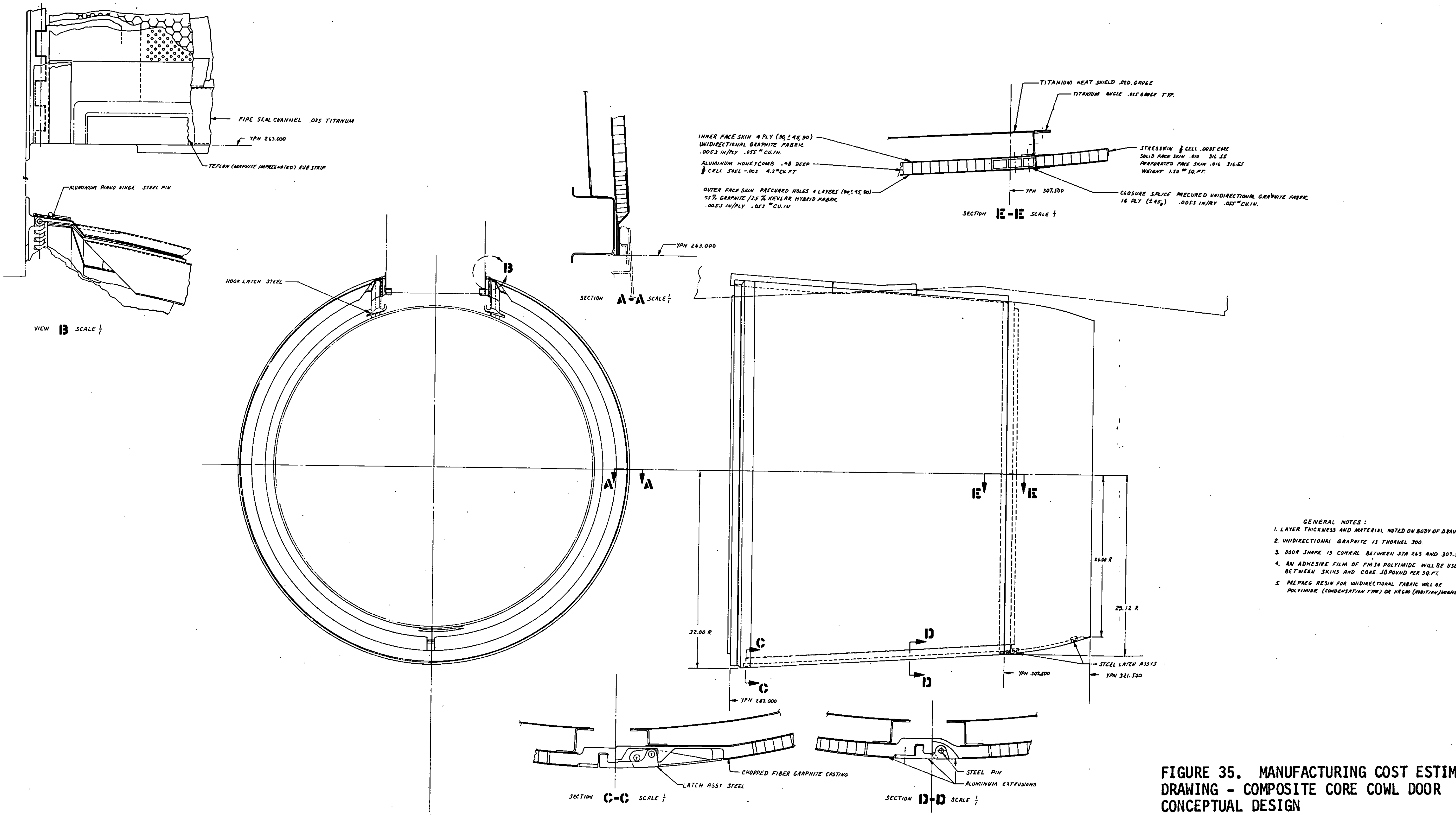


FIGURE 35. MANUFACTURING COST ESTIMATING DRAWING - COMPOSITE CORE COWL DOOR CONCEPTUAL DESIGN

TABLE 8. - CORE COWL WEIGHT BREAKDOWN

HYBRID SKIN PANELS	4.12	(9.10)
GRAPHITE SKIN PANELS	6.00	(13.25)
ALUMINUM HONEYCOMB CORE	4.26	(9.40)
ADHESIVE	5.07	(11.20)
TITANIUM	15.90	(35.10)
STRESSKIN	11.55	(25.50)
TEFLON	1.06	(2.35)
ALUMINUM	9.76	(21.55)
STEEL	2.83	(6.25)
RIVETS, NUTS AND BOLTS	1.95	(4.30)
TOTAL	62.51 kg	(138.00 lb) per nacelle

5.8.5 Aft Fan Duct - The concept of the composite aft fan duct is shown in Figure 36. This component is quite similar to the core cowl door, featuring honeycomb construction with hybrid skins of graphite and Kevlar and with aluminum [67.27 kg/m^3 (4.2 lb/ft^3)] core. However, since it is not exposed to high temperatures, an epoxy resin system was used in a co-cured fabrication process. Chopped fiberglass and graphite castings would be used to transfer loads from the latches to the sandwich panel. Total weight of this pair of ducts was estimated at 86.5 kg (191 lb) per nacelle.

The inner face skin (the one requiring acoustic porosity) would consist of four plies of hybrid 75%/25% graphite/Kevlar. The outer skin (the one exposed to the free stream around the nacelle) would also be fabricated of the same four plies of hybrid 75% graphite, 25% Kevlar material. In addition, this surface would be overlaid with one layer of Kevlar 120 style fabric to provide resistance to impact damage. The weight breakdown for this component, which was estimated at 86.5 kg (191 lb) per pair (nacelle), is given in Table 9.

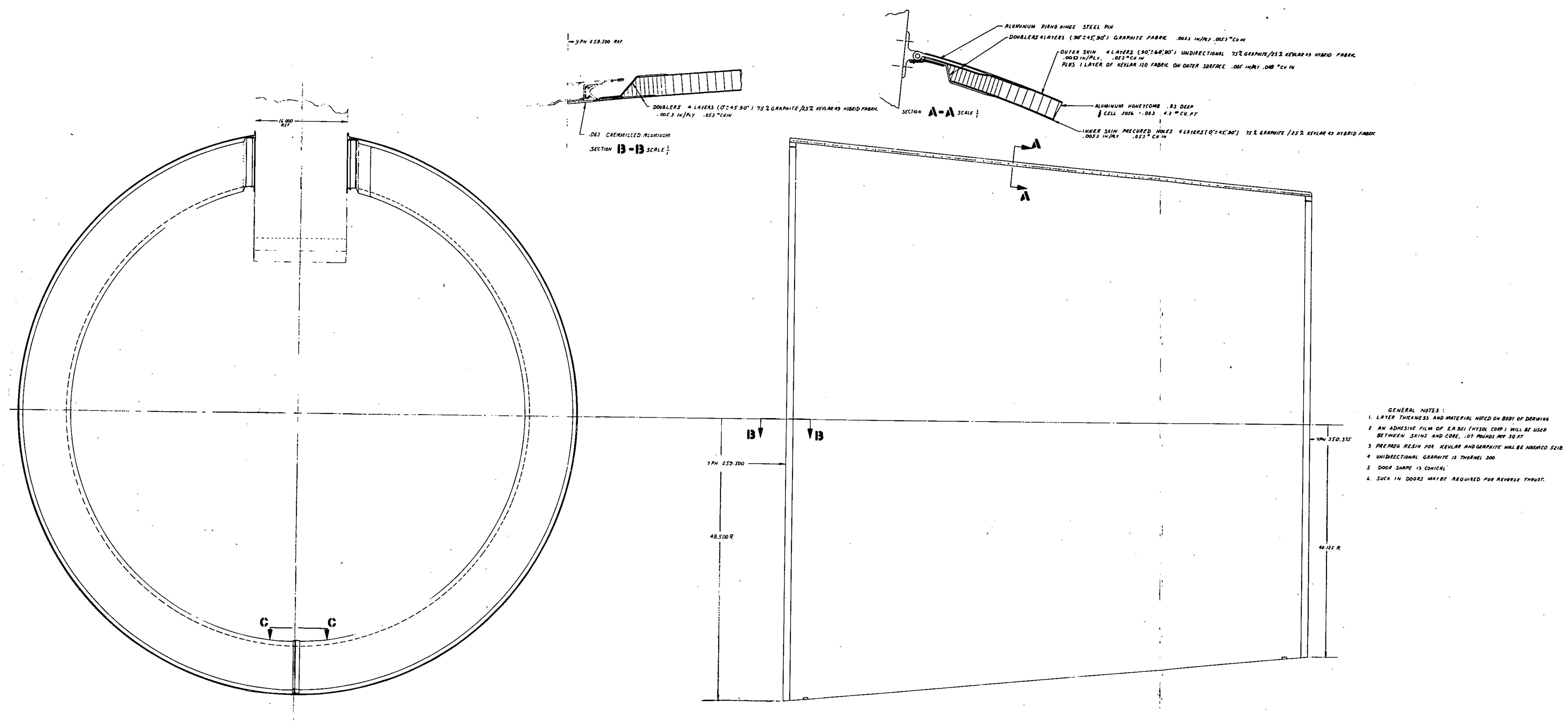


FIGURE 36. MANUFACTURING COST ESTIMATING DRAWING - COMPOSITE AFT FAN DUCT CONCEPTUAL DESIGN

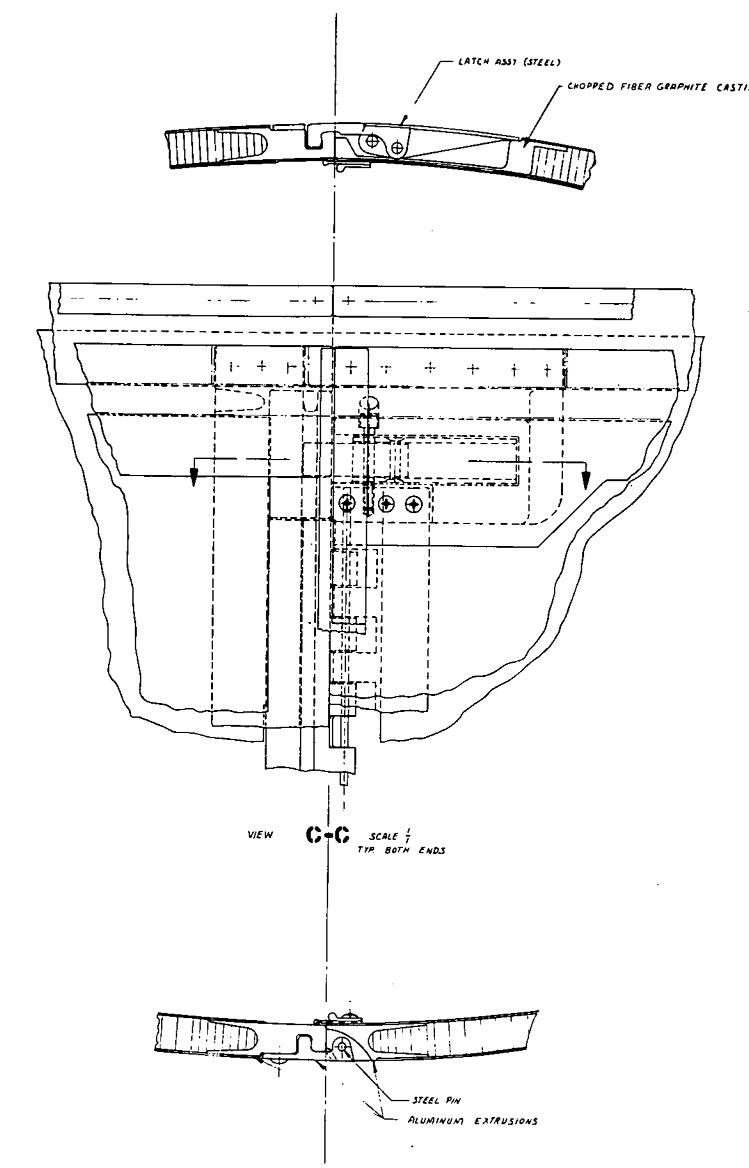


FIGURE 36. MANUFACTURING COST ESTIMATING DRAWING - COMPOSITE AFT FAN DUCT CONCEPTUAL DESIGN

SHEET 2 OF 2

TABLE 9. - AFT FAN DUCT WEIGHT BREAKDOWN

HYBRID SKIN PANELS	25.49	(56.26)
KEVLAR SKIN	2.30	(5.08)
GRAPHITE DOUBLERS	.79	(1.74)
ALUMINUM HONEYCOMB CORE	21.65	(47.80)
ADHESIVE	10.42	(23.00)
ALUMINUM	20.94	(46.23)
STEEL	2.33	(5.15)
GRAPHITE CASTING	.87	(1.92)
SEALS	.58	(1.28)
RIVETS, NUTS AND BOLTS	1.15	(2.54)
TOTAL	86.52 kg	(191.00 lb) per nacelle

5.8.6 Mixed Nozzle - The high temperature of the turbine exhaust ruled out application of composites for the mixed nozzle. Figure 37 shows a design concept for this part utilizing diffusion bonded titanium sandwich construction. The inner flow path incorporated acoustical treatment with linings designed to reduce turbine noise. Solid surfaces were used for the free-stream flow surfaces. In the event that diffusion bonded titanium proved unsuitable for the anticipated exhaust gas heating effects, stainless steel could be substituted at a modest weight increase. The estimated weight of the diffusion bonded titanium nozzle was 32 kg (71 lb). A comparable stainless steel part was estimated to weigh 49 kg (108 lb). The weight breakdown is given in Table 10.

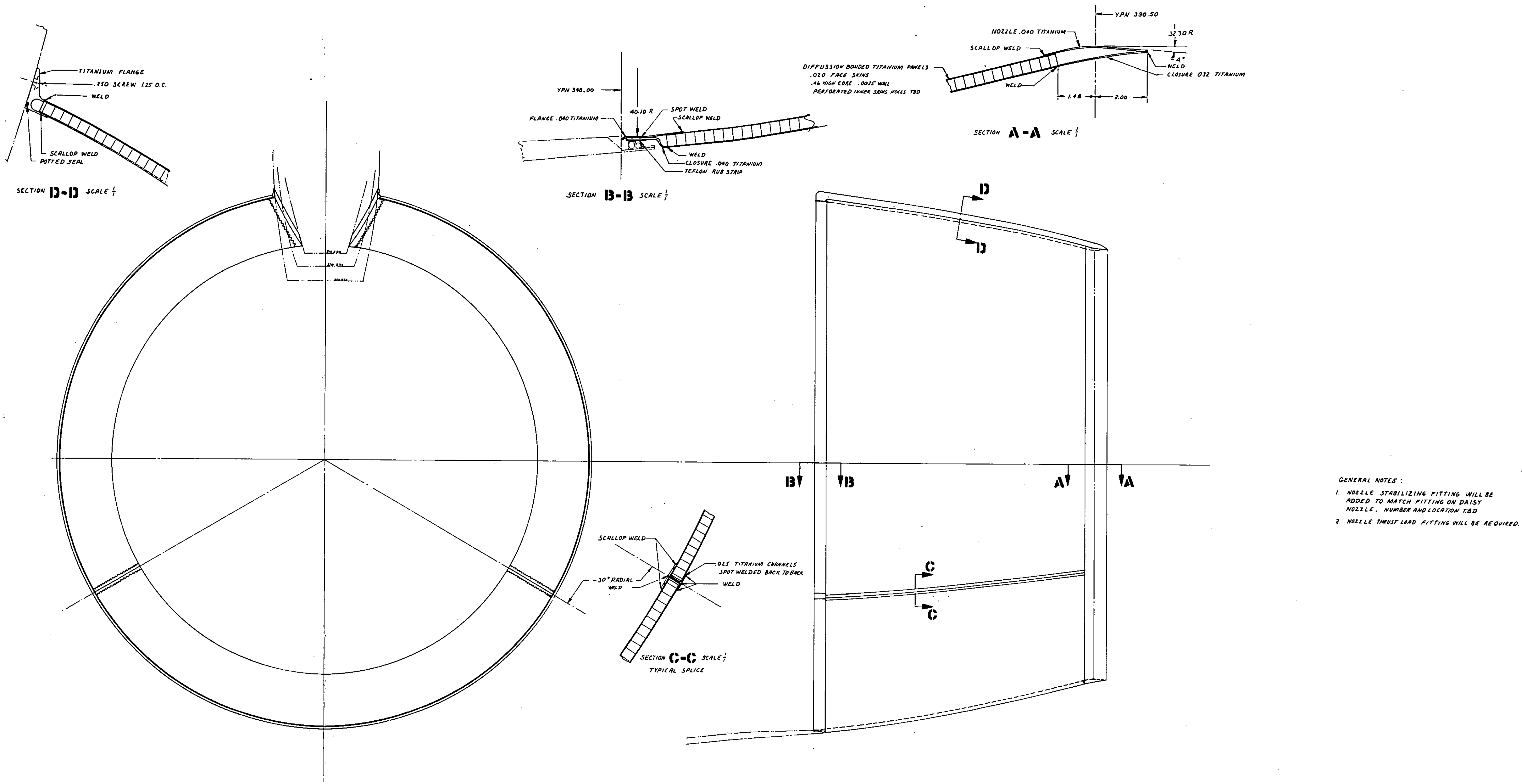


FIGURE 37. MANUFACTURING COST ESTIMATING DRAWING - MIXED NOZZLE CONCEPTUAL DESIGN

TABLE 10. - MIXED NOZZLE WEIGHT BREAKDOWN

TITANIUM PANELS	17.26	(38.1)
TITANIUM JOINT CHANNELS	.50	(1.1)
TITANIUM LEADING EDGE CLOSURE	1.49	(3.3)
TITANIUM FLANGE	1.86	(4.1)
TITANIUM NOZZLE TRAILING EDGE	4.44	(9.8)
TITANIUM UPPER FLANGES	4.76	(10.5)
TEFLON STRIP	.18	(0.4)
RIVETS, NUTS AND BOLTS	1.68	(3.7
TOTAL	32.16 kg	(71.0 lb) per nacelle

5.9 Special Requirements of the Tail Engine Installation

Among the many considerations that were accounted for in this study were the special requirements of the center engine position in the tail of the aircraft. In this installation the short nose cowl typical of wing engine installations shown in Figure 30, is replaced by a long inlet that is integral with the vertical stabilizer. Considerations that were taken into account in designing for the tail position, shown in Figure 38, included: the necessity for carefully tailoring aerodynamic flow paths to minimize interference drag between the tail engine nacelle, the aft fuselage and the vertical and horizontal stabilizers; accommodating the relative motion between the engine and the vertical stabilizer structure; and latching arrangements for the fan cowl access doors that differ from those on the wing engine. Also, the unique provisions made for maintenance and servicing access to the tail engine were accounted for.

5.10 Overall Design Constraints

A number of constraints were placed on this study in order to limit the scope of the program. Among these constraints were avoidance of any significant increases in total installation weight to prevent the possibility of wing flutter or the exceeding of pylon strength margins.

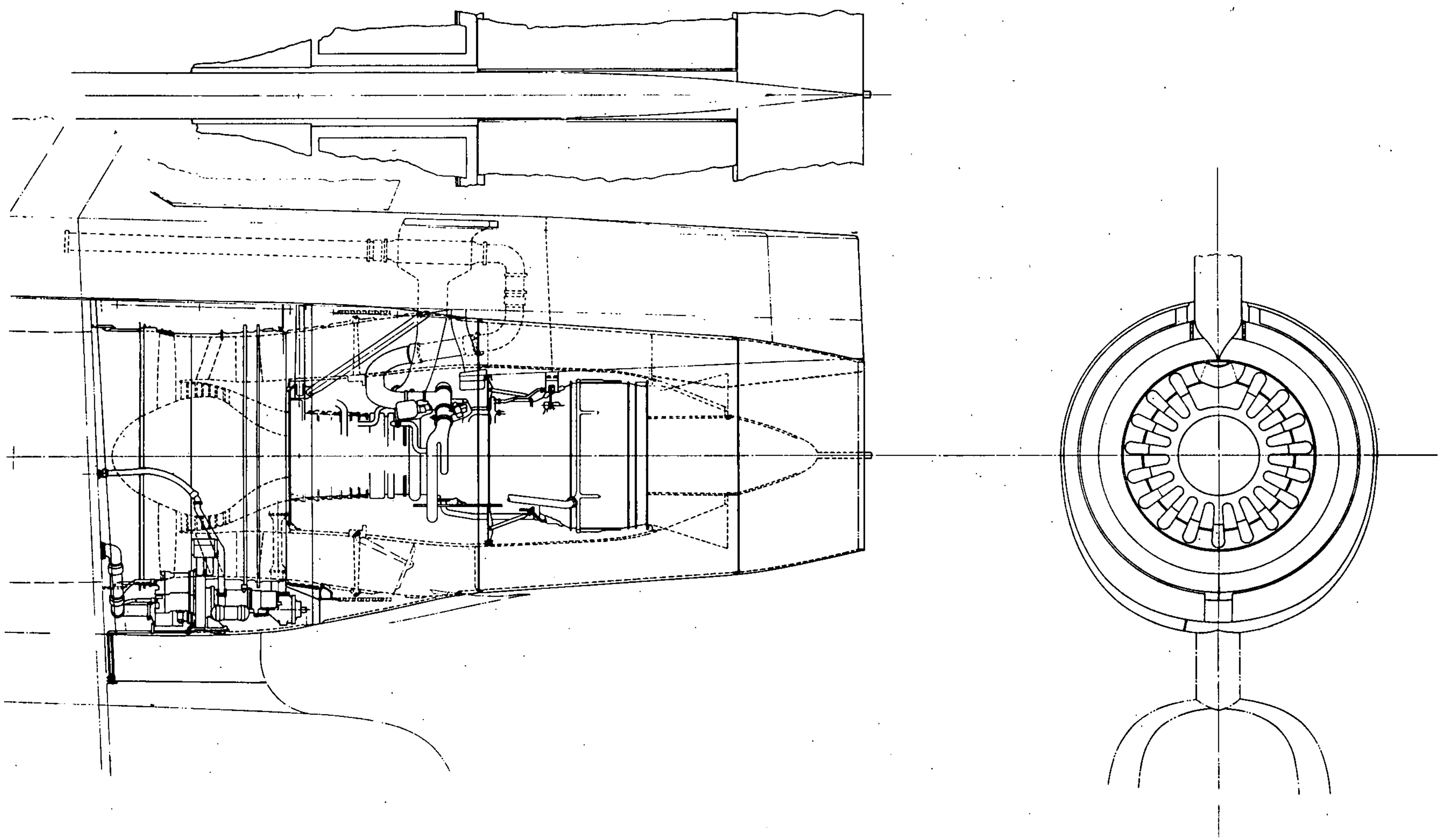


FIGURE 38. LONG DUCT NACELLE, TAIL ENGINE INSTALLATION

Another influence or constraint on the design was the limitation on wing engine inlet length. Because of the study baseline WBT forward cargo and baggage door locations, any substantial increase in inlet length would create a severe restriction in the loading envelope. In addition, a substantially longer inlet would represent a potential pylon flutter problem during the emergency descent flight condition due to the increased external flow area. A study of the noise reduction that might be realized by increasing the inlet length 1.02 m (40 inches) indicated that a 1 to 2 dB decrease in noise could be expected for a 90 kg (200 lb) per wing inlet increase. The application of bulk absorber materials within the current inlet space envelope limits appeared to offer approximately the same noise reduction at a lower weight penalty.

5.11 Fire Prevention and Containment Requirements

A key consideration in the design of an engine installation for a commercial transport aircraft is the prevention, containment and extinguishing of nacelle fires. The installation must provide for preventing fires from occurring and must provide for preventing fires spreading from one nacelle zone to another or from the nacelle into the airframe. With conventional metal construction used in current commercial transport aircraft nacelles, titanium or steel is used to provide the containment required. Figure 39 shows the nacelle fire zones.

In considering advanced composite materials for nacelle construction applications the fire containment requirements must be carefully considered. With metal structure, the weight and cost penalties related to fire containment are fairly minimal; however, if the advanced composites must be overlaid with metal to provide fire containment, the weight penalties may be significant.

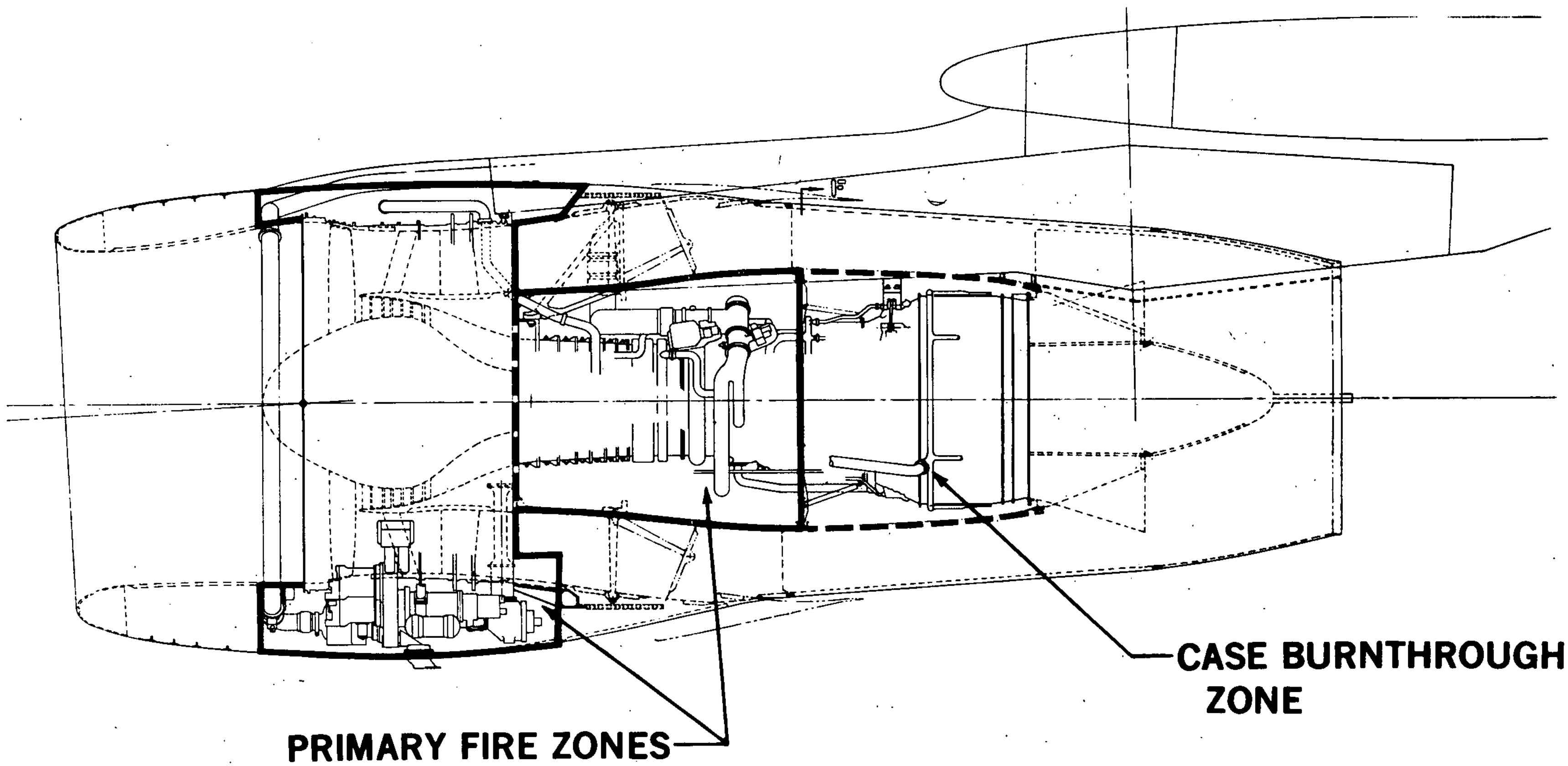


FIGURE 39. NACELLE FIRE ZONES

The problem of fire containment was specifically investigated in the present study for the fan cowl door design. For the CF6 engine installation this door encloses the accessory zone where many of the ignition sources and a variety of flammable liquids are located. It has been recognized for some time that high silica glass is an excellent insulation material both electrically and thermally, though it has limited strength. The basic design of the composite fan cowl door was a honeycomb construction with a graphite skin on the interior side (the one that would be exposed to fire). Graphite has excellent strength characteristics at elevated temperatures but is destroyed by an oxidizing flame. The concept shown in Figure 33 has four plies of graphite to meet the strength requirements of this door with an overlay of high-silica glass to prevent oxidation of the graphite. The certification requirement established by the FAA to demonstrate fire resistance is exposing the part to a 1367°K (2000°F) flame for 15 minutes. For fire barriers the requirement is that no burnthrough occur. To test the concept developed for the fan cowl door, a one-foot square, one-inch thick sample panel was built up. An oxygen acetylene torch was used to provide the flame, adjsuted for a 1367°K (2000°F) temperature at the face of the specimen. The test setup is shown in Figure 40.

Figure 41 shows the sample panel one minute after the start of the test. The epoxy resin system on the exposed face caught fire and continued to burn as long as the flame was applied or until all the epoxy resin in the area of the flame had burned out. An equilibrium condition was reached between 5 and 10 minutes after the start. Figure 42 shows the test article under stabilized conditions. Figure 43 shows the flame side and Figure 44 shows the back side of the test specimen at the conclusion of the test. The white center portion on the flame side (Figure 43) is the bare unimpregnated high silica glass. There were no discontinuities, tears or breaks at any point in the area of the flame impingement. As can be seen on the back side of the panel, Figure 44, the Kevlar skins that would form the flow side, or outside part of the fan cowl door, were not penetrated. Throughout the duration of the test, the back side of the test panel was never more than just warm to the touch. The wrinkling that occurred in the specimen took place primarily during the cooldown after the test. It was felt that this test adequately demonstrated the feasibility of

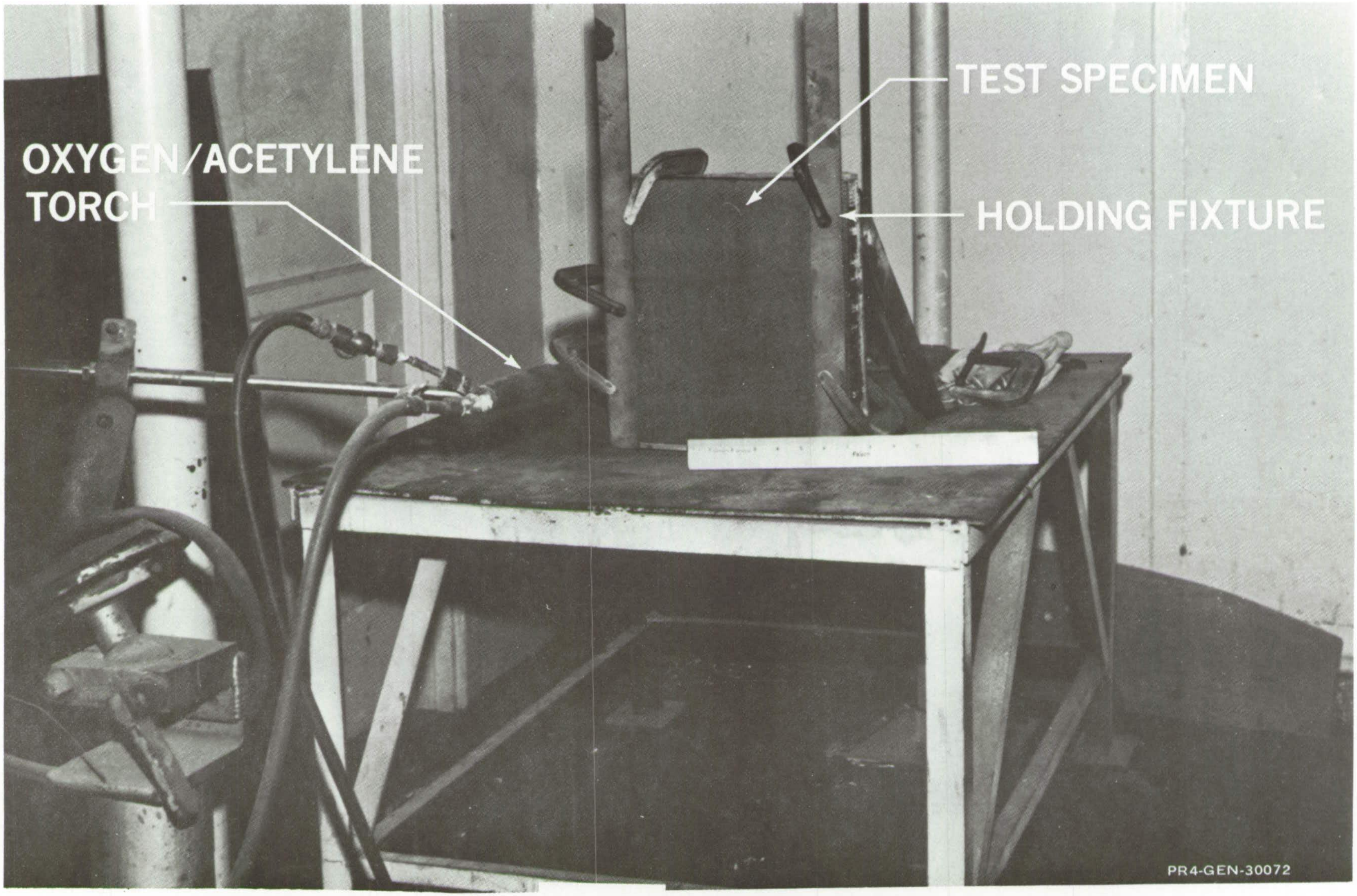


FIGURE 40. COMPOSITE PANEL FIRE RESISTANCE TEST SET-UP

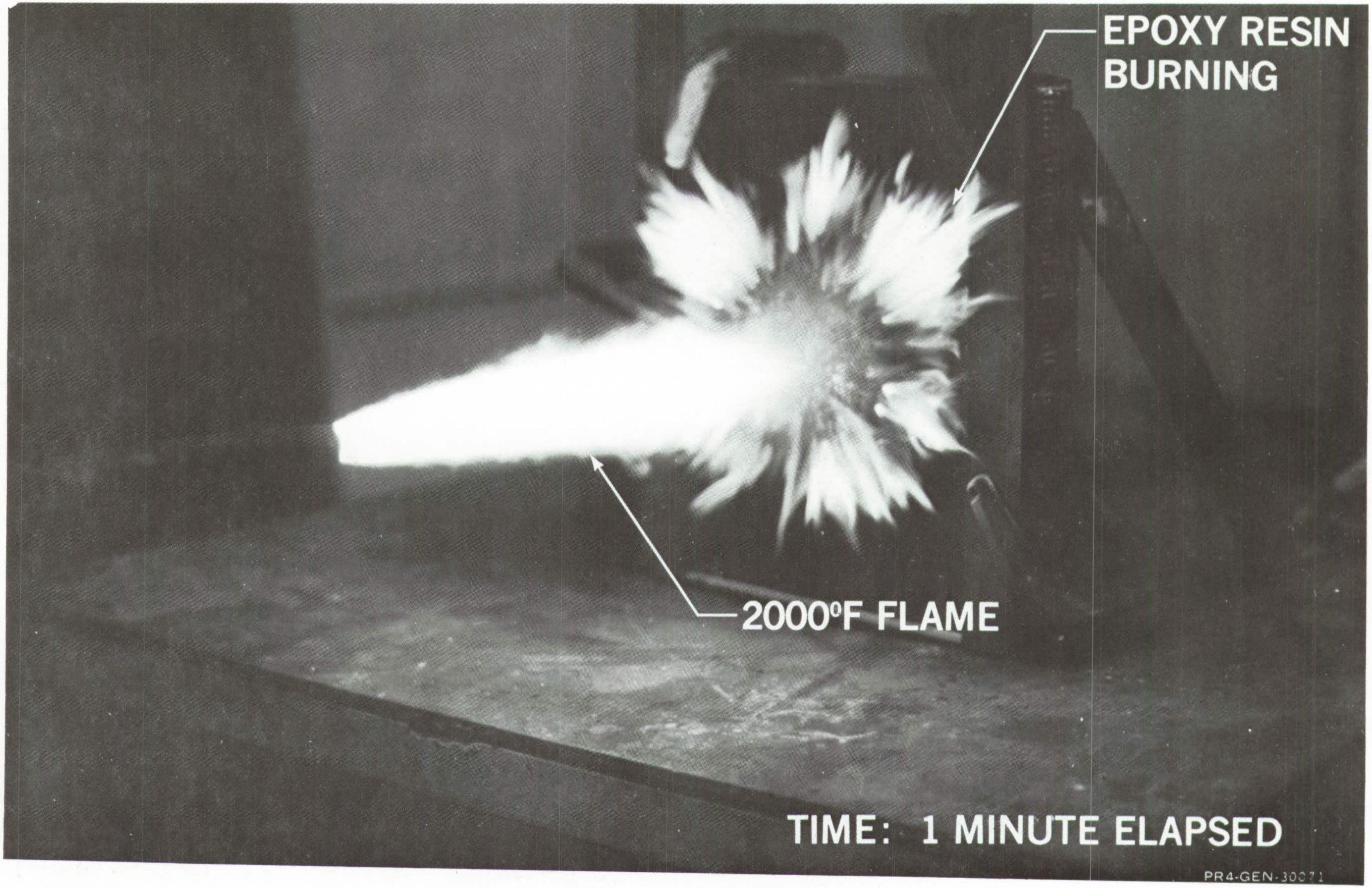


FIGURE 41 - COMPOSITE PANEL FIRE RESISTANCE TEST - ONE MINUTE AFTER TEST START

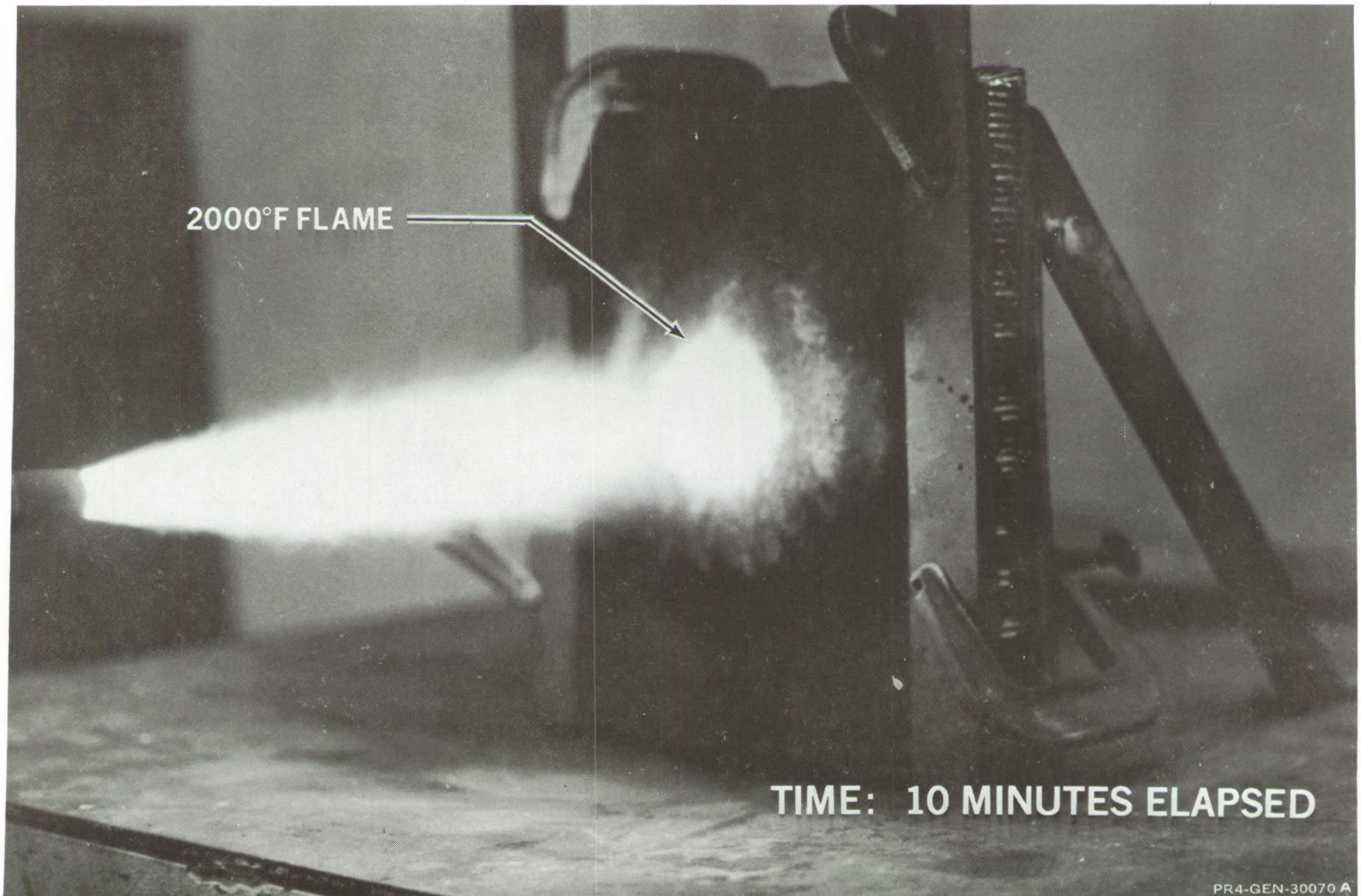
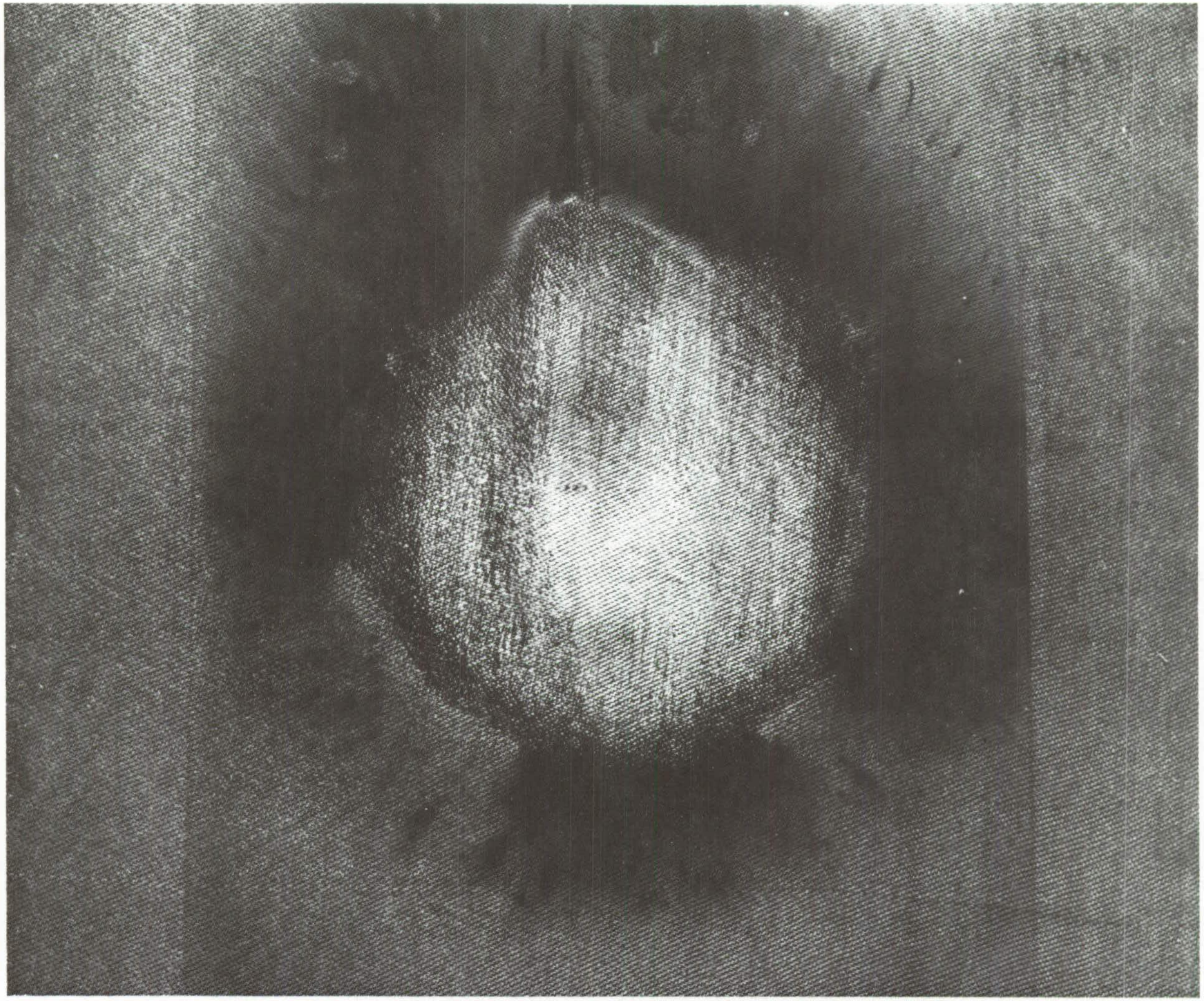
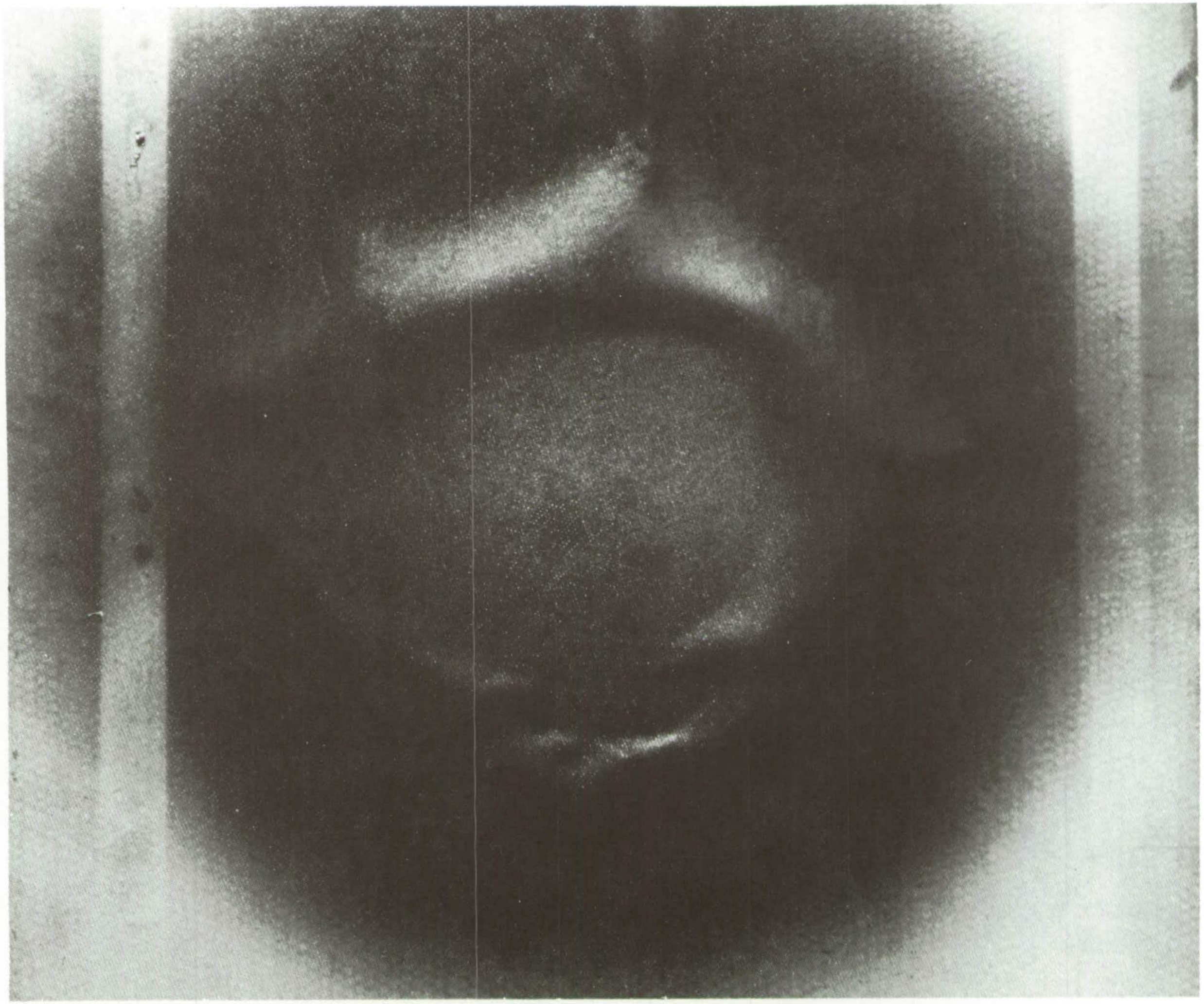


FIGURE 42. COMPOSITE PANEL FIRE RESISTANCE TEST - STABILIZED CONDITIONS



POST TEST — FLAME SIDE

FIGURE 43. COMPOSITE PANEL FIRE RESISTANCE TEST - POST-TEST SPECIMEN CONDITIONS, FLAME SIDE



POST TEST — BACK SIDE

FIGURE 44. COMPOSITE PANEL FIRE RESISTANCE TEST - POST-TEST SPECIMEN CONDITIONS, BACK SIDE

meeting, with additional technology development, the fire barrier requirements of the fan cowl door. The tests also demonstrated that under some conditions, one ply of a high-silica glass would protect underlying strata of graphite from erosion.

Each design case, however, has its own problems and must be treated separately. Under conditions of any adverse pressure differential across a panel which is perforated or porous on one side, the simple test method described above would not be adequate to demonstrate fire resistance. The nose cowl inner barrel is one example of a case in which the pressure gradient between the porous side and the impermeable side of the duct linings require a more-sophisticated design. Figure 30 illustrated two potential approaches to the design of a practical duct lining. Further analysis and experimentation will be required to develop the technology necessary to produce acceptable designs at minimum weight and cost. For example, methods of protecting graphite, other than with high-silica glass, may be preferable under some design conditions. There are also a number of other materials available that could be used in place of the high-silica glass.

5.12 Sonic Fatigue Considerations

As shown in Figure 45, the nacelle presents a significant challenge to materials from the standpoint of acoustically-induced fatigue. These sonic-fatigue loads are much higher than those encountered anywhere else on the airplane. Sufficient information is available (Ref. 13 and 14) to assure that advanced composites will have sonic fatigue resistance at least equivalent to the metal parts in current use. Analytical and experimental programs are underway to determine the analytical techniques needed to evaluate various types of advanced constructions using composite materials.

5.13 Strength Considerations

Figure 45 also identifies some of the significant strength considerations that were applied in developing the concept for load-carrying, thin-wall composite structures featuring integral acoustic treatment. This integral

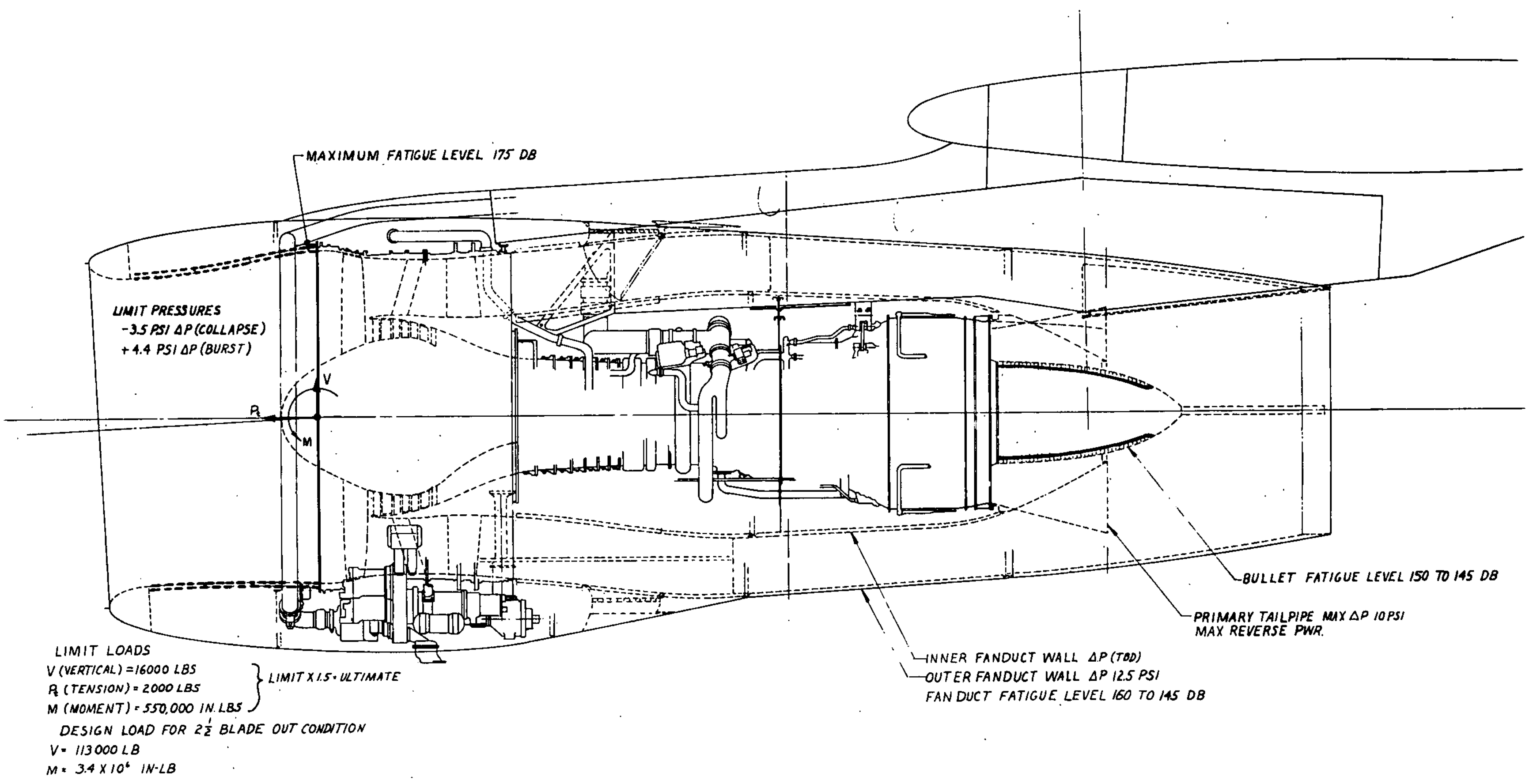


FIGURE 45. NACELLE DESIGN LOADS AND PRESSURES

concept is a key to meeting the weight-reduction goal that is vital to the viability of the long-duct, mixed-flow nacelle.

5.14 Environmental Considerations

Another important consideration involved in developing design concepts and selecting materials for the nacelle is the operating environment. Figure 46 indicates some of the design considerations that apply to nacelle components. Contamination from dirt, dust and other materials found in and around airports along with ice accretions, rain and wide ranges in temperature must be accounted for. These considerations are important in the selection of materials for a given application. For instance, the acoustical treatment in the nose cowl required porous or perforated sheets. Provision must be made to drain water or other fluids that pass through the porous face, to prevent failure of the panel as a result of freezing and to minimize potential corrosion problems. Also, many of the nacelle components, such as the core cowl doors, are subjected to relatively high temperatures during normal operation.

5.15 Fabrication Considerations

An important element of the process of developing advanced composite designs is understanding the parts fabrication processes. Unlike the process of designing metal parts, a unique feature of advanced composite component design is that the designer must simultaneously design the material and the end part. Among the many factors that must be considered are: designing to accommodate the bonding together of pre-cured details vs co-curing the components of a complete part after assembly; how to provide the porosity when acoustic treatment is required; how to handle edge closures, fittings, doublers, and mechanical attachments; and whether to use unidirectional three-inch or twelve-inch-wide tape or the wider broadgoods which sacrifice some of the strength/weight ratio potential of composites in favor of speeding up the part lay-up process.

Providing porosity for the duct linings in the inlet and exhaust passages in the nacelle is of special concern. Currently the perforated surfaces

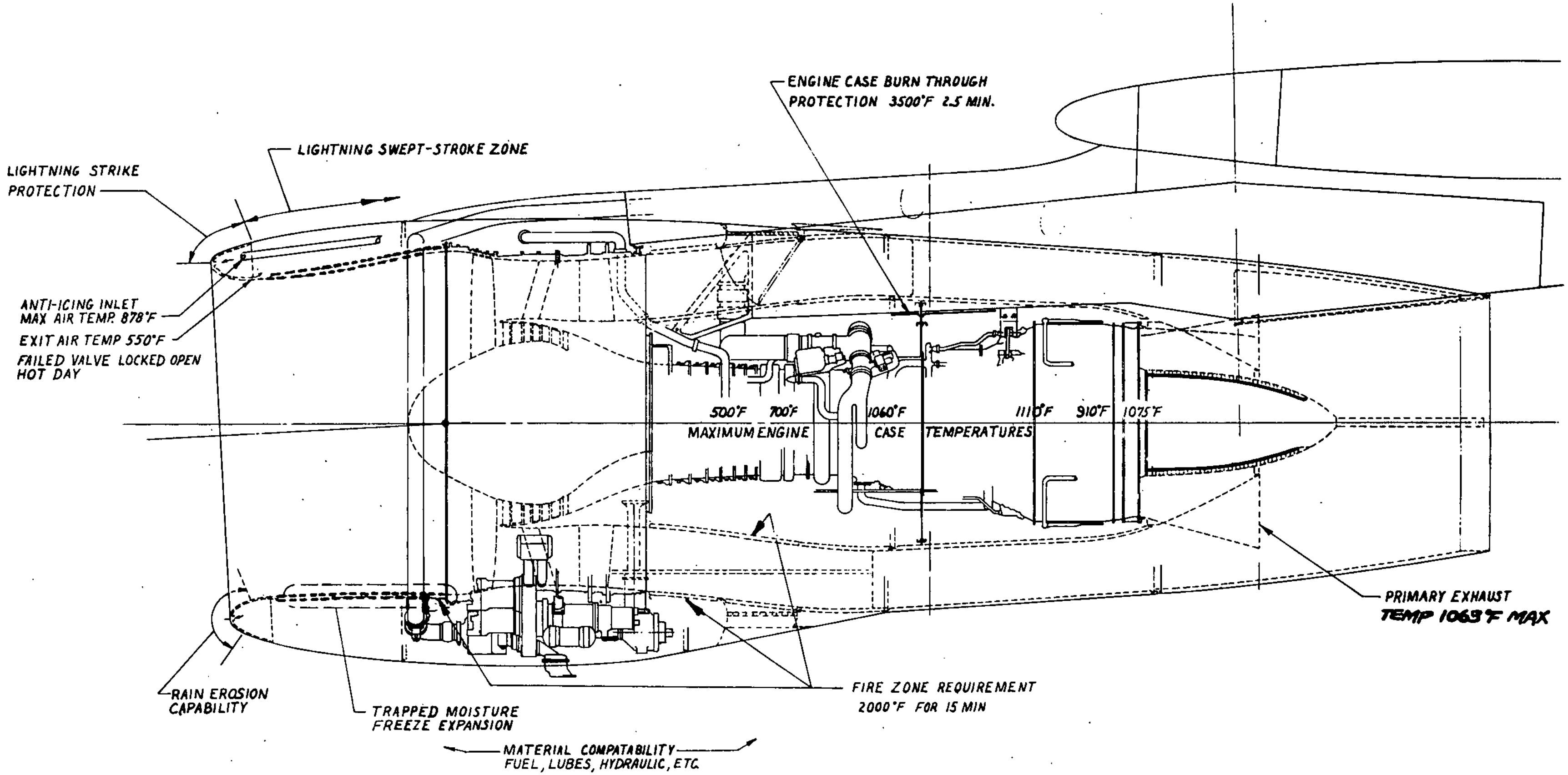


FIGURE 46. NACELLE ENVIRONMENT

used in bonded aluminum honeycomb require prepunched and stretch-formed face sheets. This method requires multiple fabrication steps and fairly close tolerance fitup between the face sheets and the core material, i.e., manufacturing procedures that entail high labor costs. Pre-curing of composite perforated face sheets dictates that balanced or fully symmetrical laminates be used to avoid warpage. Balanced laminates in turn sacrifice some of the potential weight savings due to the number of extra plies required.

Integrally woven acoustic core appears to offer a good solution to the cost and weight problem described in the previous paragraph, especially in the nose cowl. However, the integrally woven method is not free of draw-backs. For instance, producing a cured acoustic X- or truss-core requires installation and removal of a large number of mandrels needed to maintain the shape of core elements during the cure process. This use of mandrels dictates making provisions for adding closures and fittings after removal of the mandrels following the first cure cycle. Holding the number of cure cycles to a minimum is necessary to minimize the cost of advanced composite components.

Use of a spiked mandrel has been shown by GE to be cost effective for producing perforated composite parts currently used in the CF6 fan discharge ducts. The process is applicable to production-line procedures at that time, but only for fiberglass and has not been shown to be cost effective for either Kevlar or graphite, especially for large double contoured components such as would be found in the WBT nacelles.

Another promising concept for cost and weight reduction is the adhesive application process wherein a laminating type adhesive is used in place of laminating resins to eliminate the need for laminating resins and thus eliminate the need for separate adheseive films to save weight and cut down on the number of steps involved in laying-up the part. This process has been demonstrated with a certain degree of success by other companies with 356°K (180°F) cure temperatures, but additional technology development work is required to achieve acceptable flatwise tensile and climbing-drum peel strengths at higher cure temperatures. In experimental composite specimen programs, GE has found that good fillets could not be reliably achieved due to resin flow during the 394°K (250°F) cure cycle that was required. For a part such as the WBT fan cowl door, the weight savings from elimination of the adhesive film would be on the order of 11 kg (25 lb) [22 kg (48 lb) per nacelle]. Since the door weighs only about 50 kg (110 lb), this represents a weight reduction of about 20%. However, for the fan cowl door shown in Figure 33, standard adhesive films were used on both sides of the core, providing a conservative, low-risk design approach.

6.0 ATT NACELLE CONFIGURATION

6.1 Study ATT Nacelle

Previous NASA sponsored studies of the Advanced Technology Transport (ATT) made it possible to forecast some of the improvements possible for the propulsion systems in the next generation of transport aircraft. Among the improvements foreseen were: an integrated engine nacelle, hybrid inlet systems addressing both aerodynamic and acoustic requirements, improved thrust reverser systems which are lighter and more reliable, and the wider application of composite structure concepts in the low and medium temperature areas of the nacelle. Development of resin systems suitable for more elevated temperature applications than are currently achievable will be required to implement this concept. In addition, advanced engine-driven airplane-accessory concepts and arrangements and lower cost approaches to quick engine change units will be needed to reduce the cost of ownership of future transport aircraft.

The concept of the integrated engine/nacelle is one that offers a significant improvement in propulsion system technology. The key feature is the use of the engine fan frame for external as well as the internal aerodynamic flow path surfaces. Advanced composites were most applicable to this concept to reduce both the cost and the weight of the engine/nacelle package.

The integrated nacelle concept is also attractive because it minimizes the nacelle cross sectional area, and because it would have thrust reverser systems with higher effectivenesses than those in service today at weight penalties below the 25% of the basic engine weight typical of current high bypass ratio fan engine installations. The concept for the ATT nacelle used for this effort is shown in Figure 47. The nacelle incorporated a variable geometry hybrid inlet with a two-position throat for takeoff noise attenuation and acoustic treatment for suppressing landing approach noise. The fan frame was envisioned as a composite structure. Also shown is an advanced concept for a fan thrust reverser and an unconventional accessory arrangement with all the engine and aircraft accessories located atop the engine and on the pylon beam. The nacelle concept had a mixed flow system consistent with GE's Advanced Transport Study engines, all of which utilized this cycle. Stacked acoustic treatment designed to attenuate both the low and high frequency noise generated in the core and turbine sections would be built into the centerbody, within the internal mixer. The quick engine change (QEC) concept envisioned for the ATT nacelle is shown in Figure 48.

The advanced composite fan frame constituted the basic structural component of both the engine and the nacelle. This concept was developed by GE, and is shown in Figure 49. The construction method for this component integrated wheel-and spoke-like structures with shear panels forming the flow passage surfaces. The structure would be reinforced in the rim and hub areas as needed to accommodate load concentrations. This design provided a light weight structure, capable of carrying high loads, that would be relatively easy to fabricate. This concept has been explored in depth by General Electric, and was a prime feature of the QCSEE engines and nacelles which GE is developing under contract to the NASA-Lewis.

In addition to the on-going work on composite static structures, GE is heavily involved in advanced composite programs for rotating engine parts. All-composite fan blades and other rotating components are under active development.

The hybrid inlet selected for the ATT nacelle signifies an inlet combining both active and passive sound attenuation features. The active component was the variable geometry feature used to raise the throat Mach number to provide a high level of attenuation to the fan forward-radiated noise at

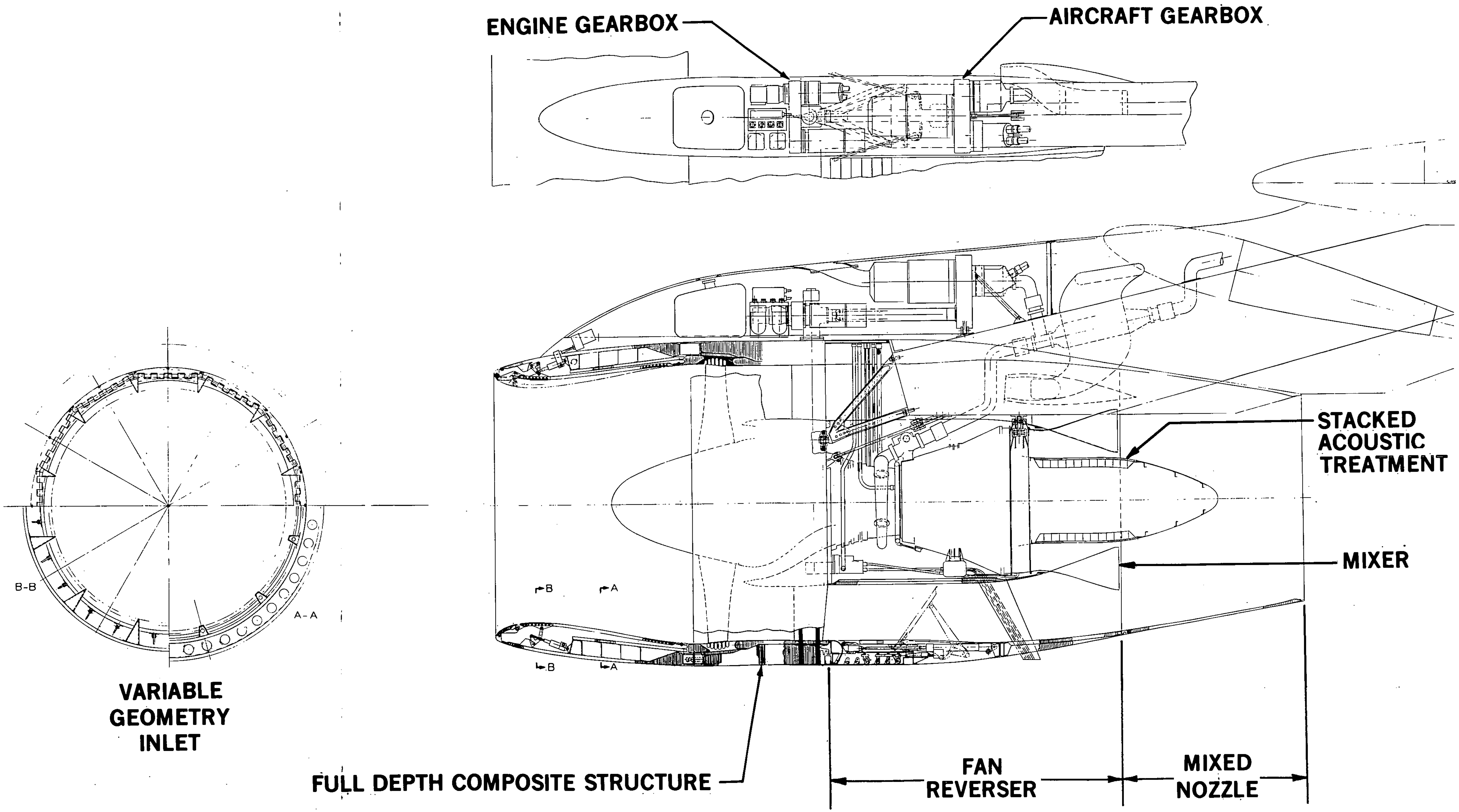


FIGURE 47. CONCEPTUAL DESIGN - ADVANCED TECHNOLOGY TRANSPORT NACELLE

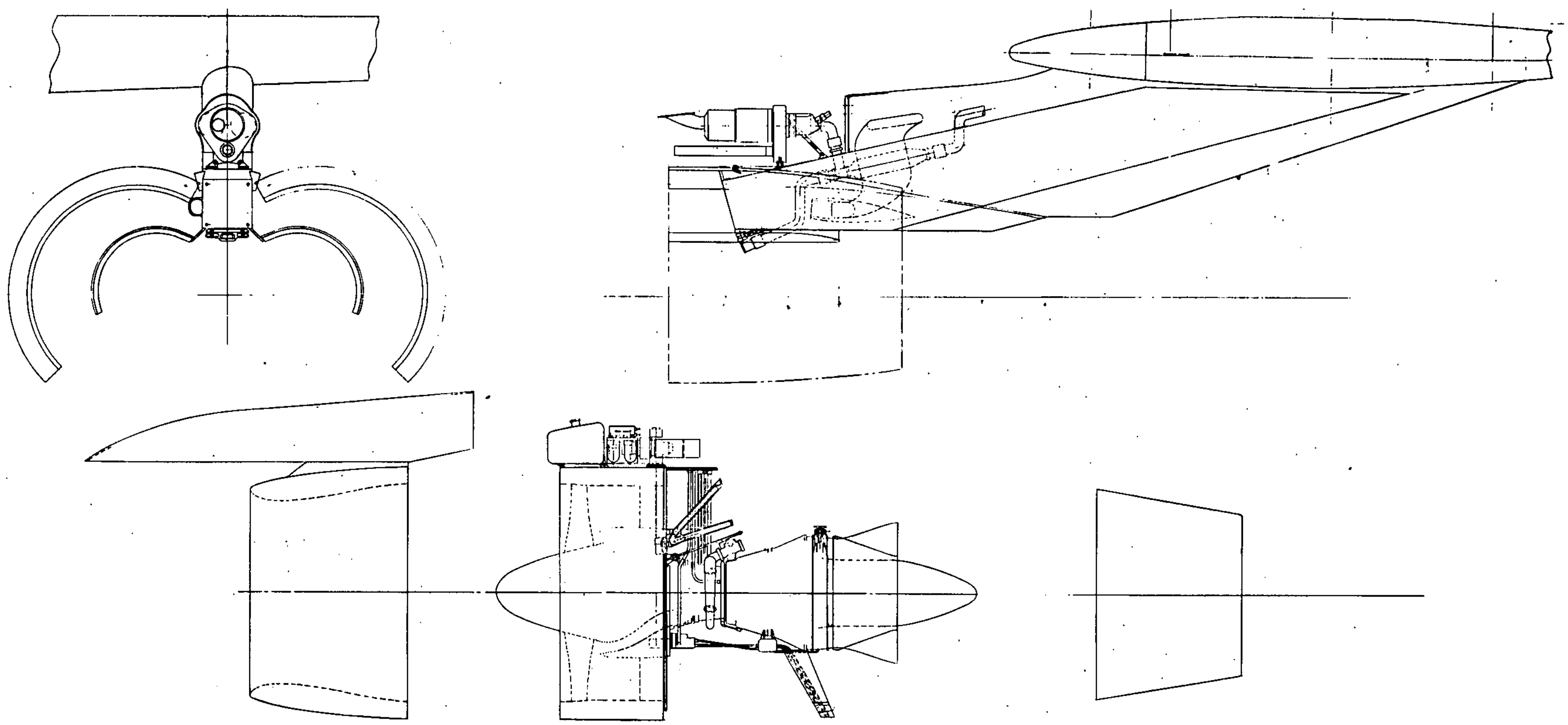


FIGURE 48. CONCEPTUAL DESIGN - ATT NACELLE MINIMUM QUICK ENGINE CHANGE (QEC) UNIT

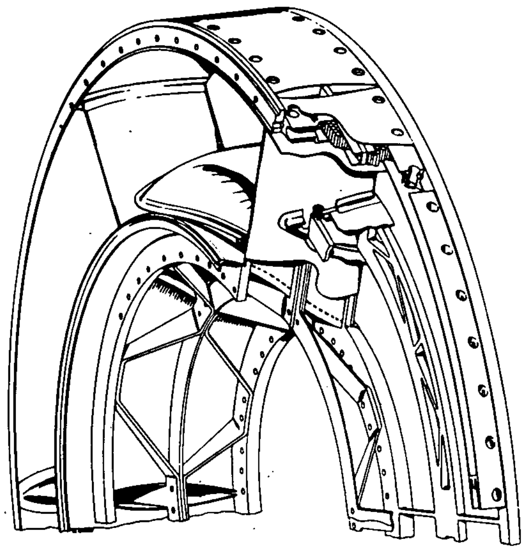


FIGURE 49. TYPICAL COMPOSITE FAN FRAME TRIMETRIC

takeoff power settings. The passive component was the duct lining treatment that would also serve to absorb forward-radiated fan noise at approach power settings. The inlet was designed to operate in two positions - one for takeoff and one for cruise. The takeoff position would produce a throat Mach number of 0.79 at the takeoff air flow condition. The inlet design characteristics are summarized in Table 11.

Based on the results of previous tests on an inlet with similar design characteristics, the inlet for the ATT nacelle would also be expected to have excellent aerodynamic performance at the Mach 0.9 cruise condition required for this study.

Figure 50 shows an advanced technology thrust reverser concept in which the entire reverser is contained within the outer wall of the fan duct. Among the advantages of this concept is that it enables the inner and outer cowls to be structurally and mechanically separated allowing significant weight reductions in both components and providing a clean low-loss fan flow passage.

TABLE 11. SUMMARY OF ATT HYBRID INLET DESIGN CHARACTERISTICS

Flight Condition	$\frac{W\sqrt{\theta_{t2}}}{\delta_{am}}$ kg/sec (lb/sec)	A_{proj} $m^2(ft^2)$	$\frac{D_{HL}}{D_{TH}}$	$\frac{D_{HL}}{D_{Max}}$	D_{Max} m(in)	A_{Throat} $m^2(ft^2)$	M_{Throat}	$\frac{\Delta A}{A}$
Takeoff	420 (925)	3.55 (37.05)	1.1235	.81	2.10 (82.5)	1.87 (19.53)	.79	.12
Max Cruise [+266°K(+18°F)]	445 (982)	↓	1.053	↓	↓	2.13 (22.2)	.70	0
Max Climb	469 (1033)	↓	↓	↓	↓	2.13 (22.2)	.79	0
Approach	265-281 (584-620)	↓	↓	↓	↓	2.13 (22.2)	.33 .35	0

NASA 1-81-75 External Forebody

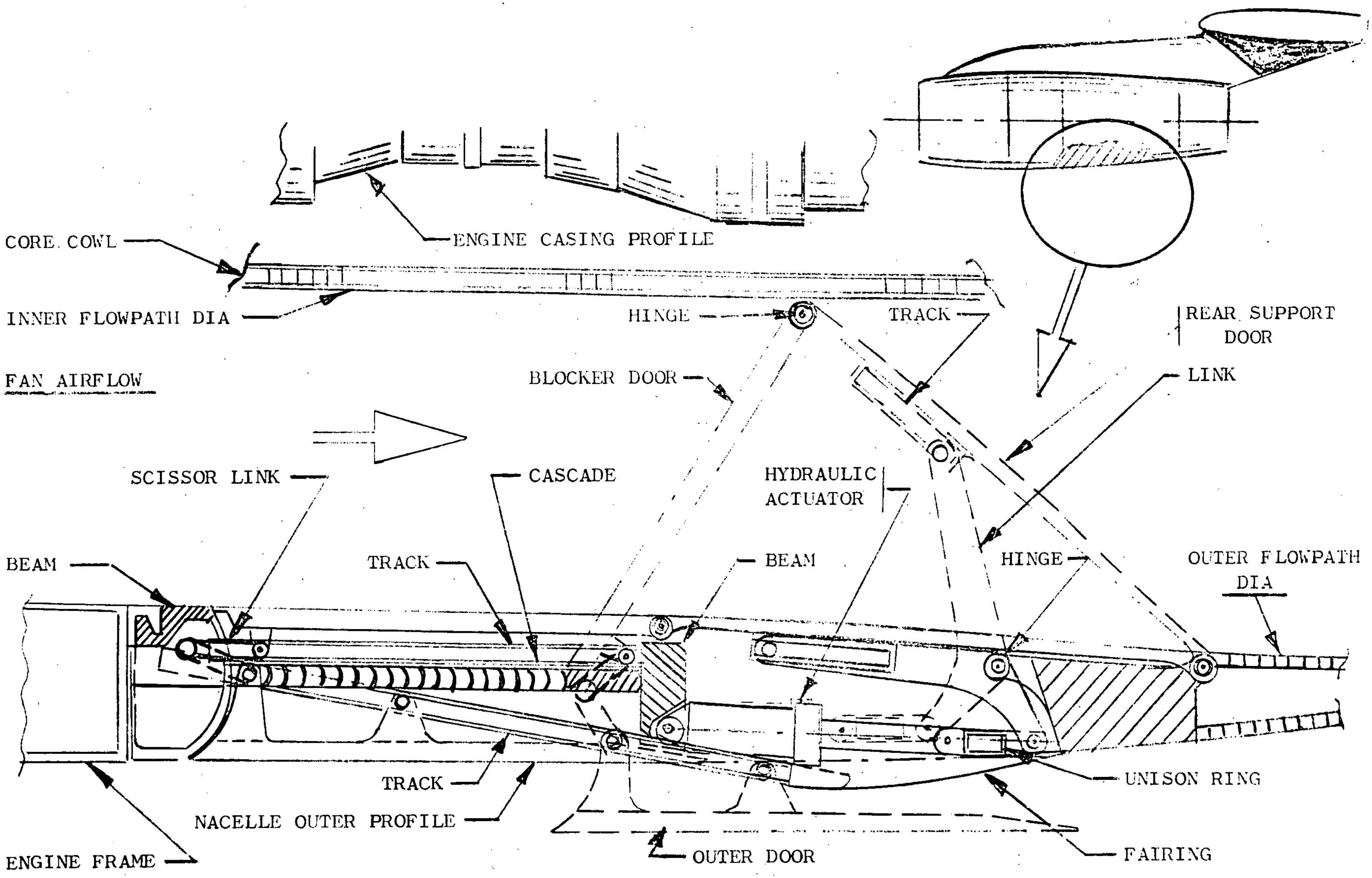


FIGURE 50. ATT NACELLE ADVANCED THRUST REVERSER CONCEPTUAL DESIGN

A tabulation of the ATT nacelle weight breakdown is given in Table 12. It can be seen that a significant improvement in installed thrust/weight ratio was offered with this design concept.

TABLE 12. ATT NACELLE WEIGHT BREAKDOWN

ENGINE WEIGHT

ITEM	WEIGHT - kg	(lb)
LOW PRESSURE SYSTEM	1143	(2520)
HIGH PRESSURE SYSTEM	472	(1040)
SUMPS, BEARINGS, DRIVES AND ACCESSORIES	288	(635)
ENGINE TOTAL	1903	(4195)

NACELLE WEIGHT

ITEM	WEIGHT - kg	(lb)
INLET	207	(456)
FAN REVERSER/COWL	446	(980)
CORE COWL	38	(83)
EBU	179	(395)
MIXER AND BULLET	88	(195)
FINAL NOZZLE	44	(98)
NACELLE TOTAL	1001	(2207)

INSTALLATION WEIGHT

ITEM	WEIGHT - kg	(lb)
ENGINE TOTAL	1903	(4195)
NACELLE TOTAL	1001	(2207)
INSTALLATION TOTAL	2904	(6402)

THRUST-TO-WEIGHT RATIO

ITEM	RATIO
BARE ENGINE	7.15
INSTALLATION	4.69

6.2 ATT Candidate Composite Materials

The materials that were considered as part of the ATT studies are summarized in Table 13. As can be seen, higher temperature resins and fibers were included. It should also be noted that many of these materials were in the very early stages of development, and, for that reason, were not considered for the wide-body studies in this particular contracted effort. Many of the same basic construction techniques that were looked at as part of the WBT studies were also applicable for most of the ATT activities. The only radical departure for the ATT was the construction technique employed for the composite fan frame assembly. Since most of the composite components that made up the ATT nacelle represented adaptations of designs developed under related study contracts at GE (Reference 15) additional specific detailed designs for this particular study were not developed. Instead weights were estimated, along with costs, for the various components that made up the ATT nacelle. These were based on the relationship of the ATT No. 4 engine thrust rating to other advanced engines on nacelle studies that have been reported through NASA and other government agencies.

6.3 Baseline ATT Component Noise Levels

Hardwall (no acoustic treatment) component noise levels were provided by GE based on prediction methods for turbofan engine noise sources developed and refined over a period of years. These methods used measurements of the component noise sources from various full-scale engines and model-scale fan rigs. These prediction methods yielded spectra and directivity for far field noise levels from the various noise components (turbomachinery, core and jet noise) for a static engine. The static noise estimates were then projected to the desired flight conditions of Table 2, empirically accounting for the doppler shift in the spectra at each angle and the effect of forward motion on the amplitude of jet noise and on fan-inlet noise.

TABLE 13. - ATT STUDY COMPOSITE MATERIALS

MATERIAL	USE	USEFUL MAXIMUM TEMPERATURE
RESINS:		
EPOXY	LOW COST MATRIX	422°K (300°F) FOR 50,000 HOURS
POLYIMIDE (P.I.)	ACCEPTABLE COST MATRIX FOR SLIGHTLY ELEVATED TEMPS.	533°K (500°F) FOR 20,000 HOURS
POLYMIDAZO-QUINAZOLINE (PIQ)	POTENTIALLY ACCEPTABLE COST MATRIX FOR HIGH TEMPERATURES	506°K (450°F) FOR 400 HOURS LABORATORY EXPERIMENTAL DATA.
FIBERS:		
GLASS	LOW COST MATRIX	589°K (600°F) FOR 50,000 HOURS
GRAPHITE	HIGH STRENGTH AND STIFFNESS TO WEIGHT	589°K (600°F) FOR 50,000 HOURS
KEVLAR 49	HIGH TENSILE STRENGTH	422°K (300°F) FOR 50,000 HOURS
QUARTZ	HIGH TENSILE AND COMPRESSIVE STRENGTH	922°K (1200°F) LONG TERM LIFE UNKNOWN
ALUM-BORSIC SILICA (ABS)	PRELIM. DATA INDICATES HIGH TENSILE STRENGTH (DENSITY SLIGHTLY HIGHER THAN GLASS)	922°K (1200°F) LONG TERM LIFE UNKNOWN

For the ATT, this procedure was the only feasible method since no actual flyover noise data were available, as in the case of the baseline WBT, to verify the prediction method. Based on previous experience, this method had been proven capable of generating reasonable predictions and was therefore expected to be suitable for estimating the baseline ATT noise levels.

Figure 51 shows the peak PNLT and EPNL values calculated for the current FAR 36 takeoff and approach locations. The higher thrust-to-weight ratio for the ATT results in significantly greater height at the 6.48 km (3.5 n mi) takeoff point for this aircraft than for the baseline WBT. Thus, even without any acoustical duct linings, the baseline ATT design would meet the current FAR 36 takeoff noise requirements because of its height at the measurement location and because of the use of long-duct mixed-flow nacelles with a higher bypass ratio and a lower jet velocity than for the CF6-50C engines on the baseline WBT.

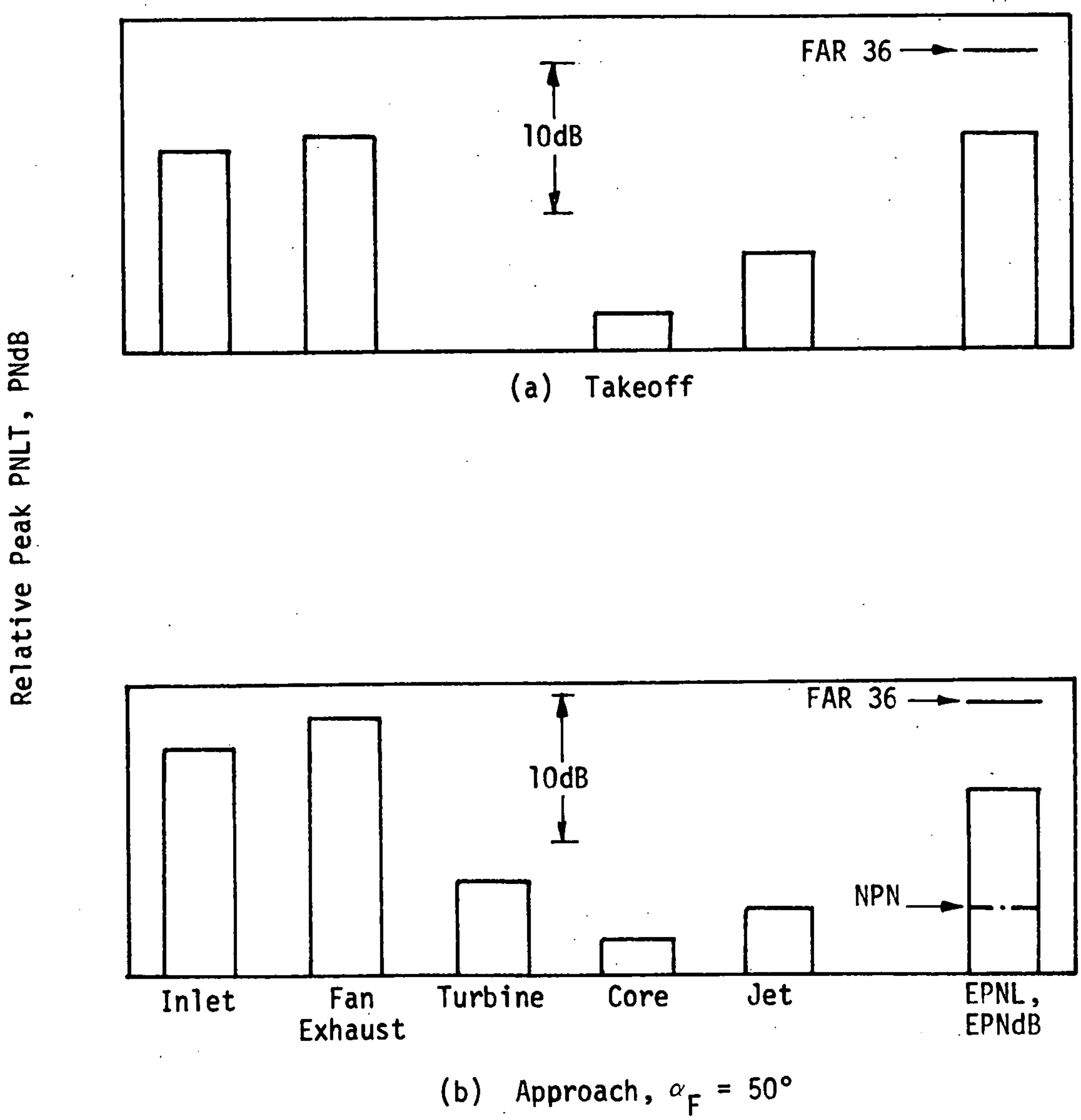


FIGURE 51. BASELINE ATT COMPONENT NOISE LEVELS AT MTOGW AND MLGW FOR FAR PART 36 MEASUREMENT LOCATIONS

At approach power settings, the level of non-propulsive noise was relatively low because of the low landing speed (compared to the landing speed of the WBT). The level of the fan-exhaust noise from the basic engine would be reduced by the incorporation of large spacing (about two fan rotor chords) between the fan and the straight (unswept) fan OGVs. The perceived annoyance of the turbine noise would be minimized by using a large number of turbine rotor blades so that at the approach power setting the fundamental turbine-blade-passage frequency would be in the 1/3-octave band centered at 8 kHz. Turbine blade loading at the approach power setting would be selected to reduce the strength of the turbine noise source. With all of these features, the baseline untreated ATT engine would meet the current FAR 36 noise requirements at approach as well as takeoff.

At the takeoff power setting, the most-important noise sources were the turbomachinery noise from the fan exhaust and inlet ducts. At approach, the fan-exhaust, inlet and turbine noise would need suppression to achieve significantly lower noise goals than current Part 36 requirements. The NPN level was estimated to be only 8 EPNdB below the EPNL of the baseline ATT and thus a noise reduction of only 3 to 4 EPNdB at approach was the most that could be expected from the addition of absorptive duct linings, unless the NPN level could also be reduced by application of some advanced technology. For the purposes of this study, no reduction in NPN was assumed.

6.4 ATT Noise Reduction Concepts

Concepts considered for reducing fan and turbine noise are shown in Figure 52. The inlet duct had two special features. The variable-geometry inlet would be designed to produce a throat Mach number of 0.79 at takeoff airflow rates should yield large reduction in forward-radiated noise. The bulk absorber lining shown on the walls of the inlet inner barrel would reduce the forward-radiated noise at approach.

The long fan-discharge duct incorporated phased (stepped) duct linings on the inner and outer duct walls. The cross-duct dimensions were kept relatively large so that the airflow Mach number would be as low as

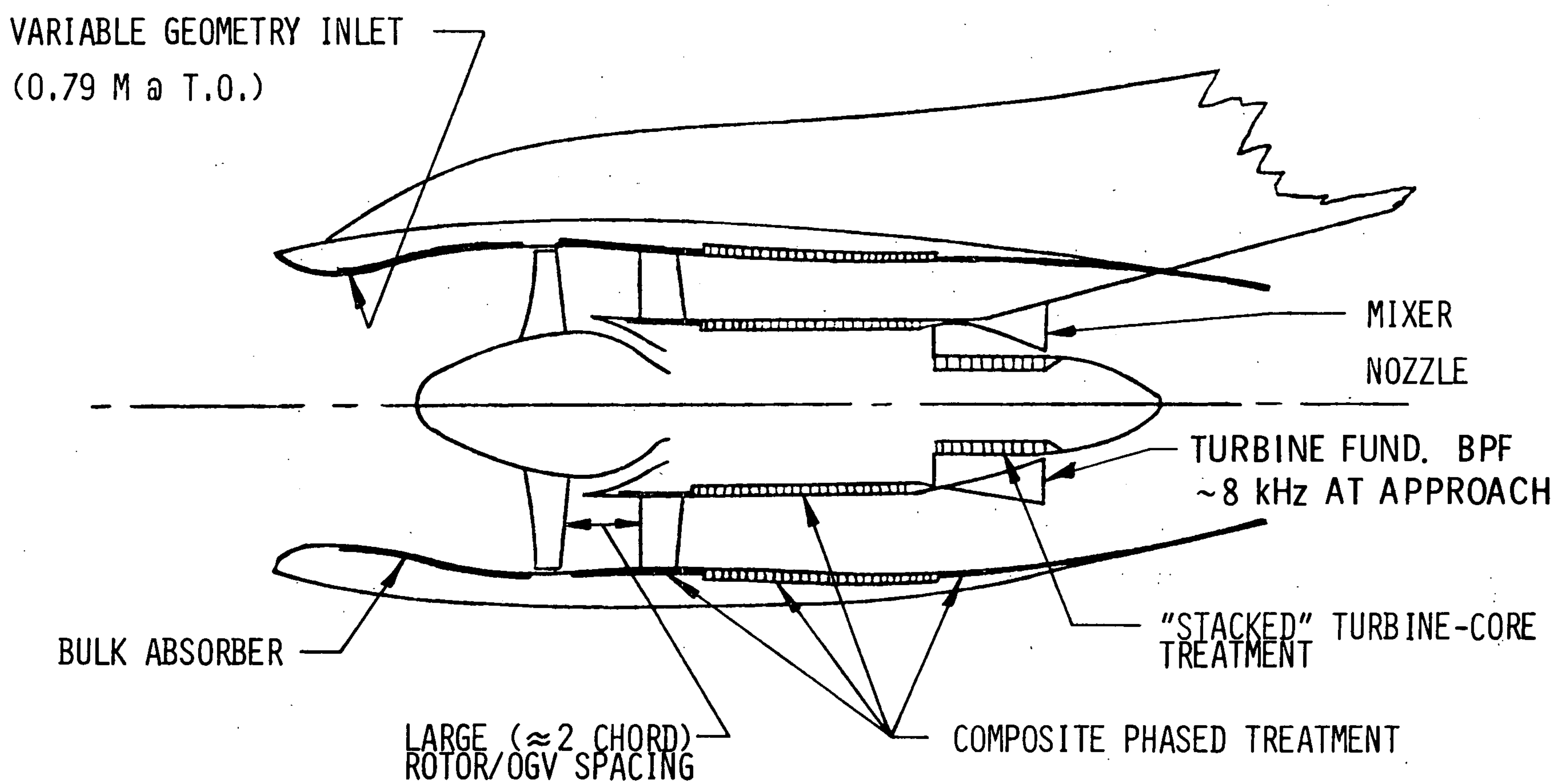


FIGURE 52. ACOUSTIC DESIGN FEATURES OF ATT LONG DUCT, MIXED FLOW NACELLE

feasible to minimize flow-noise generation over the linings and to maximize sound absorption. The phased treatment would be made from advanced light-weight composite materials integrated into the structure of the duct walls.

Turbine noise treatment would be installed on the exhaust centerbody and on the wall of the mixed-flow nozzle downstream of the exit plane of the mizer nozzle. The centerbody treatment is labeled "stacked turbine - core treatment" to indicate a concept for simultaneously reducing both the 8 kHz turbine noise and the low-frequency (typically 250 to 500 Hz) core noise, should core noise suppression be necessary in the future.

7.0 EVALUATION OF WBT NACELLE CONFIGURATIONS

7.1 Aerodynamic Performance Analysis

7.1.1 Introduction - Estimates were made of the internal and external performance changes for each of the nacelle configurations.

The results shown in Table 14 were obtained by applying pressure loss/SFC and drag/SFC functions to installed engine cycle data. Figures 53 and 54 show duct pressure losses and installation drags which have been accounted for.

7.1.2 External Performance - External nacelle pressure drag was estimated by a Douglas-developed $(L/D)_{eq}$ method. Figure 55 shows the $C_{D_{\pi_p}}$ versus $(L/D)_{eq}$ curve that was used. This curve is based on GE correlations of wind tunnel test data on TF39 and TF34 nacelles. The current CF6, short core cowl, and long duct nacelles of the present study have been spotted on the curve.

External nacelle friction drag was based on constant Prandtl-Schlichting skin friction coefficient corrected for compressibility, supervelocity, and roughness. Estimated values of cruise pressure and friction drag are summarized in Figure 56. The pylon aero loss shown in Table 14 was also estimated by a Douglas-developed method.

TABLE 14. ESTIMATED CRUISE ΔSFC (%) RELATIVE TO CURRENT CF6-50

Conditions: Fn = 40 kN (9000 lb); Mach = 0.85; Altitude = 10668 m (35,000 ft)

	CONFIGURATIONS				
	I	IA	IB	IC	II
EXTERNAL					
Skin Friction	Ref.	0	0	0	+1.36
Pressure Drag	Ref.	0	+0.11	0	-0.17
Interference	Ref.	0	0	0	0
Base	Ref.	0	0	0	0
Reverser Discontinuity	Ref.	0	0	0	0
Pylon Aero	Ref.	0	-0.20	0	-0.20
TOTAL	Ref.	0	-0.09	0	+0.99
INTERNAL					
Core Cowl Scrubbing	Ref.	0	-0.214	0	-1.600
Pylon Scrubbing	Ref.	0	+0.004	0	-0.322
Plug Scrubbing	Ref.	0	-0.097	0	-0.097
Core Duct Pressure Loss	Ref.	0	-0.124	0	-0.035
Core Lip Base Drag	Ref.	0	0	0	-
Core Divergent Section Loss	Ref.	0	-0.046	0	-
Fan Duct Pressure Loss	Ref.	0	0	+0.33	+0.28
Mixing	Ref.	0	0	0	-2.64
TOTAL	Ref.	0	-0.477	+0.33	-4.41
INSTALLATION WEIGHT CHANGE	Ref.	-0.596	-1.173	-0.344	-0.802
TOTAL		-0.60	-1.74	-0.014	-4.22

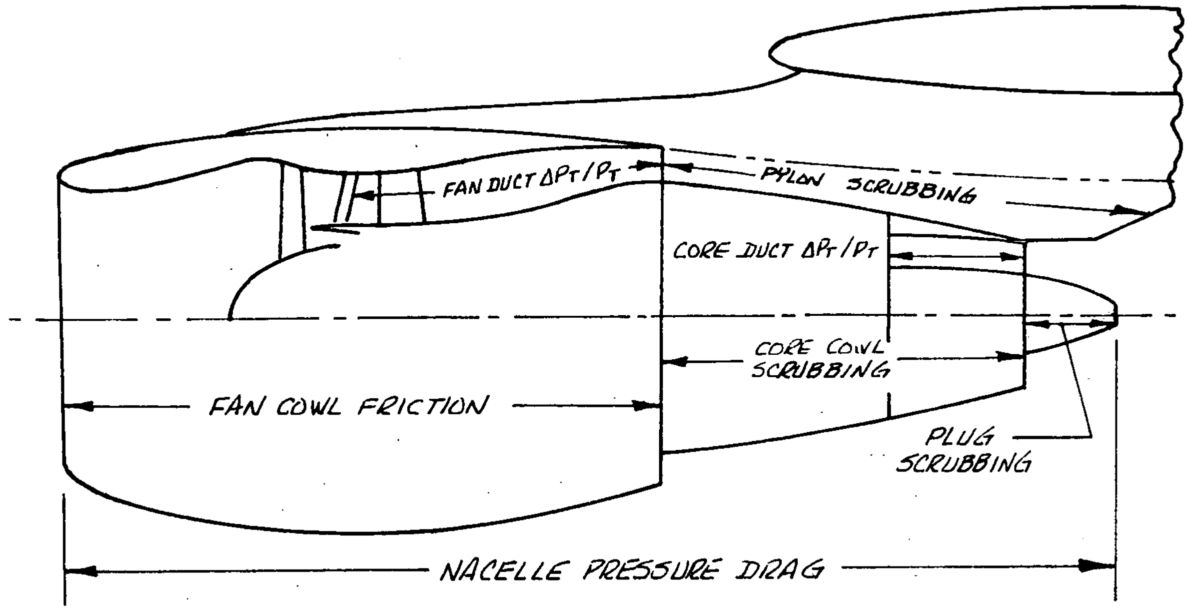


FIGURE 53. DUCT PRESSURE LOSSES AND INSTALLATION DRAGS FOR SEPARATE-FLOW CONFIGURATIONS

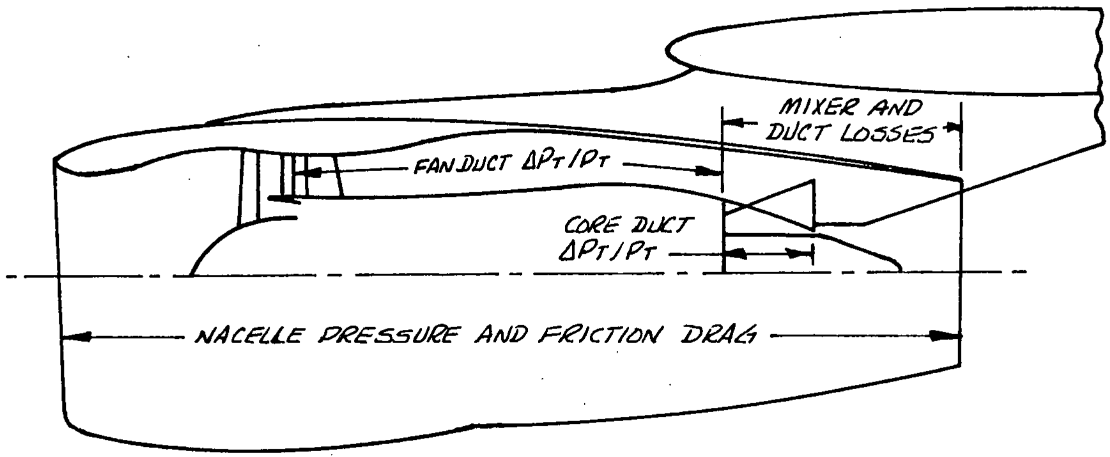
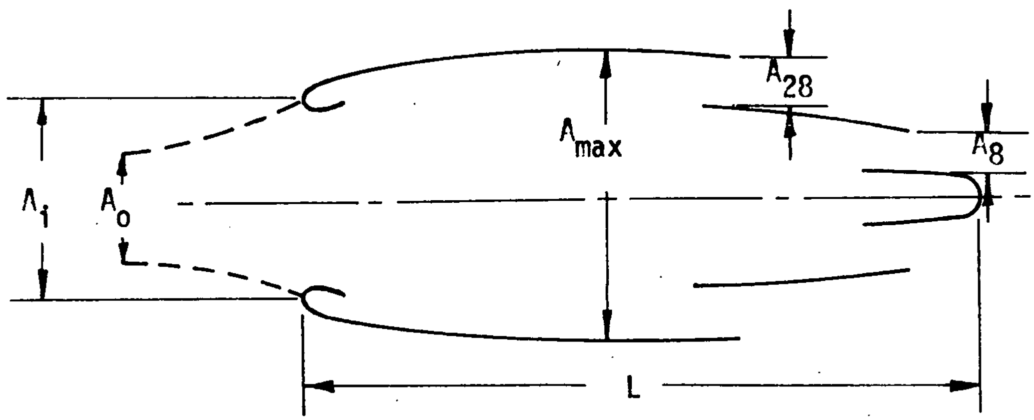


FIGURE 54. DUCT PRESSURE LOSSES AND INSTALLATION DRAGS FOR THE LONG-DUCT CONFIGURATION

$M_0 = .85$ Altitude = 10668m (35,000 feet)



$$C_{D_{\pi_p}} = \frac{D_p}{q_o\ A_{max}}$$

$$\left(\frac{L}{D}\right)_{eq} = \frac{L + D_i}{\left[\frac{4}{\pi}\ \left(A_{max} - \frac{A_o + A_{28} + A_8}{2}\right)\right]^{1/2}}$$

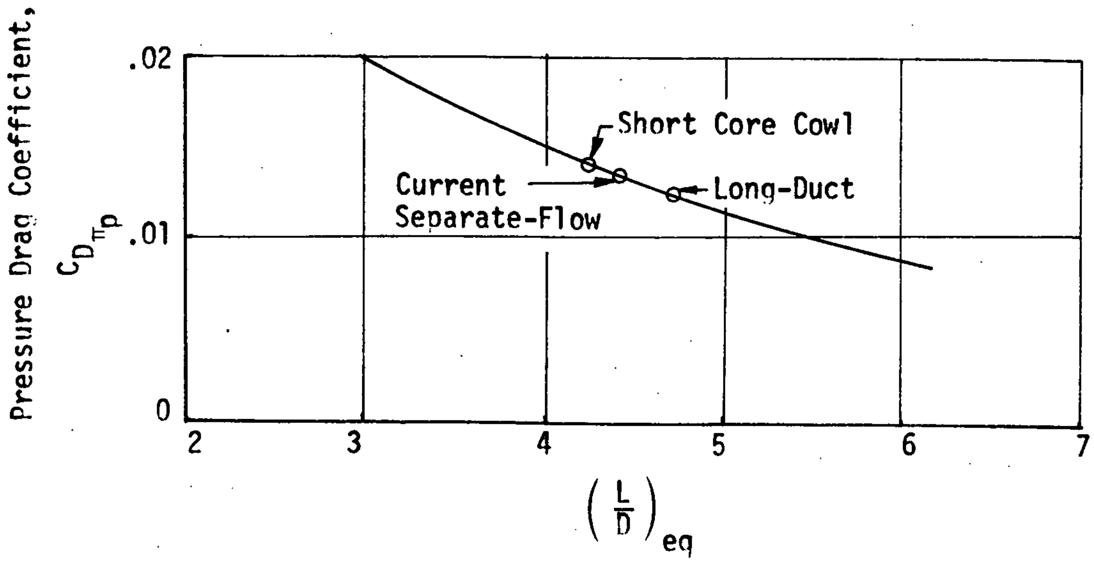


FIGURE 55. ESTIMATED NACELLE EXTERNAL DRAG

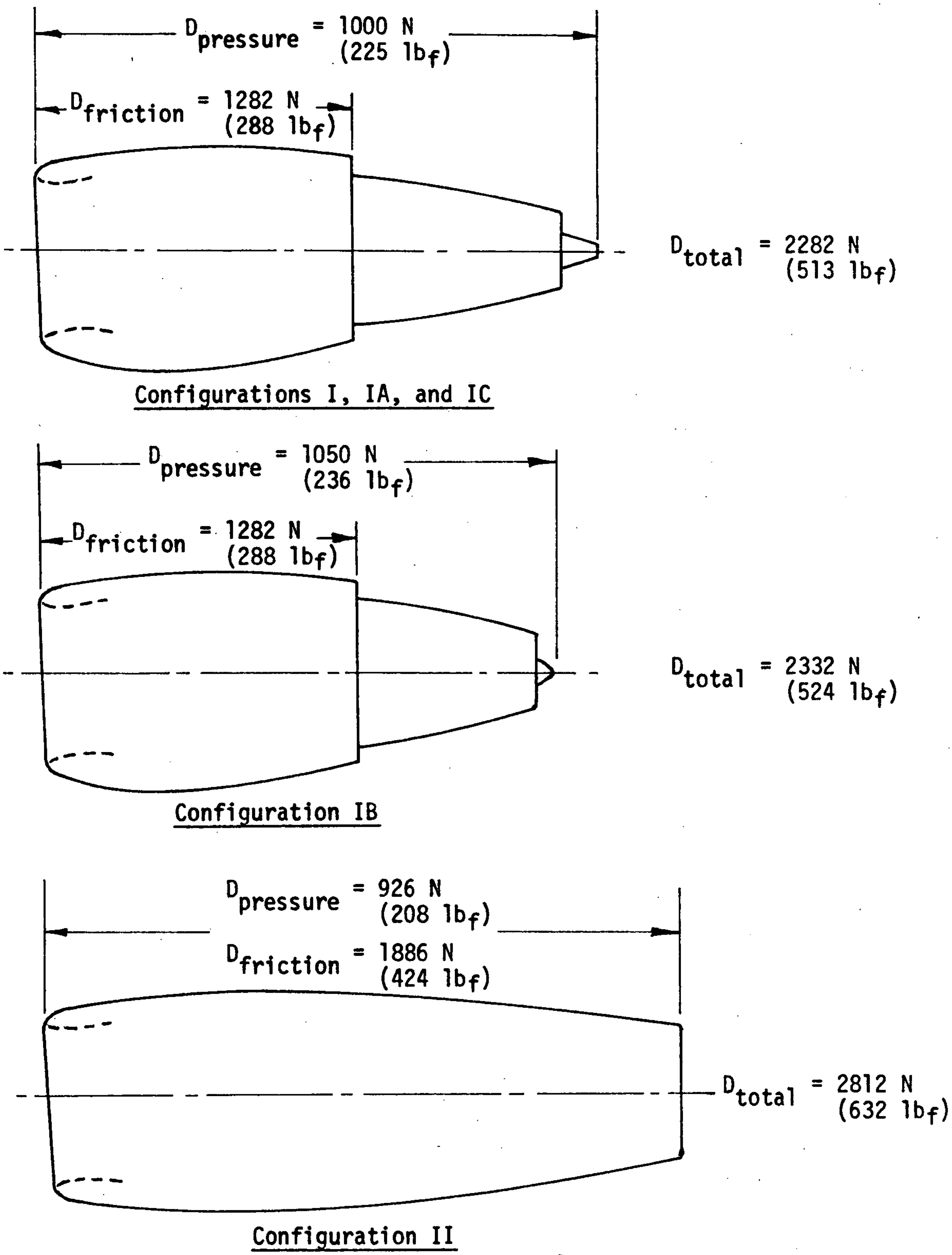


FIGURE 56. COMPARISON OF ESTIMATED NACELLE DRAG AT MACH 0.85 AND 10668 m (35,000 feet)

7.1.3 Internal Performance - Fan and core duct-pressure losses used to compile Table 14 are summarized in Table 15. For configurations other than the baseline, the losses represent estimates based on the nacelle conceptual designs described in Section 5.2 and 5.3. That is, the short core nozzle geometry, mixed flow reverser hardware, mixer sidewall machining or treatment, etc. were not defined in manufacturing detail. The long-duct losses shown are representative of the fan duct/mixer for nacelle Configuration II. In general, duct friction losses were estimated incrementally along the duct using local Prandtl-Schlichting friction coefficient; acoustic treatment loss was taken as 138% of smooth friction loss, and losses due to discontinuities were based on modification of current CF6-50 values and the methods of Reference 16 and 17.

A mixing effectiveness of 65% was used in performance calculations on configuration II. Figure 57 shows the close geometric flow-line similarity between the selected mixer and a typical scale model.

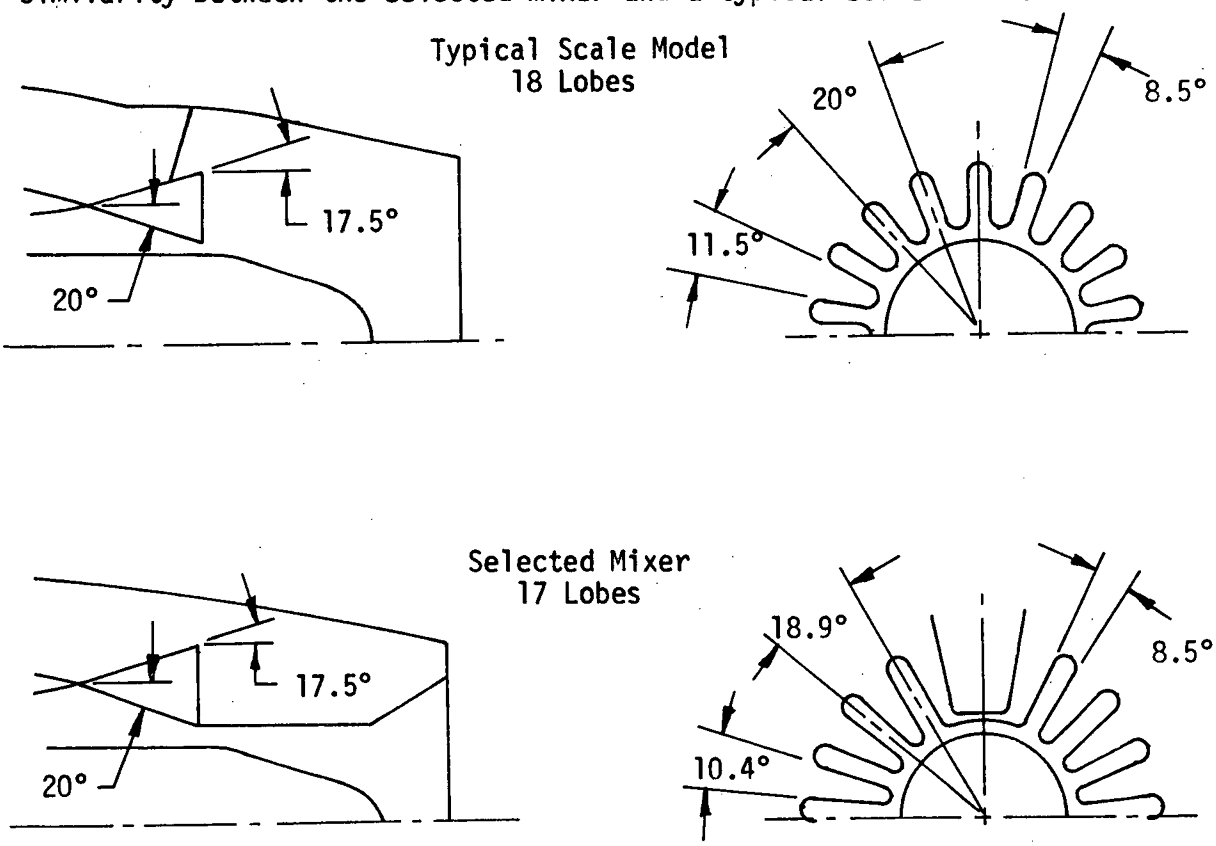


FIGURE 57. MIXER FLOW LINE COMPARISON

TABLE 15. ESTIMATED INTERNAL DUCT LOSSES

Conditions: Fn = 40 kN (9000 lb)
Mach = 0.85
Altitude = 10668 m (35,000 ft)

	$\Delta P_T/P_T$, %				
	CONFIGURATION				
FAN DUCT LOSS	I	IA	IB	IC	II
Fan Frame Struts & OGV's	.175	→	→	→	.205
Reverser	.050	→	→	→	.050
Steps and Gaps	.125	→	→	→	.171
Fan Frame Diffusion	.025	→	→	→	.025
Boost Bleed Exit Doors	.040	→	→	→	.040
Duct Friction	.942	→	→	→	.874*
Acoustic Treatment	.111	→	→	→	.387
Splitter	0	→	→	.330	0
Total Fan Duct Loss	1.468	1.468	1.468	1.798	1.752

CORE DUCT LOSS	I	IA	IB	IC	II
Turbine Frame	.126	→	.126	.126	.126
Reverser	.159	→	0	.159	0
Steps and Gaps	**	**	.044	**	.174
Duct Friction	.970	→	.744	.970	.624
Acoustic Treatment of Chem-Mill	.084	→	.115	.084	.298
Mixer Supports	0	→	0	0	.030
Total Core Duct Loss	1.339	1.339	1.029	1.339	1.252

* Does not include friction loss in the area from mixing plane to exit. This loss is accounted for in the mixing effectiveness.

** Included with reverser.

Based on data from tests on this scale model, the interface area function (Figure 25) for the selected mixer indicates a mixing effectiveness higher than 65%. The 65% used in this study lies within Frost's data scatter and is therefore considered somewhat conservative.

7.2 Weight Reduction Potential

Weight estimates were made for the various nacelle concepts studied. The weights were based on the drawings developed during the study and are listed by component in Table 16. As indicated by the tabulation, configuration IB (separate flow exhaust with a short turbine exhaust duct and no turbine reverser) offered the greatest weight reduction. This concept was estimated to reduce the weight of the three nacelles on the WBT by 959 kg (2118 lb). Configuration II was estimated to reduce the weight of the three nacelles by 656 kg (1449 lb), the second-best weight reduction for the four concepts developed in the study.

As shown in Table 16, the composite core cowl doors for Configurations IA, IB, and IC weighed 72 kg (160 lb) while the comparable part for Configuration II weighed only 63 kg (138 lb). This was due to the difference in size for those two core cowl door designs, with the door for Configuration II being significantly smaller in diameter and only slightly longer.

An additional weight estimate was made in order to determine the contribution of advanced composites to the overall appeal of the long-duct, mixed-flow nacelle. This estimate was of an all-metal long-duct nacelle and the results of this analysis indicated that such a configuration would result in a 537 kg (1185 lb) per airplane weight penalty relative to the baseline, or 1193 kg (2634 lb) penalty relative to the composite long-duct. A breakdown of the weights for that configuration is also shown in Table 16.

7.3 Noise Reductions

Evaluation of potential reductions in noise at the Part 36 locations and in the area around an airport began with estimates of the suppression of component noise. Suppression values for the effect of improved or

TABLE 16. NACELLE WEIGHT COMPARISON

Component	Component Weight - kg (lb)					
	Configuration					
	I	IA	IB	IC	II	METAL LONG DUCT
Nose Cowl	271(599)	222(491)	222(491)	222(491)	222(491)	271(599)
Fan Cowl Door	135(298)	99(218)	99(218)	99(218)	99(218)	135(298)
Fan Reverser	721(1592)	649(1433)	649(1433)	718(1585)	577(1273)	721(1592)
Core Cowl	94(208)	72(160)	72(160)	72(160)	63(138)	95(210)
Aft Fan Ducts	N.A.	N.A.	N.A.	N.A.	87(191)	186(410)
Turbine Nozzle and Reverser	225(497)	225(497)	68(150)	225(497)	N.A.	N.A.
Mixer and Plug	N.A.	N.A.	N.A.	N.A.	133(293)	133(293)
Final Nozzle	N.A.	N.A.	N.A.	N.A.	32(71)	32(71)
Total Wing Nacelle Weight	1447(3194)	1268(2799)	1111(2452)	1337(2951)	1212(2675)	1619(3573*)
Total Tail Nacelle Weight	1268(2799)	1138(2512)	981(2165)	1207(2664)	1082(2388)	1462(3228*)
Total Nacelle Weight per Airplane	4162(9187)	3674(8110)	3202(7069)	3880(8566)	3505(7738)	4699(10374)

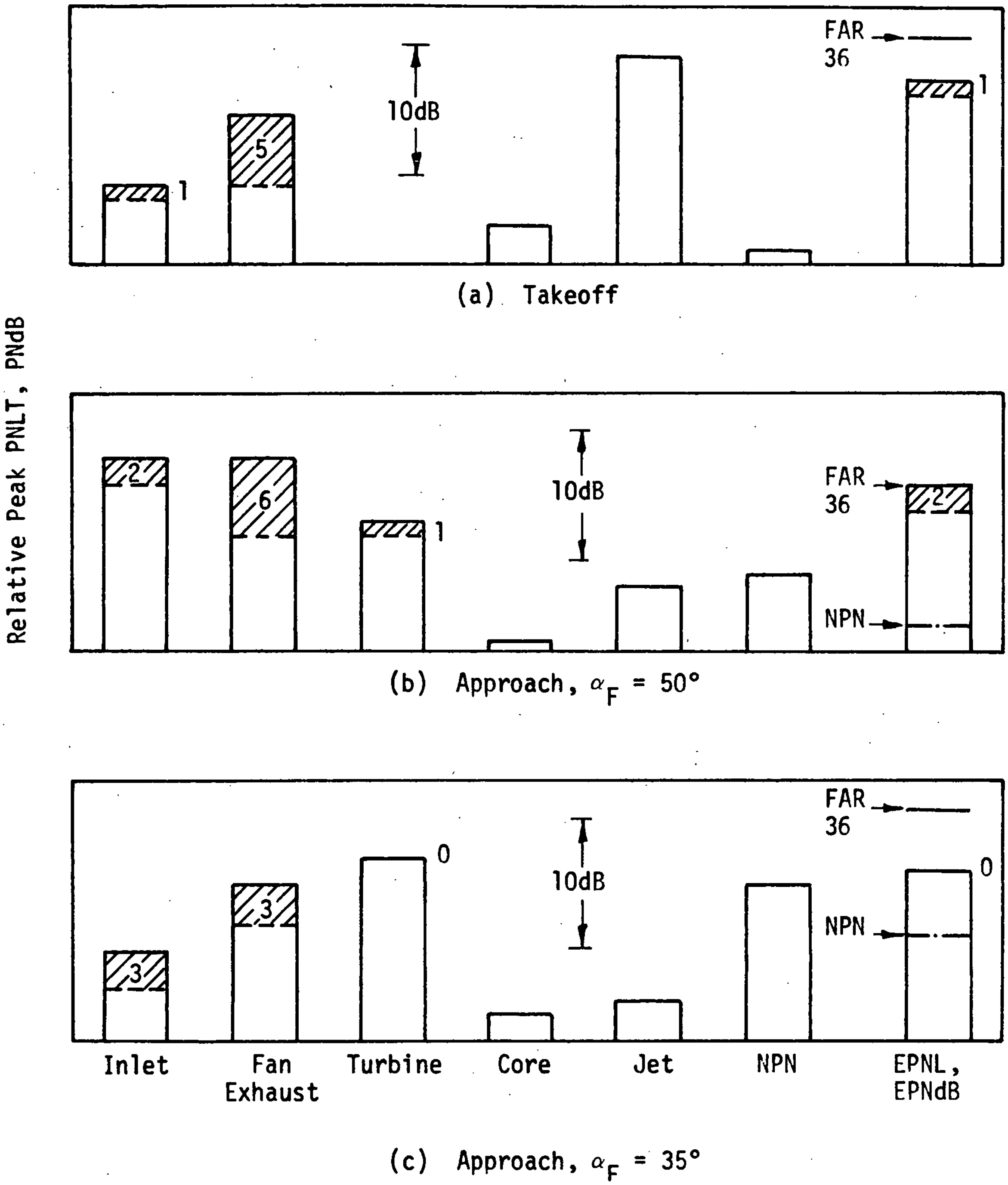
* Includes 45 kg (100 lb) per wing nacelle pylon and 68 kg (150 lb) per tail pylon for structure beef-up due to increased weight relative to baseline.

additional treatment were determined from data correlations developed from the results of previous model-scale and full-scale static tests as well as flight tests of high-bypass-ratio fan engine installations. All study nacelle configurations were assumed to have straightened fan OGVs and consequently all were credited with 1-PNdB less noise from the fan-discharge ducts at the approach and takeoff power settings compared with the fan discharge noise from the baseline WBT short-duct nacelle. Noise reductions for the bulk absorber lining in the inlet duct were predicted from the test results given in Figure 15.

Figure 58 shows the changes in inlet, fan-discharge, and turbine noise due to the bulk-absorber inlet treatment and the improved/additional treatment in the fan- and turbine-discharge ducts. At the takeoff power setting, Figure 58(a), the reductions in turbomachinery noise yielded only 1-EPNdB reduction in airplane noise because of the controlling influence of the unchanged jet noise. The 1-EPNdB reduction was estimated to be achieved by a shortening of the duration of the perceived noisiness of the total signal due to the lower level of turbomachinery noise as the airplane approached the microphone.

For the maximum-flap appraoch case, Figure 58(b), the changes in turbomachinery noise for Configuration IA resulted in a 2-EPNdB reduction in airplane noise. To have achieved more noise reduction would have required, first, more inlet treatment (by lengthening the inlet or by adding acoustically treated splitters), and, second, the provision for more treatment in the fan- and turbine-discharge ducts.

For the normal-flap approach case, Figure 58(c), the added or improved treatment did not give any reduction in airplane noise because of the high levels of turbine and non-propulsive noise. Some additional turbine noise reduction could have been achieved if more turbine acoustical treatment had been incorporated. The level of non-propulsive and core noise, however, would limit the airplane noise reduction at this flap setting no matter how much acoustical treatment was incorporated.



NOTE: SHADED PORTIONS DENOTE NOISE REDUCTIONS RELATIVE TO CURRENT WBT NACELLES.

FIGURE 58. WBT COMPONENT NOISE LEVELS FOR NACELLE CONFIGURATION IA AT MTOGW AND MLGW FOR FAR PART 36 MEASUREMENT LOCATIONS

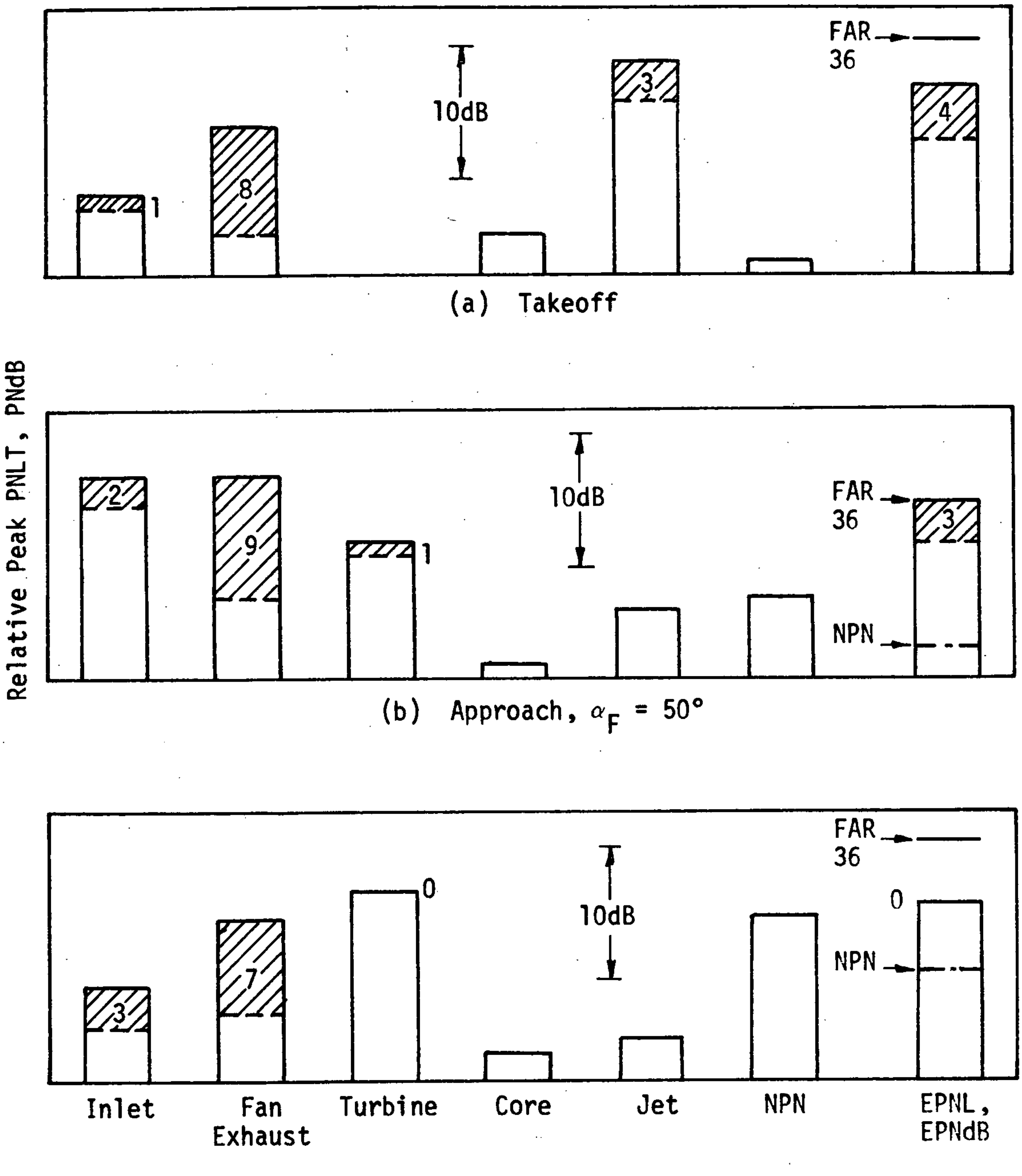
Noise reductions for nacelle Configurations IB and IC were the same as those estimated for Configuration IA. Configuration IC had more fan noise suppression than Configurations IA and IB but the same reduction in airplane noise because of the dominance of inlet noise for the 50-degree-flap case on the one hand and turbine and non-propulsive noise for the 35-degree-flap case on the other hand. At the takeoff condition, all short-duct nacelles had the same jet noise and therefore the same total airplane noise.

Component noise reductions for the long-duct mixed-flow Configuration II are shown in Figure 59. The changes in inlet noise were identical to those achieved by the short duct nacelles (Figure 58) because the same inlet was used.

For the takeoff power condition, the lower velocity of the jet exhaust, coupled with the difference in the flow fields around the jet for the separate-flow and mixed-flow nacelles (the so-called relative-velocity effect during climbout), was estimated to be able to produce 3-PNdB lower jet noise at the same engine fan speed and distance. As shown in Figure 59(a), the 3-PNdB jet noise reduction yielded 4-EPNdB suppression of airplane noise after accounting for an improvement in duration due to the reduction in fan noise. With the 1-PNdB credit for the straightened OGVs, the extensive treatment in the fan-discharge ducts was estimated to yield 8-PNdB reduction in fan noise at this takeoff power setting.

At approach, the treatment in the long fan-discharge ducts did not yield large airplane noise reductions because of the relatively high levels of inlet and turbine noise. The limited amount of turbine noise treatment included in the design for nacelle Configuration II was estimated to reduce turbine noise by 1 PNdB at the 50-degree-flap condition with an accompanying reduction of 3 EPNdB in airplane noise, Figure 59(b).

For the normal-flap case, the 3-PNdB reduction in inlet noise and the 7-PNdB reduction in fan-discharge noise were offset by the lack of suppression in turbine noise and the relatively high level of non-propulsive noise. The result was no change in airplane noise, Figure 59(c),



(c) Approach, α_F = 35°

NOTE: SHADED PORTIONS DENOTE NOISE REDUCTIONS RELATIVE TO CURRENT WBT NACELLES.

FIGURE 59. WBT COMPONENT NOISE LEVELS FOR NACELLE CONFIGURATION II AT MTOGW AND MLGW FOR FAR PART 36 MEASUREMENT LOCATIONS

compared to the total airplane noise at this flap setting for the baseline airplane with short-duct nacelles.

These acoustical evaluations for the three study short-duct nacelles and the study long-duct nacelle are summarized in Figure 60. Noise reductions are for the MTOGW and MLGW conditions at the Part 36 locations. Approach noise reduction were those associated with 50-degree flaps.

Changes in the area enclosed by the 90-EPNdB contour are shown in Figure 61. These contours were calculated using the conditions of Table 1 and a corresponding straight-out takeoff flight path and straight-in 3-degree approach glideslope. The runway is shown schematically in the center and was assumed to be 3.66-km (12,000ft) long. The calculated values of the total enclosed areas and changes in area are indicated. For Configuration IA, the area reduction was about 4 percent. For Configuration II, the area reduction was a little more than 36 percent. Some additional reduction in enclosed area could be achieved by additional suppression of inlet and turbine nosie at approach. Significant further reductions in enclosed area, however, would require larger suppression of jet noise during takeoff.

7.4 Manufacturing Cost Analysis

There is ample evidence that while traditional cost estimating techniques are good indicators of past experience and historical performance, these techniques do not provide adequate bench marks for cost projections or assessment of the impact of application of advanced technology materials. To adequately reflect these anomalies and account for the cascading beneficial effects of improvements offered with new design, material, and manufacturing concepts, assessments of specific applications were made rather than projecting generic applications in an across-the-board manner and then factoring from the conventional to the new concept. This discussion is not intended to discredit existing techniques; but, rather to provide visibility into what was considered a more appropriate approach.

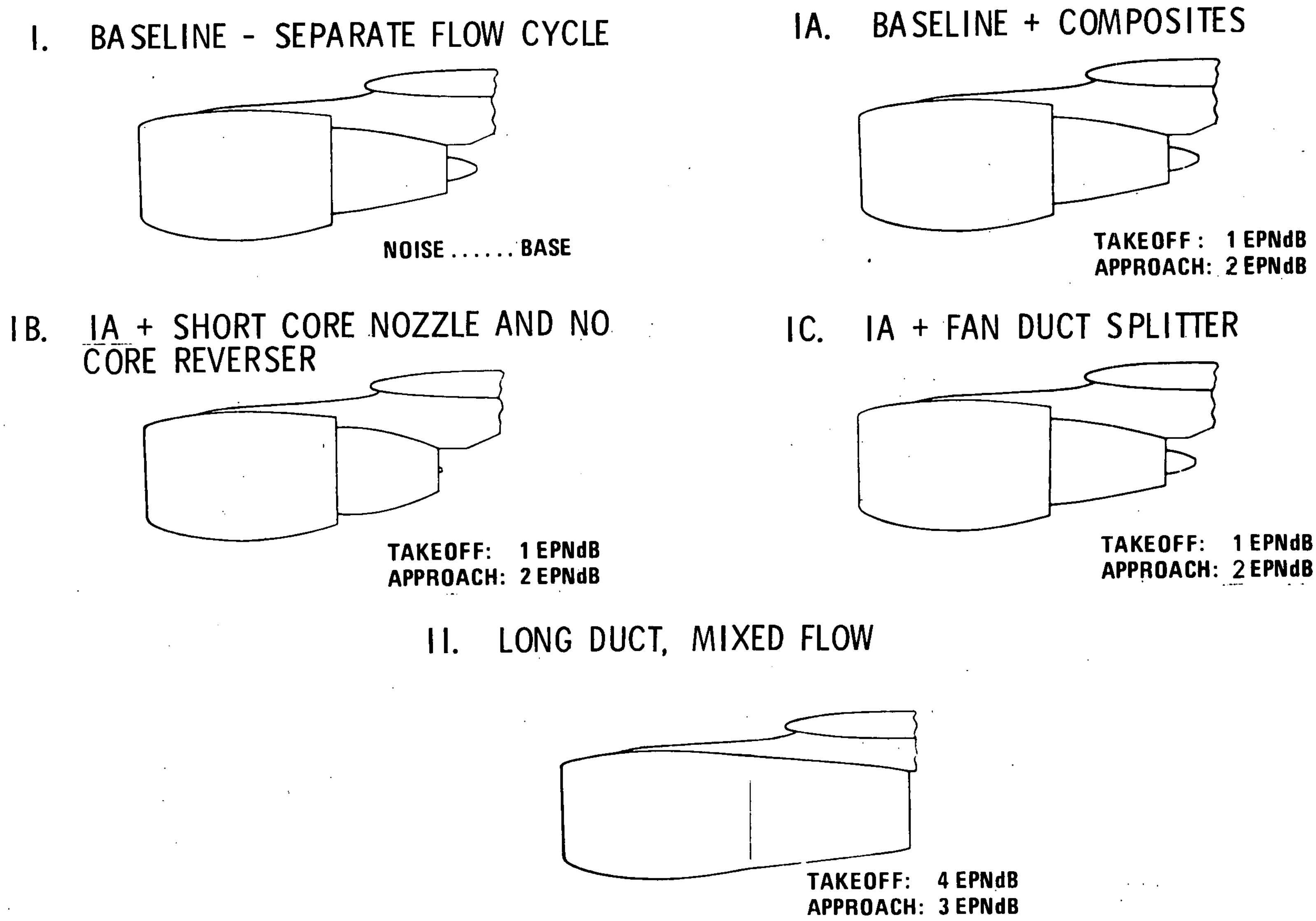
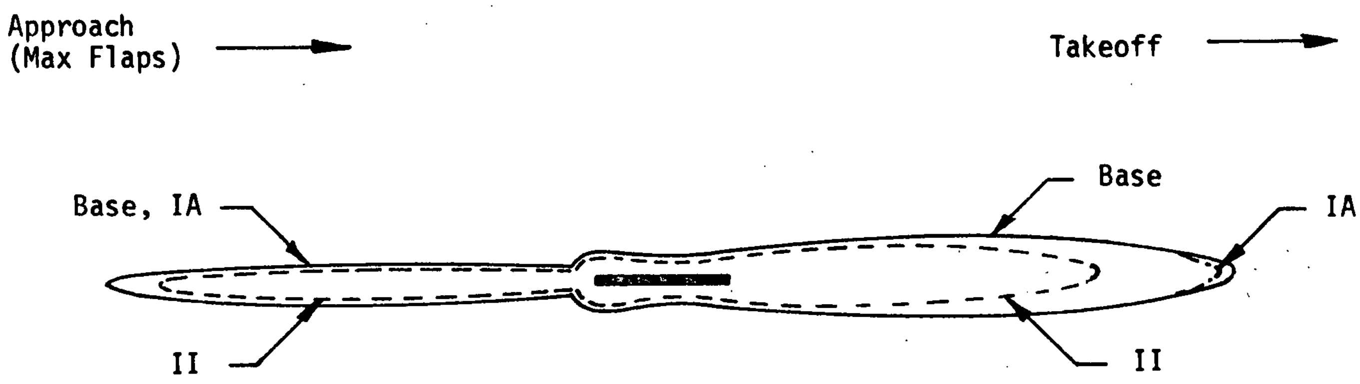


FIGURE 60. SUMMARY OF WBT ACOUSTICAL EVALUATIONS



Nacelle	Enclosed Area Sq km	Reduction In Area Percent
Base	37.3	Datum
1A	35.7	4
11	23.8	36

FIGURE 61. 90 EPNdB CONTOURS FOR WBT CONFIGURATIONS AT MTOGW AND MLGW

The hardware acquisition costs for each candidate concept were derived using a comparative industrial engineering approach rather than traditional parametric costing for the reasons stated above. This is a standard methodology employed by Douglas for new concepts and specifically designated aircraft areas. It was used in order to be able to relate the costs to the specific detailed design, fabrication, and subassembly and component processing concepts.

The Douglas cost analysis group and its support functions conducted a detailed analysis of the manufacturing cost estimating drawings. The format of these drawings provided sufficient information for estimators and planners to accomplish their tasks in a manner comparable to a production situation. With this type of format, drawings were released into the cost analysis information flow system depicted in Figure 10. Built into this system was a constant feedback approach wherein reviews and decisions were iterated among the various organization functions that contributed detailed information to the estimating process. In this particular study only the fan cowl door and the nose cowl and their respective conventional metal baselines were cycled through this procedure or system. In each case the composite designs were compared to the conventional metal designs that are part of the existing aircraft nacelles.

The purpose of the process and the format of the drawings was to:

- Identify manufacturing steps unique to the alternative design approaches
- Develop a preliminary manufacturing plan
- Identify tools, equipment and facilities
- Identify, define and apply appropriate material and labor standards and allocations
- Identify direct labor rates, burden and other factors to establish costs

Cost was considered in this study as a critical system parameter and a key measure in assessing the potential of the design concepts. Therefore, visibility, consistency and realism were principal attributes of the costing approach in order to properly and equitably discriminate among the candidates and compare to the conventional baseline. A description of this methodology follows:

A. Ground Rules and Assumptions

   1. Establish a practical set of ground rules and assumptions as a primary set of guidelines (see Table 17)

B. General Information

   1. Determine total quantity of parts to be manufactured
   2. Determine number of releases
   3. Determine number of assemblies per release

C. Determine Material Costs

   1. Determine materials types, form, weight and other quantity descriptors
   2. Assign material utilization factors to arrive at the material purchase quantity versus design weight (see Table 18)
   3. Apply material cost factors to quantity requirements

D. Direct Production Labor Elements

   1. Develop operational sequence planning documentation - Advanced Bid Worksheets (See sample in Figure 11)
      a. Identify fabrication of detailed parts or component manufacturing
      b. Identify assembly of detailed parts to provide end item or component of end item
   2. Determine types and quantities of tools as well as design and fabrication labor, and tooling material costs - jigs, dies, fixtures, etc.

TABLE 17. COST ANALYSIS GROUND RULES AND ASSUMPTIONS

- Costs developed in constant 1974 dollars
- Final cost outputs compared to a baseline configuration
- Production quantity of 300 aircraft systems
- Total of 15 releases for life of program
- Total of 20 shipsets per release
- Tooling established for a production rate of 5 shipsets per month
- Labor rates include direct labor, overhead and G&A
- Single manufacturer assumed
- Production facilities and airline repair facilities assumed available (except for tooling)
- Standard hours conform to Douglas Industrial Engineering standard rate guide
- Direct operating cost based on updated 1967 ATA "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes"
- Airline operating economics limited to DOC computations - study constraint based on funding and time

TABLE 18. RAW MATERIAL COST FACTORS

Material	Buy-To-Fly Factor	Cost Factor	
		Per Kilogram	Per Pound
Kevlar 49	1.408	$ 55.00	$25.00
Graphite	1.205	$170.85	$77.50
Adhesive	1.205	$ 56.57	$25.66
Aluminum Honeycomb Core	1.205	$ 18.01	$ 8.17
Aluminum Sheet	1.235	$ 3.62	$ 1.64
Titanium Sheet	1.235	$ 48.77	$22.12
Other Range (Steel, Plastics, Glass, Etc.)	2.857 to 1.205	$3.15 to $44.09	$1.43 to $20.00

3. Develop base standard hours for operational sequence to include set-up time and run time at unit T_{100}.

4. Convert base standard hours to estimated actual hours which provide the amount of hours necessary to manufacture the item including all tangible and intangible operations (clean-up, performance, shop services, personal allowances, etc.)

5. Project estimated actual hours to quantity requirements through progress curve application (fabrication curve, assembly curve or a combined curve).

6. Convert manufacturing estimated actual hours to direct labor dollars.

7. Determine manufacturing and tooling inspection hours as a function of the sum of fabrication/assembly and tooling hours.

8. Determine fabrication and assembly and tooling planning release hours.

9. Convert inspection and planning hours to direct labor dollars.

10. Sum all production labor elements.

With the approach described in the foregoing, the estimate for each element of the manufacturing discipline (labor, tooling, planning, inspection, etc.) was developed on its own merits from an industrial engineering standpoint.

The manufacturing cost estimating procedure described in the preceding section was applied to the fan cowl door and nose cowl concepts developed in this study. A summary of the manufacturing costs of the composite fan cowl door relative to the metal baseline is given in Figure 62. As shown, the composite design provides a significant reduction in labor costs which is only partially offset by the increased material costs. Breakdowns of the labor and material costs relative to the metal baseline are summarized in Figures 63 and 64. Figure 63 shows that the composite fan cowl door

	Cost of Advanced Composite Fan Cowl Door Relative to Baseline Metal Design (Per Door)
Labor	- $6710
Material	+ $2763
Total	- $3947

FIGURE 62. FAN COWL DOOR RELATIVE COST SUMMARY

	Cost of Advanced Composite Fan Cowl Door Relative to Baseline Metal Design (Per Door)
Recurring	
Manufacturing	- $5077
Planning	- $ 424
Tooling	- $ 355
Inspection	- $ 433
Total Non-Recurring	- $ 421
Total	- $6710

FIGURE 63. FAN COWL DOOR RELATIVE LABOR COSTS

	Cost of Advanced Composite Fan Cowl Door Relative to Baseline Metal Design (Per Door)
Aluminum	- $ 135
Titanium	- $ 218
Adhesive	- $ 6
Steel	- $ 36
Honeycomb Core	- $ 10
Kevlar -49	+ $ 370
Graphite	+ $2794
Fiberglass And/Or Other	+ $ 44
Total Recurring Material	+ $2803
Total Non-Recurring Material	- $ 40
Total	+ $2763

FIGURE 64. FAN COWL DOOR RELATIVE MATERIAL COSTS

is less labor intensive in all areas of production than the metal counterpart. Figure 64 shows that the increased material costs arise primarily from the cost of graphite, which for this study was \$177/kg (\$77.50/lb), as previously shown in Table 18. The sensitivity of the cost of the composite fan cowl door to the cost of graphite is shown in Figure 65. This figure indicates that the composite door was less expensive than the metal baseline at all graphite costs below \$412/kg (\$187/lb). Since \$177/kg (\$77.50/lb) represented an accurate current cost of graphite based on inputs from a number of suppliers, the confidence level was high that the composite fan cowl door could be produced at a lower cost than the metal baseline.

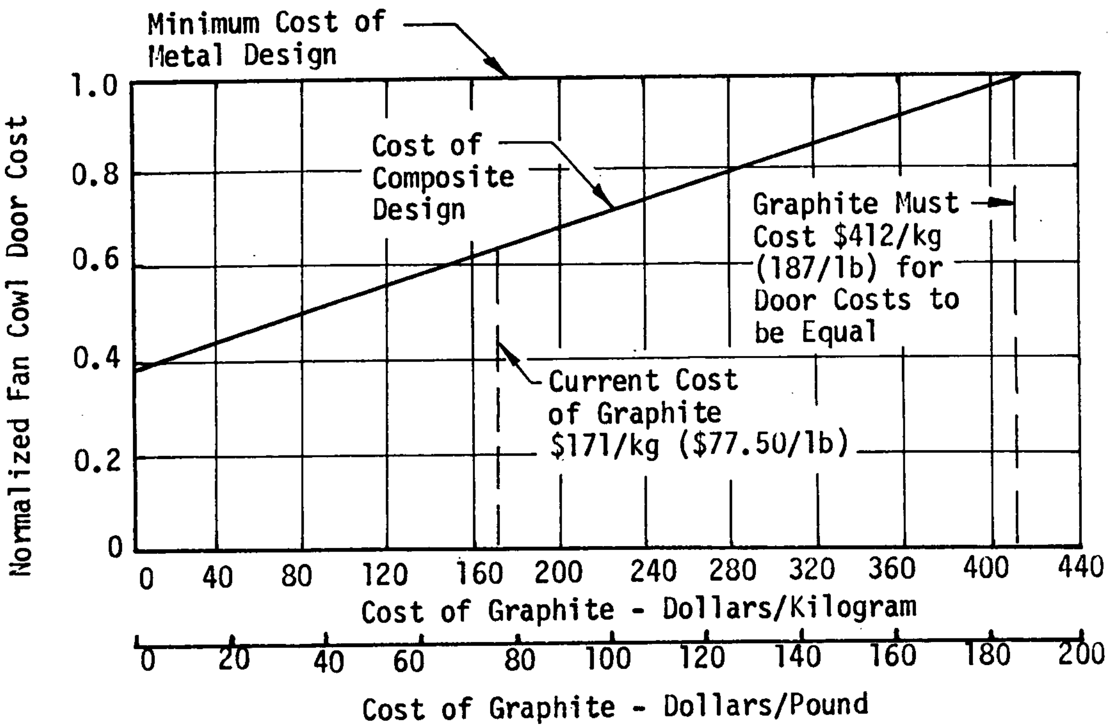


FIGURE 65. EFFECT OF COST OF GRAPHITE ON FAN COWL DOOR TOTAL COST

Figure 66 presents a summary of the manufacturing costs of the composite nose cowl (Figure 30, Configuration A) relative to the metal baseline. As in the case of the fan cowl door, the labor costs were substantially reduced; however, the material cost increases for the composite nose cowl nearly offset the labor cost reduction, resulting in a minimal total cost reduction. The breakdowns of the relative labor and material costs for the nose cowl are shown in Figures 67 and 68. Figure 67 indicates that labor costs for the composite nose cowl are lower in all areas except inspection. This increase in inspection requirements resulted primarily from the design of the acoustic inner barrel and the attach flange configuration. The material costs shown in Figure 68 are seen to be dominated by graphite, with the Kevlar costs also making a sizeable contribution.

As a result of the amount of effort required to obtain the cost estimates for the fan cowl door and nose cowl and because of the limited total scope of this study, the manufacturing costs of the remaining nacelle components were estimated by a simpler technique based on the weight breakdown for each part. Each remaining component was evaluated from the standpoint of its design and manufacturing complexity relative to the composite fan cowl door and nose cowl. The former represented the simplest composite part in the nacelle while the latter represented one of the most complex composite parts. A complexity factor was established for each of the remaining components relative to the fan cowl door and the nose cowl and that factor was used to modify the relationship of labor to material costs determined for the fan cowl door and nose cowl. In this way, the labor costs for the remaining nacelle components were established and the estimated total costs were determined by summing the material and labor cost estimates. It is recognized that the use of this technique represented a potential compromise in the accuracy of the results of the overall cost analysis. However, this compromise was considered minimal since all the components in question were similar in design concept and material choice to the fan cowl door and nose cowl. Also, the use of a complexity factor in this case was only to relate one composite design to another rather than to relate a composite design to a metal design.

	Cost of Advanced Composite Nose Cowl Relative to Baseline Metal Design (Per Nose Cowl)
Labor	- $6383 Each
Material	+ $5403 Each
Total	- $ 980 Each

FIGURE 66. NOSE COWL RELATIVE COST SUMMARY

	Cost of Advanced Composite Nose Cowl Relative to Baseline Metal Design (Per Nose Cowl)
Recurring	
Manufacturing	- $3960
Planning	- $ 257
Tooling	- $1083
Inspection	+ $ 403
Total Non-Recurring	- $1487
Total	- $6383

FIGURE 67. NOSE COWL RELATIVE LABOR COST SUMMARY

	Cost of Advanced Composite Nose Cowl Relative to Baseline Metal Design (Per Nose Cowl)
Aluminum	- $1127
Titanium	- $ 320
Adhesive	- $ 387
Steel	0
Honeycomb Core	- $ 217
Kevlar 49	+ $2023
Graphite	+ $5476
Fiberglass And/Or Other	+ $ 96
Total Recurring Material	+ $5546
Total Non-Recurring Material	- $ 143
Total	+ $5403

FIGURE 68. NOSE COWL RELATIVE MATERIAL COST SUMMARY

An example of how this procedure was applied is described below. The fan cowl door weight was 49 kg (109 lb)/door and the costs were 44% labor and 56% material. The nose cowl weight was 223 kg (491 lb), and the costs were split 69% labor and 31% material. For the aft fan duct (Figure 36), the weight was 86.5 kg (191 lb) per nacelle or 43.3 kg (95.5 lb) per duct half. Its complexity was roughly comparable to the fan cowl door, but acoustic treatment was required for the inner face. From the weight breakdown shown in Table 9, the material costs were estimated and a complexity factor was used to adjust the relationship of labor and material costs as appropriate. The labor costs were then determined and added to the material cost to get the total. For the metal final nozzle, the internal mixer, and the turbine nozzle/reverser, costs were obtained from GE or other suppliers of these types of metal nacelle components.

A tabulation of the relative costs of each of the major nacelle components, as they apply to each of the nacelle configurations, is given in Table 19. The costs shown in the Table are all relative to the total cost of nacelle Configuration I.

7.5 Airplane Operational Economic Analysis

For this study, direct operating cost (DOC) was used as the measure of the impact of advanced composite nacelles on airplane operating economics. The Douglas advanced design computer model of the 1967 (modified) ATA DOC formula was used for this study. Table 20 summarizes the major cost elements that make up the DOC analysis. A breakdown of the constants and variables that go into those major cost elements is given in Table 21. The total nacelle costs that were used to construct Table 19, were also used as inputs to vary the airframe cost for the DOC study. The weight differences from Table 16 were used to vary the airplane empty weights and the outputs of the computer program described in Section 4.3.1 were used to vary the block fuel and block time values. DOCs were calculated for each of the five nacelle configurations at mission ranges of 3704, 7223 and 9890 kilometers. The price of fuel was varied from $.035/liter ($0.13/gallon) up to $0.175/liter ($0.65/gallon).

TABLE 19. NACELLE CONFIGURATION RELATIVE COST SUMMARY

Configuration	1	1A	1B	1C	11
Nose Cowl	.135	.132	.132	.132	.132
Fan Cowl	.069	.044	.044	.044	.044
Fan Reverser	.481	.445	.445	.457	.430
Inner Core Cowl	.086	.034	.034	.034	.040
Outer Fan Duct	N.A.	N.A.	N.A.	N.A.	.042
Turbine Nozzle and Reverser	.229	.229	.088	.229	N.A.
Mixer and Plug	N.A.	N.A.	N.A.	N.A.	.048
TOTAL	1.0	.884	.743	.896	.770

TABLE 20. DIRECT OPERATING COST ELEMENTS

- Crew
- Insurance
- Airframe Maintenance
  - Labor
  - Material
- Depreciation
- Fuel
- Engine Maintenance
  - Labor
  - Material

TABLE 21. DIRECT OPERATING COST CONSTANTS AND VARIABLES

Crew	TOGW, Crew Complement, Block Time
Insurance	Annual Rate, Aircraft Price, Utilization, Block Time
Depreciation	Residual Value, Spares Factor, Depreciation Period, Utilization, Block Time, Aircraft Price
Airframe	
(Labor)	Empty Weight Less Engines, Ground Maneuver Time, Block Time
(Materials)	Aircraft Price Less Engines, Ground Maneuver Time, Block Time
Engine Maintenance	
(Labor)	SLS Thrust/Engine, Number Engines, Block Time, Ground Maneuver Time
(Materials)	Price Per Engine, Number Engines, Block Time, Ground Maneuver Time
Fuel	Fuel Price Per Gallon, Block Fuel

Figures 69, 70 and 71 show the relative DOCs for each of the configurations at the three mission ranges and at three fuel prices. In each case, the DOC of the baseline configuration is unity and the other configurations are shown relative to the baseline. In all cases, the DOC of the Configuration II long duct nacelle is at least 2% lower (better) than the baseline.

Figure 72 shows the distribution of DOC elements at the three study mission ranges for nacelle Configuration II and two fuel prices. Of significance in these figures is the contribution of fuel cost to total DOC, roughly 35% at \$0.07/liter (\$0.26/gallon) and increasing of 50 to 55% at \$0.14/liter (\$0.52/gallon). The primary source of reduced DOC for Configuration II, as shown in Figures 69 through 71, was from the reduced fuel consumption for that configuration. For example, at the 9890 km (5340 n mi) range, fuel price made up 38.7 percent of DOC at \$0.07/liter (\$0.26/gallon) for the baseline but dropped to 37.6 percent for Configuration II.

Table 22 presents a summary of the contribution of fuel cost to total DOC at the three mission ranges for fuel prices from \$0.035/liter to \$0.175/liter for the baseline, and Table 23 presents a similar summary for Configuration II.

Figure 73 shows the sensitivity of DOC to changes in fuel consumption, maintenance factor, and airplane price. These three variables represent the only major areas in which the composite nacelle was expected to have a significant cost impact and the ranges of those variables are the greatest that could be expected to accrue from changes to the nacelle involving advanced composites.

As shown in Figure 73, DOC exhibits the greatest senstivity to changes in fuel consumption over the range expected to result from the long-duct nacelle and the least sensitivity to changes in airframe price, the area where the advanced composite nacelle was expected to have the lowest relative effect.

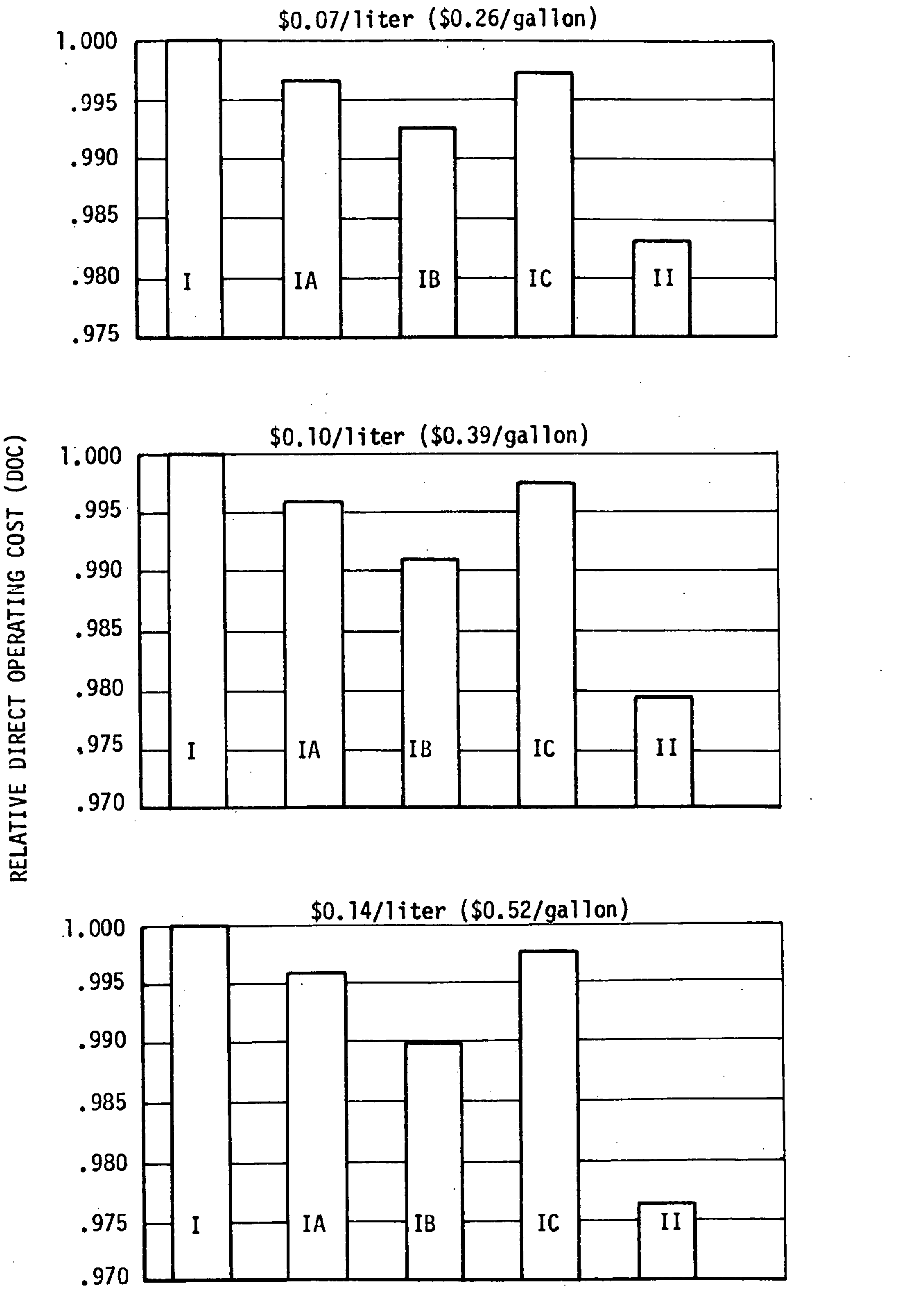


FIGURE 69. WBT RELATIVE DIRECT OPERATING COST (DOC) AT 3704 km (2000 n mi)

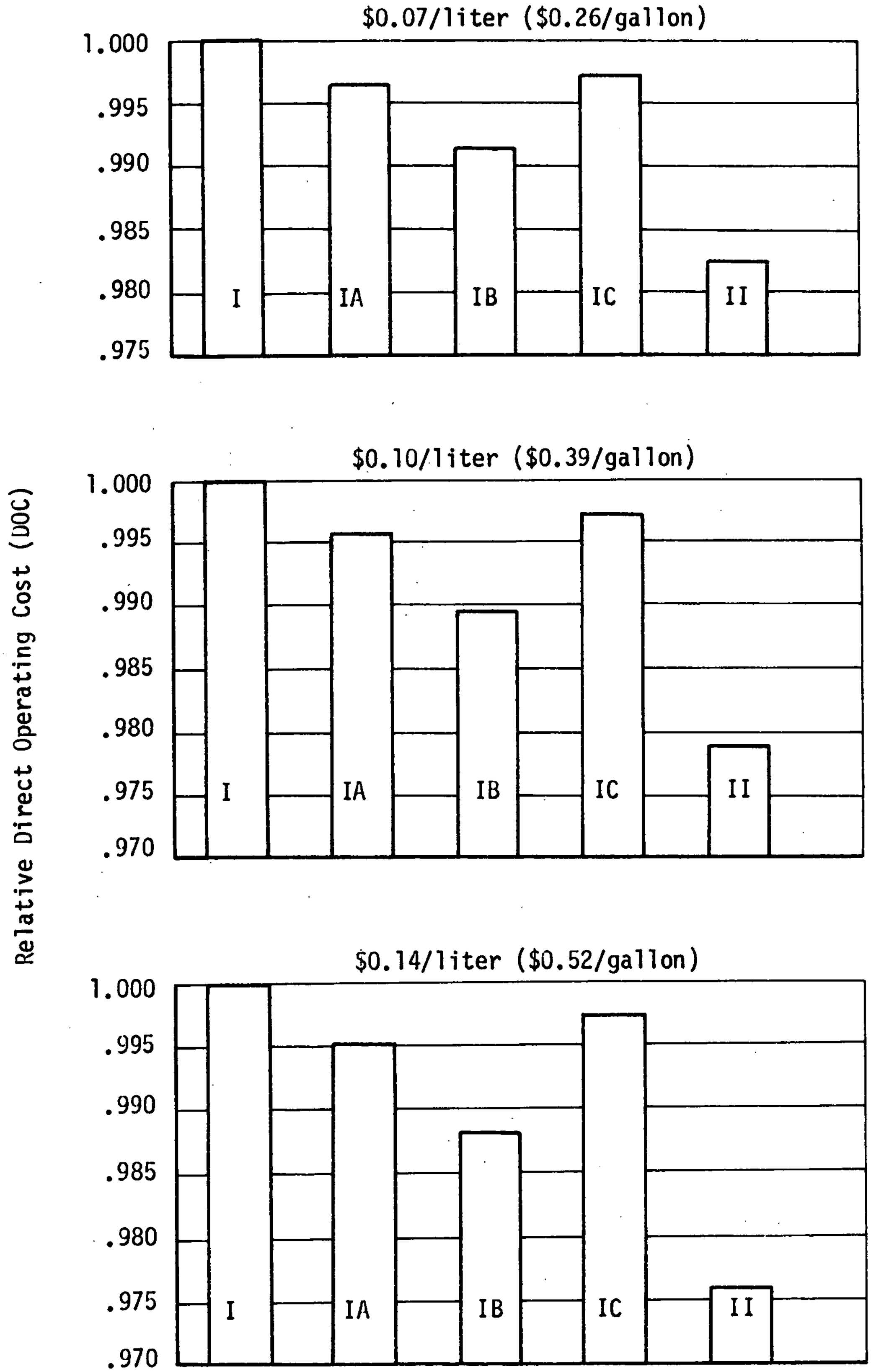


FIGURE 70. WBT RELATIVE DIRECT OPERATING COST (DOC) AT 7223 km (3900 n mi)

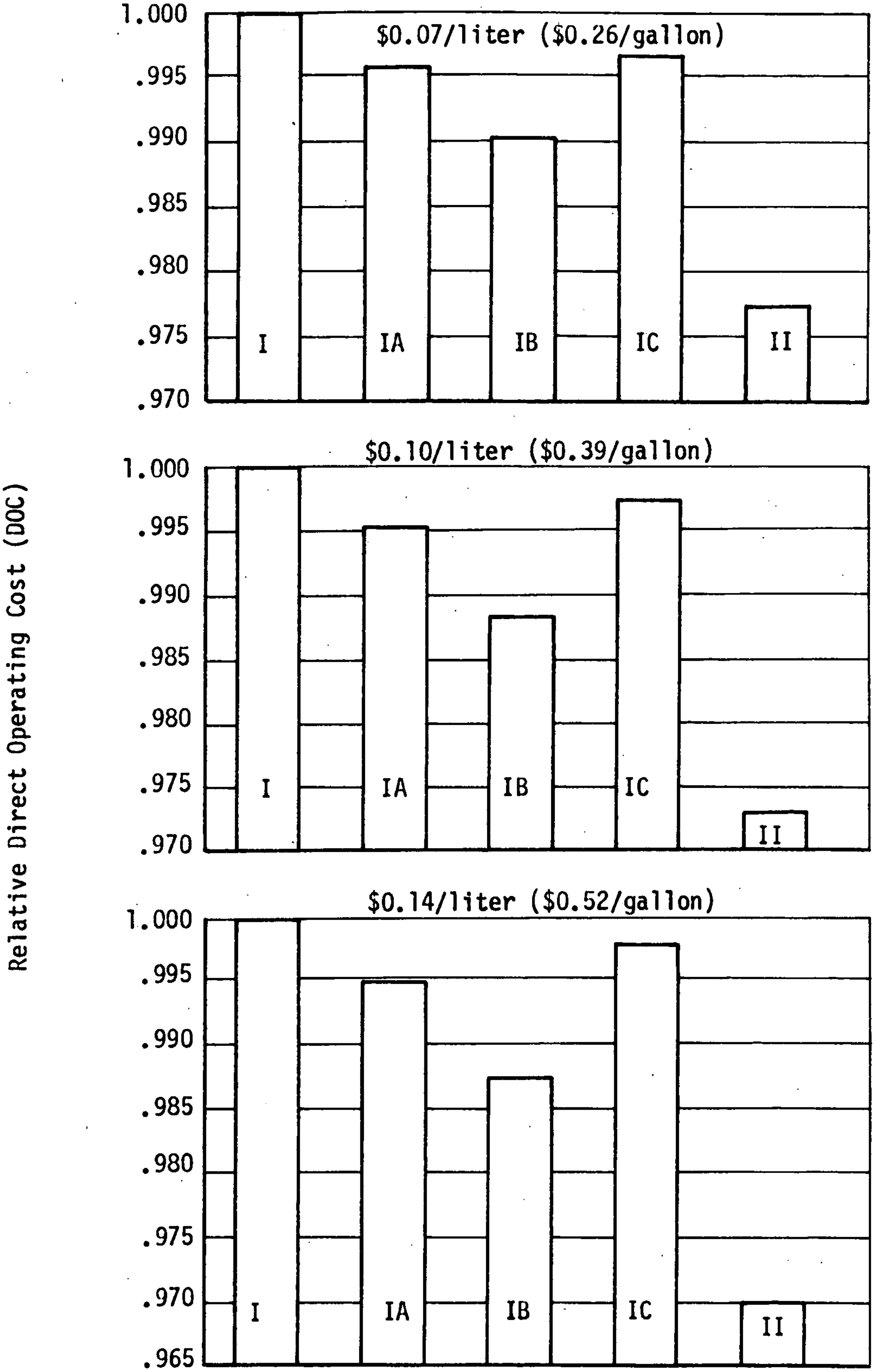


FIGURE 71. WBT RELATIVE DIRECT OPERATING COST (DOC) AT 9890 km (5340 n mi)

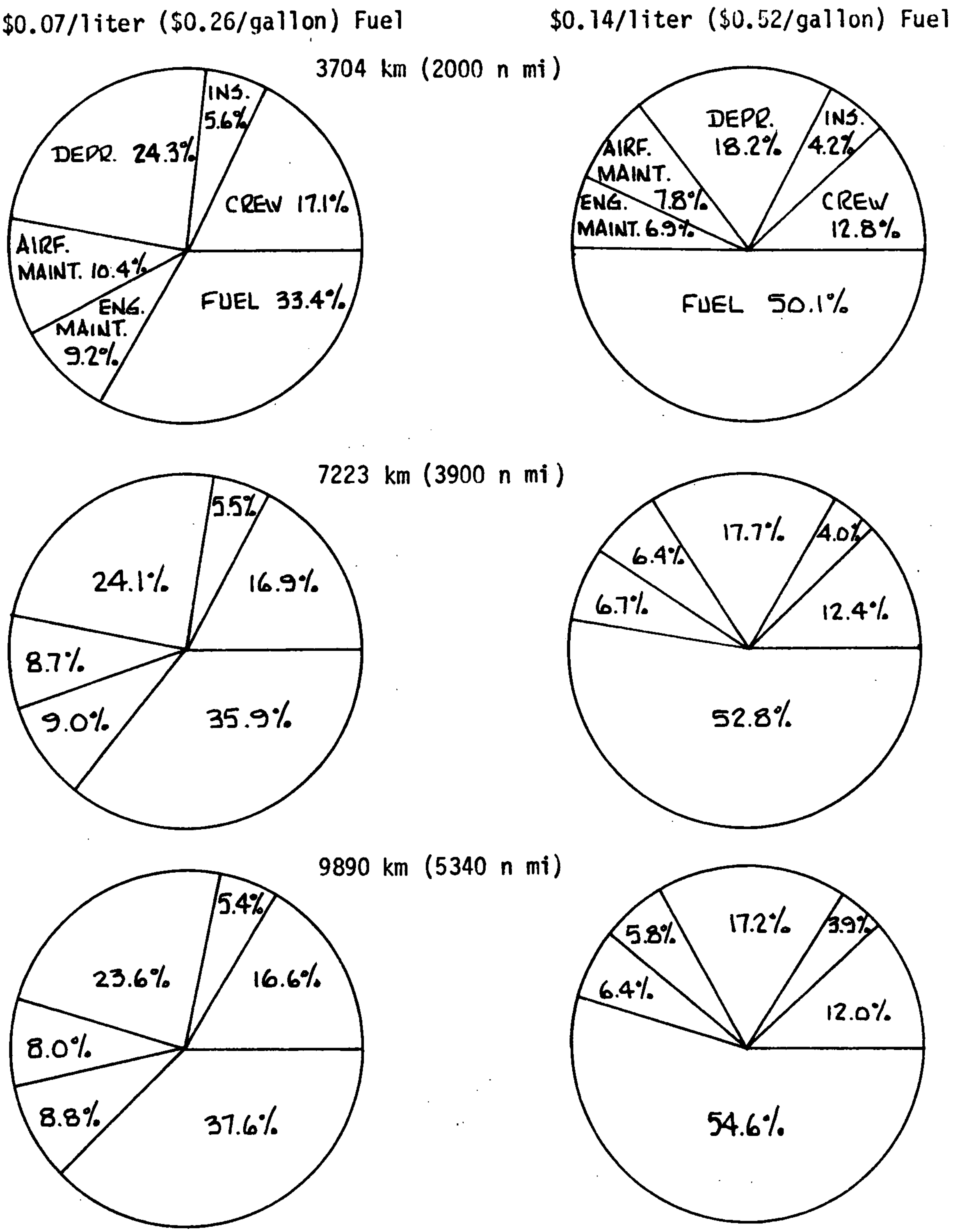


FIGURE 72. DISTRIBUTION OF DIRECT OPERATING COST ELEMENTS FOR WBT CONFIGURATION II

TABLE 22.

FUEL CONTRIBUTION TO DIRECT OPERATING COST FOR GIVEN RANGES AND FUEL PRICES FOR BASELINE NACELLE CONFIGURATION

FUEL PRICE		FUEL CONTRIBUTION TO DIRECT OPERATING COST - PERCENT		
$/liter	($/gal)	3704 km (2000 nmi)	7223 km (3900 nmi)	9890 km (5340 nmi)
.03	(.13)	20.7	22.5	24.0
.07	(.26)	34.3	36.7	38.7
.10	(.39)	43.9	46.5	48.6
.14	(.52)	51.0	53.7	55.8
.17	(.65)	56.6	59.2	61.2

TABLE 23.

FUEL CONTRIBUTION TO DIRECT OPERATING COST FOR GIVEN RANGES AND FUEL PRICES FOR NACELLE CONFIGURATION II

FUEL PRICE		FUEL CONTRIBUTION TO DIRECT OPERATING COST - PERCENT		
$/liter	($/gal)	3704 km (2000 nmi)	7223 km (3900 nmi)	9890 km (5340 nmi)
.03	(.13)	20.1	21.9	23.1
.07	(.26)	33.4	35.9	37.6
.10	(.39)	42.9	45.6	47.4
.14	(.52)	50.1	52.8	54.6
.17	(.65)	55.6	58.3	60.1

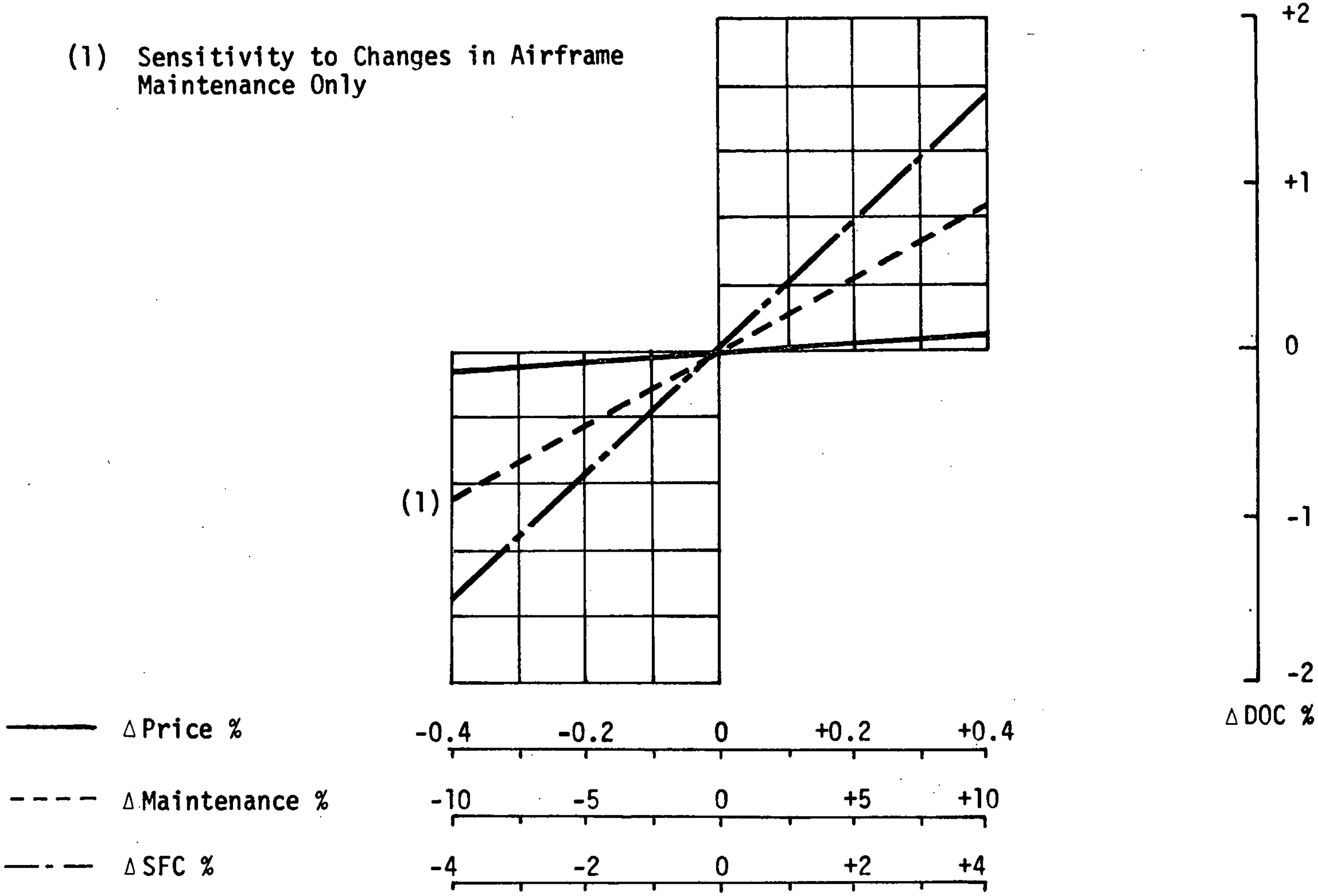


FIGURE 73. DIRECT OPERATING COST SENSITIVITIES FOR 7223 km (3900 n mi) MISSION - 3800 HR/YR UTILIZATION BASELINE AIRPLANE

7.6 Fuel Savings Analysis

The airplane performance computer program described in Section 4.3.1 was used to conduct the fuel savings analysis. The internal and external aerodynamic performance analyses described in Section 7.3 provided the inputs for varying the cruise fuel consumption of the basic airplane. The results of the weight estimates were used to vary the airplane empty weight for the various configurations. The baseline airplane was flown at the base empty weight and cruise specific fuel consumption over the mission ranges of interest and at a variety of cruise profiles. A fixed payload of 25,107 kg (55,350 lb) was used for all missions. The most fuel efficient profile for each of the three mission ranges was selected and the remaining study nacelle configurations were flown at the same profiles. For example, at 7223 km (3900 n mi), the most fuel efficient fligh profile for the baseline airplane at which the full payload could be carried was an initial cruise altitude of 10058 m (33,000 ft) with a step climb to 11278 m (37,000 ft). Therefore, the other configurations used this same profile. The result of this analysis was the tabulation in Table 24, of block fuel usage for each configuration at the three mission ranges. Since Configuration II offered the greatest block fuel reductions for each of the three ranges, the remainder of the fuel savings analysis concentrated on that configuration.

Tabulated values of block fuel usage for Configuration II were used to construct the curve of Figure 74. This curve shows the reduction in block fuel for Configuration II, relative to the baseline, as a function of mission range. To determine the total annual fuel savings for one wide body trijet, the assumed annual utilization, which for this study was 3800 hours, was divided by the block time for a specific mission range. For example, the block time for the 7223-km (3900-n mi) mission was 8.65 hours, or 439 theoretical 7223-km (3900-n mi) trips per year. Multiplying the number of trips (blocks) by the fuel savings per trip yields the total annual fuel savings per wide body trijet. Repeating the procedure for the 3704 and 9890 km (2000 and 5340 n mi) missions yielded the curve in Figure 75, using a fuel density of 0.779 kg/liter (6.5 lb/gallon).

TABLE 24. BLOCK FUEL USAGE FOR WBT STUDY NACELLE CONFIGURATIONS

Configuration	Block Fuel Usage - kg (lb)					
	Range					
	3704 km	(2000 n mi)	7223 km	(3900 n mi)	9890 km	(5340 n mi)
I	32,256	(71,206)	65,192	(143,911)	94,667	(208,977)
IA	32,173	(71,023)	65,011	(143,512)	94,382	(208,348)
IB	31,879	(70,373)	64,395	(142,153)	93,421	(206,228)
IC	32,216	(71,117)	65,087	(143,680)	94,502	(208,614)
II	30,971	(68,368)	62,302	(137,531)	90,169	(199,049)

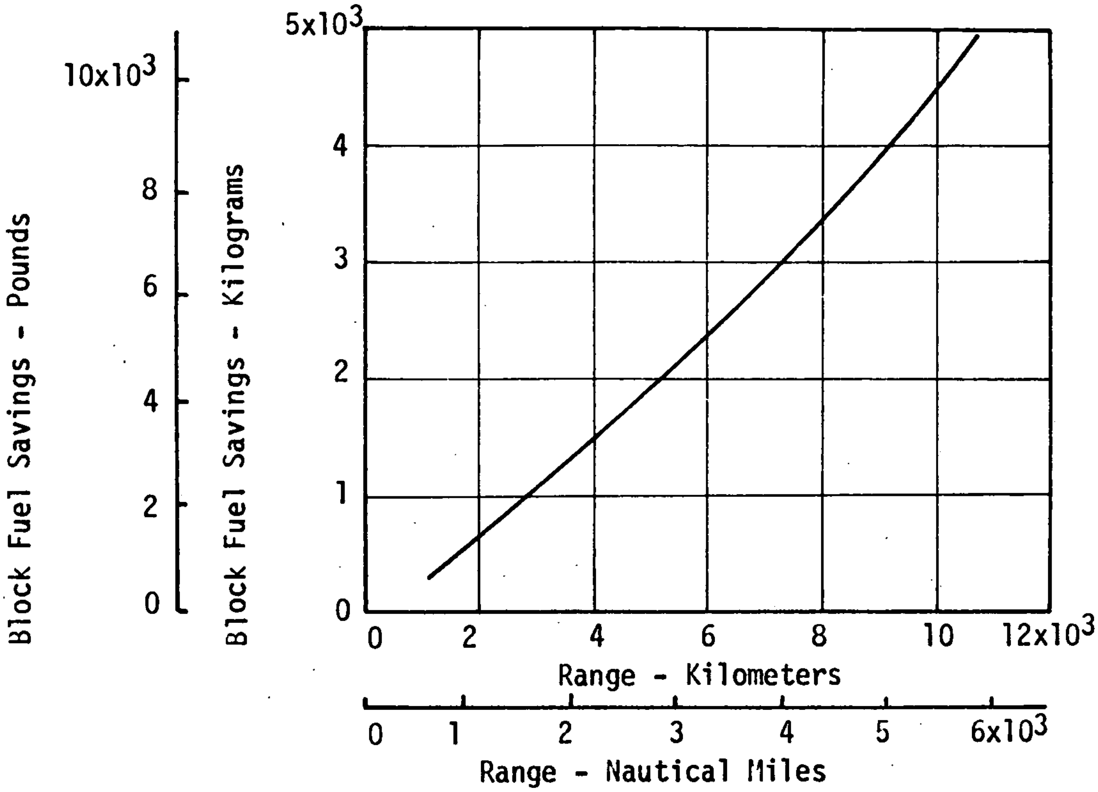


FIGURE 74. BLOCK FUEL SAVINGS FOR LONG DUCT, MIXED FLOW COMPOSITE NACELLE

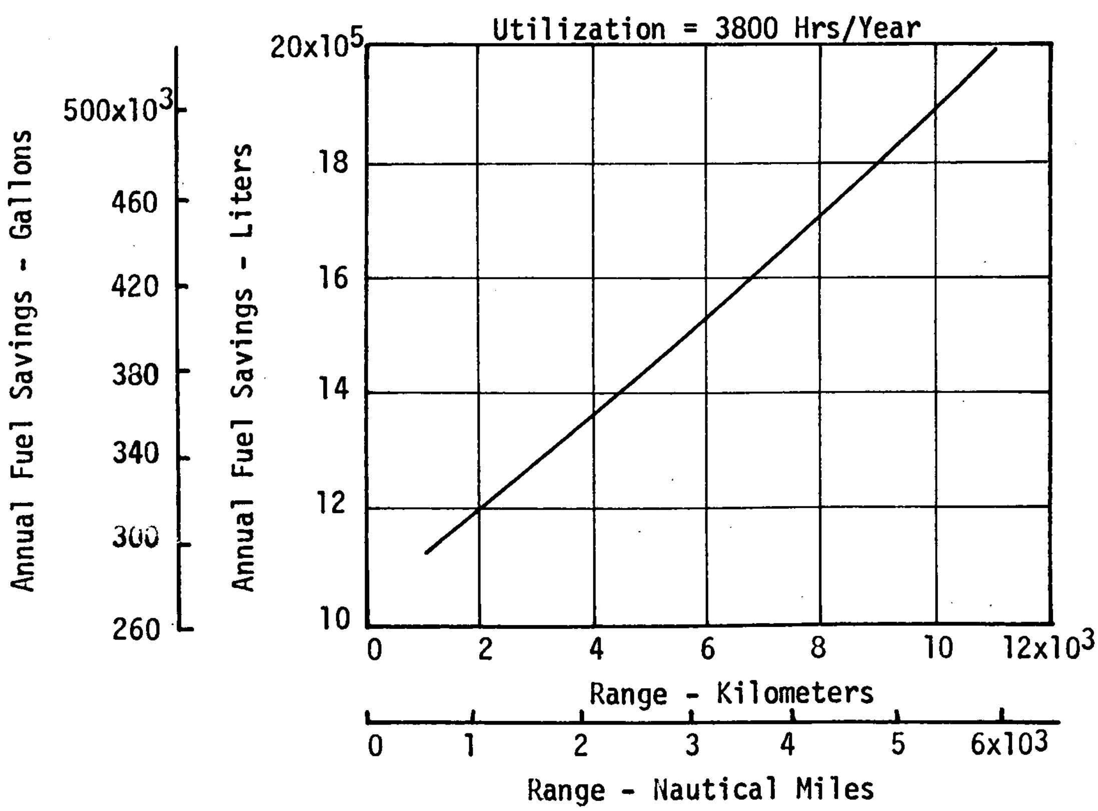


FIGURE 75. ANNUAL WIDE-BODY TRI-JET FUEL SAVINGS

Since this study looked at the costs and benefits of advanced composite nacelles on newly-produced wide-body transports, no retrofit was considered for airplanes already in service. Newly produced aircraft can be reasonably expected to have useful lives of at least 15 years. Therefore, the fuel savings that could be expected over the life of a newly produced wide body with a composite long-duct nacelle would be, conservatively, 15 times the annual fuel savings. A sample calculation for block, annual, aircraft life and representative fleet size fuel savings is shown in Figure 76.

During the years 1973 and 1974, a total of 238 wide body transport aircraft were delivered for an average of 119 aircraft/year. If the technology identified is delayed in reaching production acceptance by one year, and the 119 aircraft/year production rate continues, the \$200M figure calculated in Figure 76 represents the average resulting loss in potential fuel consumption savings per year.

Since the cost of jet fuel can be expected to rise well above \$0.07/liter (\$0.26/gallon), as indicated in Table 25, the \$200M fuel savings value is considered conservative and could easily reach or exceed \$400M, per year of delay of introduction of this technology into commercial service.

8.0 EVALUATION OF ATT NACELLE CONFIGURATION

8.1 ATT Nacelle Weight

For the ATT nacelle, an analysis was made to determine the contributions of the integrated nacelle concept and the application of advanced composites to the total nacelle weight. This analysis was conducted by comparing the ATT bare engine and installed thrust-to-weight ratios to the equivalent CF6-50 values as shown below.

A. Basic ATT #4 engine thrust/weight = 133.5 kN (30,000 lb)/1900 kg (4195 lb)
= 7.15

B. Installed ATT #4 thrust/weight = 133.5 kN (30,000 lb)/2904 kg (6420 lb)
= 4.69

For an aircraft mission of 7223 kilometers (3900 nautical miles), the study WBT baseline aircraft has the following characteristics:

Operating empty weight	-kg (lb)	118,585 (261,431)
Takeoff gross weight	-kg (lb)	220,358 (485,799)
Landing gross weight	-kg (lb)	155,680 (343,209)
Cruise fuel consumption		Base
Total fuel burned	-kg (lb)	65,278 (143,911)
Fuel reserves	-kg (lb)	11,988 (26,429)
Total fuel carried	-kg (lb)	77,112 (169,999)
Block time	-hours	8.65

Change to the airplane for the same mission with the Configuration II nacelle include:

Operating empty weight	-kg (lb)	117,928 (259,983)
Takeoff gross weight	-kg (lb)	216,350 (476,962)
Landing gross weight	-kg (lb)	154,565 (340,752)
Cruise specific fuel consumption		-3.42%

The computer printout for this mission with the modified nacelles showed the following:

Fuel burned	-kg (lb)	62,384 (137,531)
Reserve fuel	-kg (lb)	11,531 (25,420)
Total fuel carried	-kg (lb)	73,760 (162,610)

The block fuel (fuel burned) change for this mission is therefore:

$$\begin{array}{rr} & 65{,}278\ \text{kg}\ (143{,}911\ \text{lb}) \\ - & \underline{62{,}384\ \text{kg}\ (137{,}531\ \text{lb})} \\ & 2{,}894\ \text{kg}\ \ (6{,}380\ \text{lb}) \end{array}$$

FIGURE 76. SAMPLE FUEL SAVINGS CALCULATION

The annual fuel savings for this same mission can be determined as follows:

Annual utilization	3800 hours
Block time	8.65 hours

The theoretical number of flights of this length that could be made is therefore:

3800   8.65 = 439

For this number of flights, the annual fuel savings becomes:

439 flights x 2894 kg (6380 lb)/flt = 1,270,466 kg (2,800,820 lb), or

1,630,937 liters (430,895 gallons)

The corresponding values for 3704 km (2000 nmi) and 9890 km (5340 nmi) are shown below:

3704 km	Block fuel savings:	32,299 - 31,012	= 1,287 kg
	Total annual flights:	3800 4.64	= 819
	Total annual savings:	$\frac{1.287 \times 819}{0.779\ \text{kg/liter}}$	= 1,353,085 liters
9890 km	Block fuel savings:	94,785 - 90,289	= 4496 kg
	Total annual flights:	3800 11.65	= 326
	Total annual savings:	$\frac{4496 \times 326}{0.779\ \text{kg/liter}}$	= 1,881,509 liters

Fifteen year fuel savings using 7223 km as the average mission would therefore be:

1,630,937 liters (430,895 gallons)/year x 15 years =

24,464,055 liters (6,463,425 gallons)

The total fuel savings for one year's production of wide body aircraft at the 1973-1974 average rate, for the total 15 year expected lives of those aircraft would be:

119 aircraft x 24,464,055 liters (6,463,425 gallons) =

2,911,222,545 liters (769,147,575 gallons)

At a fuel cost of \$0.07/liter (\$0.26/gallon), this potential savings becomes:

2,911,222,545 liters x \$0.07/liter (769,147,575 gallons x \$0.26/gallon)

= \$199,971,876 for one year's production of wide body aircraft over the total lifetime of those aircraft.

FIGURE 76. SAMPLE FUEL SAVINGS CALCULATION (CONCLUDED)

TABLE 25. U. S. AIRLINE INDUSTRY JET FUEL PRICE INCREASE

	Quantity (Billions of Gallons)	Cost ($ Millions)	Average Cost (Dollars/Gallon)
1. 1974 Cost			
JP Fuel Consumed Annually by U. S. Carriers			
Old Crude @ $0.125/Gallon	3.0	375	
New Crude @ $0.238/Gallon	2.3	547	
Imported Crude @ $0.300/Gallon	2.3	690	
Refining and Profit @ $0.058/Gallon		441	
TOTAL	7.6	2053	0.27
2. New Tariffs, Taxes and Government Price Increases			
Old Crude			
Price Increases $0.113/Gallon from decontrol of old crude	3.0	339	
Price increases $0.048/Gallon from excise tax	3.0	144	
New Crude			
Price increases $0.048/Gallon from excise tax	2.3	110	
Imported Crude			
Price increases $0.071/Gallon from tariff	2.3	163	
TOTAL	7.6	756	0.10
3. 1975 Cost			
Old Crude @ $0.286/Gallon	3.0	858	
New Crude @ $0.286/Gallon	2.3	657	
Imported Crude @ $0.371/Gallon	2.3	853	
Refining and Profit @ $0.058/Gallon		441	
TOTAL	7.6	2809	0.37

C. CF6-50C bare engine thrust/weight = 222.5 kN (50,000 lb)/3823 kg (8440 lb)
= 5.924

D. Configuration II composite nacelle
thrust weight = 222.5 kN/3823 kg + 1212kg
= 4.498

E. Configuration II metal nacelle
thrust weight = 222.5 kN/3823 kg + 1619 kg
= 4.162

If the ATT #4 engine and nacelle did not employ the integrated design concept, but did utilize advanced composites, a thrust/weight ratio of 4.498 (from item D above) could be expected. The resulting nacelle weight would then be as follows:

133.5 kN/4.498 = 3022 kg - 1900 kg (engine)
= 1121 kg nacelle only

The ATT no. 4 integrated nacelle weight was shown in Table 12 to be 1000 kg. The weight savings from the integrated design concept, therefore, was 1121 kg minus 1000 kg, or 121 kg (267 lb) total.

The ATT nacelle without composites and without the integrated design concept could be expected to have a thrust/weight ratio similar to the CF6-50C in a metal long duct nacelle, or 4.162 (Item E). The weight of the ATT nacelle in that case would be as follows:

133.5 kN/4.162 = 3265 kg - 1900 kg (engine
1365 kg - 1000 kg = 365 kg (805 lb)

Therefore, the composite, integrated nacelle design concept for the ATT no. 4 engine installation is worth 365 kg (805 lb) compared to a conventional installation design using conventional metallic hardware. In addition, substitution of a fixed geometry inlet for the variable geometry inlet used in this study would increase the 365 kg value by 50 kg.

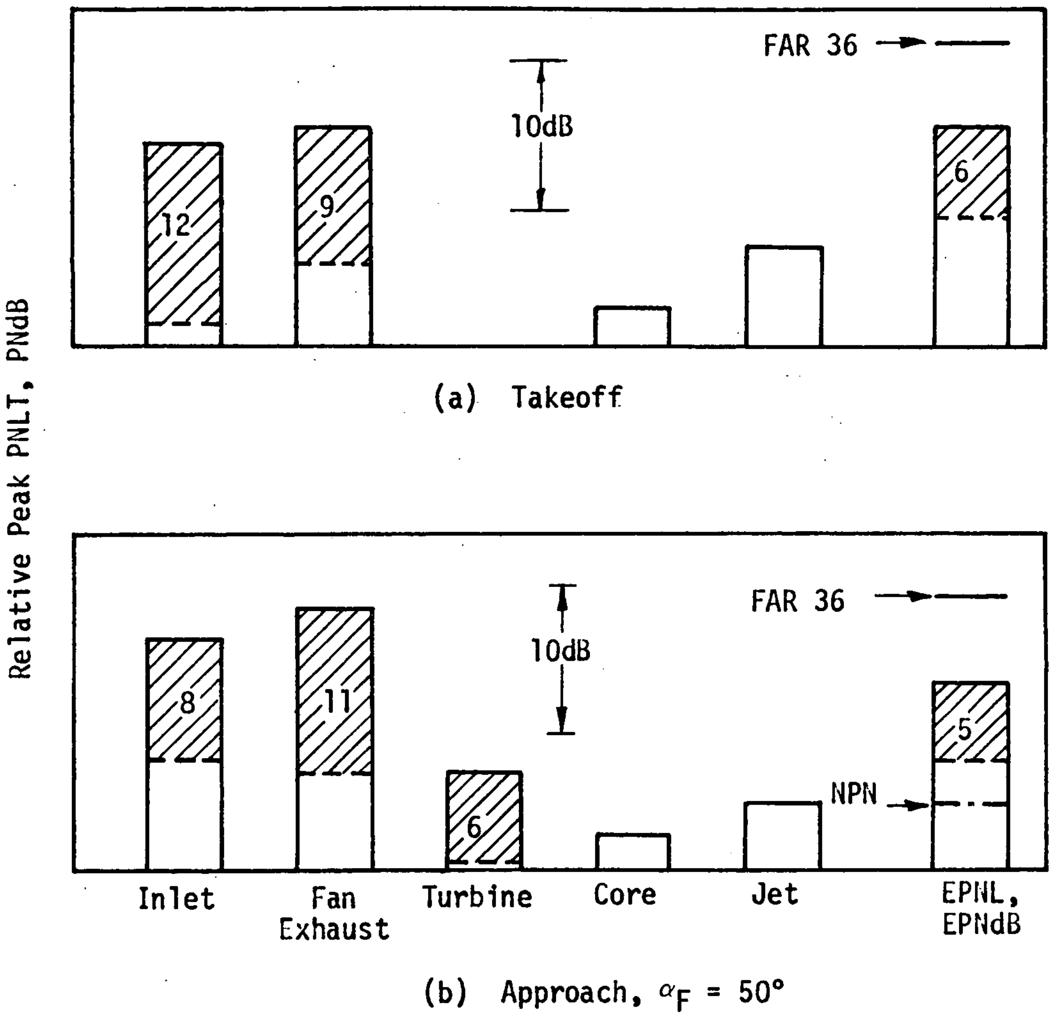
8.2 Noise Reductions

Evaluation of the acoustical treatment installed in the long-duct mixed-flow nacelle around the GE ATT no. 4 engines followed the methodology of the WBT nacelle evaluations. Figure 77 shows the reductions in the component noise levels that were estimated relative to the levels for the hardwall nacelle.

At takeoff, Figure 77(a), the high-throat-Mach-number inlet and long treated fan-discharge duct combined to achieve a 6-EPNdB reduction in airplane noise at the 6.48-km (3.5 n mi) point. At approach, Figure 77(b), the bulk-absorber inlet linings, and the advanced fan-discharge and turbine treatments combined to reduce the airplane noise by 5 EPNdB to a level of 95 EPNdB, or only 3 EPNdB above the estimated level of non-propulsive noise.

The estimated 12-PNdB reduction in inlet noise at the takeoff power setting was based on test results provided by GE and shown in Figure 78 for an ATT-type single-stage fan. The results were calculated in terms of the peak perceived noise level on a 152.4-m (500 ft) sideline as a function of average throat Mach number. At the design throat Mach number of 0.79 during climbout, the projected noise reduction for the hybrid inlet was 12 PNdB or much more than could be obtained solely from acoustical treatment on the wall of the inlet duct. The high attenuation valves achieved justified the selection of the variable-geometry inlet.

Comparisons of 90-EPNdB contours are shown in Figure 79. For reference, the ATT contour is compared to that produced by a current 2-engine WBT airplane. There was almost a 60-percent reduction in enclosed area relative to the contour area for the current 2-engine WBT airplane. For this specific aircraft design, these low community noise levels would represent a tremendous improvement in the state of the art.



NOTE: SHADED PORTIONS DENOTE NOISE REDUCTIONS RELATIVE TO UNTREATED ATT NACELLES.

FIGURE 77. SUPPRESSED ATT COMPONENT NOISE LEVELS AT MTOGW AND MLGW FOR FAR PART 36 MEASUREMENT LOCATIONS

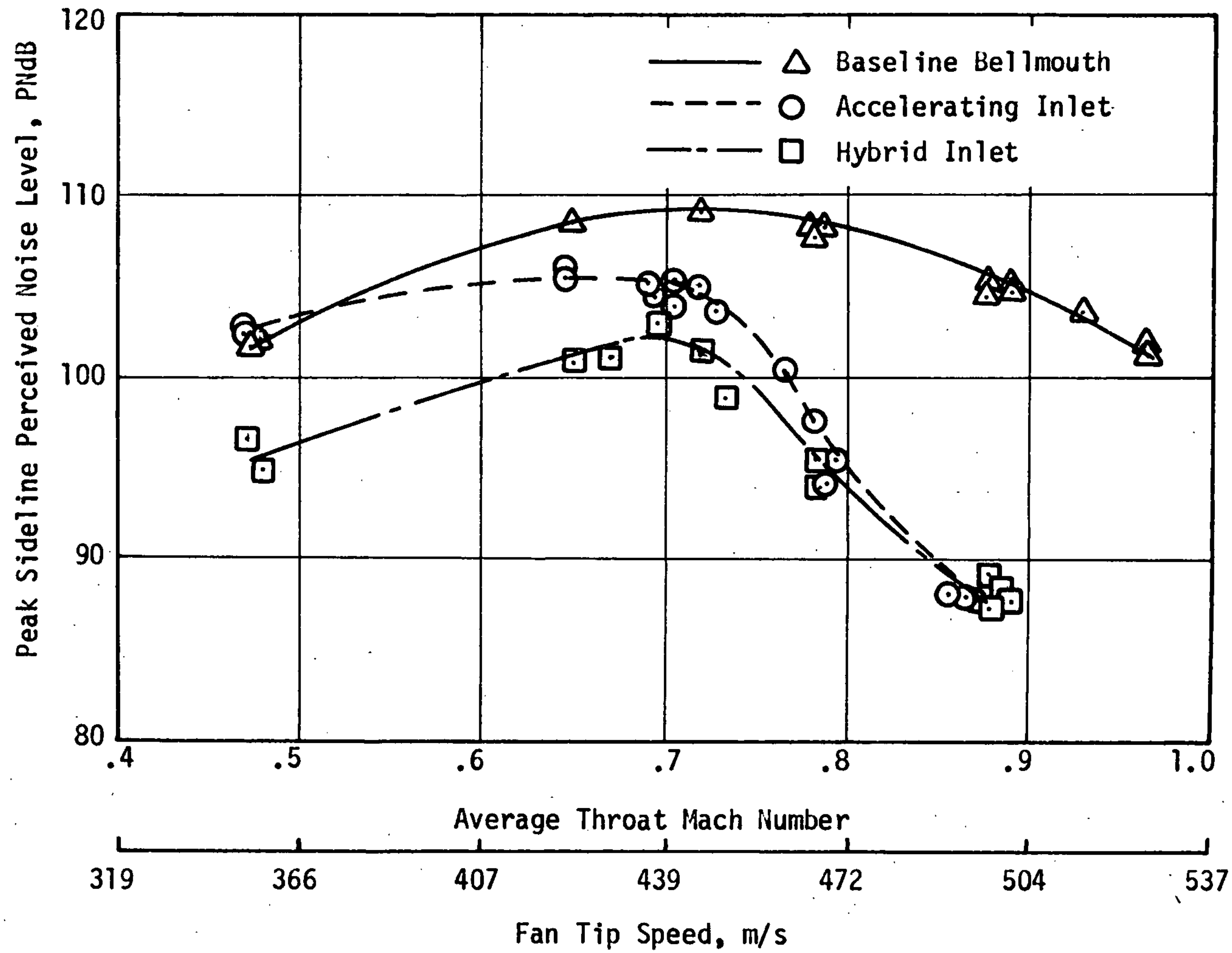
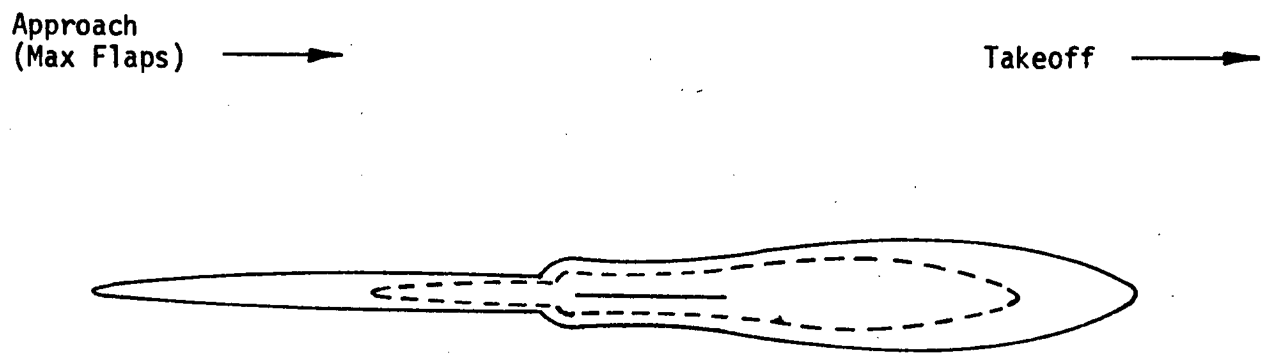


FIGURE 78. FAN-NOISE-SUPPRESSION MODEL-SCALE TEST RESULTS FOR AN ACCELERATING-FLOW INLET AND A HYBRID INLET. (MEASURED DATA SCALED TO FULL-SIZE. ATT TYPE SINGLE-STAGE FAN AND PROJECTED TO 152.4-m (500 FT) SIDELINE.)



	Airplane	Enclosed Area Sq km	Change in Area Percent
———	2 Engine WBT	15.6	Datum
- - - -	ATT	6.5	58

FIGURE 79. 90-EPNdB CONTOURS FOR ATT AND CURRENT 2-ENGINE WBT

8.3 ATT Nacelle Manufacturing Cost

A detailed manufacturing cost analysis of the ATT nacelle was not conducted as part of this contracted effort for a number of reasons. In the first place, the study of reference 15 looked in great detail at the manufacturing costs associated with a similar design concept. Second, the development of a "baseline" metal design was not considered within the scope of this study and the lack of a suitable baseline did not permit comparisons to be made to establish the benefits of advanced composites for the selected nacelle. Third, it was felt that the results of the manufacturing cost analyses conducted for the WBT portion of the study would entail less uncertainty and could be considered representative for future ATT work. Finally, at the mid-term oral review, when it became evident that there was significant potential payoff to the WBTs from the application of advanced composites in nacelles, it was mutually agreed between NASA and Douglas to de-emphasize the ATT portion of the study and concentrate on the WBT activities. It should be noted, however, that the technology employed in the ATT nacelle design is similar to that being pursued on the NASA-Lewis QCSEE program. The hardware development involved in the QCSEE program should provide a substantial basis for cost projections of these more-advanced composite nacelles.

8.4 ATT Airline Operating Economics

As was the case for the WBT, DOC was used as the measure of airline operating economic impact of the ATT nacelle. However, since the ATT nacelle and airplane were single-point designs, no comparative DOC analyses were made. The analyses that were conducted used the Douglas Advanced Design computer DOC program and appropriate inputs on airframe costs from a Douglas parametric prediction method. This method yielded price levels of advanced airframe designs by taking into account such factors as empty weight, technology level, engine type and estimated cost, and expected time frame for introduction into service. Costs of the ATT no. 4 engines were obtained from GE. The DOC analyses were made for mission ranges of 926 and 5556 km (500 and 3000 n mi) for the basic design. Sensitivity of DOC to changes in nacelle weight (±25%) and nacelle cost (±25%)

were also conducted for the two ranges. Figure 80 shows the distribution of DOC by element at 926 and 5556 km for fuel prices of \$0.07 and \$0.14/liter (\$0.26 and \$0.52/gallon). The sensitivity of DOC to nacelle weight and cost changes is shown in Figure 81 for 926 km (500 n mi) and Figure 82 for 5556 km (3000 n mi).

9.0 WBT RESEARCH AND TECHNOLOGY RECOMMENDATIONS

These studies conducted for the NASA showed that the long-duct mixed-flow nacelle, fabricated with advanced composites, would reduce fuel consumption through performance improvement and weight reduction technology. The noise reduction possibilities can allow quieter aircraft, or more fuel efficient derivative aircraft without increasing noise.

The cost-benefit analysis evaluation of nacelle design concepts showed that significant reductions in fuel consumption and noise were possible because the weight advantage of advanced composites made a long-duct mixed-flow nacelle with the attendant additional/improved acoustical treatment a practical consideration. The benefits were identified by conducting multi-disciplinary studies in consonance with the needs expressed in Reference 4 where Dr. Alan Lovelace pointed out that future use of composites demands integration of several technologies. The conceptual design studies reported herein showed that cost effective acoustical-treatment and propulsive-efficiency improvements could be achieved through the synergistic effects of integrating propulsion, acoustic, aerodynamic, structure and manufacturing technologies.

Specifically, the studies showed that fuel consumption, noise, weight and cost could be reduced by designing the engine nacelle around advanced composites. The long-duct mixed-flow concept showed the most promise for improved SFC and noise reduction; however, application of advanced composites also improved the performance of short-duct designs for the baseline WBT. Both the weight savings, and the expected manufacturing cost reductions will be of major importance to applications of this advanced technology. Without the weight and cost advantages offered by the application of advanced composites, the adoption of a long-duct nacelle would increase both the selling price

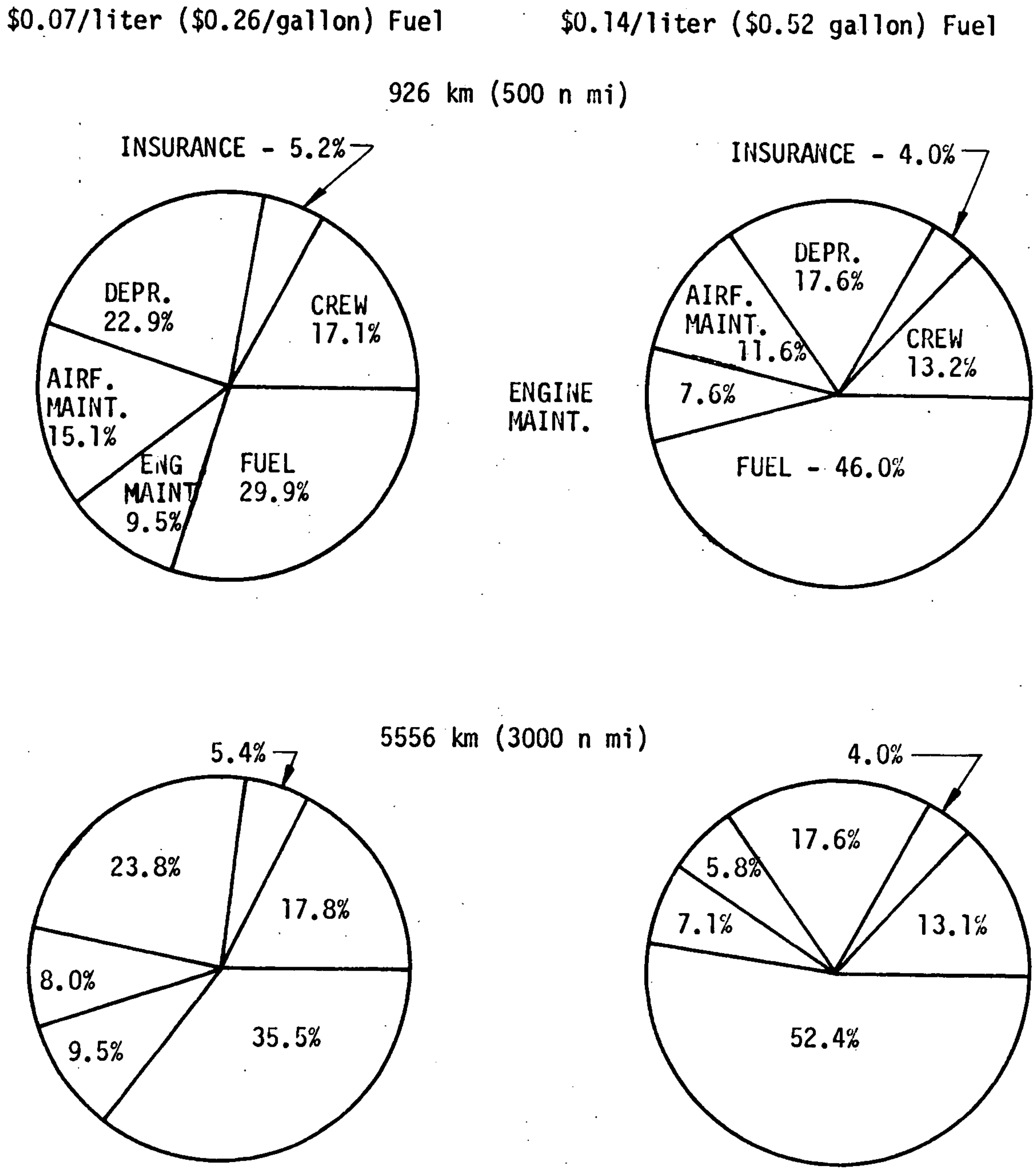


FIGURE 80. DISTRIBUTION OF ATT DIRECT OPERATING ELEMENTS FOR BASELINE DESIGN

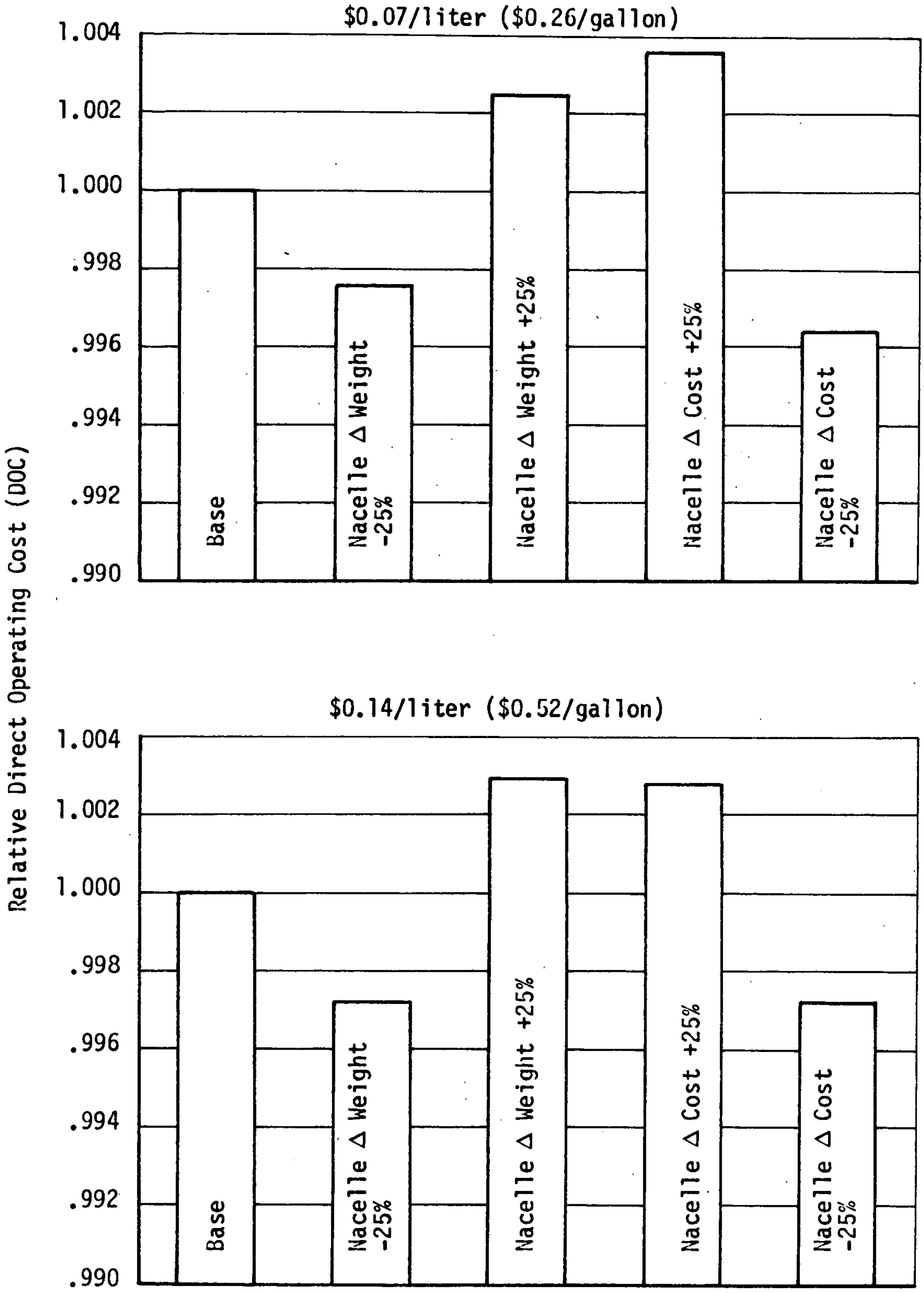


FIGURE 81. ATT DIRECT OPERATING COST SENSITIVITY TO CHANGES IN NACELLE WEIGHT AND COST AT 926 KILOMETERS (500 n mi)

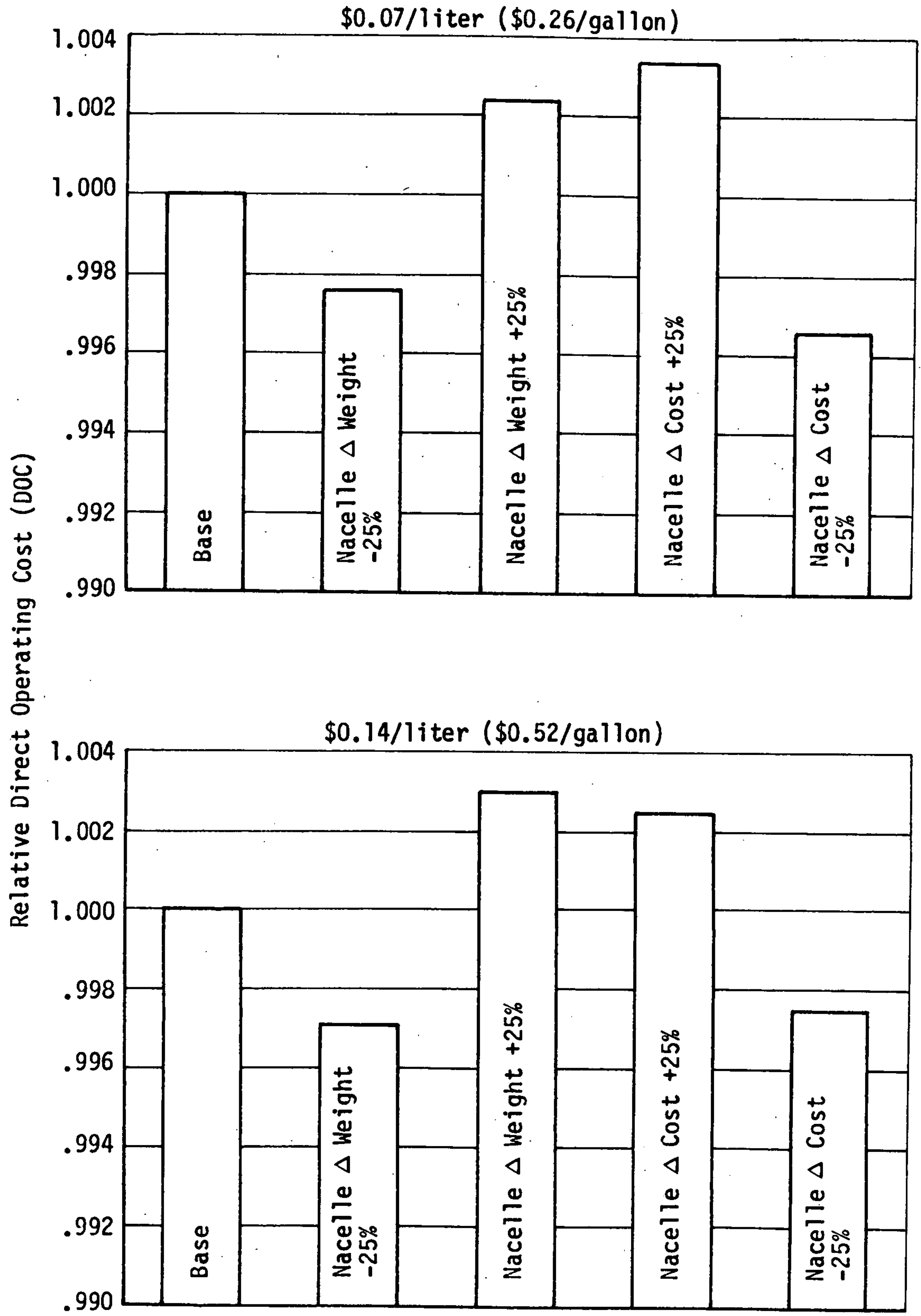


FIGURE 82. ATT DIRECT OPERATING COST SENSITIVITY TO CHANGES IN NACELLE WEIGHT AND COST AT 5556 KILOMETERS (3000 n mi)

and empty weight of the airplane, both of which are detrimental to acceptance of the technology.

The final tasks addressed in this study were (1) identification of areas where technology development was required before acoustic-composite materials could be applied to the eventual manufacture of nacelles on future newly produced derivatives of current WBT airplanes and (2) recommendation of the research and development programs needed before acoustic-composite nacelles could be used in airline operations. In addition, descriptions are given for the full scale testing needed to demonstrate that the predicted performance improvements and noise reduction are realized and that composite structural durability and maintainability suitable for airline service is achieved. Actual public benefits require instilling prior confidence in the aviation community before the technology benefits would be accepted for commercial aircraft.

The recommended objectives for a follow-on technology program in line with fuel conservation national priorities and other social and economic needs are shown in Figure 83.

FIGURE 83. ADVANCED ACOUSTIC COMPOSITE NACELLE PROGRAM OBJECTIVES

- Maximum Benefits from Advanced Nacelle Composites through Integration of the Technologies
- Technology Advancements in Order of Priority:
  - Fuel Savings . . . . National Priority
  - Weight Reduction
  - Noise Reduction
  - Cost Reduction

  (Weight, Noise and Cost Reduction) . . . . Social and Economic Needs

The program recommendations are made for a minimum program that establishes limited technology goals and an expanded program that encompasses convincing technology demonstrations.

9.1 Basic Areas for Technology Development and Demonstration

Realizing the maximum benefits from the new technology identified in this study requires technology development in the five major areas shown in Table 26. In the area of performance, it must be demonstrated that the long-duct nacelle will produce lower installed drag and that improved propulsive efficiency will result from mixing the fan and turbine exhaust streams.

TABLE 26. NEW TECHNOLOGY REQUIREMENTS

Installed Performance

- o Reduce Drag with Long Duct Nacelle
- o Improve Propulsive Efficiency with Mixer Nozzle

Noise

- o Reduce Jet Noise during Takeoff with Mixer Nozzle
- o Improve Inlet Noise Suppression during Approach with Bulk Absorber
- o Improve Fan and Turbine Noise Suppression during Approach with Increased Treated Area and Improved Treatment

Fabrication

- o Reduce Weight Using Advanced Composites
- o Reduce Component Fabrication Costs by Simplified Construction

Fire Resistance

- o Burnthrough Resistance for All Applicable Nacelle Components

Durability and Maintainability

- o Maintain or Reduce Current Maintenance Costs by Durable Constructions

In the area of noise, flyover noise tests must be conducted to determine whether the noise reductions that have been estimated analytically for the long-duct mixed-flow nacelle will occur in practice. The principal objective is demonstration of the reduction in jet noise at takeoff power during climbout, although demonstrations are also required of the reductions in turbo-machinery noise during the landing approach. These tests would be structured to determine the effectiveness of a bulk absorber in reducing inlet noise, the effect of turbine treatment on high-frequency turbine noise, and the effect of the internal mixer, and mixed-flow exhaust system, on the generation and propagation of turbine noise and noise generated in the wake behind the exhaust nozzle.

In the area of fabrication, full-size acoustic-composite nacelle components must be designed and built to validate that the reductions in weight and costs that were estimated can be realized with composite materials.

Fire burnthrough resistance technology for the advanced composite materials is needed. The initial flame exposure tests conducted as part of Task IV of this study, and described in Section 5.11, provided encouraging results. The FAA fire burnthrough resistance requirement of 15 minute exposure to a 1367°K (2000°F) flame was met by static composite specimens bonded with polymer resins. Further, more-comprehensive technology development is required to ensure that composite parts subjected to pressure loads and in an aerodynamic flow-field, can be satisfactorily developed to pass the same requirements.

Since nacelle structural components are expected to endure the life of the airframe (50,000 or more hours), durable and maintainable composites are necessary. In-service evaluations are required to show that maintenance costs associated with the use of advanced-composite nacelles will be equal to or lower than those of the metal nacelles currently in airline service. Without such substantiation, excessive financial risk is involved in use of advanced composites.

A summary of the technology needs and verifications required to provide confidence in the technology is given in Table 27. Full-scale tests are considered essential for final substantiation of new technology.

9.2 Choice of Airplane for Technology Demonstrations

An advanced medium-range transport is generally forecast to be the next airplane configuration to be developed. The timing of its introduction into airline service is not expected before the end of this decade, and it is commonly expected that some versions will be powered by one of the new

TABLE 27. - TECHNOLOGY READINESS ASSESSMENT

AREA	NEEDS	VERIFICATION REQUIREMENT
PERFORMANCE		
DRAG REDUCTION	HIGH-SPEED WIND-TUNNEL TESTS	FLIGHT TESTS
PROPULSIVE EFFICIENCY IMPROVEMENT	MODEL-AND FULL-SCALE TESTS	FLIGHT TESTS
NOISE		
JET NOISE REDUCTION	FULL-SCALE GROUND TESTS	FLIGHT TESTS
INLET NOISE REDUCTION	FULL-SCALE GROUND TESTS	FLIGHT TESTS
FAN AND TURBINE NOISE REDUCTION	FULL-SCALE GROUND TESTS	FLIGHT TESTS
FABRICATION		
METAL HOT-SECTION PARTS	EXISTING TECHNIQUES	NONE
ADVANCED ACOUSTIC-COMPOSITES WITH ORGANIC MATRIX MATERIAL	BASIC TECHNOLOGY FOR ADVANCED FABRICATION TECHNIQUES	FULL-SCALE FABRICATION AND FLIGHT TESTS
FIRE RESISTANCE		
FIRE BURNTHROUGH RESISTANCE OF ADVANCED COMPOSITES WITH NON-METALLIC MATRIX	BASIC TECHNOLOGY DEVELOPMENT	LABORATORY TESTS
DURABILITY		
WEIGHT AND COST OF LONG-LIFE COMPONENTS	TECHNOLOGY FOR LOW-COST DURABLE CONSTRUCTIONS	IN-SERVICE SUBSTANTIATION

"ten-ton" engines, such as the CFM International CFM56 (or P&WA JT10D). These engines are in the 90 to 135 kN (20,000 to 30,000 lb) thrust range class and have bypass ratios of 5 to 6. Additional performance benefits related to the use of a supercritical airfoil for the wing, toleration of reduced static stability through the use of active control systems, composite structures, and advanced acoustic-composite nacelles may provide the impact on selling price and DOC needed to offset inflationary pressures on construction and operating costs. Meanwhile, the most likely application of technology advancements will be for the improvement of current wide-body transports, Reference 2. Replacements for these aircraft are not forecast before 1985, and during this interim period, the introduction of growth or advanced versions of these airplanes is expected. Thus, as summarized in Table 28, it is logical to develop and demonstrate technology advancements using a WBT as the basis. Having done this, the technology would be available and timely for application to the all-new, advanced medium-range transport. The fabrication of the large parts needed for the WBT airplane is expected to present more of a challenge than will be the case with the new medium transport. Thermal expansion problems compound with size. Thus, if the technology were developed for smaller size engines, it might not directly apply to the WBT.

TABLE 28. - TECHNOLOGY UTILIZATION IN 1980s

APPLICATION	PROBABILITY OF USE	COMMENTS
RETROFIT	VERY LOW	o REQUIRES SCRAPPING GOOD HARDWARE o TIME IS REQUIRED TO PHASE IN WHILE USEFUL AIRFRAME LIFE IS DECREASING
NEWLY PRODUCED NARROW BODY TRANSPORTS	LOW	PRODUCTION PHASE OUT EXPECTED
NEWLY PRODUCED CURRENT WIDE BODY TRANSPORT	MEDIUM	PROBABILITY WOULD BE HIGH IF CURRENT CONFIGURATIONS PRODUCED RATHER THAN DERIVATIVES
NEWLY PRODUCED DERIVATIVES OF CURRENT WIDE BODY TRANSPORTS	VERY HIGH	PROBABLE CONFIGURATION OF NEWLY PRODUCED WBT TRANSPORTS
NEW ADVANCED MEDIUM RANGE (NARROW BODY) REPLACEMENT	VERY HIGH	REQUIRES USE OF ADVANCED TECHNOLOGIES TO BE ECONOMICALLY VIABLE

9.3 Choice of Engine for Technology Demonstrations

All the successful transports produced so far have undergone growth in range and/or payload during their production life, and thus have created a requirement for more takeoff thrust. With turbofan engines, the thrust growth has been obtained by increasing turbine inlet temperature and decreasing bypass ratio. The effect of these changes has been reflected in increases in airport community noise levels, especially jet noise during takeoff.

Future versions of current WBT aircraft will likely be powered by engines having even more thrust than the most-powerful engine available today (hence trending toward increased noise during takeoff) and will likely land at weights exceeding the heaviest currently certified (hence trending toward increased noise during landing). If the takeoff and landing noise reductions predicted for the long-duct mixed-flow nacelle can be demonstrated on a growth version of the WBT engine, it will provide confidence that growth versions of WBT aircraft can be developed that generate no more, and possibly less, noise during takeoff and landing than do the current WBT airplanes. Thus, application of these technology advancements promises that the air transportation system can offer both quieter and more efficient service by further reducing airport community noise levels and the energy expended per seat-mile flown.

9.4 Fundamental Objectives of Full-Scale Program

The flight test program must be structured to demonstrate the actual noise reduction attributable to using mixed-flow nacelles on a wide body transport aircraft and whether this nacelle configuration will actually lower the cost of ownership. In addition, the tests must permit identification and quantification of the performance difference between the long-duct mixed-flow nacelle and the separate-flow nacelle currently used.

9.5 Flyover Noise Tests

The research and technology plan recommended for the long-duct, mixed-flow, advanced acoustic-composite nacelle includes a flight test to measure takeoff and approach noise. The experience of researchers in the government and the aircraft industry over the last 20 years confirms the need for flyover noise testing to verify engineering estimates of the acoustical effects of various engine and nacelle design concepts.

The need for flight demonstrations to measure the effects of jet noise suppressors has long been accepted. A timely confirmation of this need is found in References 18 and 19 which deal with noise from both lobed and circular exhaust nozzles. For the long-duct, mixed-flow nacelle, jet noise suppression will be achieved by changing the relative velocities and the jet mixing. A key element in the test program will be the demonstration of the predicted jet noise reduction during actual takeoffs.

With regard to advancing the state-of-the-art of acoustical technology, substantiation of the estimated changes in turbine and inlet noise ranks next in importance to validation of the jet noise reduction. High-frequency turbine noise must propagate through the turbulent flow within the exhaust nozzle and then out through the turbulent exhaust jet to reach observers in the far field. Forward motion modifies these flow fields and may even affect the turbine noise signal. Propagation through the velocity and temperature gradients in the turbulent shear layer at the jet boundary is modified by the effect of forward motion. Reference 20 discusses these phenomena in detail.

In addition to a better understanding of the effect of forward motion on turbine noise, there exists a need to understand how the mixer nozzle on the turbine exhaust will effect the propagation of turbine noise out through the mixed fan/turbine exhaust stream and how the nozzle and the acoustic linings on the walls of the exhaust passage interact to suppress turbine noise. Reference 18 describes the results of recent tests with lined and unlined exhaust nozzles and showed that significantly different results were obtained from the flight tests than from static tests, thus bearing out the need for in-flight measurements of turbine noise to validate the estimates of the reduction of this important noise source.

The minimum cost program provides for flight test evaluation of the changes in jet and turbine noise, but not evaluation of the inlet noise change. An alternate program structured around utilizing new long-duct nacelles at all three engine positions would make feasible the measurement of inlet noise reduction. Such a program would also provide information on the effects of forward motion on inlet noise and supplement the data base contained in Reference 21 through 24. Flight tests are considered mandatory to evaluate the estimated changes in inlet noise because of differences between static and flight conditions in the arodynamic characteristics of the inlet flow field as well as the intensity and distribution of turbulence interacting with the pressure field of the rotor. Techniques to correctly simulate these flight effects have not been developed.

9.6 Recommended Research and Technology Program

The program plan shown in Figure 84 was developed to satisfy the research and technology requirements described above at the least total cost. The program is aimed at demonstrating composite nacelle durability through a long-term in-service evaluation designed to fit into airline operations without imposing restrictions or limitations on the operator. The program spans six years and is made up of four major phases. The first phase is comprised of analysis, design, and laboratory testing and lasts approximately 18 months. The second phase is devoted to a full-scale ground test and this lasts approximately 14 months. Phase 3 is a flight-test period of approximately 8 months. Phase 4 is the in-service evaluation, spanning a period of approximately 3-1/2 years.

In the first phase, strength allowables would be determined for the composite material components through physical-property testing. The FAA would participate so that the ground work for subsequent certification would be completed and documented in this phase. Prior to the service-evaluation phase, inspection and repair procedures for the composites would be developed. This work would be coordinated with the participating airlines. Fire-resistance technology would be explored through both analytical and experimental techniques so that it could be integrated into the detailed design for the long-duct, mixed-flow, advanced-composite nacelle for the wide-body-transport engine.

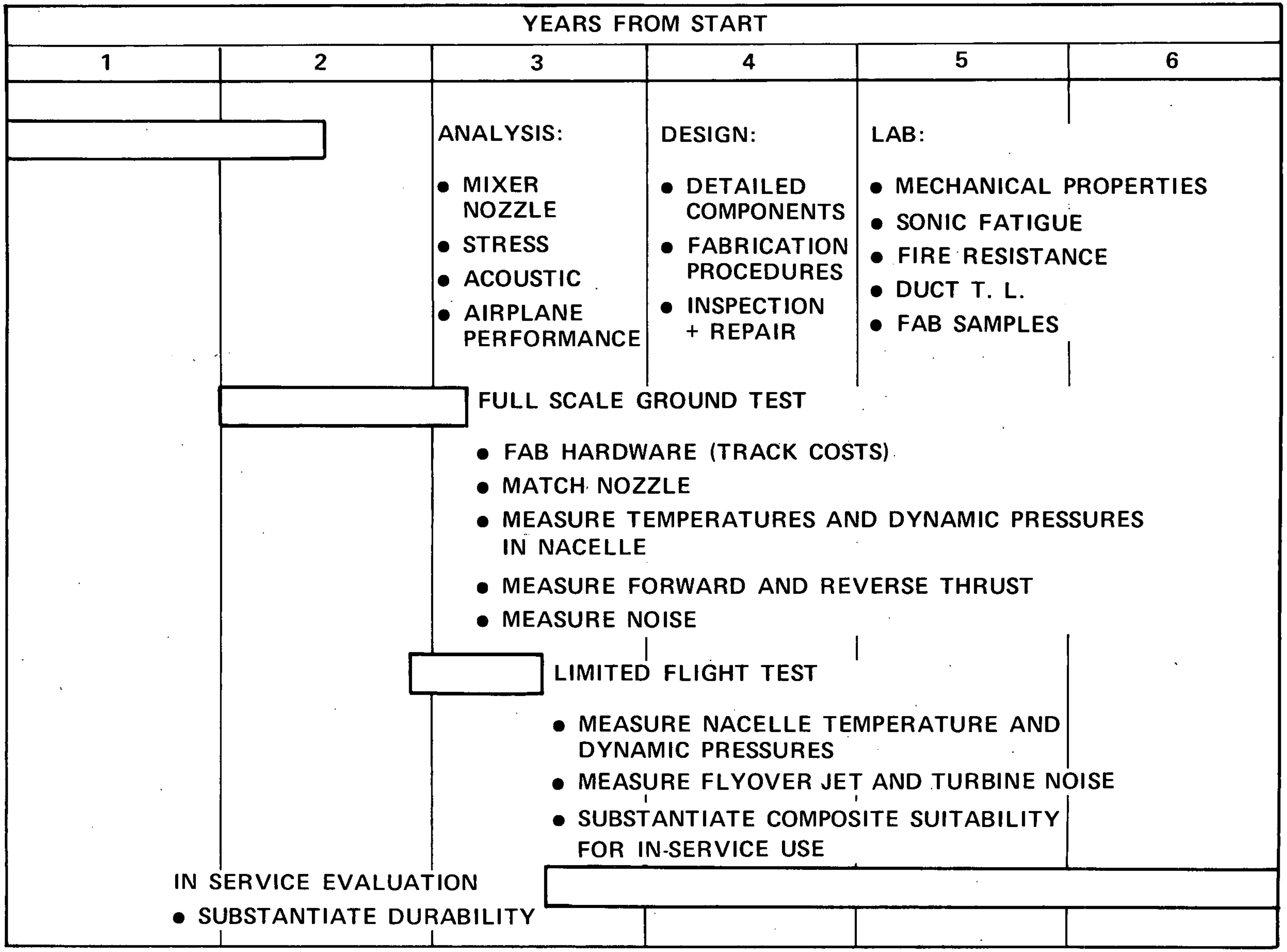


FIGURE 84. - PROGRAM SCHEDULE FOR RECOMMENDED PROGRAM

Acoustical analyses would be addressed to defining the duct-lining design requirements and the acoustic loads on nacelle components. The effort would include determination of the acoustic design requirements for the treatment in the inlet, turbine exhaust, and fan discharge ducts. Consistent with the integrated systems approach, the acoustical design analyses would consider the impact of aerodynamic, environmental, and structural requirements in order to realize the largest reduction in noise consistent with performance, efficiency, and cost considerations.

Candidate duct lining designs would be tested in a duct-transmission-loss test facility. The appropriate ratio of treatment length to passage height, duct Mach number, and sound source modal distribution would be simulated. The results of these tests would be used to design the linings for ground static tests of the full-size long-duct nacelle. In addition, technology development activities would be pursued to establish a mechanically acceptable bulk absorber for the inlet inner barrel. These activities would be concentrated on the materials aspects and would include full-scale ground acoustical evaluations and full-scale ground and in-flight mechanical integrity testing. Since the bulk absorber was intended to be used with nose cowl configuration A (Figure 30), it would be possible to delete the bulk absorber feature from the nose cowls that would be fabricated for the in-service evaluation phase if development experience indicated that use of the bulk absorber in commercial airline service represented an area of risk.

Estimates of the acoustic loads imposed on the inlet and fan-duct will be made to identify the design requirements. Sonic-fatigue tests of candidate lining designs would be conducted to verify the adequacy of strength margins and to assist in establishing the fatigue life of the advanced acoustic-composite linings for the flight-test and service-evaluation phases.

The full-scale ground test program would encompass nacelle configuration development and thrust reverser effectiveness testing to demonstrate the effect of allowing the primary flow to expand into the final nozzle when the fan flow is blocked and diverted outward and forward through the reversing cascades. In addition, data would be obtained on mixer nozzle performance parameters as well as temperature and pressure distributions in all nacelle zones. The durability of composite components as well as the suitability of the system for flight would also be demonstrated.

The nacelle configuration envisioned for the full-scale ground test is shown in Figure 85. Components expected to be common to the in-service evaluation short-duct nacelle are so indicated.

Figure 86 shows the overall plan and allocation of hardware for flight tests. For the minimum-cost program, parts intended for the in-service evaluation of composites for nacelles would be installed in a wing-engine position. The long-duct nacelle used for the ground tests would be installed in the tail-engine position. This installation would yield data on jet and turbine noise reduction, internal flow characteristics, and nacelle environmental conditions.

The in-service evaluation phase would measure the effects on the composites of exposure to thermal cycling from operation of the inlet ice protection system and from the mixing process in the fan discharge duct where the temperature can be as high as 395°K (250°F). The effects of long-term exposure of composites to high-noise and vibration levels would also be evaluated. This phase would measure the capacity of the composites to stand up to the use and abuse attendant to engine servicing and maintenance actions by airline personnel, as well as to the exposure to all forms of weather and solvents such as water, turbine fuel, lubricating oil, hydraulic fluid, de-icing fluid, airplane cleaning agents, paint strippers, etc.

To estimate the funding requirements for the program, a detailed schedule was prepared for the major elements of the four phases of the recommended program. This schedule is shown in Figure 87. Cost estimates for each of these elements were based on past experience with similar programs. Estimates for the annual and cumulative program costs are shown in Figure 88. The peak cost occurs in the second year where costs of fabrication and testing associated with the full-scale ground tests would be incurred. The cumulative costs peak in the fourth year. The costs incurred in the fifth and sixth years are low because the tasks are limited to evaluating the condition of the various acoustic-composite nacelle components at the conclusion of the service test periods, documenting the findings, drawing

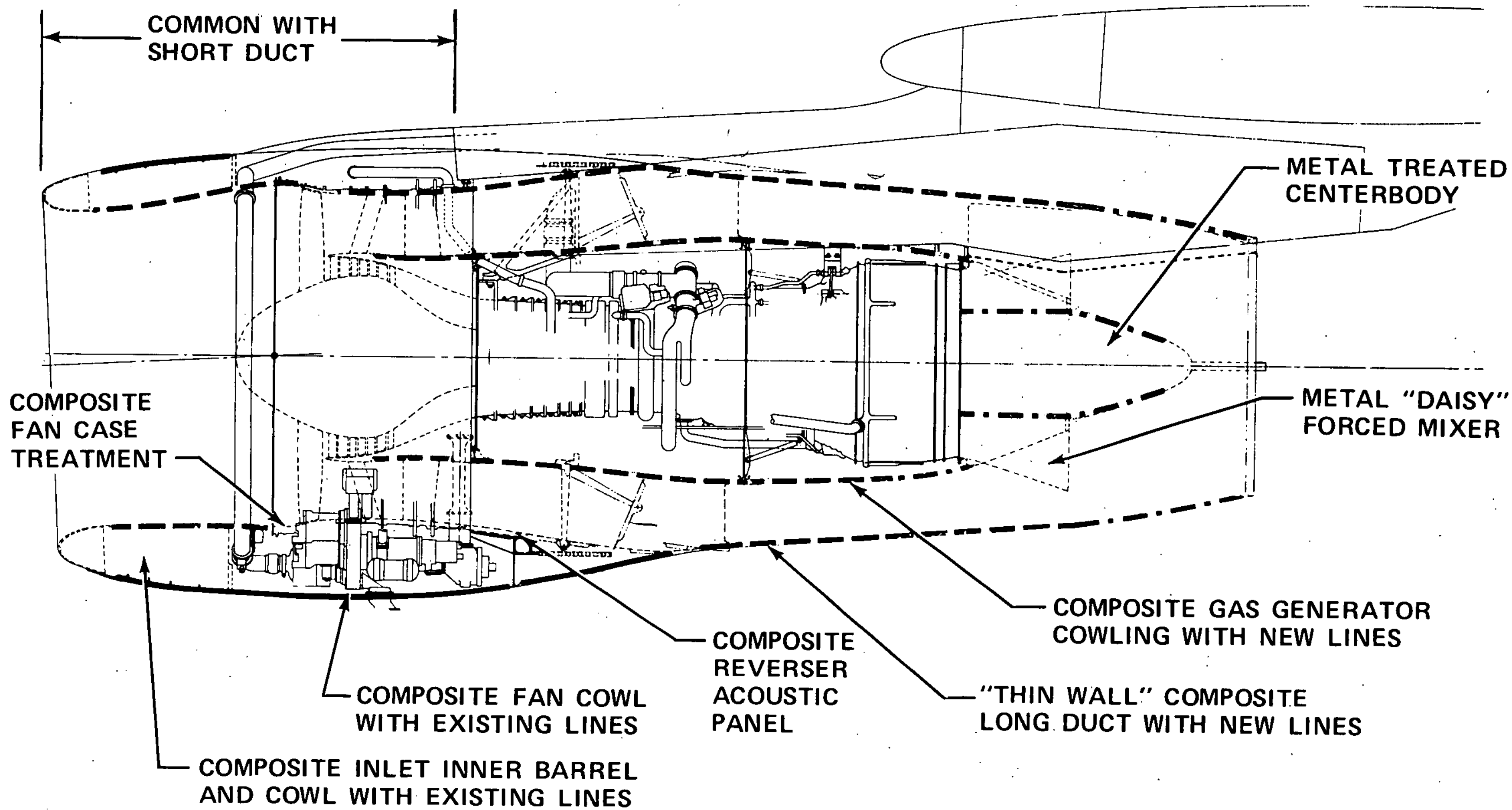
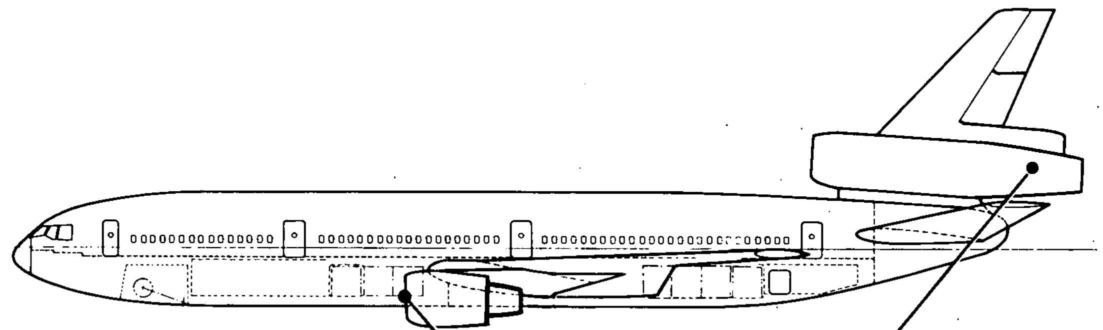


FIGURE 85. - NACELLE FOR FULL-SCALE GROUND TESTS



COMPOSITE INLET, FAN COWL, FAN FRAME PANEL AND REVERSER PANEL

- o SUBSTANTIATE DURABILITY FOR SERVICE EVALUATION
- o SUBSTANTIATE ENVIRONMENT WITHIN DESIGN LIMITS

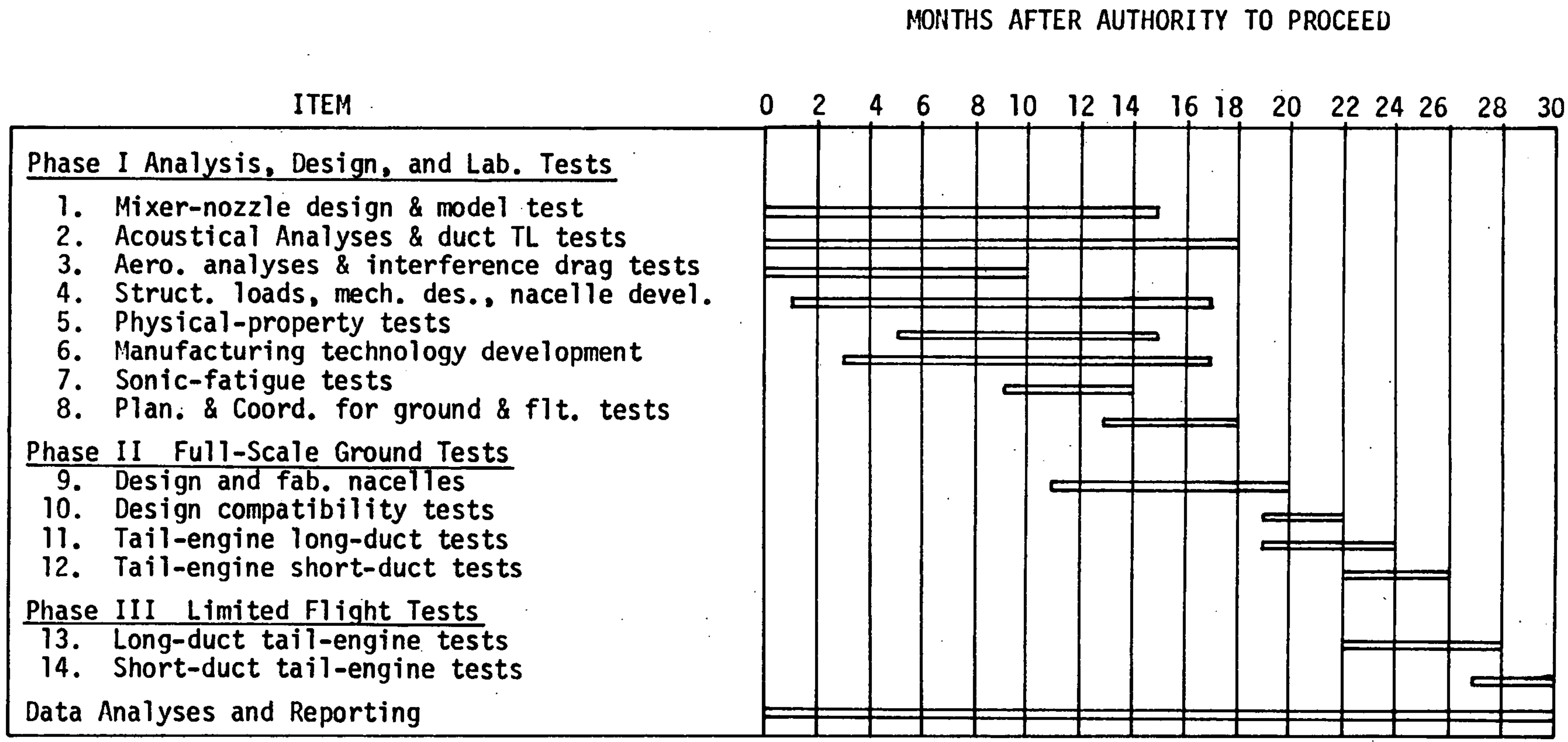
COMPOSITE LONG FAN DUCT

- o TREATED TO MEASURE JET NOISE
- o INTERNAL FLOW MEASUREMENTS
- o MEASURE LONG DUCT NACELLE ENVIRONMENT

PROGRAM PLAN

- **COMPARATIVE FLIGHTS WITH AND WITHOUT MODIFICATIONS**
- **FAN FRAME PANEL ON WING ENGINE FOR MAXIMUM NOISE EXPOSURE**
- **INLET AND FAN COWL ON WING ENGINE FOR HANDLING EXPOSURE**
- **REVERSER ACOUSTIC PANEL FOR TEMPERATURE AND MAXIMUM FAN DUCT NOISE EXPOSURE**

FIGURE 86. - HARDWARE AND PROGRAM PLAN FOR LIMITED FLIGHT TESTS



NOTE: Schedule for Service Evaluation Tests (Phase IV) would be from month 30 to month 72.

FIGURE 87. - DETAILED SCHEDULE FOR MAJOR ELEMENTS OF RECOMMENDED PROGRAM

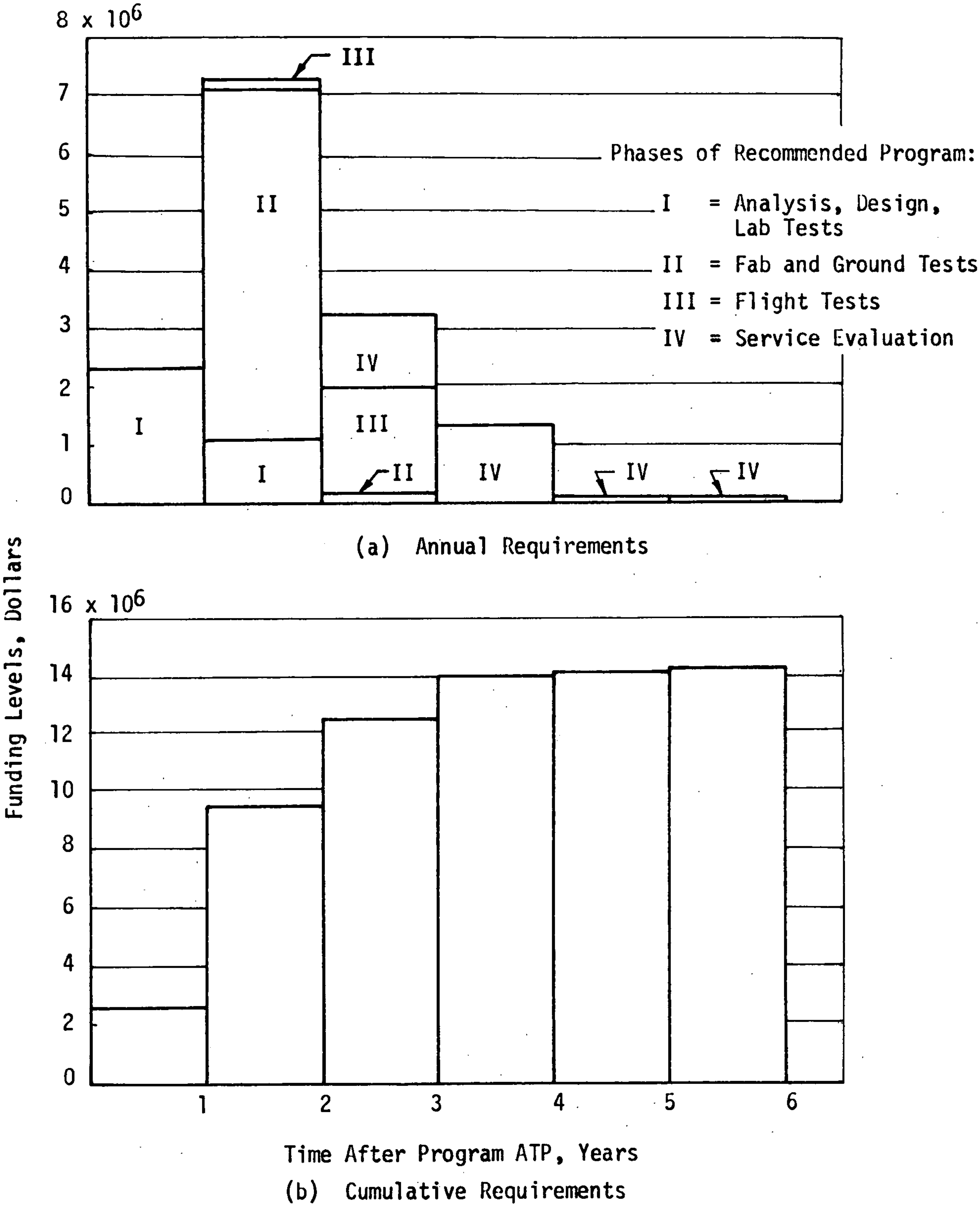


FIGURE 88. PROJECTED FUNDING REQUIREMENTS FOR RECOMMENDED PROGRAM

conclusions and making recommendations for future use of the data derived.

9.7 Alternate Expanded Program

An alternate experimental flight test program would expand the minimum program of Section 9.6 to include installing long-duct nacelles in the wing and tail engine positions to identify the performance effects including those on fuel consumption and flyover noise. Figure 89 identifies certain components of airplane drag that require testing to substantiate analytic estimates.

Figure 90 shows some of the acoustic technology benefits that could be expected from this program.

The effect of the bulk absorber linings on inlet noise attenuation would be the principal additional area of acoustic technology that would be explored in the flight-test phase of the program. This area is crucial because of the importance of capability of the lining to function as a load carrying member as well as a noise absorber. Inlet noise reduction is crucial from another point of view because, as indicated in Figure 59, noise radiated from the inlet controls the total perceived noisiness during the landing approach. The effect of forward motion on inlet noise would also be investigated. The flight test phase would provide a unique opportunity to obtain information, on a wide-bodied transport powered by high bypass ratio engines, needed to improve methods used to predict engine and airplane component noise levels. The other technology items noted in Figure 90 (jet noise suppression, turbine noise suppression, and the effect of the mixer nozzle on the generation and propagation of turbine and fan noise) are not dependent on proceeding with the alternate expanded program and hence would be addressed in the recommended minimum-cost tail-engine program.

Figure 91 shows the schedule for the major items peculiar to the alternate expanded program. All of the work indicated for the minimum-cost program, except for the flight tests, would be included in the alternate expanded program. The flight testing in the expanded program addresses testing that

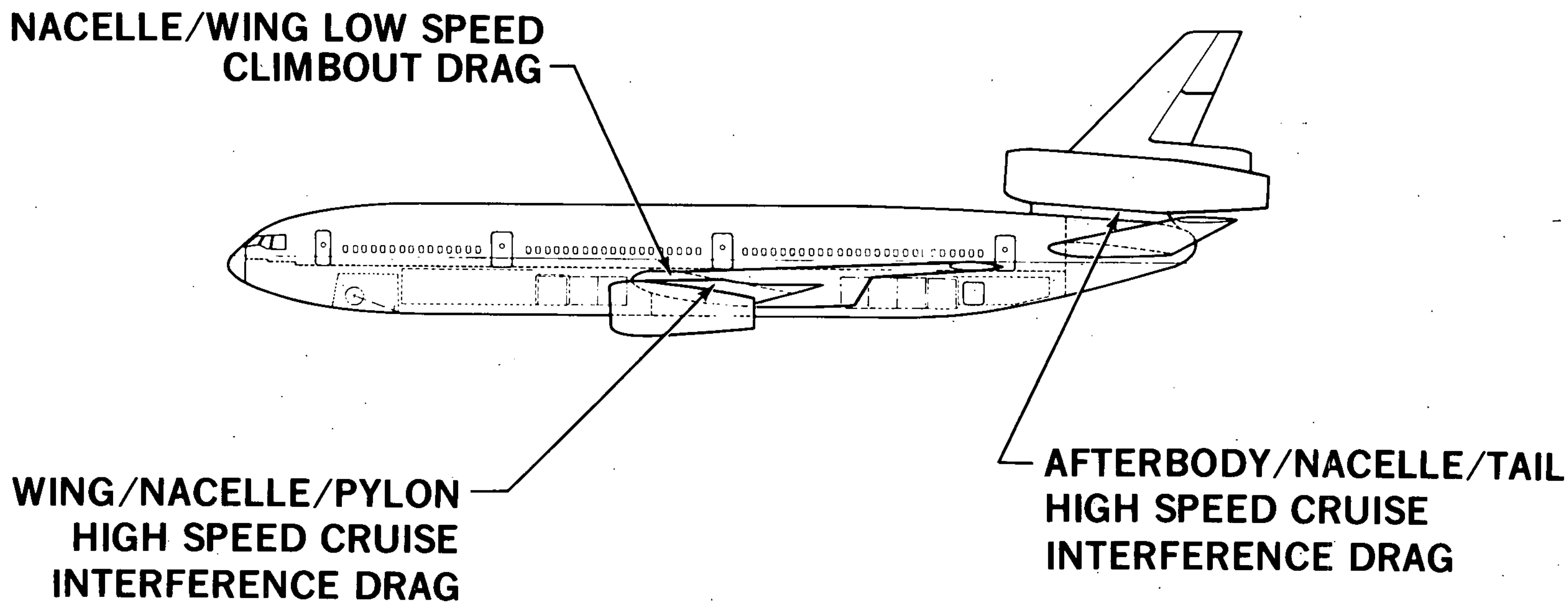
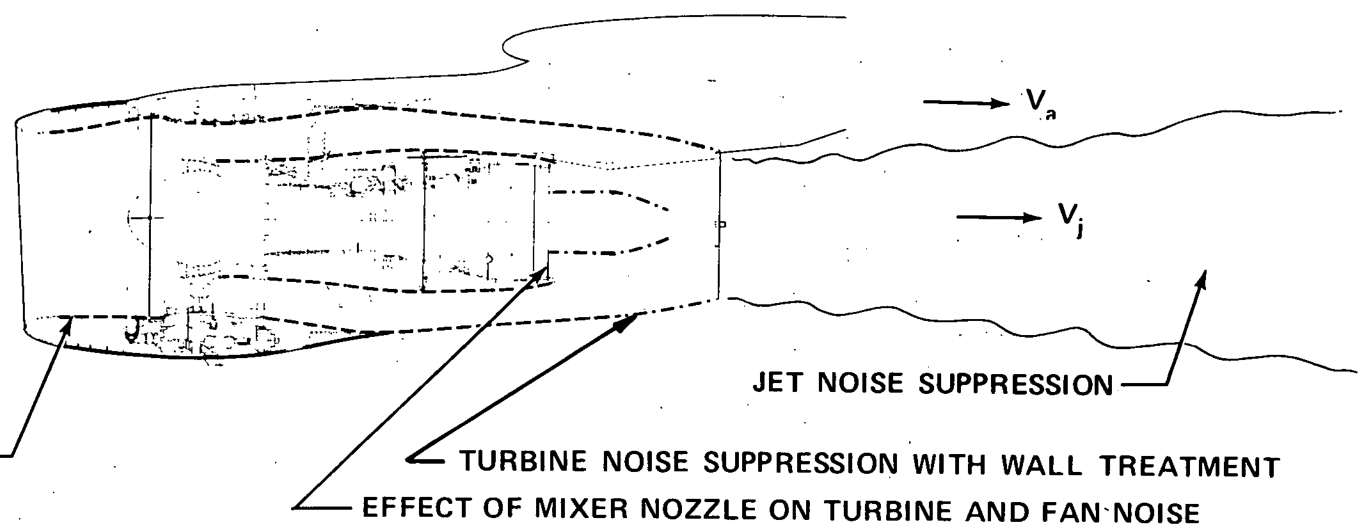


FIGURE 89. - DRAG COMPONENTS TO BE MEASURED IN ALTERNATIVE PROGRAM

GROUND TESTS

- BULK ABSORBER INLET LININGS
- JET NOISE SUPPRESSION WITH LONG DUCT AND MIXER

FLIGHT TESTS



- STATIC-TO-FLIGHT EFFECTS FOR JET NOISE AND INLET NOISE
- PREDICTION OF FLYOVER NOISE LEVELS FOR WBT AIRPLANES INCORPORATING FUTURE ADVANCED ACOUSTIC COMPOSITE NACELLES

FIGURE 90. - ACOUSTIC TECHNOLOGY AREAS IN ALTERNATIVE PROGRAM

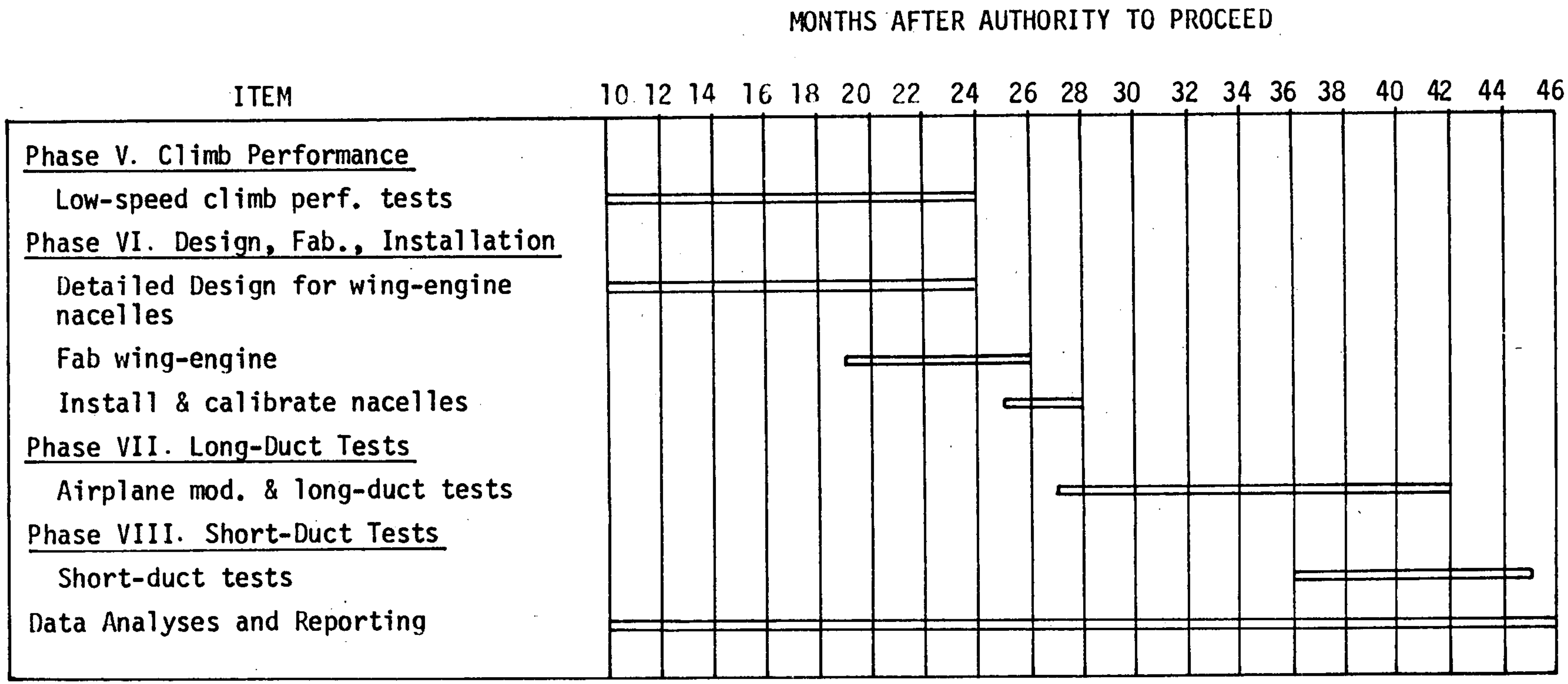


FIGURE 91. - PROGRAM SCHEDULE FOR THE MAJOR ADDITIONAL ITEMS REQUIRED FOR THE ALTERNATIVE EXPANDED PROGRAM WITH LONG-DUCT ACOUSTIC-COMPOSITE NACELLES ON THREE ENGINES

can only be accomplished if all three nacelles are modified, e.g., inlet noise-suppression tests. The start of the in-service evaluation phase would not be delayed significantly in the expanded program because certain of the tasks would be done in parallel to ensure that appropriate nacelle components would be available for installation on commercial transports in the third year of the program.

The funding requirements for the alternative expanded program are shown in Figure 92. The largest funding demands occur in the second and third years. This reflects the costs of design, fabrication, and installation of the long-duct nacelles (Phase VI in Figure 101) and the flight testing (Phases VII and VIII in Figure 101). The costs of the total program (combination of the minimum tail-engine program and the expanded three-engine program) are shown in Figure 93. The largest cost is incurred in the second year of the program and is estimated to be $12.5M. The third year cost is estimated at almost $8M. The program cumulative cost is estimated to be slightly over $26M.

10.0 ATT RESEARCH AND TECHNOLOGY RECOMMENDATIONS

ATT propulsion system studies should be continued by NASA to assure the development of a data base that will be ready when needed. The technology fallout from cooperative efforts on the part of NASA and the military services should be applied to such development efforts as composite fan blades and composite engine frames. An engine-nacelle integration study should be conducted by a team representing airplane and engine manufacturers to address ways of reducing fuel consumption and cost of ownership. The cost of ownership study is needed to determine the relationships between the costs of integrating the engine and nacelle and the cost of airline spare parts.

There are three acoustical technology areas related to the ATT integrated-nacelle concept where additional research effort is needed to develop the potential benefits. These areas are: (1) the hybrid inlet, (2) the combination high frequency/low frequency linings in the turbine-discharge duct, and (3) phased or bulk absorber linings in the fan-discharge ducts. Other areas that could yield potentially good payoffs include hot-section bulk absorbers and advanced attenuation schemes for mixed flow nozzles.

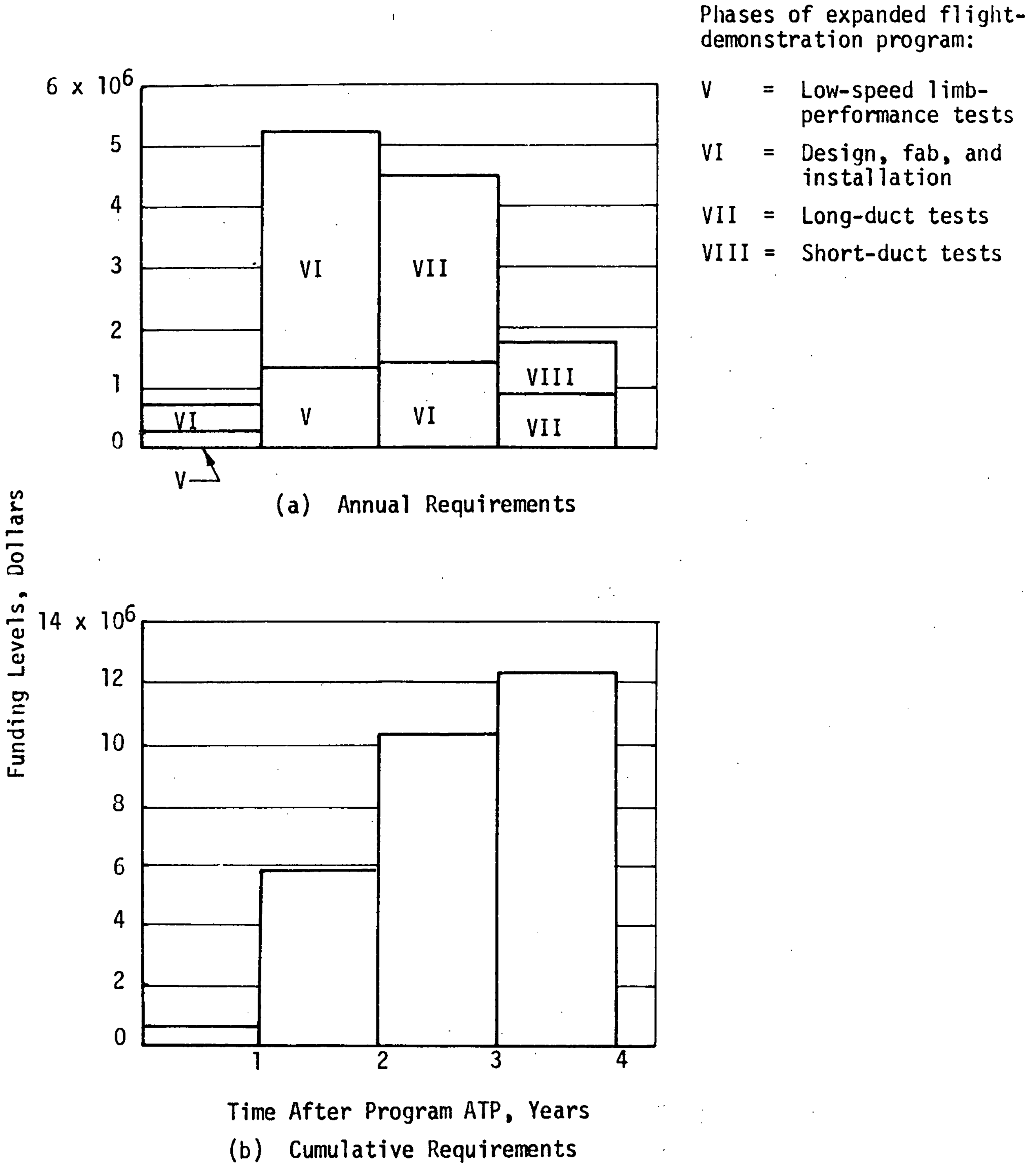


FIGURE 92. PROJECTED FUNDING REQUIREMENTS FOR ADDITIONAL TASKS OF THE ALTERNATIVE EXPANDED FLIGHT - DEMONSTRATION PROGRAM

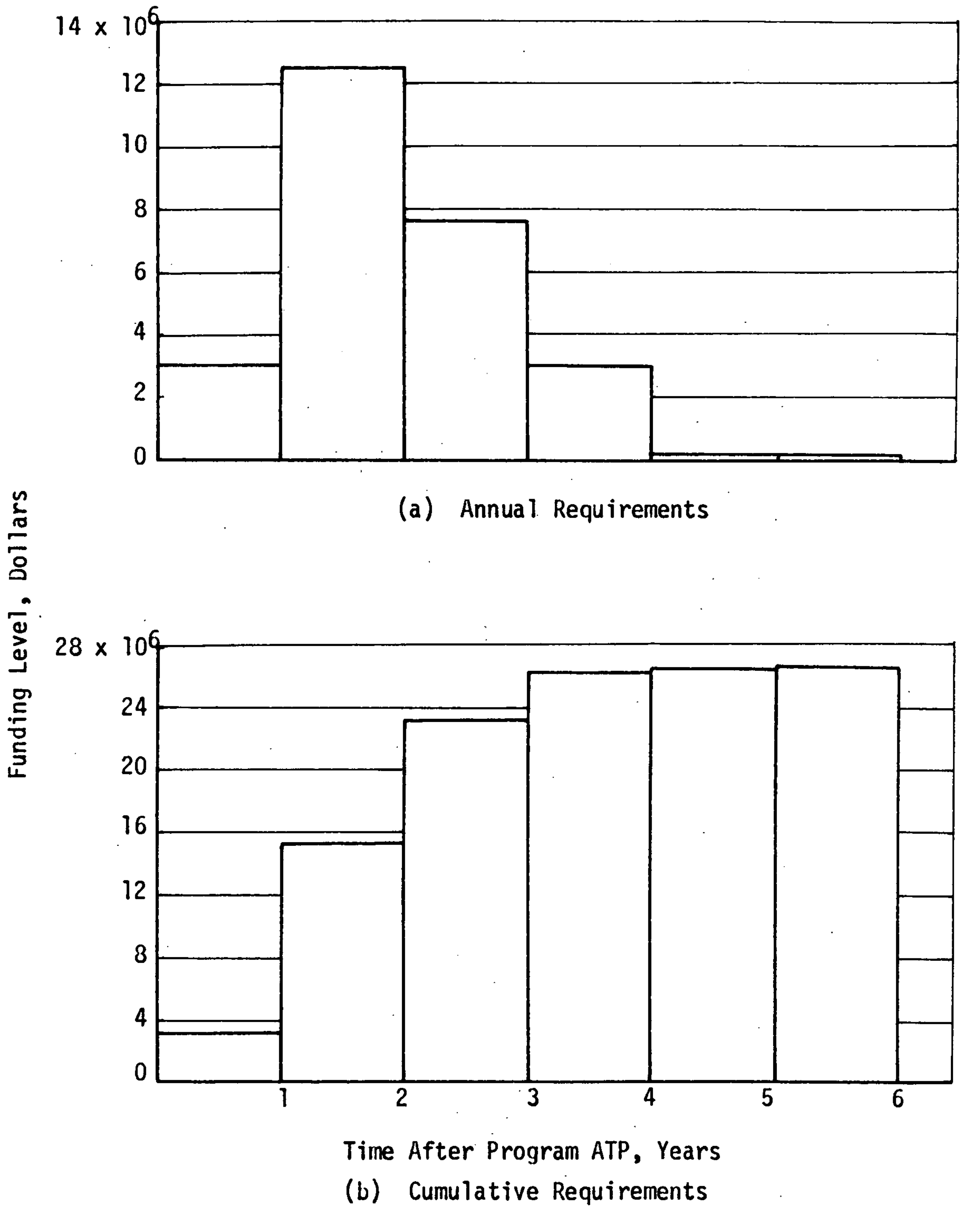


FIGURE 93 . PROJECTED FUNDING REQUIREMENTS FOR COMBINATION OF MINIMUM RECOMMENDED PROGRAM AND EXPANDED FLIGHT-DEMONSTRATION PROGRAM

The discussion of the ATT noise-reduction concepts indicated significant acoustical benefit, for an engine of the ATT type, from a variable-geometry inlet producing a high throat Mach number during climbout to reduce inlet noise under the takeoff flight path. Reduction of inlet noise at approach power would be obtained from the use of advanced bulk-absorber linings similar to those considered for the WBT airplanes. Combining these two noise-reduction concepts in a full-scale inlet and demonstrating its performance is needed to provide data to compare with predicted acoustical performance.

Advanced lining concepts for the turbine and fan-discharge ducts need to be developed and tested. The effort should include duct-transmission-loss tests (using heated air for the turbine-noise/core-noise linings) to provide data needed to select candidate lining designs. Full-scale tests should then be conducted with a long-duct, mixed-flow nacelle fitted to a high-bypass-ratio turbofan similar to the proposed ATT engine. Special test hardware is needed to enable the reductions in fan noise, turbine noise, and low-frequency core noise to be distinguished and identified.

11.0 CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

The studies for the wide body transport, showed major fuel and nacelle construction cost savings were possible from the application of advanced composites in engine nacelle design. The fuel savings could exceed $1 billion over a five-year period. Concurrently, the area enclosed by the 90 EPNdB noise contour could be reduced by more than 35 percent. Although the greatest fuel savings were related to the long-duct, mixed-flow nacelle configuration, the application of advanced composites to the short-duct nacelle configuration also offered significant improvements.

Technology fallouts could be applied in developing new military and airline transports and in improving the current generation of wide body transports. Application of this technology is very much dependent on successfully demonstrating the durability of advanced composites in the operators' environment as well as confirming the performance advantages.

Commercial service experience is necessary to demonstrate that advanced composites in nacelle structures are suitably durable. This experience cannot be provided by any ongoing NASA or Air Force programs because military aircraft utilization rates are typically only 400 to 900 hours per year as opposed to the 3000 to 4000 hours per year typical of airlines utilization would drag out the service demonstration to the extent that the fuel savings and noise alleviating benefits could not be realized before 1985, at the earliest. Thus, the durability demonstrations must be performed on commercial transports to yield data as soon as possible to permit timely application of the technology toward meeting the nation's energy conservation requirement.

The ATT studies showed that acoustical benefits similar to those projected for WBT airplanes could also be realized by the development of advanced acoustic-composite nacelles. With a high-Mach-number hybrid inlet, composite nacelle treatment, and a mixed-flow long-duct nacelle, there was a 60-percent reduction in the area enclosed by the 90-EPNdB contour relative to the contour area for a current 2-engine WBT airplane.

11.2 Recommendations

It is recommended that a follow-on to this advanced-composite nacelle study should be conducted. This follow-on program would include flight testing directed toward implementing the application of the technology identified. Newly produced versions of current wide body transports as well as new transport aircraft powered by high-bypass-ratio turbofan engines would benefit from the follow-on program. It is further recommended that an airframe company be the prime contractor for this phase of the program since expertise in integrating the nacelle/pylon/wing structure and aerodynamics is the key to realizing all of the benefits and since it is necessary that the trades between cost, weight, performance, and noise be accurately assessed. In addition, because FAA certification prior to installation of the nacelle design is required as a condition of certificating the airlines it is used on, the airframe company's expertise in handling this matter will be both appropriate and proper. Therefore, it is strongly recommended that the demonstration of the advanced composite nacelle be implemented as soon as possible to avoid losing the substantial fuel savings that are predicted. The 1973-1974 wide-body-transport production was 119 aircraft, and each of these aircraft has a useful life of at least 15 years. Thus a delay of just one year in the introduction of this technology could result in not realizing fuel savings of over $200 million based on the current $0.07 to $0.08/liter ($0.26 to $0.30/gallon) cost of aviation turbine engine fuel. The maximum benefit of this new technology to the public and the air transportation industry will be obtained by NASA sponsorship of the recommended follow-on program at the earliest possible time. NASA should also consider the many areas and facets of the outlined programs which could provide for NASA in-house endeavors, including the substantial use of NASA manpower and facilities.

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