CR 152096

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AUGUST 1977

Prepared under Contract No. NAS2-8612
Modification 4
Lockheed-California Company
Burbank, California
for

NASA

National Aeronautics and
Space Administration

Ames Research Center
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16. ABSTRACT

This study was performed to further assess the advantages of a propfan powered aircraft for the commercial air transportation system. The advantages of the propfan aircraft were assessed by comparison with an equivalent turbofan transport. Comparisons were accomplished on the basis of fuel utilization and operating costs, as well as aircraft weight and size.

Advantages of the propfan aircraft, concerning fuel utilization and operating costs, were accomplished by considering:

- Incorporation of new propfan performance and acoustic data
- Revised mission profiles (longer design range and reduction in cruise speed)
- Utilization of alternate and advanced technology engines

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FOREWORD

This document, LR 28283, is the final technical report of the Lockheed California Company's analytical study of the further assessment of the fuel conservation merits of an advanced propfan powered transport aircraft. The study, reported herein, is a supplement to the previous analytical study entitled "Study of Cost/Benefit Tradeoffs for Reducing the Energy Consumption of the Commercial Air Transportation System" (Report Number 137926) performed under Contract NAS2-8612 for the National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California. This report presents the results of work performed under Modification Number 4 to Contract NAS2-8612.

Mr. Louis J. Williams of the V/STOL Systems Office at the NASA Ames Research Center was the technical monitor and advisor for this study.

The study was performed within the Commercial Advanced Design Division of the Lockheed-California Company, Burbank, California.

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SUMMARY

This study is an extension of the previous RECAT propfan studies, documented by NASA Report CR 137926, which show savings in fuel and operating costs for a 1985 IOC propfan aircraft, at a 1500 nautical mile, Mach 0.8 design mission and 60¢/gallon fuel cost, of 17.8 and 8.2 percent respectively when compared to an equal technology turbofan aircraft. The objective of this study was the examination of further potential savings in fuel and operating costs for the propfan aircraft by incorporating:

- New propfan data
- Revised design mission profiles
- Additional engine performance characteristics

The results of this study are summarized in Tables 1, 2, and 3, and show that:

- New propfan data does not alter the previous RECAT findings - impact of higher exterior noise levels is offset by measured directivity characteristics and higher propulsive efficiency. Fuel and DOC savings of the revised baseline propfan over the baseline turbofan is 17.6 and 7.8 percent respectively.
- Reduced cruise speed decreases acoustic treatment requirements and increases fuel efficiency of the propfan aircraft. Fuel and DOC savings of the propfan over the turbofan (both at Mach 0.75 cruise) is 21.0 and 10.0 percent respectively.
- Incorporation of the Allison PD 370-22 turboshaft engine confirms the previous RECAT results. Fuel and DOC savings of the propfan over the baseline turbofan is 17.8 and 10.1 percent respectively.
- Incorporation of 1990 technology engines offer fuel and DOC savings of 11 and 7.5 percent respectively over the 1985 technology engines. Fuel and DOC savings of the 1990 propfan over the 1990 turbofan is 17.1 and 7.8 percent respectively.

TABLE 1. PROPFAN SAVINGS FOR STUDY CONDITIONS

	SAVINGS OF PROPFAN OVER TURBOFAN--PERCENT			
	DESIGN MISSION (100% L.F.)		475 N.M. (58% L.F.)	
STUDY CONDITION	BLOCK FUEL	DOC (60¢)	BLOCK FUEL	DOC (60¢)
Previous RECAT Baseline (1500 N.M., Mach 0.8)	17.8	8.2	20.4	8.2
Revised Baseline - New Propfan Data (1500 N.M., Mach 0.8)	17.6	7.8	19.6	8.1
Design Range Increased (2000 N.M., Mach 0.8)	16.5	8.0	18.5	8.3
Cruise Speed Reduced (1500 N.M., Mach 0.75)	21.0	10.0	22.9	10.2
Higher Press. Ratio Engine - PD 370-22 (1500 N.M., Mach 0.80)	17.8	10.1	19.8	10.3
1990 Engine Technology (1500 N.M., Mach 0.80)	17.1	7.8	19.1	8.1

TABLE 2. FUEL EFFICIENCY FOR STUDY CONDITIONS

STUDY CONDITION	DESIGN RANGE - 100% L.F.		475 NM, - 58% L.F.	
	TURBOFAN (LB/ASM)	PROPFAN (LB/ASM)	TURBOFAN (LB/ASM)	PROPFAN (LB/ASM
Previous RECAT Baseline	.0956	.0786	.1808	.1439
Revised Baseline	.0956	.0788	.1808	.1454
Design Range Increased	.0957	.0799	.2414	.1967
Cruise Speed Reduced	.0932	.0736	.1764	.1359
PD 370-22	.0956	.0785	.1808	.1449
1990 Engine Technology	.0847	.0702	.1603	.1296

TABLE 3. EFFECT OF STUDY CONDITIONS ON AIRCRAFT PERFORMANCE FOR DESIGN MISSION (100% L.F.) AND 60¢/GALLON FUEL

	PROPFAN SAVINGS - %		TURBOFAN SAVINGS - %	
STUDY CONDITION	FUEL	DOC	FUEL	DOC
Mission Effects				
Increased Design Range	N/A	1.1	N/A	0.9
Decreased Cruise Speed	6.5	2.3	2.5	0
Technology Effects				
High Press. Ratio Engine	0.3	3.3	N/A	N/A
1990 Technology Engines	10.8	7.4	11.4	7.5

Savings Are Relative to Baseline Design Airplanes as Follows:

1. Propfan - 1500 NM., 0.8 Mach, STS 476, Revised Propfan Data
2. Turbofan - 1500 NM., 0.8 Mach, JT10D

The propfan and turbofan aircraft previously studied were restrained to a 1985 IOC with a design range of 1500 nautical miles, Mach 0.8 cruise speed, and a payload of 200 passengers. The engines employed were a rematched version of the Pratt and Whitney STS 476 turboshaft using a Hamilton Standard eight bladed propfan operating at 800 feet per second rotational tip speed and a scaled version of the Pratt and Whitney JT10D turbofan. Advanced technology incorporated into the airframe design included:

- Supercritical wing
- Active controls
- Advanced composite materials for cost effective secondary structure

Incorporation of the above resulted in a 4.5 percent reduction in aircraft empty weight. Direct operating costs were calculated using 1973 dollars and the cost factors shown in Table 4.

Maintenance factors, identical to those utilized for the previous RECAT study, were as follows:

- Airframe Maintenance - Maintenance cost per cycle was reduced by 25 percent for the propfan due to decreased maintenance requirements for wheels, brakes, and landing gear.
- Engine Maintenance - Propfan engine maintenance was adjusted using factors previously provided by Pratt and Whitney for the turboshaft engine and by Hamilton Standard for the gearbox and propeller (Reference NASA CR 137926, Appendix A and B).

Maintenance labor cost per flight hour was reduced by 0.017 man-hours per engine flight hour from the baseline turbofan engine and then gearbox and propeller maintenance was added. No change was made for engine labor cost per cycle.

Turboshaft maintenance material cost per flight hour was adjusted using thrust relationships with gearbox and propeller cost added. Turboshaft maintenance labor cost per cycle was adjusted using thrust relationships but with no addition for gearbox and propeller.

Assessment of fuel savings and operating cost advantages was accomplished during this study at the following conditions:

TABLE 4. COST FACTORS

1973 DOLLARS	PROPFAN	TURBOFAN	COMMENTS
Cost Breakdown			
Flyaway Cost (Millions $)	14.15	13.39	Avg. unit cost based on 350 units
Airframe	10.34	10.09	
Propulsion	3.31	2.80	Dev. cost amortized over 250 units-15% profit
Avionics	0.50	0.50	
D.O.C. Factors			
• Flight Crew Cost ($/Hr.)	223	223	
• Maintenance Factors			1973 rates
– Labor Rates ($/Hr.)	6.10	6.10	
– Maintenance Factors			To adjust ATA formulas
Airframe Labor/Cycle	0.57	0.60	
and/Hour	0.57	0.60	Propfan brakes and wheels
Airframe Material/Cycle	0.47	0.60	
Airframe Material/Hour	0.75	0.75	
Engine Labor/Cycle	0.60	0.60	
Engine Labor/Hour	0.78	0.75	Includes engine, gearbox
Engine Material/Cycle	0.49	0.60	and propeller for
and/Hour	0.65	0.75	propfan/turboprop
– Burden (Factor)	1.8	1.8	
• Fuel ($/Lb.)	0.088	0.088	60¢/Gallon
• Oil ($/Lb.)	1.0	1.0	
• Insurance (%)	1.0	1.0	
• Depreciation			
Years	16	16	
Spares (%)	15	15	
Salvage (%)	10	10	
• Utilization (Hr./Yr.)	2900	2900	

- Resize the 1985 IOC propfan airplane for the new propfan data
- Resize the 1985 IOC propfan airplane for a 2000 nautical mile design range to allow wider usage of the airplane
- Resize the 1985 IOC propfan airplane for a cruise speed of Mach 0.75 to take advantage of additional fuel savings and potential reduced acoustic treatment requirements.
- Incorporation of an alternate turboshaft engine (PD 370-22) with component technology and overall pressure ratio comparable to the JT10D-2 turbofan.
- Incorporation of the Pratt and Whitney STS 487 turboshaft engine, representative of 1990 IOC technology and comparison with an equivalent 1990 IOC technology turbofan - STF 477.

The fuel conservation merits and the advantages in direct operating cost of the propfan powered aircraft was evaluated by utilizing an equal technology turbofan powered aircraft and comparing the two at identical design and mission conditions.

The new propfan data supplied by Hamilton Standard reflects the results of their wind tunnel tests of an 8 bladed propfan model and includes their predictions for a 10 bladed propfan. The effect on the new data was a slight increase in propulsive efficiency accompanied by a slight increase in generated sound pressure level for the 8 bladed propfan at 800 fps tip speed. Directivity of the generated noise was re-defined, allowing more efficient utilization of the acoustic treatment material in the aircraft fuselage.

The near field noise generated by the propfan necessitates acoustic treatment of the fuselage to maintain the cabin interior noise at a level consistent with current wide body turbofan aircraft. For this study, the Hamilton Standard supplied acoustic characteristics for the propfan (Appendix A) were utilized in conjunction with a "Double Limp Wall" concept to establish the transmission loss through the fuselage wall and the required mass treatment needed to attain acceptable interior noise levels. A discussion of the acoustic analysis method utilized and the results obtained is included as Section 3. The acoustic treatment concept utilized for this study is the addition of "limp" (non structural) mass, such as lead vinyl, to the fuselage to obtain the required transmission loss. This concept results in approximately 5000 pounds of additional fuselage weight for the baseline propfan airplane (additional weight over that required for the baseline turbofan airplane). Since experimental verification of this acoustic analysis concept (double limp wall) has not been accomplished, uncertainties exist concerning the magnitude of fuselage treatment required. To compensate for this uncertainty, Lockheed has included the conservatism of assuming that treatment of the entire fuselage diameter and cabin length will be required. As subsequently discussed, additional acoustic assessment (both analytical and experimental) is required.

This study shows that an advanced propfan powered aircraft, utilizing the Hamilton Standard 8 bladed propfan, is a viable alternate to the turbofan powered aircraft and offers significant savings in fuel and operating costs without compromising passenger comfort. Additionally, the reduction in cruise speed to 0.75 Mach, consistent with current operation of short and medium range transports, offers further significant savings in fuel and operating costs.

Assessment of the Hamilton Standard data for a 10 bladed propfan indicates a further potential advantage in fuel and DOC savings since the projected sound pressure levels are reduced. This reduction in SPL along with an increase in blade passage frequency results in a significent reduction in acoustic treatment weight.

To realize the potential fuel and operating cost savings available with the advanced propfan powered aircraft, and to further enhance its viability, the following actions must be implemented:

- Further investigation of ten and twelve bladed propfans to assess their characteristics (performance, acoustics, mechanical design, and economics) and the impact on aircraft performance

- Investigate propfan aircraft acoustic treatment concepts and configurations to further assess noise transmission mechanism in conjunction with aircraft fuselage wall structure/requirements

- Investigate further advances in turboshaft engine technology for additional improvements in fuel consumption and engine economic characteristics

- Investigate alternate engine/aircraft installation configuration to minimize the effect of propfan exterior noise transmission to the fuselage interior

- Investigate the maintenance characteristics and costs of thrust reverser mechanism and aircraft tires/brakes for the turbofan and propfan aircraft to enhance the maintenance cost data, used for operating cost comparisons.

INTRODUCTION

The energy restrictions imposed in late 1973 by the oil embargo and the compelling need for energy conservation in all sectors of our national transportation system led to a concerted effort by the air transportation industry to conserve fuel. Resolvement of the oil embargo, though alleviating the energy crisis of 1973, did not negate the need for fuel conservation. The escalation in fuel prices which have resulted combined with those prices projected for the future indicate a severe economic impact which must be offset by advancements in aircraft technology and operating procedures. Forecasts of the demand for air transportation shows a doubling or tripling by the year 1990 in all our major metropolitan areas. These projections along with the economic impact of estimated fuel prices for 1990 dictate a concerted effort to provide aircraft which are significantly more fuel efficient.

The previous RECAT study, part of the Aircraft Energy Efficient (ACEE) program, investigated practical means of achieving reduced fuel consumption in commercial air transportation in the following areas:

- Current aircraft types
- Revised operational procedures
- Modifications to current aircraft
- Derivatives of current aircraft
- New near-term fuel conservative aircraft.

Results of the previous RECAT study showed that significant potential savings in fuel and operating costs are available by utilizing the propfan propulsion system. The Hamilton Standard propfan is a multibladed, highly loaded, variable pitch propeller utilized in conjunction with an advanced turboshaft engine. Advanced aerodynamic characteristics of the propfan, which include thin blades with swept tips and advanced airfoils, produce a significantly higher propulsive efficiency, than that attained with a standard propeller design, and operation at Mach numbers competitive with turbofan powered aircraft.

In the previous study, a turbofan and a propfan airplane were designed and optimized for minimum fuel and operating cost for a 1500 nautical mile range, Mach 0.80 cruise speed design mission. Comparisons of fuel usage and operating costs for the design mission showed that the propfan aircraft results in a savings in fuel and operating costs (at 60¢/gal. fuel cost) of 17.8 percent and 8.2 percent respectively. The turbofan aircraft employed a scaled version of the Pratt and Whitney JT10D turbofan engine. A Pratt and Whitney STS 476 turboshaft engine with the Hamilton Standard 8 bladed propfan, 800 feet per second tip speed, was utilized for the propfan aircraft.

The study reported by this document examined the further potential for fuel and operating cost savings of the advanced propfan aircraft for the following conditions:

- New propfan data
- Revised design mission profiles
- Additional engine performance characteristics.

Propfan performance and acoustic characteristics, resulting from wind tunnel testing by Hamilton Standard of their propfan model, were supplied for assessment of the impact on aircraft performance. The new propfan data results in a slight increase in propulsive efficiency and in generated sound pressure level at the design point of 30,000 feet, Mach 0.8 with the 8 bladed, 800 fps propfan. Also included was a redefinition of acoustic directivity.

The previously used design range of 1500 nautical miles limited acceptance of the aircraft in airline fleet studies. A design range of 2000 nautical miles, equivalent to the B727-200, could provide a much wider potential use of the propfan aircraft. Also, preliminary analysis indicates additional fuel savings may be available with the propfan propulsion by reducing the cruise speed to a value consistent with current operating experience for short to medium range transports. Mach 0.75 was selected as the reduced cruise speed.

The turbofan and turboshaft engines used equal component technology but the loss of fan supercharging in the STS 476 turboshaft engine resulted in a lower overall pressure ratio than the JT10D-2 turbofan. An alternate turboshaft engine, Allison PD 370-22, with both component technology and overall pressure ratio comparable to the JT10D-2, was incorporated. Studies of unconventional engine cycles conducted under NASA-Lewis Research Center contract have identified two comparable advanced technology engines which could be available for a 1990 IOC. These engines, identified as the Pratt and Whitney STF 477 turbofan and STS 487 turboshaft, were incorporated.

The mission profile used for all performance calculations is included as Figure 1 and the study ground rules are presented in Table 5.

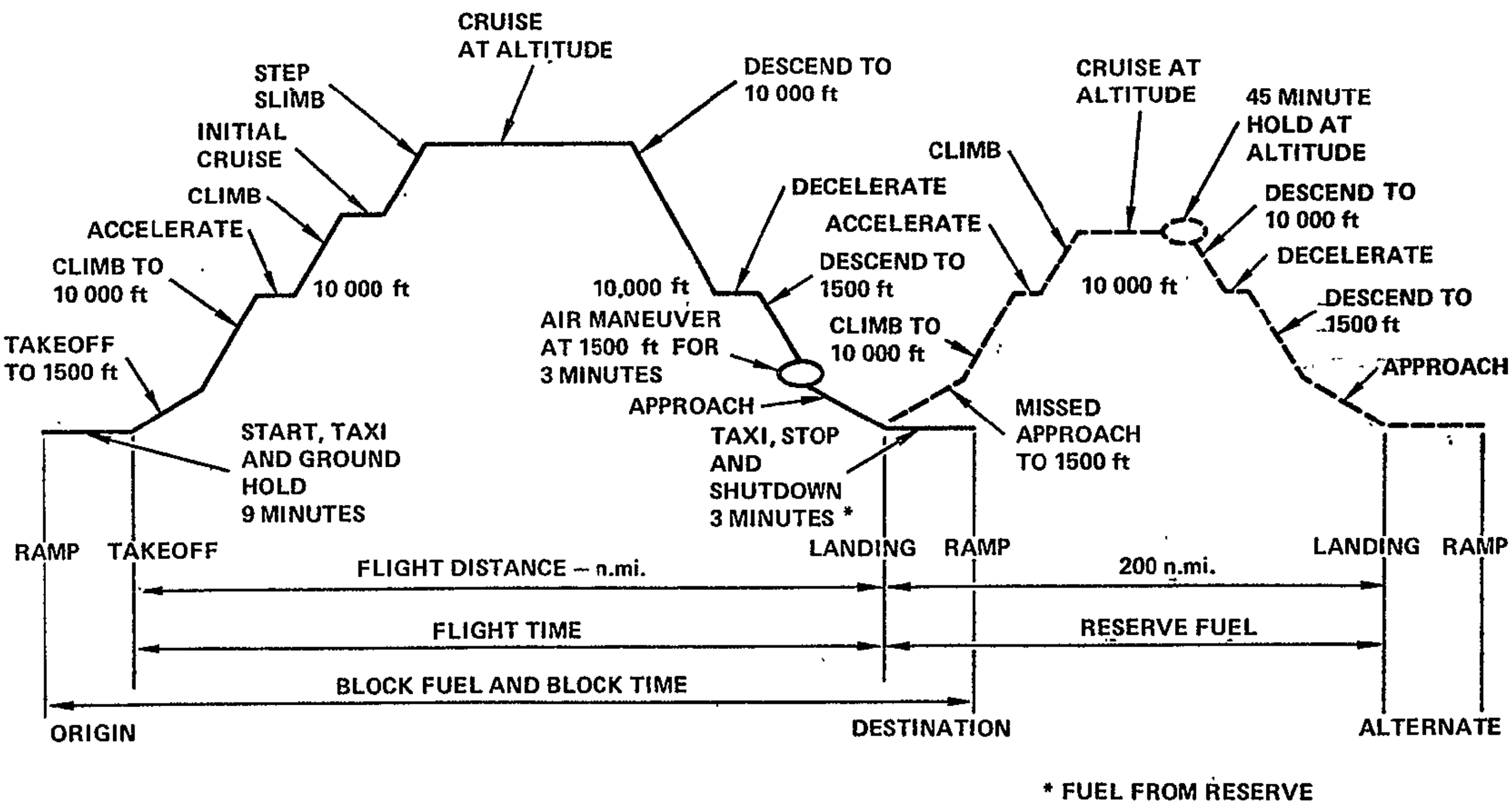


Figure 1. Domestic Mission Flight Profile

TABLE 5. STUDY GROUND RULES

Economic Parameters

- 1973 Dollars
- 60¢/Gallon Fuel
- Depreciation Period = 16 Years With 10% Residual
- Spares = 15% of Flyaway Cost
- Insurance Rate = 1%
- Production Quantity = 250 Aircraft
- Inflation = 5%
- Discount Rate = 8%

Configuration

- 200 Passengers
- Wide Body Fuselage
- Four Engines

Mission

- M 0.80 and M 0.75 Cruise
- 1500 n.mi. and 2000 n.mi. range
- Initial Cruise Altitude 30,000 feet
- Field Length 7000 feet
- Approach Speed 135 knots

Advanced Technologies

- Supercritical wing
- Active controls
- Advanced composites

ABBREVIATIONS/SYMBOLS/CONVERSIONS

Abbreviations

ASM	Airplane Seat Nautical Mile
ASSET	Advanced System Synthesis and Evaluation Technique (Lockheed Computer Program)
blk-hr	Block-hour
BPF	Blade passage frequency
DOC	Direct operating cost
EPNdB	Equivalent perceived noise level, decibels
EPR	Engine overall pressure ratio
FAR	Federal Air Regulation
ft	Feet
gal	Gallon
in.	Inch
kt	Knot
lb	Pound
LF	Load factor
LFL	Landing field length, ft.
MAC	Mean Aerodynamic Chord
MEW	Manufacturer's empty weight, lb.
min	Minutes
n.mi.	Nautical mile

OEW	Operating empty weight, lb
Pax	Passenger
SFC	Specific fuel consumption, lb fuel/hr/lb thrust
shp	Shaft horsepower
SL	Sea Level
SLS	Sea level static
TOFL	Takeoff field length, ft
TOGW	Takeoff gross weight, lb

Symbols

AR	Aspect ratio, b^2/S
b	Wing span, ft
c	Wing Chord, ft
c_b	Propeller blade chord, ft
C_D	Drag coefficient
C_L	Lift coefficient
d	Distance between inner and outer fuselage walls
D	Drag force, lb
D_p	Propeller diameter, ft
dB	Decibel
F_N	Net thrust force, lb
f	frequency, Hz
f_n	natural frequency, Hz
f_r	Ring frequency, Hz
M	Mach number
MCR	Cruise Mach Number
M_H	Helical tip Mach number

S	Wing area, ft^2
t/c	Thickness ratio
T/W	Thrust to weight ratio
W/S	Wing loading, lb/ft^2
η	Propeller efficiency
λ	Wing sweep angle, degrees

Conversions

To Convert From	To	Multiply By
Fahrenheit	Celsius	$T_c = (5/9)(T_F-32)$
foot	meter	0.3048
$foot^2$	$meter^2$	0.09290304
$foot^3$	$meter^3$	0.028316846592
foot/second	meter/second	0.3048
gallon	$meter^3$	0.003785411784
horsepower (550 ft-lb/sec)	watt	745.69987
inch	meter	0.0254
knot	meter/second	0.5144444444
nautical mile	meter	1852
pound (force)	Newton	4.4482216152605
pound (mass)	kilogram	0.45359237

SECTION 1

AIRCRAFT DESIGN EVALUATION

Table 6 provides a matrix of the design and mission characteristics utilized to evaluate the aircraft investigated during this study. Evaluation of the aircraft was accomplished for both a 1985 and 1990 IOC and included the following:

- New Propfan data
- Revised mission profiles
- Additional engine performance characteristics

The propfan and turbofan aircraft designed during Task 7 of the previous RECAT study were utilized as the baseline configurations for this study. Each of the study conditions depicted in Table 6 resulted in re-sizing of the baselines to obtain the optimum point design characteristics. The criterion utilized to select optimum point design characteristics was minimum direct operating cost, at 60¢/gallon fuel cost. This criterion is identical to that utilized for the previous RECAT study.

1.1 TURBOFAN AIRCRAFT

1.1.1 Baseline

The baseline turbofan powered aircraft, CL1320-11 is shown in the general arrangement drawing, Figure 2, and the general characteristics are shown in Table 7. As previously documented in NASA Report CR 137926, the airframe technology levels include a supercritical wing, active controls, and advanced composite secondary structure.

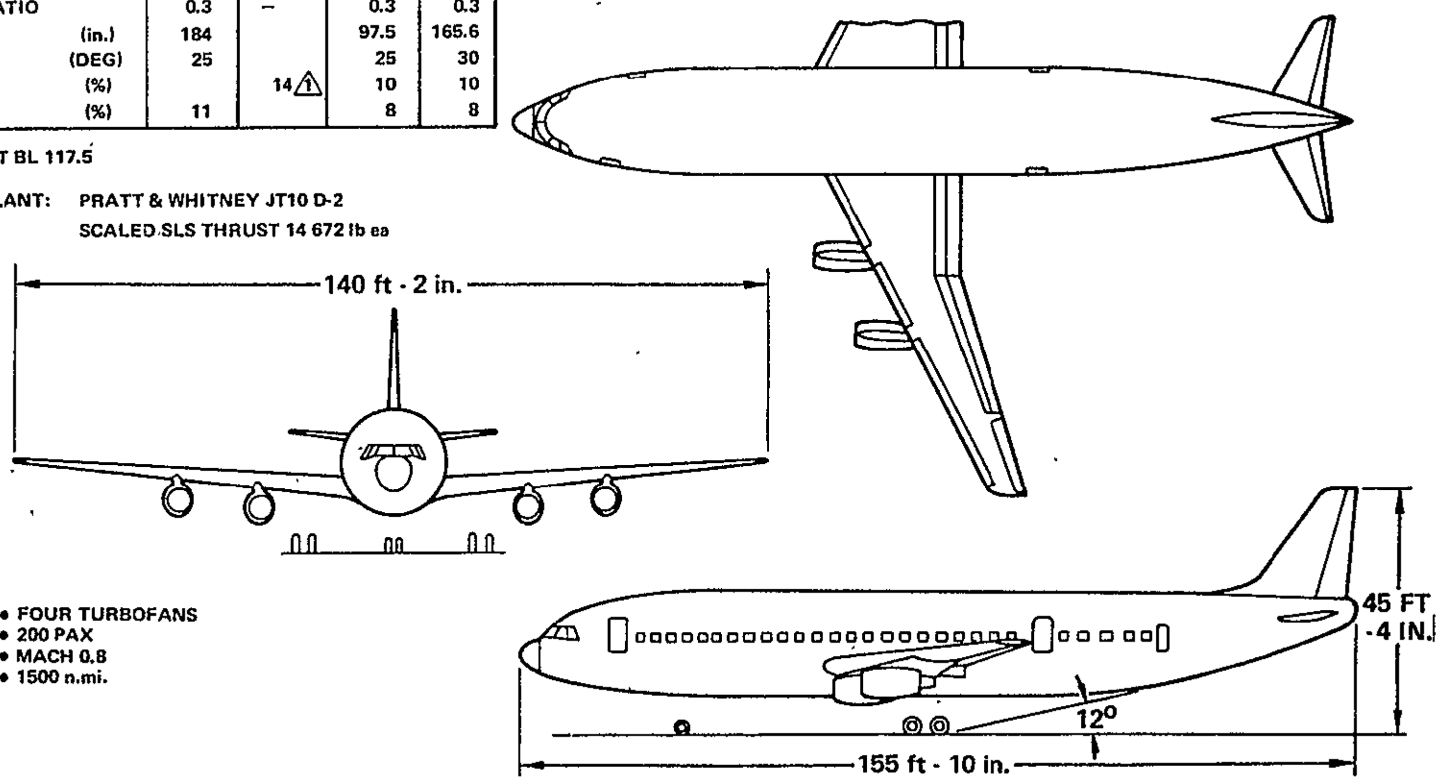
TABLE 6. STUDY MATRIX FOR AIRCRAFT CONFIGURATIONS

	1985 IOC										1990 IOC	
	BASELINE		INCREASED RANGE		DECREASED CRUISE SPEED		ALTERNATE ENGINE		OFF DESIGN CRUISE SPEED		1990 TECH ENGINE	
	P/F	T/F	P/F	T/F	P/F	T/F	P/F	T/F	P/F	T/F	P/F	T/F
Range (nm)	1500	1500	2000	2000	1500	1500	1500	N/A	1500	N/A	1500	1500
Cruise Speed (m)	0.8	0.8	0.8	0.8	0.75	0.75	0.8		0.75		0.8	0.8
Pax	200	200	200	200	200	200	200		200		200	200
Fuel Cost (¢/gal)	30/60	30/60	30/60	30/60	30/60	30/60	30/60		30/60		30/60	30/60
Cruise Alt (ft)	30K	30K	30K	30K	30K	30K	30K		30K		30K	30K
Field Length (ft)	7K	7K	7K	7K	7K	7K	7K		7K		7K	7K
App. Speed (kts)	135	135	135	135	135	135	135		135		135	135
Powerplant	STS 476	JT10D-2	STS 476	JT10D-2	STS 476	JT10D-2	PD370-22		STS 476		STS 487	STF 477

CHARACTERISTICS		WING		HORIZ	VERT
		BASIC	TOTAL		
AREA	(ft^2)	1955	2209	275	253
ASPECT RATIO		10	–	5	1.6
SPAN	(ft)	139.8		37	20.1
ROOT CHORD	(in.)	258	303 △1	137	232
TIP CHORD	(in.)	77		41	70
TAPER RATIO		0.3	–	0.3	0.3
MAC	(in.)	184		97.5	165.6
SWEEP	(DEG)	25		25	30
T/C ROOT	(%)		14 △1	10	10
T/C TIP	(%)	11		8	8

△1 AT BL 117.5

POWER PLANT: PRATT & WHITNEY JT10 D-2
SCALED SLS THRUST 14 672 lb ea



- FOUR TURBOFANS
- 200 PAX
- MACH 0.8
- 1500 n.mi.

Figure 2. General Arrangement-Turbofan Baseline Aircraft

TABLE 7. TURBOFAN BASELINE AIRCRAFT CHARACTERISTICS (CL 1320-11)

WEIGHTS	
Max. Takeoff Gross Wt (lb)	217015
Max. Landing Gross Wt (lb)	205000
Operational Empty Wt (lb)	138402
Max. Fuel Capacity (lb)	50000
POWER PLANTS	
Number and Type	4-JT10D-2 (Scaled)
Bypass Ratio	5.4
SLS Thrust/Engine (lb)	14672
BODY	
Length (ft)	155.8
Max. Diameter (in)	235
Accommodations	200 (10/90) 8 Abreast

WING AND EMPENNAGE

	WING	HORIZONTAL TAIL	VERTICAL TAIL
Area (sq. ft)	1955	275	253
Aspect Ratio	10	5	1.6
Span (ft)	139.8	37	20.1
Sweep (deg)	25	25	30
Mac (in)	184	97.5	165.6

The selected design was a 4 engine, wide body aircraft with a design range of 1500 nautical miles, 0.8 Mach cruise speed, and 200 passengers. Additional mission constraints were an initial cruise altitude of at least 30,000 feet, takeoff field length of 7000 feet maximum, and a maxiuum approach speed of 135 knots. The results of the parametric study used to size the baseline turbofan aircraft are shown in Figure 3. Sizing of the aircraft for minimum DOC, at 60¢/gallon fuel, resulted in a wing AR of 10 and a t/c of 12%. Design and performance characteristics of the baseline turbofan aircraft are included in Table 8.

The supercritical wing has an aspect ratio of 10 and a sweep (.25C) of 25 degrees. Active controls, allowing smaller, lighter airframes, are incorporated into the airframe design for the turbofan aircraft. A 3 percent reduction in wing weight is obtained by employing active ailerons to provide maneuver and gust load alleviation. Relaxation of static stability margins through use of an active horizontal tail results in a reduction in tail size and a corresponding 30 percent reduction in tail weight. The net reduction in empty weight, due to incorporation of active controls, is 1.2 percent. Secondary structure employing advanced composite materials includes the fixed wing leading edge, fuel tank baffles, floor supports, interior doors, and dividers. The reduction in empty weight, attributed to composite structure, is 3.3 percent. Incorporation of advance composites and active controls results in a total empty weight reduction of 4.5 percent.

Included in the baseline configuration is the JT10D turbofan engine, scaled to the aircraft performance and mission requirements. The features of the engine, designated JT10D-2, are included in Table 9.

1.1.2 1985 Technology Assessment

The 1985 technology assessment of the turbofan powered aircraft consisted of re-sizing the baseline configuration to assess the impact on mission fuel

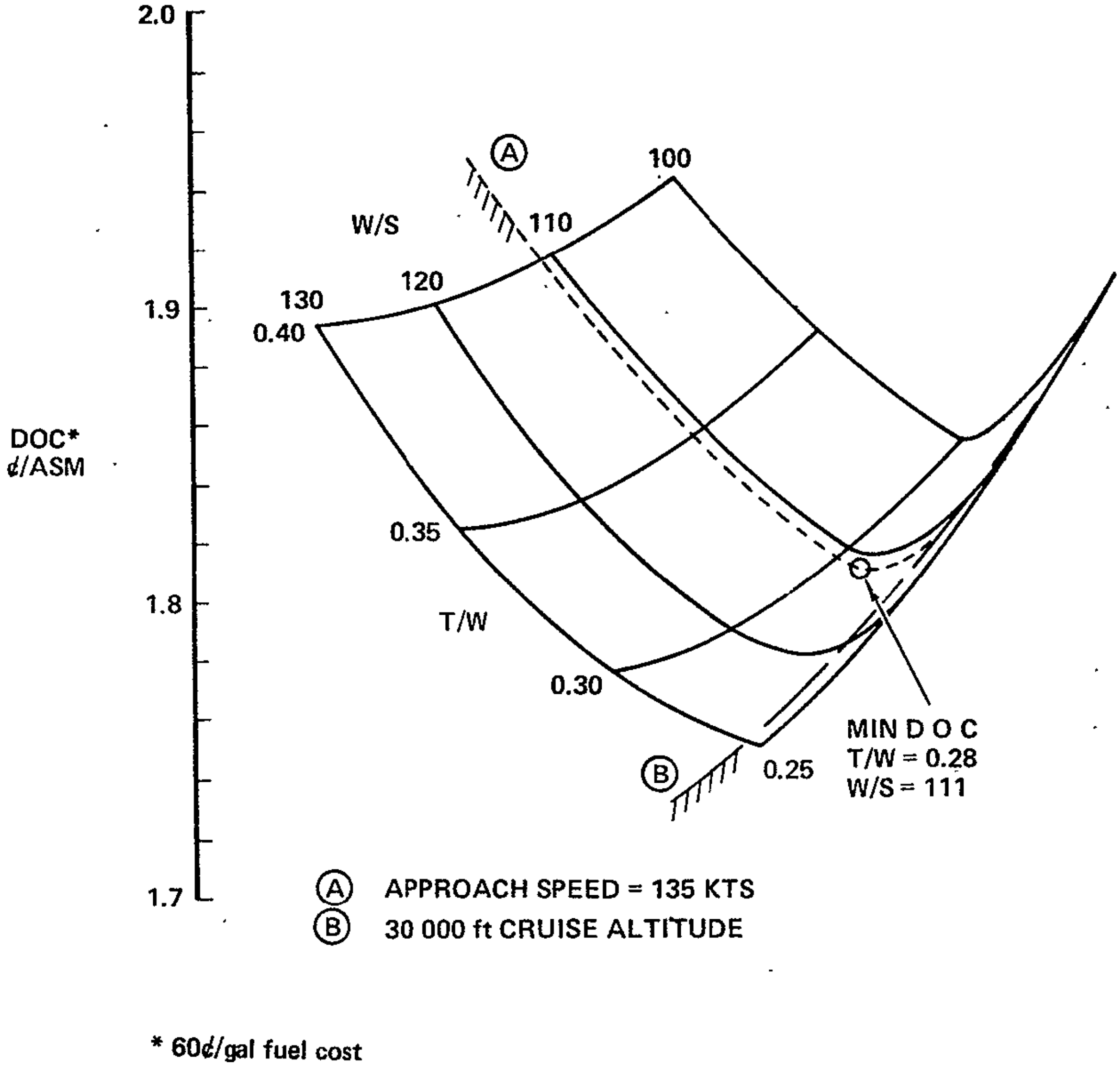


Figure 3. Selection of Baseline Turobfan Airplane Design

TABLE 8. DESIGN AND PERFORMANCE CHARACTERISTICS OF TURBOFAN AIRCRAFT

	1985 IOC			1991 IOC
	BASELINE CONFIG	INCREASED RANGE	REDUCED CRUISE	1990 ENGINE
Engine Identification	JT10D-2	JT10D-2	JT10D-2	STF 477
Cruise Speed	0.8M	0.8M	0.75M	0.8M
Design Range (nm)	1500	2000	1500	2000
No. Passengers	200	200	200	200
W/S (lb/ft^2)	111	115	112	109.8
T/W	0.28	0.28	0.24	0.26
AR	10	10	10	10
t/c (%)	12	12	12	12
TOGW (lb)	217015	230386	212365	206212
OEW (lb)	138402	141697	134648	132298
Thrust/Engine (SLS,lb)	15191	16127	12582	13249
Wing Area (ft^2)	1955	2003	1896	1878
Wing Span (ft)	139.8	141.5	137.7	137.0
DOC @30¢/gal 1500 nm (¢/ASM)	1.381	1.364	1.381	1.294
DOC @30¢/gal 475 nm (¢/ASM)	1.737	1.715	1.737	1.627
DOC @60¢/gal 1500 nm (¢/ASM)	1.809	1.793	1.810	1.674
DOC @60¢/gal 475 nm (¢/ASM)	2.236	2.216	2.236	2.069
Block Fuel - 1500 nm (lb)	28673	38276	27962	25418
Block Fuel - 475 nm (lb)	9965	13303	9717	8832
Fuel Efficiency (lb/ASM)	0.0956	0.0957	0.0932	0.0847
Cruise SFC (lb/hr/lb)	0.656	0.656	0.641	0.588
Initial Cruise Alt. (ft)	37000	37000	31000	32000
TOFL (ft)	5577	5787	6845	5930
LFL (ft)	6154	6138	6174	6123
Approach Speed (Kt)	135	135	135	135
Propulsion Weight (lb)	13436	14379	11217	10015

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TABLE 9. ENGINE FEATURES FOR JT10D-2 (SCALED) TURBOFAN

• Description	Twin Spool - Design fan press. ratio of 1.69 - bypass press. ratio of 5.4. Single stage fan, 12 stage compressor, 2 stage HP turbine, 4 stage LP turbine
• Scaling Factor	0.618
• Installed Thrust (SLS - lb)	14672
• Overall Press. Ratio (30,000 ft, 0.8 mach)	28:1
• Max. Turbine Inlet Temp. (°F)	2400
• Engine Length (in)	97.8
• Engine Diameter (in)	52.6
Engine Maintenance Cost ($/Flt hr)	122.6

requirements and direct operating cost of changes in design range (2000 nautical miles in lieu of 1500 nautical miles) and cruise speed (0.75 Mach in lieu of 0.80). Re-sizing criteria for each turbofan design was again minimum DOC at 60¢/gallon fuel cost.

An increase in the design range provides a potential wider usage of the aircraft in current fleet operations equivalent to the B727-200 design range. Likewise, the original cruise speed of Mach 0.80 may have unduly compromised the propfan aircraft and preliminary analysis indicates that additional fuel savings are available with a reduced cruise speed of Mach 0.75.

1.1.2.1 Design Range Increase

Increasing the design range to 2000 nautical miles necessitated a re-sizing of the aircraft utilizing the same type of parametric analysis conducted for the previous baseline design. For this parametric analysis, wing AR, t/c, W/S and T/W were varied as shown in Table 10. A total of 144 designs were accomplished using the ASSET, parametric analysis program. Plots of DOC versus t/c for each AR were drawn so that optimum values for minimum DOC could be selected. Figure 4, depicting DOC at 60¢/gallon versus t/c for the range of

TABLE 10. PARAMETRIC STUDY MATRIX TURBOFAN - JT10D-2
0.8 MACH, 200 PAX/2000 NM

AR	t/c	W/S				T/W			
8	9	100	110	120	130	0.24	0.26	0.28	0.30
8	12	100	110	120	130	0.26	0.28	0.30	0.32
8	14	100	110	120	130	0.27	0.29	0.31	0.33
10	9	100	100	120	130	0.22	0.26	0.30	0.34
10	12	100	110	120	130	0.24	0.28	0.32	0.36
10	14	100	110	120	130	0.24	0.28	0.32	0.36
12	9	100	110	120	130	0.22	0.26	0.30	0.34
12	12	100	110	120	130	0.24	0.28	0.32	0.36
12	14	100	110	120	130	0.24	0.28	0.32	0.36

AR's considered, shows the basis for selection. The selected values for AR and t/c of 10 and 11.5% (rounded to 12) are consistent with the results of wing optimization studies previously accomplished for the RECAT study for 60¢/gallon fuel cost. ASSET carpet plots are utilized to select W/S and T/W values for minimum DOC and the mission constraints (i.e., field length, approach speed, cruise altitude, etc.). Figure 5 is the ASSET carpet plot for minimum DOC (60¢/gallon) for the turbofan aircraft at the 2000 nautical mile design mission, and depicts the selection of the point design parameters. Point design parameters selected were AR = 10, t/c = 12%, W/S = 115, and T/W = 0.28. Design and performance characteristics of the turbofan aircraft sized for the 0.8 Mach, 2000 nautical mile design mission are shown in Table 8.

The effect of re-sizing the baseline turbofan aircraft for the 2000 nautical mile, Mach 0.8 mission is an increase in block fuel of approximately 26 percent which is consistent with the 25 percent increase in range and the

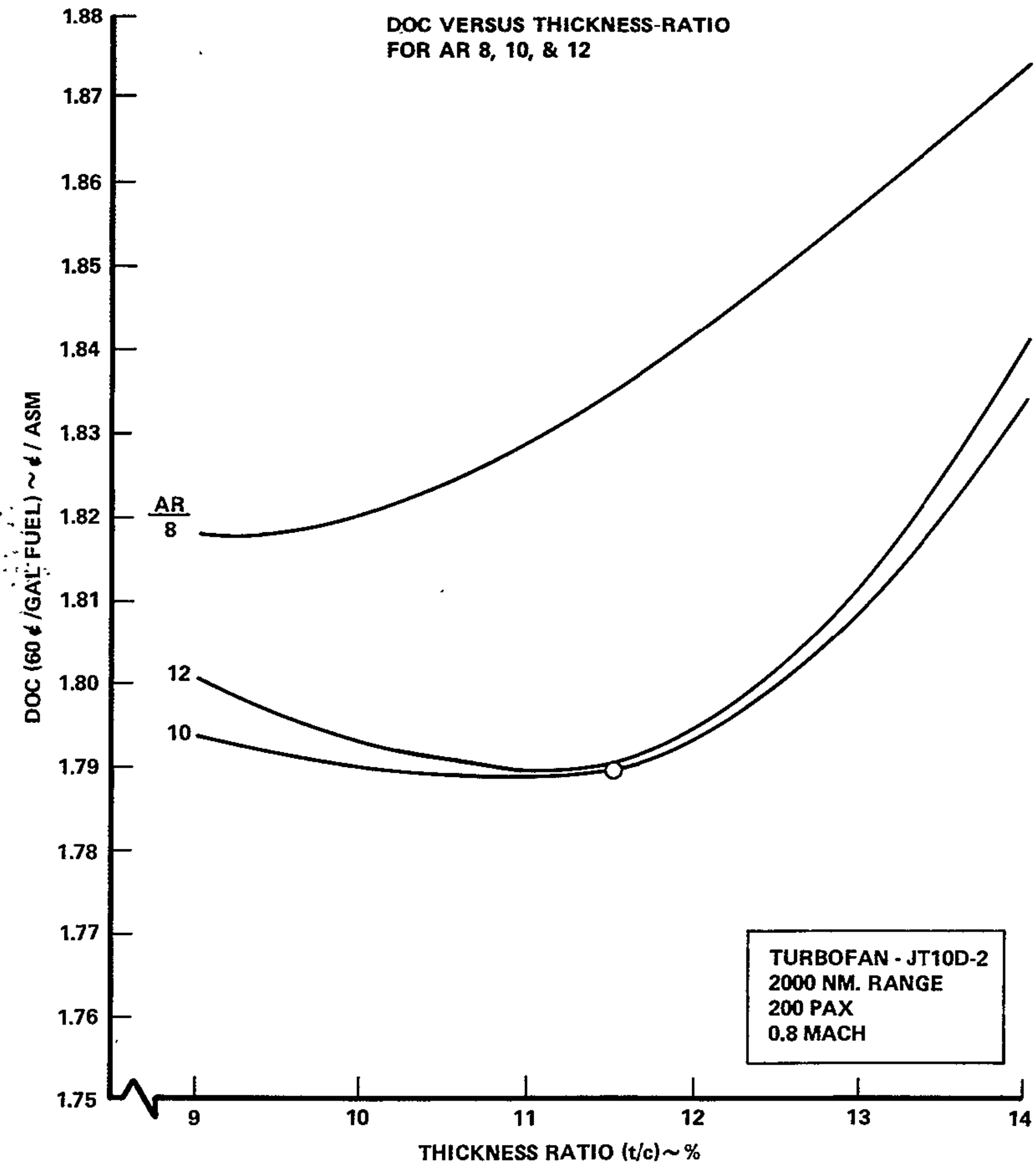


Figure 4. Turbofan DOC versus t/c - 2000 NM. Range

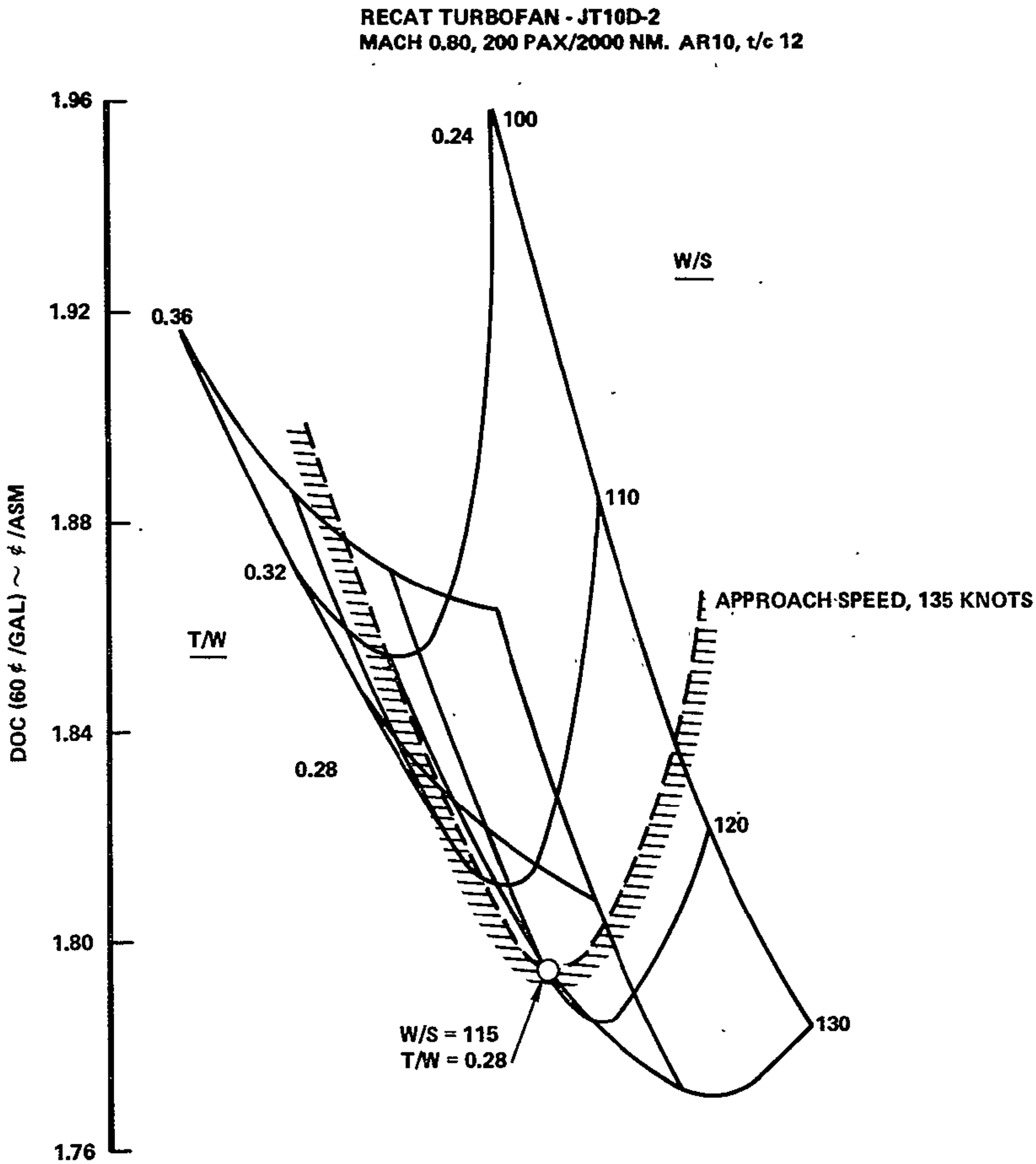


Figure 5. Asset Crossplot - Turbofan DOC (2000 NM. Range)

small increases in fuel required for take-off and climb due to the increased aircraft weight. Increasing the design range to 2000 nautical miles does effect a small savings in DOC at 60¢/gallon fuel cost.

1.1.2.2 Cruise Speed Reduction

A cruise speed of Mach 0.75 was selected as being consistent with current operator practice for short to medium range transports. Re-sizing of the turbofan aircraft for this mission was accomplished to provide a basis for comparison of the fuel savings available with the propfan aircraft at Mach 0.75 cruise speed.

The baseline turbofan was resized using the ASSET parametric analysis. Wing AR and t/c were held constant at 10 and 12 respectively and W/S and T/W were varied as follows:

W/S	T/W
100	.22
110	.24
120	.26
130	.28

Figure 6, the ASSET carpet plot of minimum DOC at 60¢/gallon fuel cost for the Mach 0.75, 200 PAX/1500 n.mi. turbofan aircraft, depicts the selection of optimum values for W/S and T/W utilized as the point design parameters. Point design parameters selected were:

AR	=	10
t/c	=	12%
W/S	=	112
T/W	=	.24

Design and performance characteristics of the turbofan powered aircraft, sized for Mach 0.75 cruise and 1500 nautical mile range, are included in Table 8.

The effect of re-sizing the turbofan aircraft for the 1500 nautical mile, Mach 0.75 mission is a savings in block fuel of 2.5 percent with no measurable

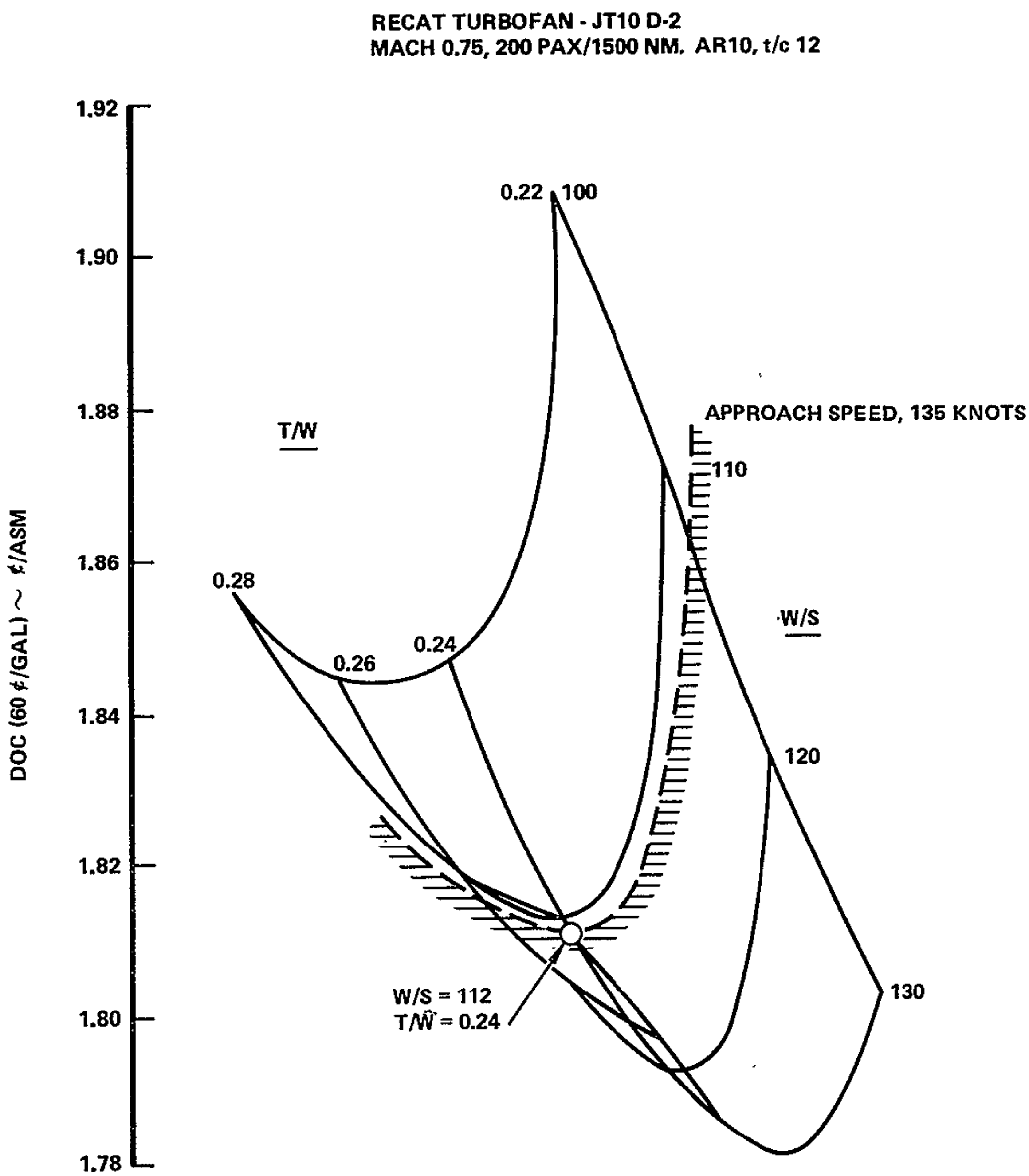


Figure 6. Asset Crossplot - Turbofan DOC (0.75 Mach)

change in DOC at 60¢/gallon fuel cost. The small decrease in block fuel at the 1500 nautical mile design range is attributed to an approximate 2 percent improvement in average cruise SFC.

1.1.3 1990 Technology Assessment

Previous studies accomplished under contract to NASA-Lewis Research Center of unconventional engine cycles have identified two comparable advanced technology engines for the turbofan and turboprop powered aircraft. These engines, the Pratt and Whitney STF 477 turbofan and STS 487 turboshaft, are representative of those which could be available for a 1990 IOC aircraft.

The 1990 technology assessment of the turbofan powered aircraft consisted of re-sizing the baseline turbofan for incorporation of the STF 477 engine at the 1500 nautical mile, Mach 0.8 mission and ascertaining the fuel savings and operating cost advantages. Baseline airframe technology levels remained unchanged. The re-sizing criteria was minimum DOC at 60¢/gallon fuel cost.

1.1.3.1 Advanced Technology Turbofan Engine

The Pratt and Whitney STF 477 turbofan engine was selected as representative of the best configuration for conserving fuel while presenting a practical configuration, attractive economic factors, and reasonable availability (1990 IOC) for advanced technology transport aircraft. The STF 477 engine is a two spool design with an overall pressure ratio of 45:1 and maximum turbine inlet temperature of 2600°F as compared to 28:1 and 2400°F for the JT10D-2 turbofan engine. A description of the engine parameters is shown in Table 11.

Performance data for the STF 477 engine, along with engine and nacelle dimensions, engine weight, and appropriate scaling factor was provided by Pratt and Whitney for adaptation to the RECAT turbofan aircraft design mission requirements.

1.1.3.2 Aircraft Optimization

Optimization of the 1990 turbofan aircraft was accomplished by re-sizing the baseline to incorporate the STF 477 turbofan engine in lieu of the JT10D-2. Utilization of the STF 477 engine necessitated alterations of the ASSET subroutines for configuration, weight, drag, and engine performance consistent

TABLE 11. STF 477 ENGINE PARAMETERS

PARAMETRIC DESCRIPTION

Base Size, Thrust, N(lbf)*	118100(26550)
Scaling Range, Thrust, N(lbf)*	71200-178000(16000-40000)
Nominal Cruise Design Cycle at Mn 0.83 and 10,058m(33,000 ft)	
Fan Pressure Ratio	1.70:1
Bypass Ratio	8.0 :1
Overall Pressure Ratio	45:1
Maximum Combustor Exit Temperature, °C(°F)	1427 (2600)
Inlet Flow (Corrected), kg/sec(lbm/sec)	472(1040)
Acoustics (Engine Plus Nacelle)	FAR 36 minus 10 EPNdB

PERFORMANCE (Representative Conditions)

Condition	Altitude		Mach No.	Net Thrust		TSFC	
	km	(ft)		N	(lbf)	kg/hr/N	(lbm/hr/lbf)
Take-off*	0	0	0.147	93635	(21050)	0.0358	(0.351)
Max. Climb**	9.14	(30000)	0.8	32912	(7399)	0.0588	(0.577)
Max. Cruise**	9.14	(30000)	0.8	29910	(6724)	0.0586	(0.575)

WEIGHTS AND DIMENSIONS

Base Engine Weight, kg (lbm)	1787(3940)
Dimensions	
Maximum Diameter, m(in.)	1.92(75.6)
Overall Length, m(in.)	2.88(113.2)
Nozzle Throat Areas	
Duct, m^2 ($in.^2$)	1.150(1783)
Primary, m^2 ($in.^2$)	0.303(470)
Engine Maintenance Cost ($/Flt-Hr)	118.28

*Sea level static take-off, 28.9°C (84°F) ambient temperature; U.S. Standard Atmosphere, 1962; 100% ram recovery; no customer bleed or power extraction; representative nozzle thrust coefficient.

**Estimated performance calculated on basis of: U.S. Standard Atmosphere, 1962; 100 percent ram recovery; 1.04 kg/sec (2.3 lbm/sec) mid-compressor bleed; 1.01 kg/sec(2.4 lbm/sec) duct bleed; 112 kw (150 hp) extraction; standard day; representative nozzle thrust coefficients.

with the performance and dimensional data supplied for the engine. For the parametric analysis, Wing AR and t/c were maintained at 10 and 12 % respectively and values of W/S and T/W were varied as follows:

$$W/S = 100, 110, 120, \text{ and } 130$$

$$T/W = .24, .26, .28, \text{ and } .30$$

Figure 7, the ASSET carpet plot, depicts the selection of W/S and T/W values to be utilized for the turbofan aircraft point design. Point design parameters selected are AR = 10, t/c = 12, W/S = 109.8, and T/W = .26. The performance and design characteristics of the turbofan aircraft with the STF 477 engine at 1500 nautical mile, Mach 0.8 mission, are shown in Table 8.

Utilization of the STF 477 turbofan engine results in a 1990 IOC turbofan aircraft at the 1500 nautical mile design mission with a block fuel savings of 11.4 percent and a DOC savings of 7.5 percent, at 60¢/gallon fuel cost, when compared to the 1985 IOC baseline turbofan aircraft. These savings are the result of an improvement in engine SFC characteristics, at cruise, of approximately 10 percent and a reduction in propulsion system installed weight of approximately 25 percent.

1.2 PROPFAN AIRCRAFT

The propfan powered aircraft designed during Task 7 of the previous RECAT study was utilized as the baseline configuration for this study. Re-sizing of the the baseline configuration was accomplished for each of the study conditions to obtain the best point design consistent with minimum DOC at the 60¢/gallon fuel cost.

Installed propfan engine performance is based on engine manufacturers uninstalled engine data corrected for 100 hp per engine power extraction, 100 percent engine air inlet total pressure recovery, zero bleed flow rate, and 99 percent gearbox efficiency as noted in Table 12. The 100 percent recovery is based on the assumption that inlet duct losses are equal and opposite to the pressure rise across the propfan. Cabin pressurization and environmental control are provided by an engine driven compressor to avoid the potentially large losses associated with bleeding the turboshaft engines.

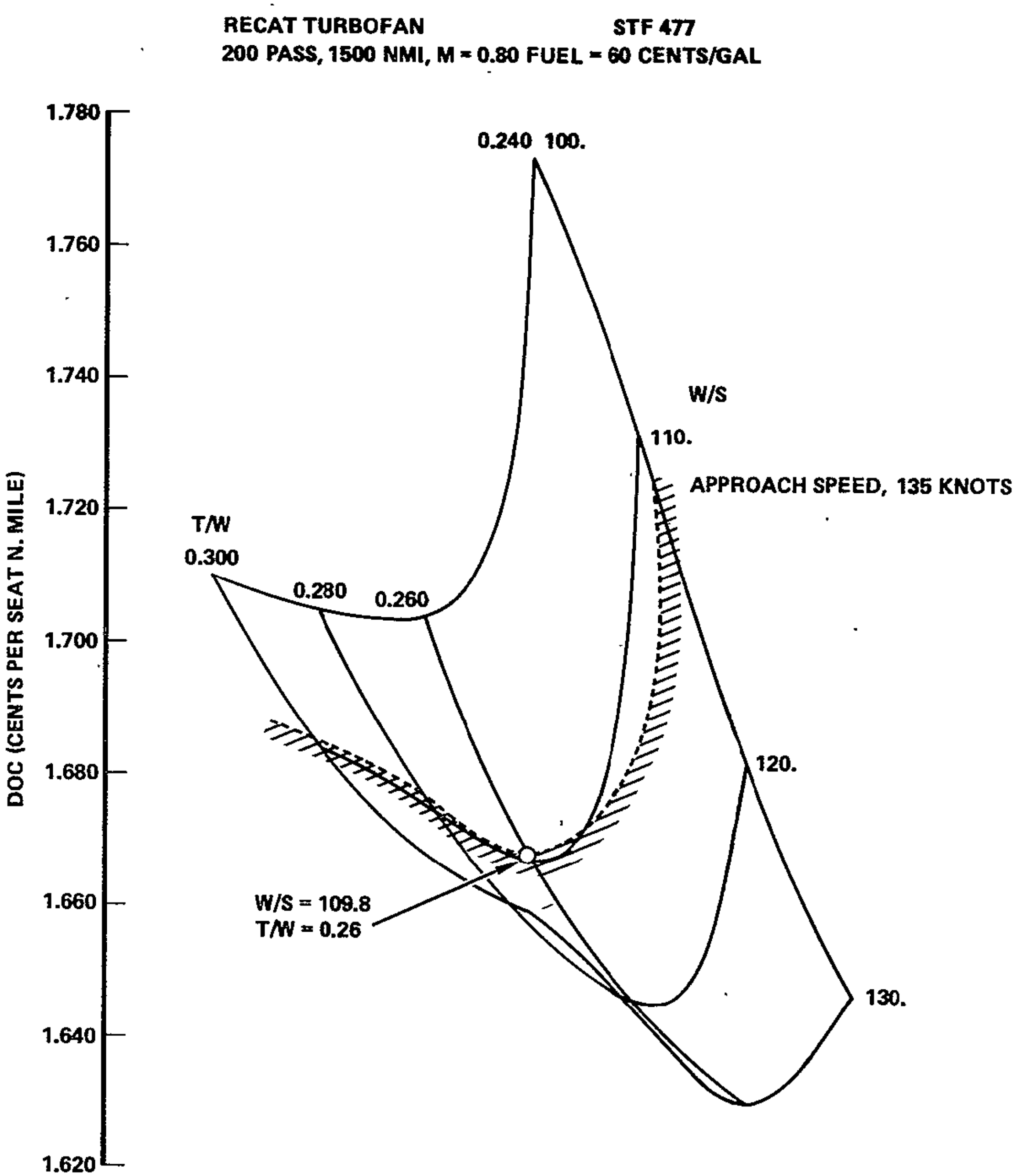


Figure 7. Asset Crossplot - Turbofan DOC (STF 477 Engine)

TABLE 12. ENGINE INSTALLATION LOSSES

Cruise M = 0.80

	Propfan	Turbofan
Inlet recovery, P_{T_2}/P_{T_0}	1.00	0.998
IP compressor bleed, %	0	2.0
Horespower extraction	100	50
Fan Duct loss % $\Delta P_T/P_T$	0	0.80
Gear Efficiency	0.99	-
Core cowl drag % $\Delta FN/FN$	-	1.6

Notes (1) Exhaust nozzle thrust and airflow coefficients included in uninstalled engine performance

(2) Nacelle drag included in aircraft drag

All propfan engine performance is based on Hamilton Standard projected levels of efficiency for a propfan design having eight blades, each with 0.12 integrated lift coefficient and 200 activity factor, and operating at 800 fps tip speed. Initial point designs for the propfan aircraft were computed using the propfan performance and acoustic characteristics and installation considerations incorporated in the previous RECAT. Subsequent data, supplied by Hamilton Standard as a result of their continuing propfan testing, indicates an increase in the propfan induced external sound pressure levels as well as a slight improvement in performance. This data necessitated a re-sizing of the propfan aircraft and generation of new point designs consistent with new performance values and the increase in required acoustic treatment.

Unlike the turbofan engine, the output of the turboshaft engine is shaft power which is transmitted through a gearbox and converted to useful thrust by the propfan. As discussed in Report No. CR137926 for the previous RECAT study, selection of the propfan disk loading (diameter), geometry (blade type and number), and tip speed is dependent on a tradeoff between net efficiency (fuel consumption) and installation weight (including acoustic treatment weight) and their impact on aircraft performance (DOC). For example, Figure 8 shows that decreased cruise point design disk loading (increased prop-diameter) results in improved propfan efficiency. While this results in lower propulsion system specific fuel consumption, the increased installation weight associated with the larger propfan diameter and increased near field sound pressure levels may potentially counteract the benefits of higher fuel efficiency. The increased weight results in a heavier aircraft, larger propulsion system, and higher fuel flow rates. Figure 8 indicates that while peak efficiency for the baseline STS 476 powered aircraft is achieved at a disk loading of 25 Shp/D^2, the optimum value for minimization of DOC and TOGW is 37.1 Shp/D^2, as shown in Figure 9.

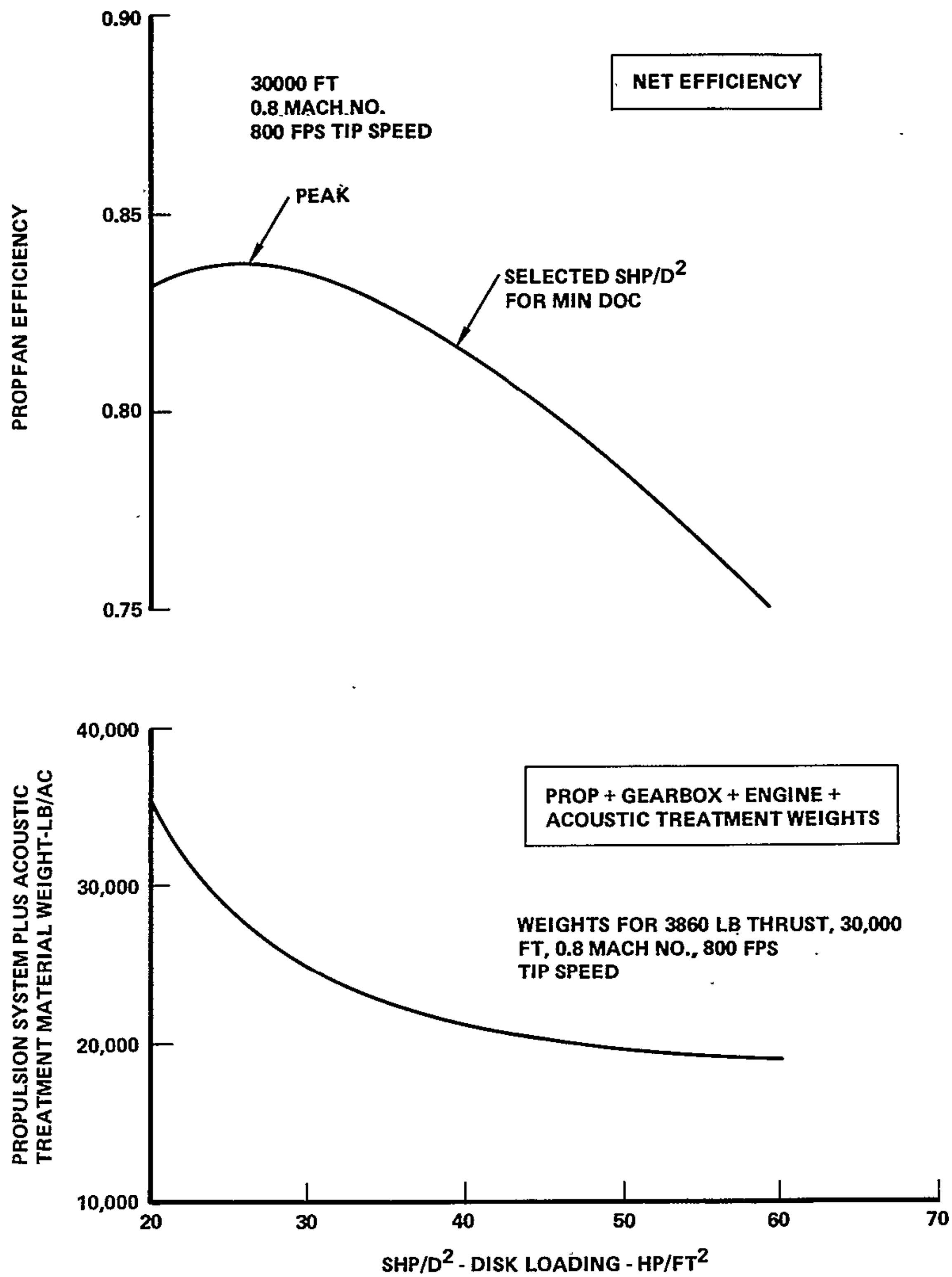


Figure 8. Propfan Efficiency and Propulsion System Weight Trends with Disk Loading

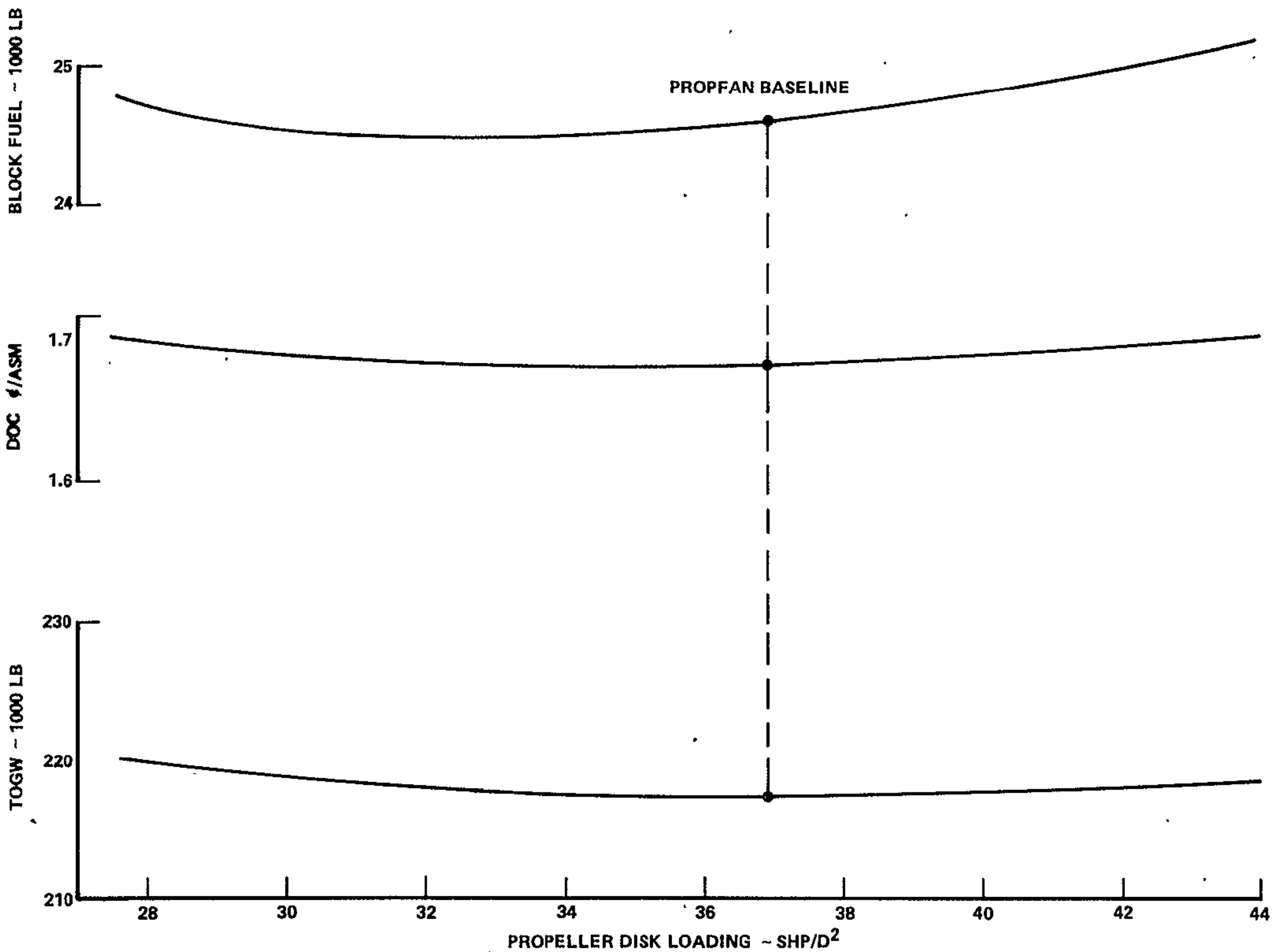


Figure 9. TOGW, DOC, and Block Fuel vs. Propeller Disk Loading

Similar propfan sizing studies for the other aircraft resulted in the following design disk loading and propfan diameter:

Design Mach No.	Range	Engine	Design Disk Loading	Prop Diameter
0.8	1500	STS476	37.1	12.6
0.75	1500	STS476	35.9	11.4
0.8	2000	STS476	37.1	12.6
0.8	1500	PD370-22	42	11.5
0.8	1500	STS487	46	11.0

Assessment of the fuel conservation and operating cost advantages of the propfan aircraft was accomplished for both a 1985 and 1990 IOC configuration. The 1985 propfan baseline was resized to reflect updated propfan and acoustic characteristics. Subsequent assessment of the propfan consisted of re-sizing to 1) increase the design range to 2000 nautical miles to provide potential as a replacement for the B727-200 aircraft; 2) decrease the cruise speed to Mach 0.75 to obtain added fuel savings for the turboshaft engine at slower speed; and 3) incorporate an alternate turboshaft engine which has an overall pressure ratio and component technology comparable to the JT10D-2 turbofan. Assessment of a 1990 propfan configuration consisted of re-sizing the 1985 baseline to incorporate an advanced turboshaft engine, representative of the engine technology expected to be available for a 1990 IOC. All final aircraft point designs generated during this study incorporate the Hamilton Standard updated propfan data, presented in Appendix A.

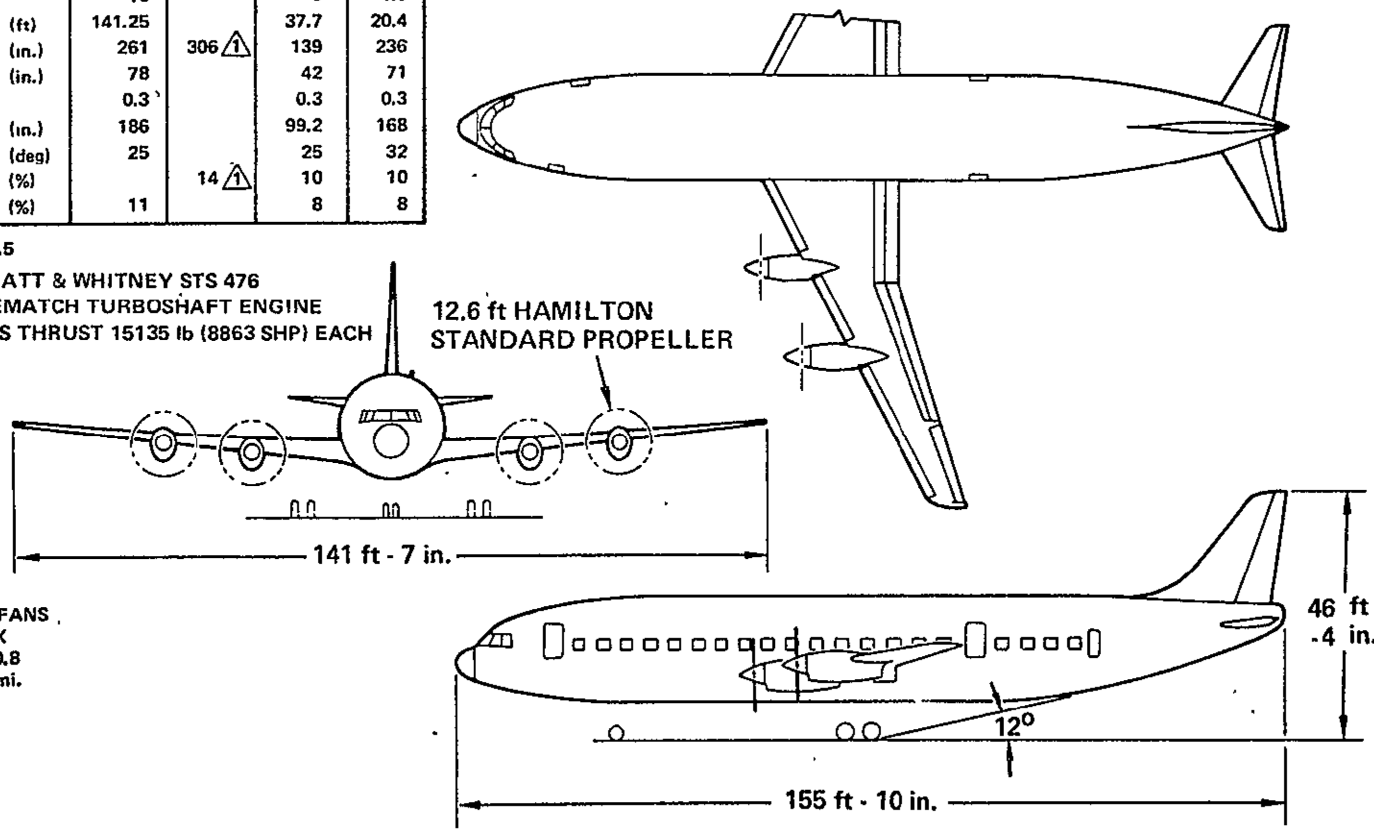
1.2.1 RECAT Baseline

The baseline propfan aircraft of the previous RECAT study, is shown in the general arrangement drawing, Figure 10, and the general characteristics are shown in Table 13. The airframe technology levels are identical to those utilized for the turbofan baseline. The propulsion system is a rematched version of the Pratt and Whitney STS 476 turboshaft engine using the Hamilton Standard 8 bladed propfan operating at a tip speed of 800 feet per second. Features of the rematched STS 476 turboshaft engine are shown in Table 14.

CHARACTERISTICS		WING BASIC	WING TOTAL	HORIZ	VERT
AREA	(ft^2)	1995	2250	284	261
ASPECT RATIO		10	–	5	1.6
SPAN	(ft)	141.25		37.7	20.4
ROOT CHORD	(in.)	261	306 ⚠1	139	236
TIP CHORD	(in.)	78		42	71
TAPER RATIO		0.3		0.3	0.3
MAC	(in.)	186		99.2	168
SWEEP	(deg)	25		25	32
T/C ROOT	(%)		14 ⚠1	10	10
T/C TIP	(%)	11		8	8

⚠1 AT BL 117.5

POWER PLANT: PRATT & WHITNEY STS 476
REMATCH TURBOSHAFT ENGINE
SLS THRUST 15135 lb (8863 SHP) EACH



- 4 PROPFANS
- 200 PAX
- MACH 0.8
- 1500 n.mi.

Figure 10. General Arrangement-Baseline RECAT Propfan Aircraft

TABLE 13. BASELINE RECAT PROPFAN

Weights

Maximum takeoff gross weight (lb)	217 466
Maximum landing gross weight (lb)	205 000
Operational empty weight (lb)	146 417
Maximum fuel capacity (lb)	50 000

Powerplants

Number & Type	4 STS 476 rematch
Propeller	12.6 ft/8 bladed
SLS thrust/engine (lb)	14135 (8863 shp)

Body

Length (ft)	155.8
Maximum diameter (in.)	235
Accommodations (No. Pax)	200 (10/90%) 8 abreast

Wing and Empenage

	Wing	Horizontal Tail	Vertical Tail
Area (sq ft)	1995	284	261
Aspect ratio	10	5	1.6
Span (ft)	141.3	37.7	20.4
Sweep (deg)	25	25	32
MAC (in.)	186	97.5	165.6

TABLE 14. BASELINE RECAT ENGINE CHARACTERISTICS

	P&W STS 476 Rematch (Scaled)
• Description	Turboshaft Engine of Comparable Technology to JT10D-2. New Compressor and LP Turbine. Engine Rescheduled to Meet LCC Requirements
• Scaling Factor	0.964
• Installed Rating	
Thrust (SLS, STD.) - lb	14 135
shp (SLS, STD.) - hp	8 863
Max shp (250 KEAS, SL, + 18°F) - hp	10 488
• Overall Pressure Ratio 36 000 ft M = 0.80 Cruise	20:1
• Max Combustor Exit Temp °F	2400
• Engine Length - in.	84.3
• Engine Diameter - in.	21.8

The baseline RECAT propfan airplane was optimized for minimum direct operating cost, at 60¢/gallon fuel cost, for a design range of 1500 nautical miles, 0.8 Mach cruise speed, and 200 passengers. Additional constraints imposed were an initial cruise altitude of 30,000 feet minimum, takeoff field length of 7,000 feet maximum, and a maximum approach speed of 135 knots.

The propfan aircraft, developed for the previous RECAT study, utilized performance, weight, and acoustic data for the 8 bladed propfan at 800 fps. tip speed as supplied by Hamilton Standard, per Report SP 02A76 and SP 05A76. Propeller disk loading and diameter, along with the magnitude of acoustic treatment in the aircraft fuselage, was determined using this data as described in Section 7.2 of Report No. CR 137926. A propeller disk loading of 37.1 Shp/D^2 was selected by considering the tradeoffs between propeller efficiency and installation weights and the impact on aircraft performance. At the selected disk loading for the turboprop baseline, 3089 lbs. of acoustic treatment in the aircraft fuselage is required to attain interior (cabin) noise levels of 90 dB or less.

1.2.1.1 Revised Baseline

As part of this study effort, the propfan performance and acoustic characteristics were updated by Hamilton Standard, as shown in Appendix A, to incorporate their latest wind tunnel test results. Data supplied includes both an 8 bladed and 10 bladed propfan, each operating at tip speeds of 600, 700, and 800 fps, at Mach numbers of 0.7, 0.75, and 0.8. Figure 11 shows a comparison of revised to original efficiencies at 0.8 Mach number. A detailed discussion of the propfan acoustic characteristics and the effect on fuselage treatment methods and results is included in Section 3 of this report.

Propeller disk loading was maintained at 37.1 Shp/D^2 for the revised baseline propfan aircraft. Because of the increased propfan SPL (Section 3), the weight of acoustic treatment for the revised baseline increases by approximately 2130 lbs from 3089 (previous RECAT) to 5220 lbs. The acoustic treatment weight of 5220 lbs. is obtained by interpolating between the values (at 37.1 Shp/D^2) depicted in Figures 25 and 26, Section 3, for the point design cruise thrust of approximately 3200 lbs required for the revised baseline propfan airplane.

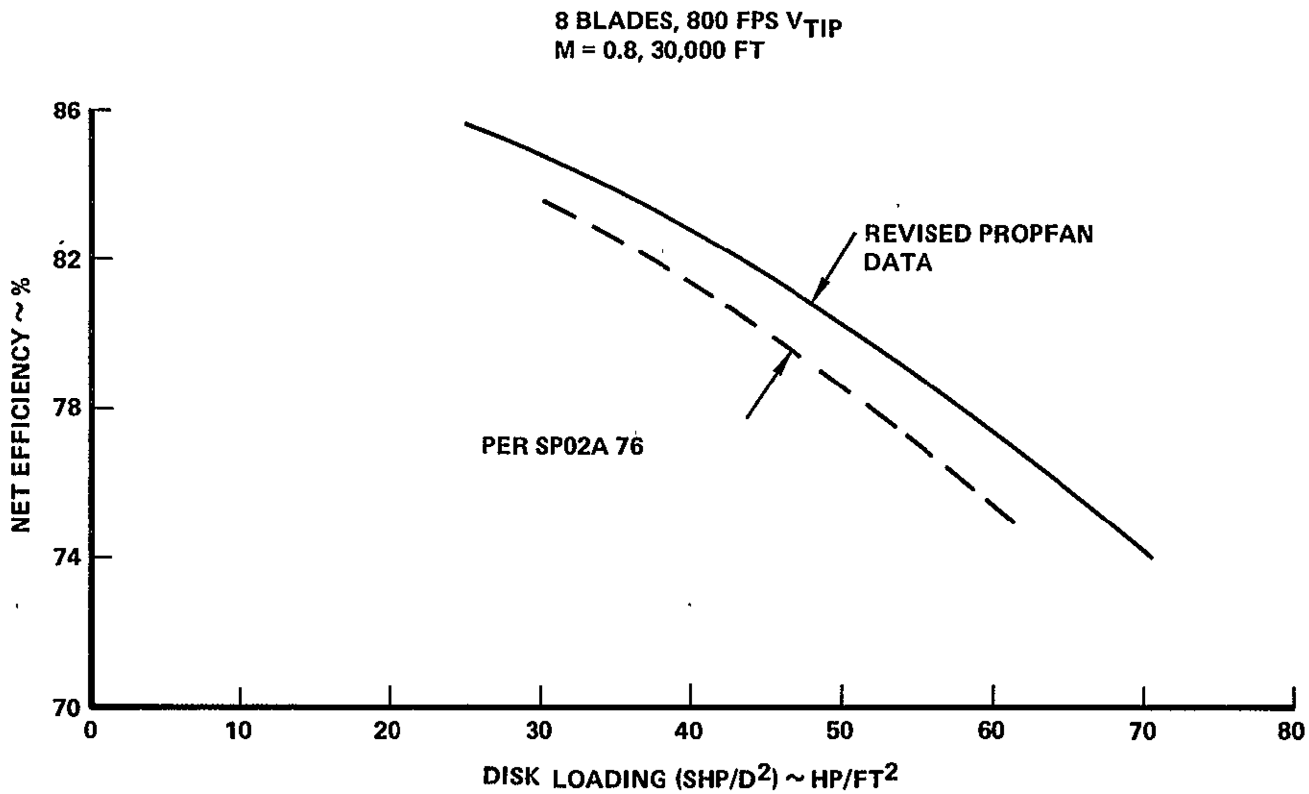


Figure 11. Effect of Disk Loading on Propfan Efficiency

The design and performance characteristics for the revised propfan baseline are shown in Table 15. The effect of the revised propfan data on the baseline configuration is an increase in block fuel of 269 lbs and an increase in DOC at 60¢/gallon fuel of 0.01¢/ASM for the Mach 0.8, 1500 nautical mile design Mission.

The sensitivities of changes in propfan efficiency and acoustic material weight on the baseline aircraft fuel and DOC savings are shown in Figures 12 through 15. These data indicate that a 1 percent decrease in propfan efficiency affects DOC (0.5%) the same as a 1000 lb. increase in acoustic treatment material. At the baseline disk loading of 37.1 Shp/D^2, net efficiency increases by approximately 1.7 percent while installed weight increases by approximately 2130 lbs due to the increased acoustic treatment required.

1.2.2 1985 Technology Assessment

For the propfan powered aircraft, the 1985 technology assessment consisted of re-sizing the baseline configuration, based on minimum direct operating cost, at 60¢/gallon fuel cost, for a design range of 2000 nautical miles in lieu of the 1500 nautical mile range; a cruise speed of 0.75 Mach in lieu of 0.80; and incorporation of an alternate turboshaft engine with an overall pressure ratio comparable to the JT10D-2 turbofan. In addition to re-sizing the baseline configuration, as stated above, an assessment of the performance impact was made when the cruise speed of the baseline configuration was reduced to Mach 0.75 with no re-sizing.

As previously discussed in Section 1.2 of this report, the change in design range was accomplished to provide a potentially wider use of the propfan airplane in current fleet operations and the change in cruise speed was accomplished to obtain the potential additional fuel savings available with the turboshaft engine.

TABLE 15. DESIGN AND PERFORMANCE CHARACTERISTICS OF PROPFAN AIRCRAFT

	1985 IOC				1990 IOC
	Revised Baseline	Design Range	Cruise Opt.	Alter. Engine	1990 Engine
Engine Identification	STS 476	STS 476	STS 476	PD 370-22	STS 487
Cruise Speed	0.8M	0.8M	0.75M	0.8M	0.8M
Design Range (NM.)	1500	2000	1500	1500	1500
No. Passengers	200	200	200	200	200
W/S (lb/ft^2)	109	112	108	108	107.5
T/W	0.26	0.25	0.22	0.22	0.18
AR	10	10	10	10	10
E/C (%)	12	12	12	12	12
TOWG (lb)	220572	231282	211264	211034	205749
OEW (lb)	149124	151223	142711	141081	138513
Thrust/Ang (SLS, lb)	13785	14455	11613	11607	9257
Wing Area (ft^2)	2042	2068	1992	1959	1932
Wing Span (ft)	142.9	144.5	141.2	140.4	139.0
DOC @30¢/Gal-1500NM.(¢/ASM)	1.314	1.294	1.283	1.282	1.228
DOC @30¢/Gal-475NM.(¢/ASM)	1.641	1.584	1.603	1.602	1.503
DOC @60¢/Gal-1500NM.(¢/ASM)	1.667	1.649	1.629	1.627	1.543
DOC @60¢/Gal-475NM.(¢/ASM)	2.055	2.033	2.008	2.006	1.901
Block Fuel - 1500NM. (lb)	23625	31970	22086	23559	21072
Block Fuel - 475NM. (lb)	8012	10840	7487	7987	7143
Fuel Efficiency (lb/ASM)	0.0788	0.0799	0.0736	0.0785	0.0702
Cruise SFC (lb/hr/lb)	0.528	0.531	0.504	0.536	0.489
Initial Cruise Alt (ft)	31000	30000	30000	30000	30000
TOFL (ft)	4650	5009	5415	4555	4645
LFL (ft)	6056	6018	6033	5994	6024
Approach Speed (Kt)	135	135	135	135	135
Propulsion Weight (lb)	16471	16652	13332	11675	10882

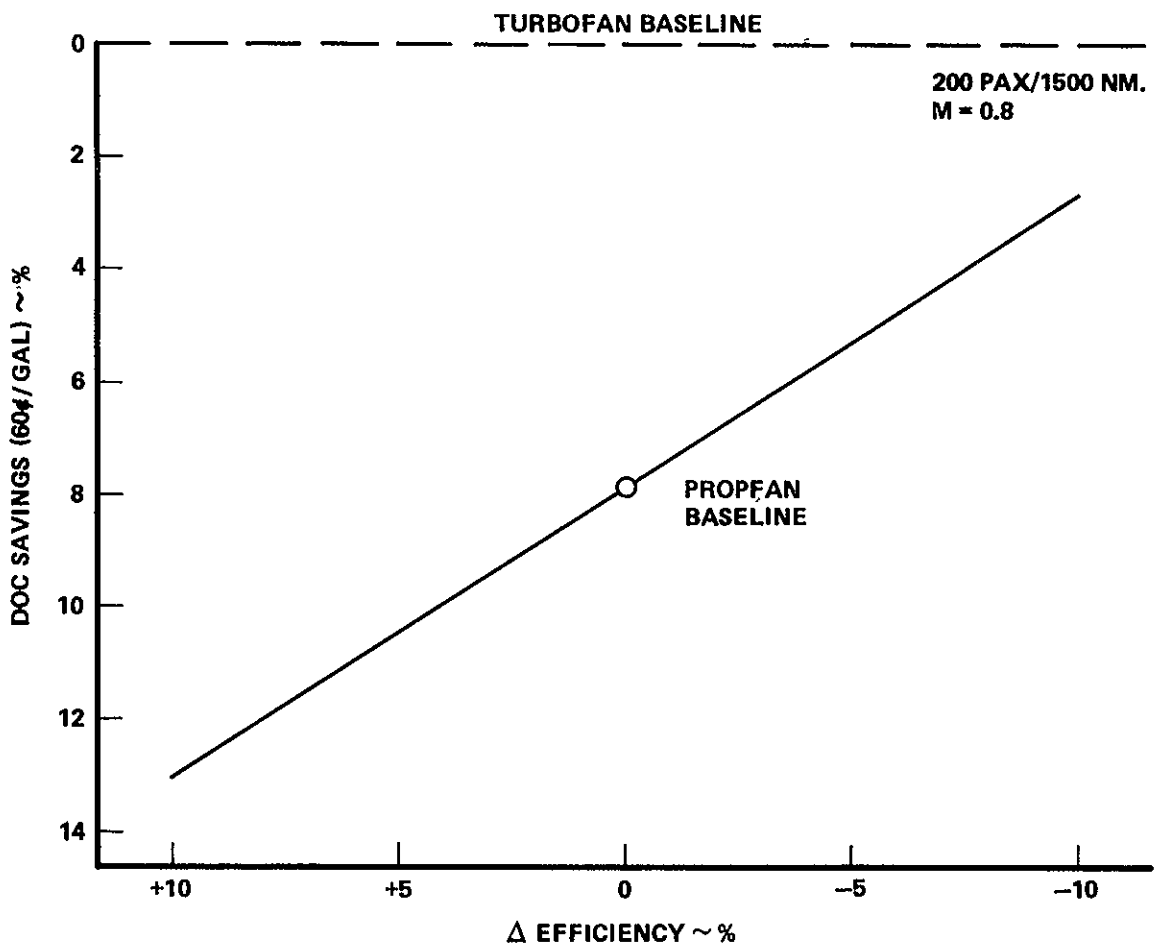


Figure 12. DOC Sensitivity to Propfan Efficiency

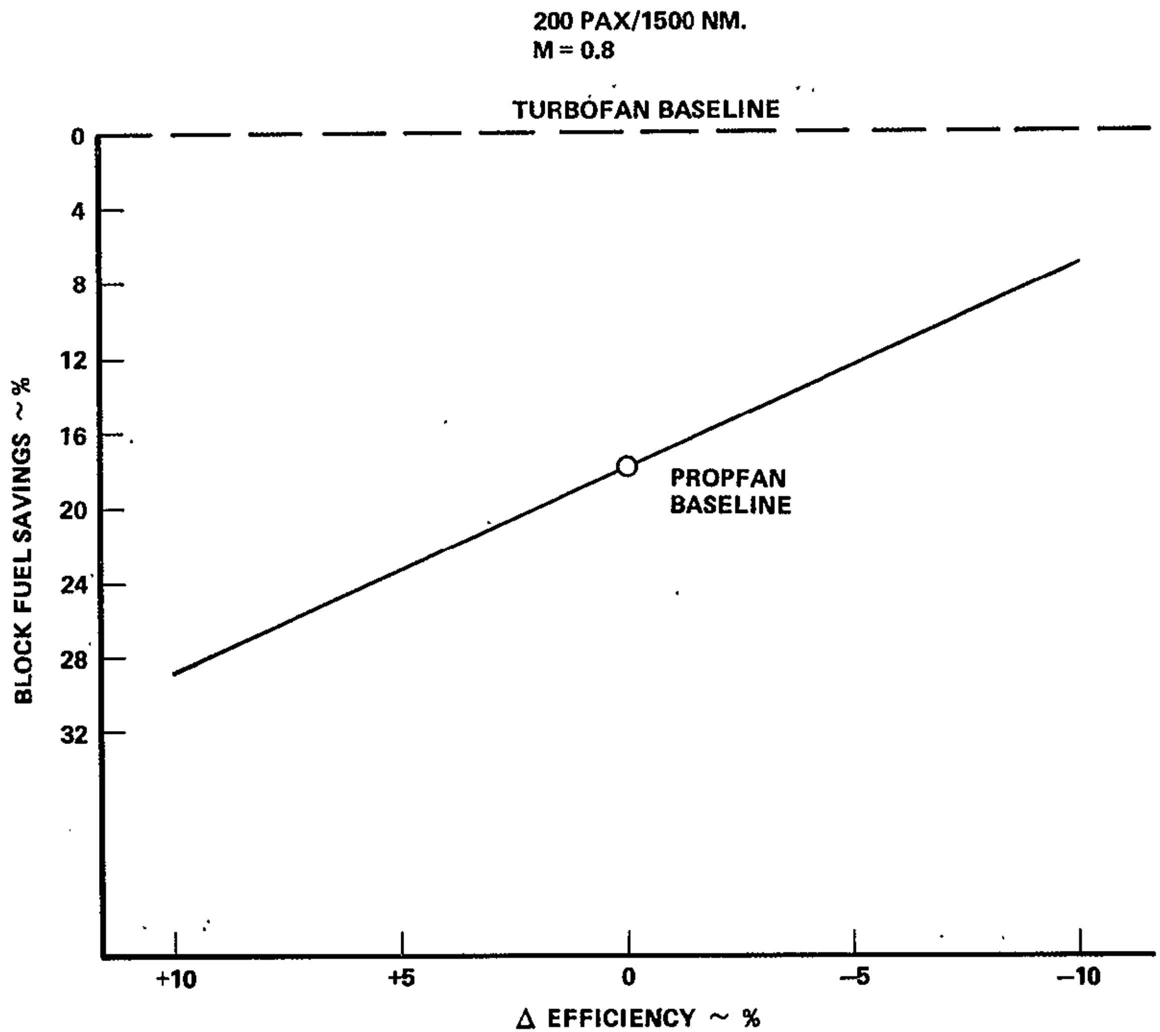


Figure 13. Block Fuel Sensitivity to Propfan Efficiency

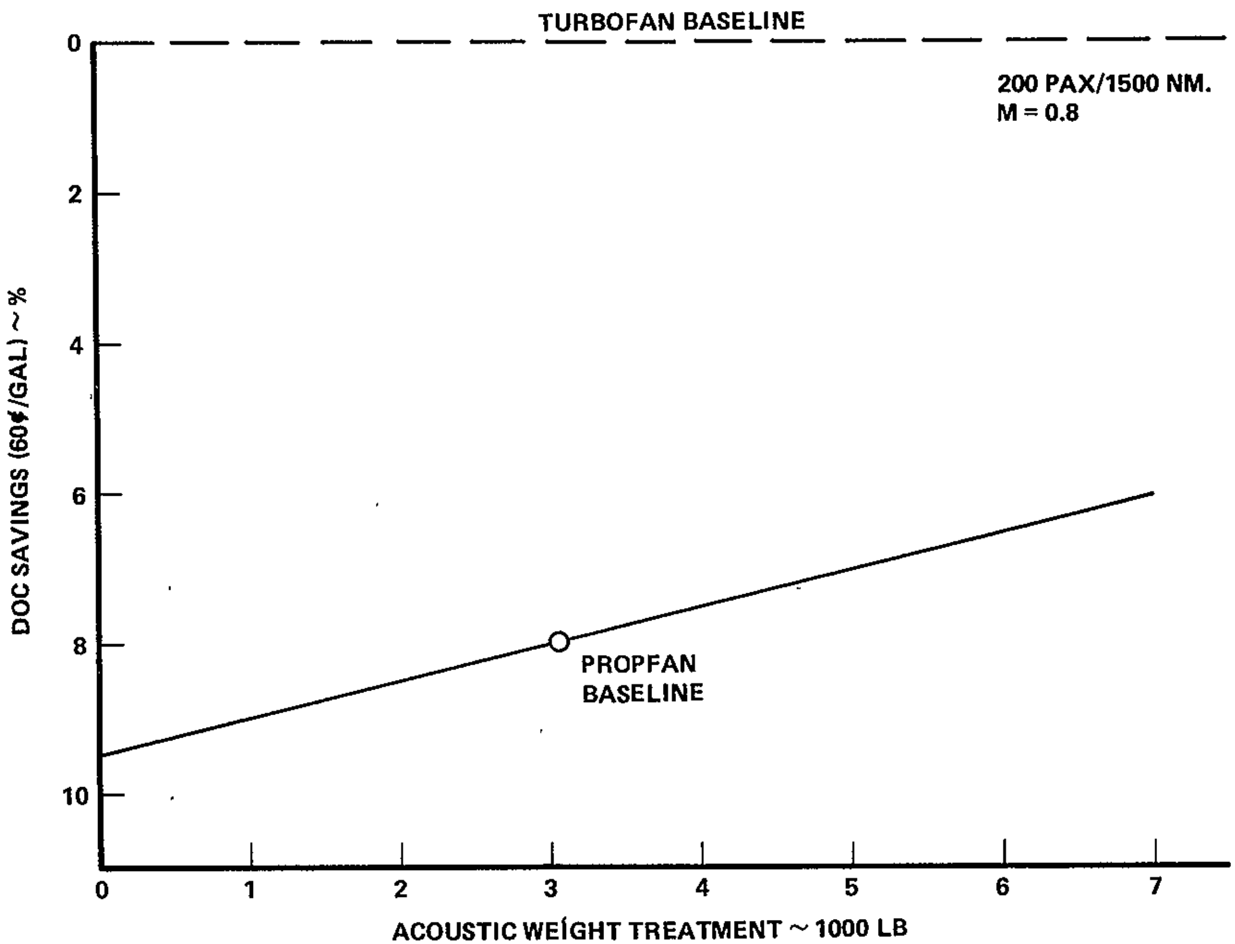


Figure 14. Effect of Acoustic Weight on DOC Savings

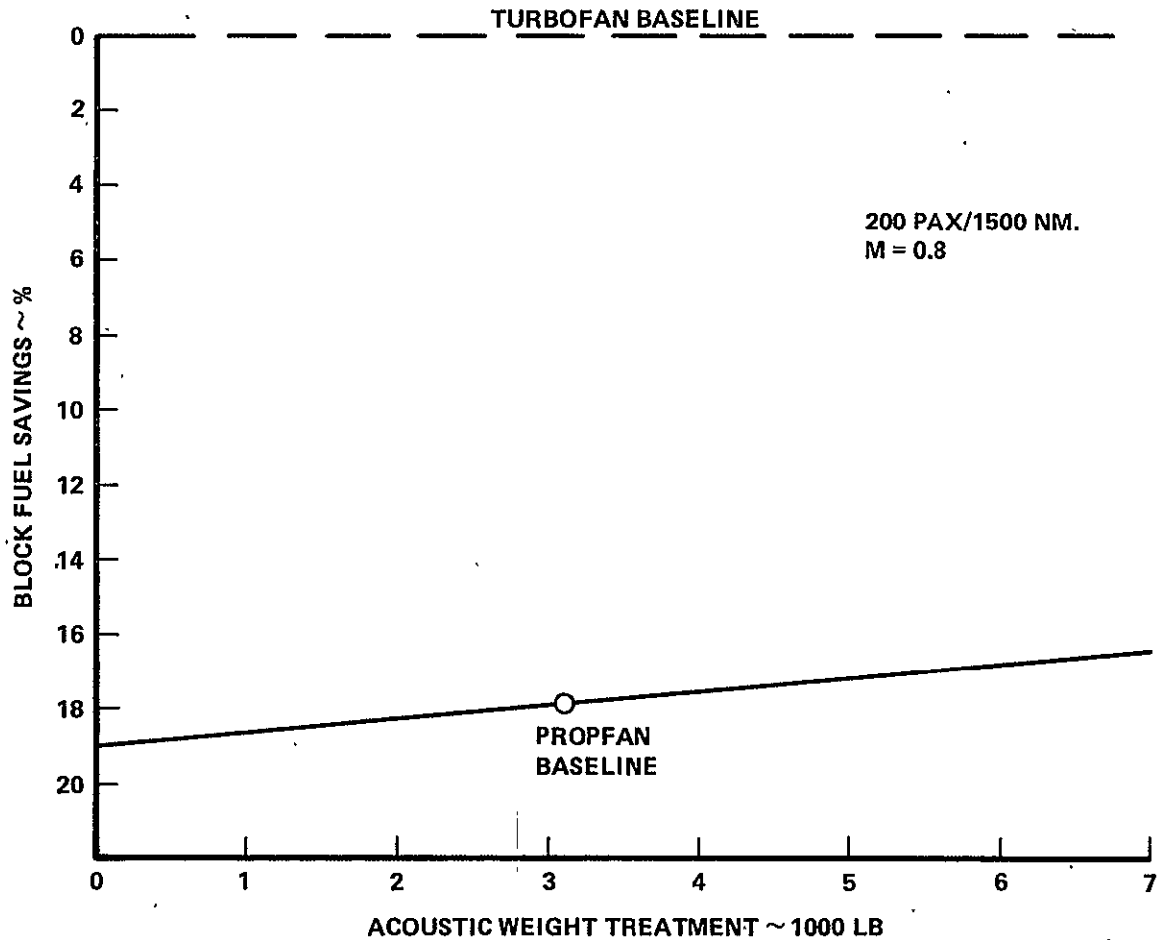


Figure 15. Effect of Acoustic Weight on Block Fuel Savings

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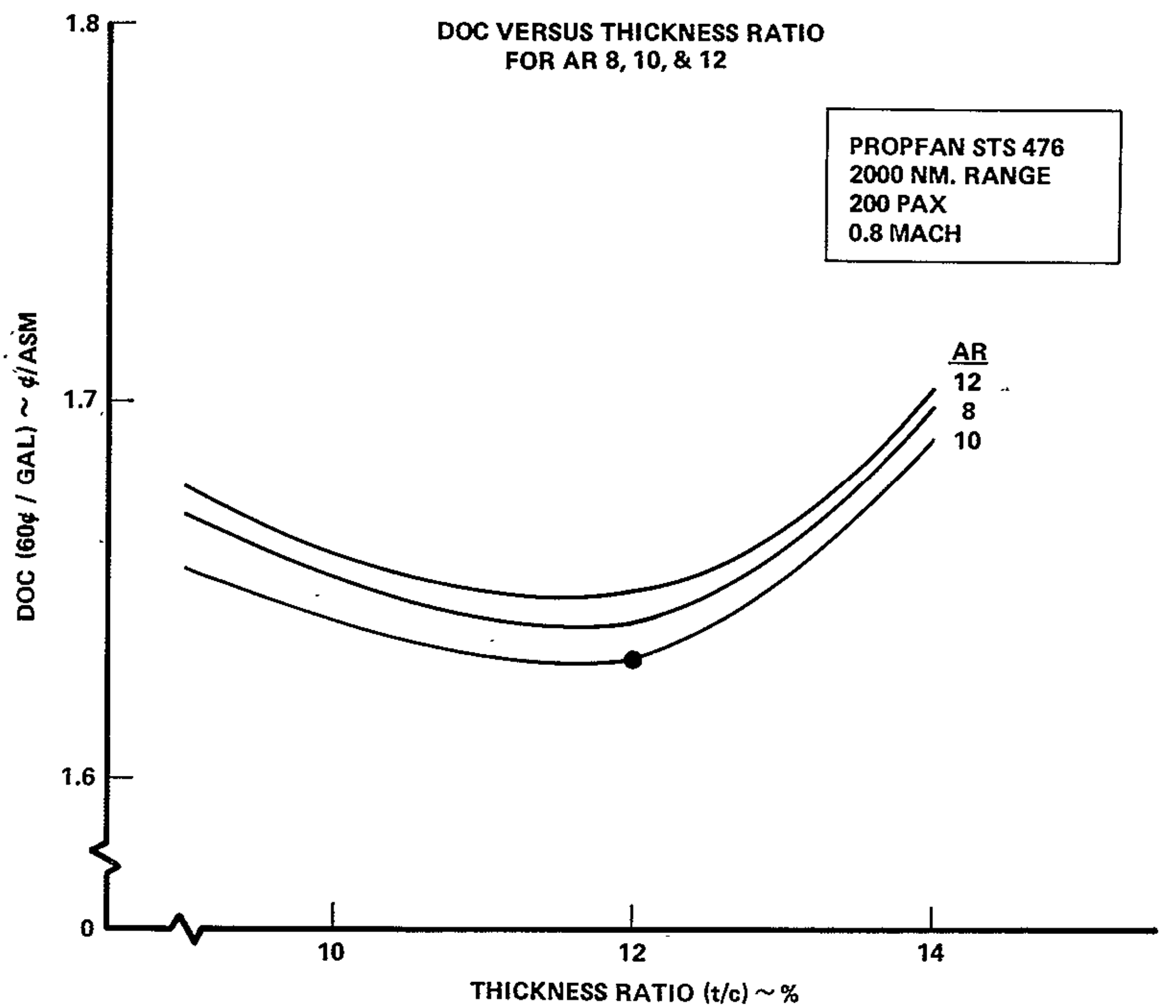

Figure 16. Propfan DOC Versus t/c - 2000 NM. Range

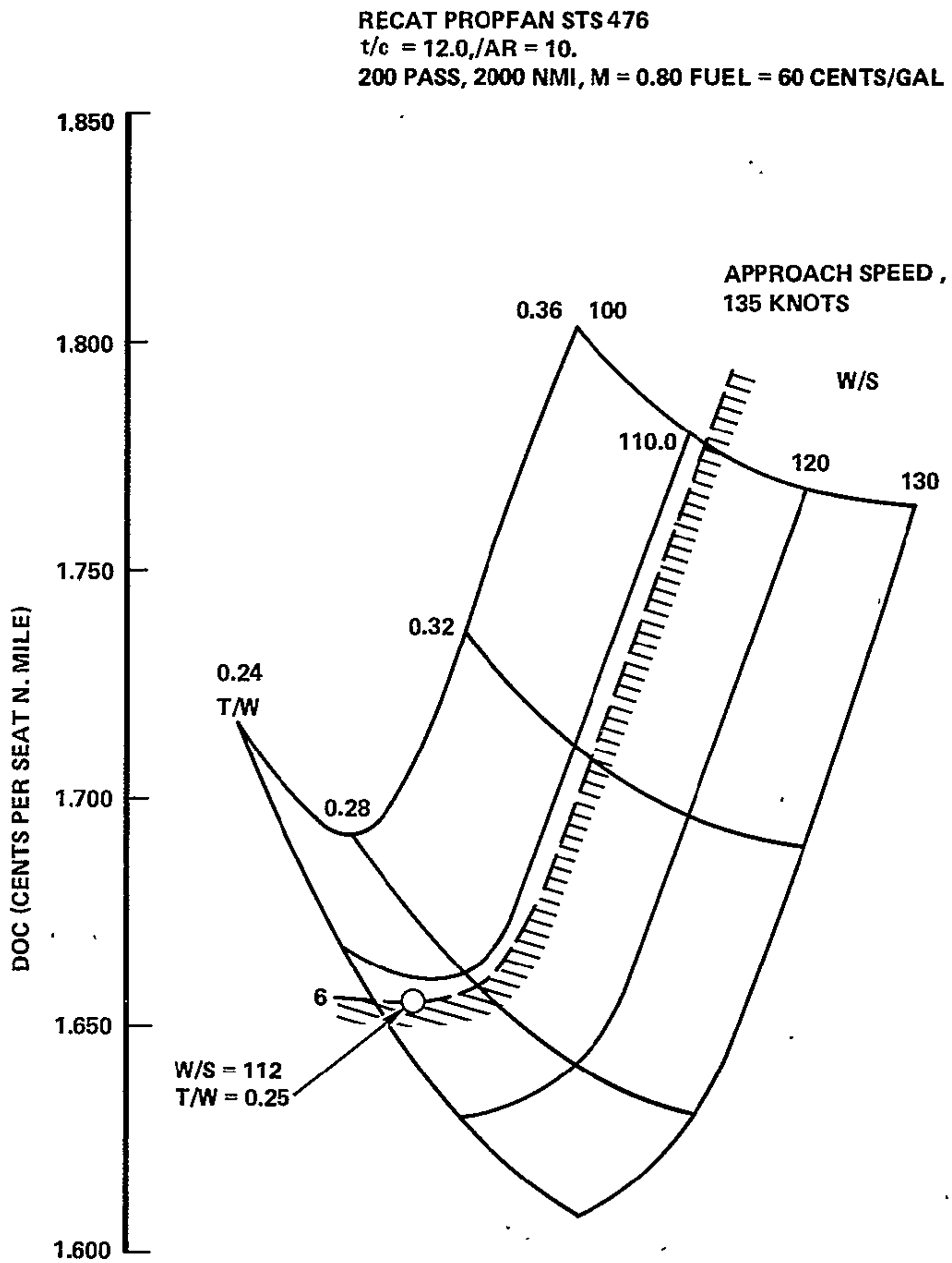

Figure 17. ASSET Crossplot - Propfan DOC (2000 NM. Range)

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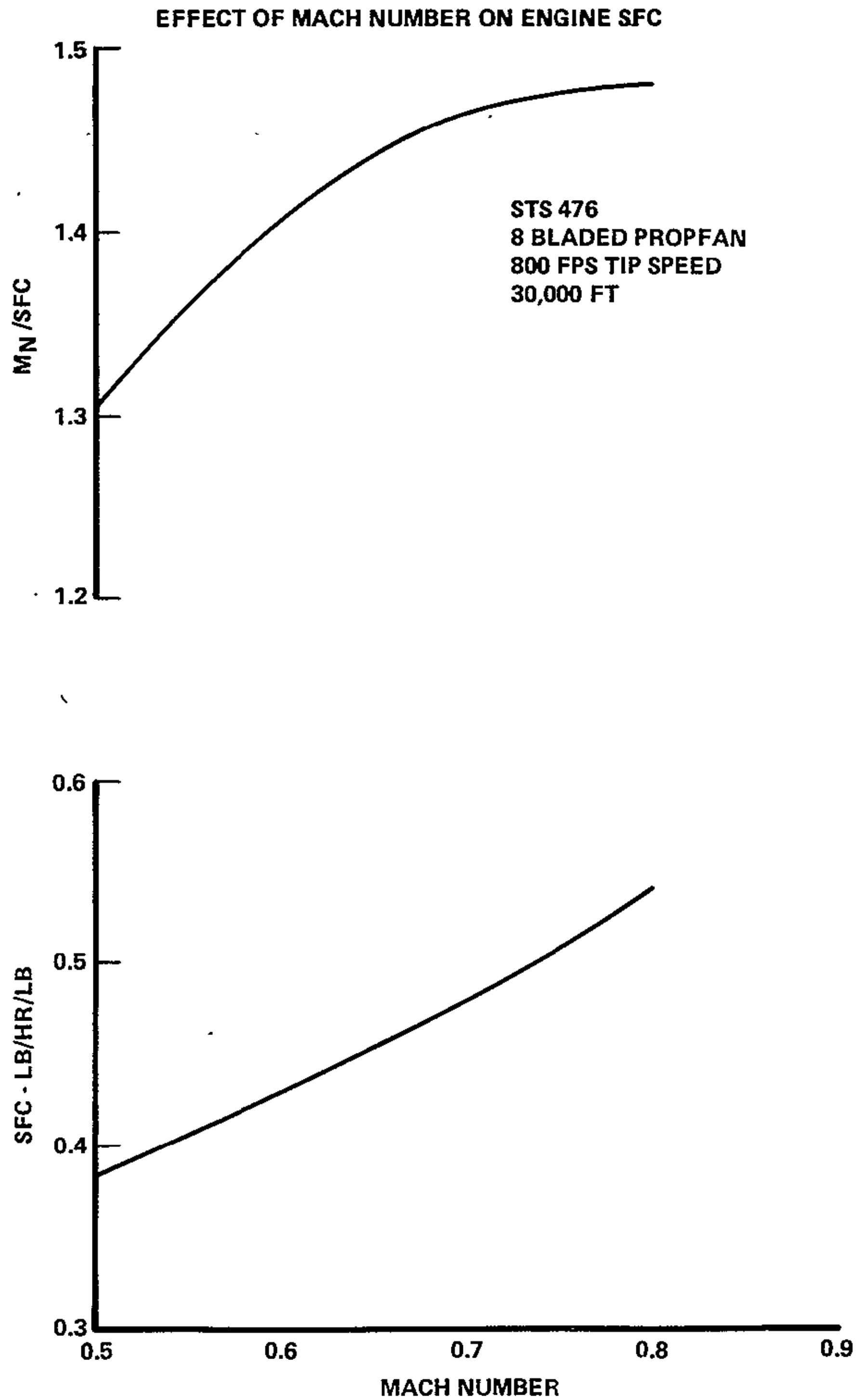

Figure 18. Effect of Mach Number on Engine SFC

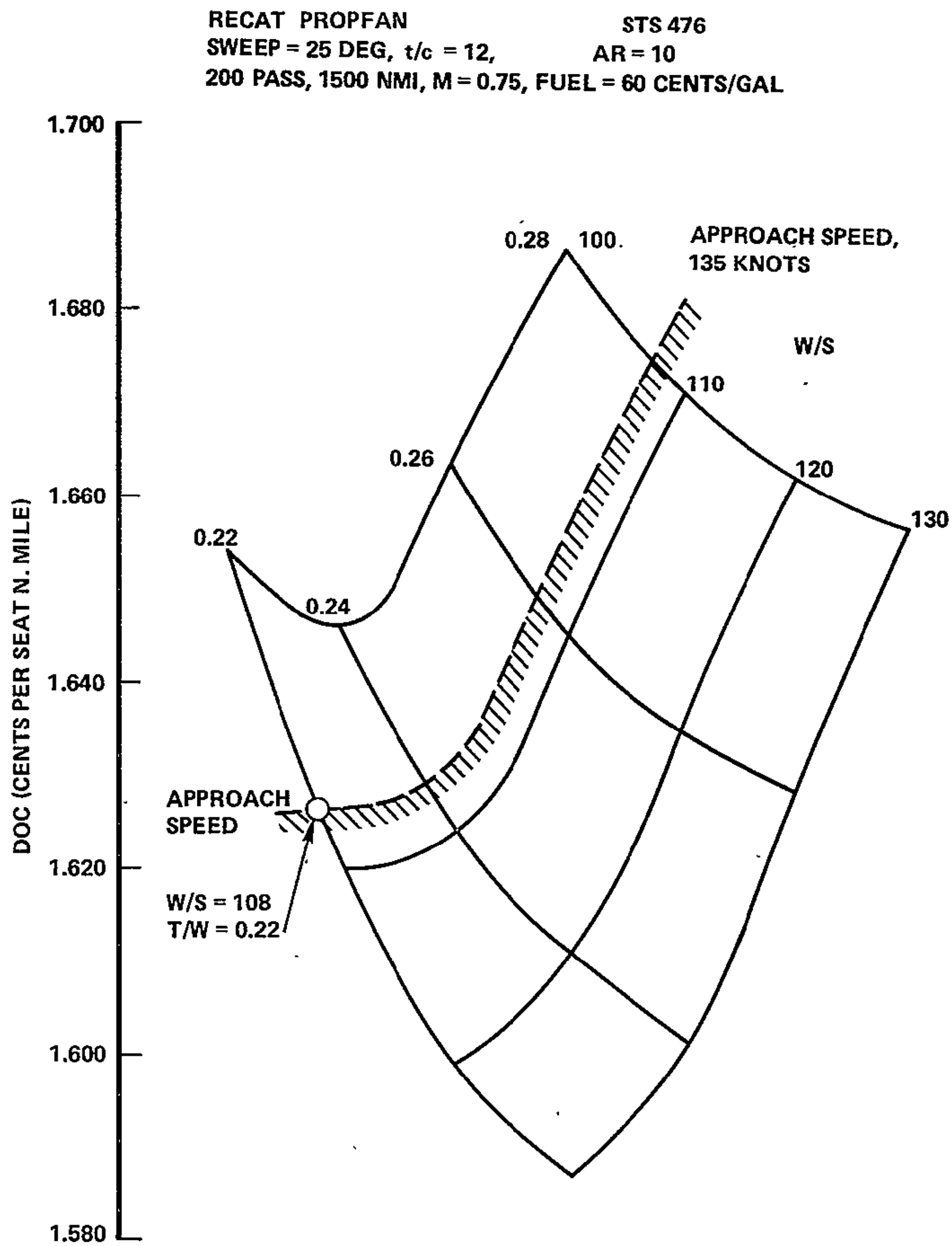

Figure 19. ASSET Crossplot - Propfan DOC (0.75 Mach)

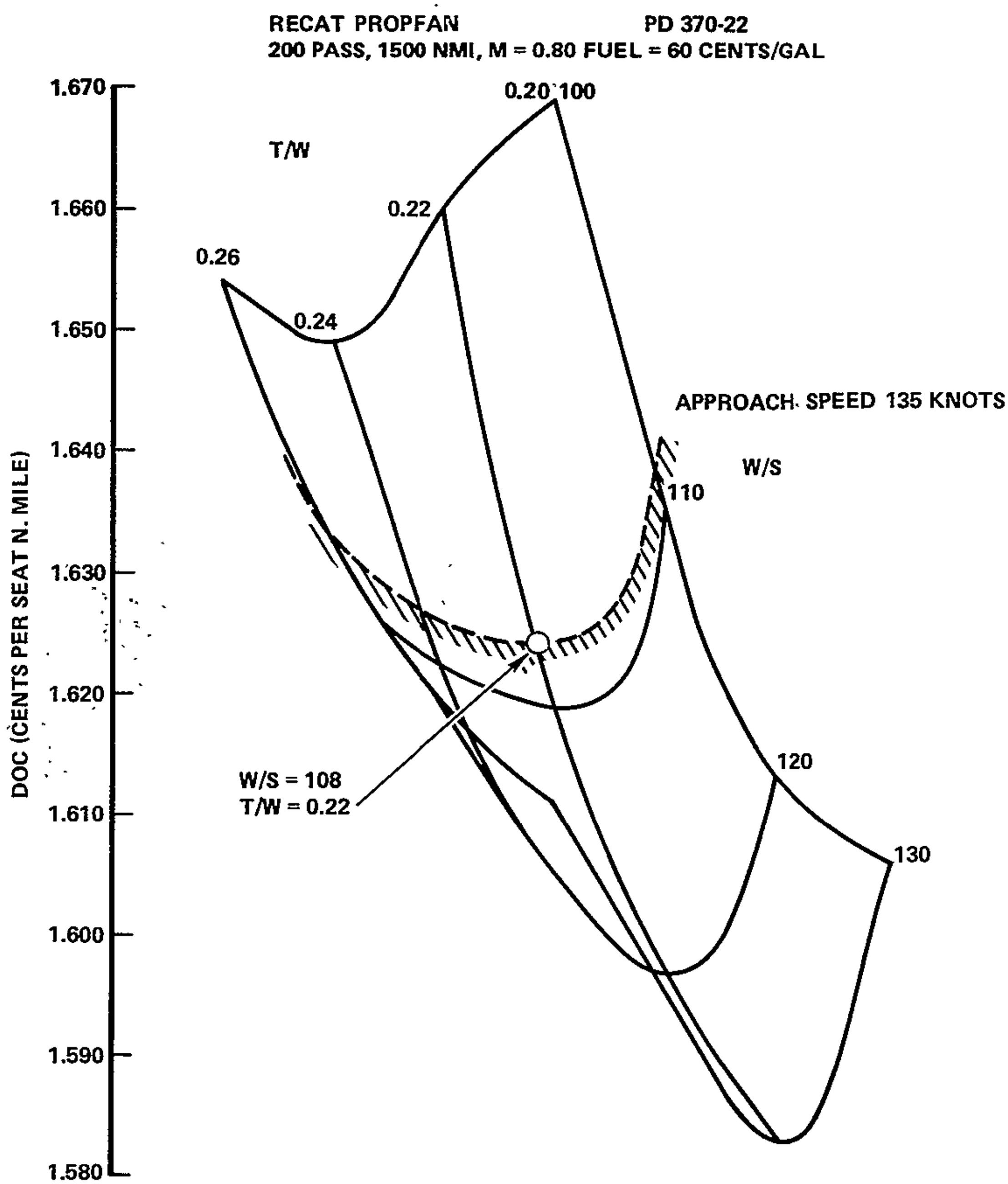

Figure 20. ASSET Crossplot - Propfan DOC (PD 370-22 Engine)

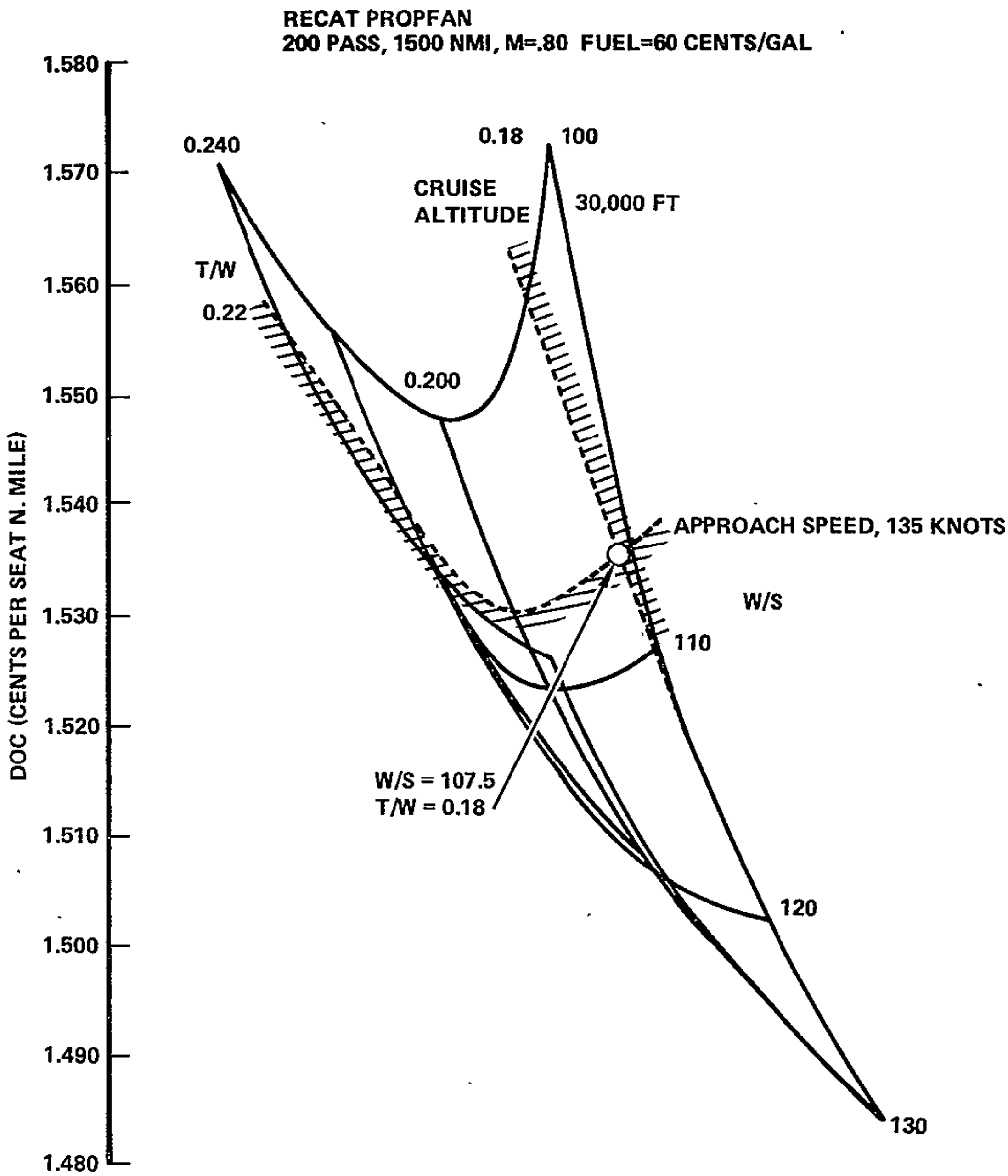

Figure 21. ASSET Crossplot - Propfan DOC (STS 487 Engine)

1.2.2.1 Design Range Increase

Assessment of the propfan aircraft at an increased design range of 2000 nautical miles resulted in a resizing of the aircraft using the ASSET parametric analysis. For this parametric analysis, wing AR, t/c, W/S, and T/W were varied as shown in Table 16. From these design combinations optimum values of AR and t/c for minimum DOC were selected. Figure 16, depicting DOC (60¢/gal.) versus t/c for the range of AR's considered, shows the basis for selection of an AR of 10 and t/c of 12%. ASSET carpet plots were then utilized to select the optimum values of W/S and T/W for minimum DOC consistent with the mission constraints (field length, approach speed, and cruise altitude). Figure 17, is the ASSET carpet plot for minimum DOC (60¢/gal.) for the propfan aircraft at the 2000 nautical mile mission, and depicts selection of the point design parameters. Point design parameters selected were AR = 10, t/c = 12%, W/S = 112, and T/W = .25. Design and performance characteristics for the Mach 0.8, 2000 nautical mile mission are shown in Table 15.

The effect of resizing the propfan aircraft for a 2000 nautical mile, Mach 0.8 mission is an increase in block fuel of approximately 26 percent. This increase in block fuel results from a 25 percent increase in range and a slight decrease in fuel efficiency as follows:

Fuel efficiency @ 1500 NM. = 0.0788 lb/ASM

Fuel efficiency @ 2000 NM. = 0.0799 lb/ASM

Decrease in fuel efficiency for the 2000 NM. range is due to the increase in thrust required for the heavier airplane and the requirement for 225 lbs. of additional acoustic treatment weight for this higher cruise thrust. Additional DOC savings of approximately 1 percent is realized as a result of the increased range.

TABLE 16. PARAMETRIC STUDY MATRIX

PROPFAN - STS 476, 0.8 MACH, 2000 N.M. RANGE

AR	t/c	W/S				T/W			
8	9	100	110	120	130	.22	.26	.30	.34
8	12	↕	↕	↕	↕	.24	.28	.32	.36
8	14	↕	↕	↕	↕	.24	.28	.32	.36
10	9	↕	↕	↕	↕	.24	.28	.32	.36
10	12	↕	↕	↕	↕	.24	.28	.32	.36
10	14	↕	↕	↕	↕	.24	.28	.32	.36
12	9	↕	↕	↕	↕	.22	.26	.30	.34
12	12	↕	↕	↕	↕	.24	.28	.32	.36
12	14	100	110	120	130	.24	.28	.32	.36

1.2.2.2 Cruise Speed Reduction

As previously stated, reduction of the cruise speed for the propfan aircraft has the potential of additional fuel savings due to the improvement in the fuel consumption characteristics of the turboshaft engine at the reduced thrust level. Figure 18 depicts the trend of fuel consumption versus Mach number for the turboshaft engine. Mach 0.75 was selected as the reduced cruise speed since this value is consistent with current practice on short to medium range transports. Reducing the cruise speed to Mach 0.75 effects additional fuel savings (additional to engine fuel consumption characteristics) since the propfan noise and the required thrust are both reduced which in turn allow a reduction in acoustic treatment weight.

Resizing of the baseline propfan aircraft was completed with minimum DOC at 60¢/gallon fuel cost as the criteria for optimization. Values of W/S and T/W were varied as follows for the parametric analysis:

$$W/S = 100,\ 110,\ 120,\ \text{and}\ 130$$

$$T/W = .22,\ .24,\ .26,\ \text{and}\ .28$$

Figure 19 depicts the selection of optimum W/S and T/W values consistent with minimum DOC at 60¢/gallon fuel cost for the turboprop point design at Mach 0.75 cruise. Design and performance characteristics of the propfan aircraft, for the 1500 nautical mile, Mach 0.75 design mission, are shown in Table 15.

The effect of reducing the design cruise speed to Mach 0.75 is a savings in block fuel and DOC, at 60¢/gallon fuel cost, of 21.1 percent and 10 percent, respectively, when compared to the baseline (1500 nautical mile, Mach 0.8) turbofan aircraft.

1.2.2.3 Alternate Turboshaft Engine

Subsequent to the previous RECAT study, an alternate turboshaft engine, Detroit Allison Diesel PD 370-22, was identified which offers an overall pressure ratio and component technology comparable to the JT10D-2 turbofan. Utilization of this engine in the propfan aircraft offers the potential of additional fuel savings. The PD 370-22 engine has an overall pressure ratio of 25:1 and maximum turbine inlet temperature of 2500°F as compared to 28:1 and 2400°F for the JT10D-2 turbofan. A description of the PD 370-22 engine parameters is shown in Table 17.

Installed performance data, along with engine and nacelle dimensions, engine weight, and appropriate scaling factor, was provided by Allison for adaptation to the RECAT design mission. The Hamilton Standard 8 bladed prop fan, operating at 800 fps tip speed, was utilized. Installation guidelines previously supplied by Hamilton Standard were applied, where appropriate. A propfan disk loading of 42 Shp/D^2 was selected from the propeller sizing study which resulted in a requirement of 4720 lbs of acoustic treatment in the aircraft fuselage.

The propfan baseline aircraft (revised) was resized to incorporate the PD 370-22 turboshaft engine for a 1500 nautical mile, Mach 0.8 design mission. Resizing of the aircraft was accomplished using the ASSET parametric analysis with the following variations in W/S and T/W:

W/S	T/W
100	0.20
110	0.22
120	0.24
130	0.26

The ASSET carpet plot, shown as Figure 20, depicts the selection of values for W/S and T/W, based on minimum DOC at 60¢/gal. fuel cost, for the point design. Point design parameters selected were AR = 10, t/c = 12%, W/S = 108, and T/W = 0.22. Design and performance characteristics of the aircraft are included in Table 15.

The effect of incorporating the PD 370-22 engine for the 1500 nautical mile, Mach 0.8 design mission is a savings in mission fuel of 1.1 percent and a savings in DOC, at 60¢/gal. fuel cost, of 2.0 percent due to a decrease in installed propulsion system weight relative to the revised STS 476 baseline.

TABLE 17. ENGINE DATA COMPARISON

	JT10D-2 △1	STF 477	STS 476 △1	PD 370-22	STS 487
• CYCLE	TURBOFAN	TURBOFAN	TURBOSHAFT	TURBOSHAFT	TURBOSHAFT
• MANUFACTURER	P&W	P&W	P&W	DDAD	P&W
• IOC (yr)	1981/82	1990+	1983	1985	1990+
• RATING (SLS)					
THRUST (lb)	24500	26550	NA	NA	NA
HORSEPOWER (hp)	NA	NA	9294	12328	20624
• TIT (^{o}F)	2470	2600	2400	2500	2800
• PRESSURE RATIO	27.3	45	20	25	40
• BYPASS RATIO	5.6	8.0	NA	NA	NA
• WEIGHT (lb) △2	4800	3940	2180	1566	2134
• UNINSTALLED PERFORMANCE △3					
M = 0.8 35000 FT NRP					
THRUST (LB)	5683	6530	3363	3832	5480
SFC (LB/HR/LB)	0.638	0.542	.515	0.509	0.444

NOTES:

△1 Engines for initial RECAT study, NASA CR 137926

△2 Turboshaft engine weights for gas generator only (does not include gearbox or prop weights)

△3 Performance calculation assumes the following:

Turbofan: uninstalled with 18400 BTU/LB fuel heating value

Turboshaft: uninstalled with 82% propeller efficiency, 99% gearbox efficiency and 18400 BTU/LB fuel heating value.

1.2.2.4 Off Design Cruise Speed Effects

Included as a part of this study, an assessment of the baseline propfan aircraft design, flying at cruise speed of Mach 0.75, was accomplished. Resizing for this mission condition was not accomplished so that the effect of operation of the aircraft, sized for a specific design mission and operated at an off-design condition (consistent with current operator experience) could be assessed. The propfan aircraft baseline configuration, CL 1320-15, was subjected to the same mission profile utilized throughout the study with the cruise speed reduced from Mach 0.8 to Mach 0.75. Take-off gross weight of the aircraft was maintained at 217,466 pounds (identical to the baseline) and the effect of reduced cruise speed on aircraft performance and economics was determined.

For the design mission range of 1500 nautical miles, flying the propfan aircraft at a cruise speed of Mach 0.75 effects a savings in mission fuel of approximately 2.4 percent and a savings in DOC, at 60¢/gal. fuel cost, of approximately 1.1 percent relative to the same aircraft at Mach 0.8. For the same mission fuel as the baseline aircraft, the design range can be increased to approximately 1600 nautical miles (approximately 6.2 percent increase).

1.2.3 1990 Technology Assessment

The 1990 technology assessment consisted of incorporating an advanced technology turboshaft engine, Pratt and Whitney STS 487, representative of that which could be available for a 1990 IOC aircraft. The airframe technology levels (supercritical wing, advanced composites, and active controls) utilized for the 1985 IOC aircraft were retained as was the 8 bladed, 800 fps tip speed propfan.

Resizing of the propfan powered aircraft was accomplished during this assessment for the 1500 nautical mile, Mach 0.8 design mission with the STS 487 turboshaft engine. Resizing criteria was minimum DOC at 60¢/gal. fuel cost.

1.2.3.1 Advanced Technology Turboshaft Engine

The Pratt and Whitney STS 487 turboshaft engine resulted from a Pratt and Whitney contract with NASA-Lewis Research Center to study unconventional engines designed for low energy consumption for medium and long range transport application. The STS 487 engine employs the same advanced technology features as the STF 477 turbofan. A description of the engine design parameters is included in Table 17.

Performance data for the STS 487 engine, along with engine and nacelle dimensions, engine weight, and appropriate scaling factor was provided by Pratt and Whitney for adaptation to the RECAT design mission requirements.

1.2.3.2 Aircraft Optimization

Optimization of the 1990 technology propfan aircraft was accomplished by resizing the baseline configuration to incorporate the STS 487 turboshaft engine and the 8 bladed, 800 fps tip speed propfan. Utilization of the STS 487 engine necessitated alterations of the ASSET sub-routines for configuration, weight, drag, and engine performance consistent with the performance and dimensional data supplied by Pratt and Whitney for the engine and by Hamilton Standard for the propfan. The propfan baseline configuration was resized using the ASSET parametric analysis with minimum DOC at 60¢/gal. fuel cost as the optimization criteria. For the parametric analysis, wing AR and t/c were maintained at 10 and 12% respectively with values of W/S and T/W varied as follows:

W/S	T/W
100	0.18
110	0.20
120	0.22
130	0.24

Figure 21, the ASSET carpet plot, depicts the selection of W/S and T/W values to be utilized for the aircraft point design.

Point design parameters selected were AR = 10, t/C = 12%, W/S = 107.5, and T/W = 0.18. The performance and design characteristics of the aircraft with the STS 487 engine at the 1500 nautical mile, Mach 0.8 design mission are shown in Table 15.

Incorporation of the STS 487 turboshaft engine results in a 1990 IOC aircraft at the 1500 nautical mile design mission with a block fuel savings of 10.8 percent and a DOC savings of 7.4 percent, at 60¢/gal. fuel cost, when compared to the 1985 IOC baseline aircraft. These savings are the result of an improvement in engine SFC at cruise, of approximately 7.6 percent and a reduction in propulsion system installed weight of approximately 34 percent.

SECTION 2

PROPFAN TECHNOLOGY BASE

Initial assessment of the fuel conservation potential of the turboprop aircraft, Task 7 of the previous RECAT study (Report CR 137926), utilized the 8 bladed propfan operating at a tip speed of 800 fps. Performance and acoustic characteristics of the propfan were supplied by Hamilton Standard per their reports SP02A76, dated 27 February 1976, and SP09A76, dated March 1976.

Subsequent to the initiation of this study, updated performance and acoustic characteristics, for the propfans were supplied by Hamilton Standard as a result of their ongoing propfan wind tunnel tests. This data, supplied on 13 June 1976, is included as Appendix A of this report. The effect of the revised propfan data is a slight increase in efficiency accompanied by a slight increase in induced SPL for the 8 bladed, 800 fps tip speed propfan. Also included in the revised data package, is definition of the directivity of propfan induced SPL (directivity of impingement on fuselage wall). Incorporation of the revised acoustic characteristics and directivity pattern resulted in a revision to the acoustic treatment methodology utilized for the aircraft fuselage wall. This revision in methodology and resultant acoustic treatment weights is discussed in Section 3 of this report.

The propeller sizing study, for the various turboprop aircraft designs, was reviewed with the following disk loadings and acoustic treatment weights established:

CONFIGURATION	DISK LOADING	REVISED ACOUSTIC WEIGHT (lb)	ORIG. ACOUSTIC WEIGHT (lb)
STS 476, 1500 NMI, 0.8M	37.1 SHP/D^2	5220	3089
STS 476, 2000 NMI, 0.8M	37.1 SHP/D^2	5445	3089
STS 476, 1500 NMI, 0.75M	35.9 SHP/D^2	4405	1636
PD 370-22, 1500 NMI, 0.8M	42 SHP/D^2	4720	2634
STS 487, 1500 NMI, 0.8M	46 SHP/D^2	4390	2470

The above listed acoustic treatment weights (revised) and attendant propeller efficiencies at the selected disk loadings were incorporated into the turboprop aircraft designs. The net effect of this data on aircraft performance is a slight increase in block fuel of approximately 0.1 percent and an increase in DOC, at 60¢/gal. fuel cost, of approximately 0.6 percent for the 1500 nautical mile, Mach 0.8 design mission.

SECTION 3

ACOUSTIC TREATMENT METHOD

3.1 TYPICAL TURBOFAN CABIN NOISE ENVIRONMENT

For current widebody turbofan aircraft, the maximum interior noise level at high speed cruise conditions is dominated by turbulent boundary layer induced vibrations of the cabin wall. The cabin wall vibrations cause acoustic radiation to the interior in a manner similar to a loudspeaker. The transmitted boundary layer noise is broadband in its frequency content, exciting many structural vibration modes, the listener perceives an innocuous "whooshing" sound. The peak boundary layer excitation frequency is of the order of U_o/δ where U_o is the free stream velocity and, δ , is the boundary layer thickness. Since the boundary layer external pressure fluctuation spectrum varies slowly with frequency, near the peak frequency, the maximum interior sound pressure will occur at frequencies near U_o/δ, but within a frequency band where also a condition of coincidence exists (phase velocity equality) between the boundary layer turbulent pressure fluctuation pattern and the flexural waves in the fuselage.

The boundary layer thickness on a typical fuselage can be estimated at 120 percent of the equivalent flat plate boundary layer thickness. The 20 percent factor allows for roughness and adverse pressure gradients. At Reynolds Numbers above 100 million (typical full scale flight) the boundary layer velocity profile varies approximately as the one seventh power of distance normal to the surface (Ref 1 p 536). In this case the boundary thickness is 5.14 times skin friction coefficient, C_F, times L, the distance from the nose. At a Mach number of 0.85 and at 30,000 ft, the Reynolds Number is 2.42×10^6 per foot. For a representative aft cabin point, L = 150 ft, $Re_1 = 364 \times 10^6$, $C_F = 0.00180$, the flat plate boundary layer thickness would be, $\delta_{fp} = 0.00924L$.

Increasing this by 20 percent yield $\delta/_L = 0.0109$ at a point L = 150 from the nose, hence $\delta = 1.66$ ft. The external free stream velocity is 827 ft/sec, and the typical peak frequency for aft cabin noise (at L = 150 ft) would be 490 Hz. In the forward cabin the BL excitation frequency would be 3 times higher and perhaps twice as high in the mid cabin. Typical measured maximum interior noise levels at window seats for these turbofan aircraft range from 90 to 95 dB for OASPL and the A weighted SPL's are from 80 to 85 dBA.

3.2 PROPFAN PASSENGER COMFORT CRITERION

For turboprops a preliminary interior noise comfort criterion has been selected at 90 dB SPL for the transmitted blade passage frequency harmonic tone. For a pure tone at a blade passage frequency of 160 Hz the 90 dB tone SPL value would correspond to an "A weighted" SPL of 75 dBA (Ref. 2, p 16-13). The second harmonic tone in this example is at 320 Hz and a 90 dB tone would correspond to a value of 83 dBA. In order that the sum of the first two harmonics should not exceed 75 dBA, it would be necessary that each tone could contribute only 72 dBA. This means that if the fundamental tone level was allowed to be 87 dB then the second harmonic could be 79 dB.

The transmission loss concept utilized for this study is a heavily damped, massive double wall construction separated by an airspace, as shown in Figure 22. This concept produces 18 dB of added transmission loss for each doubling of frequency above the "mass-air-mass frequency" (air space stiffness resonance frequency of the double wall masses). The double "limp wall" mass law theory has important consequences in that higher harmonics are rapidly suppressed. The theory is discussed more fully in Section 3.4.1 below. Data received from Hamilton Standard for the current 8-bladed propfan shows that the external tone level SPL values for the first four harmonics, relative to the OASPL, are -1, -9, -15 and -20 dB, at a tip speed of 800 ft/sec. From these data it is clear that one would expect the interior tone level SPL for the second harmonic (2 times f_{BP}) to be lower by 26 dB than the blade passage frequency tone level.

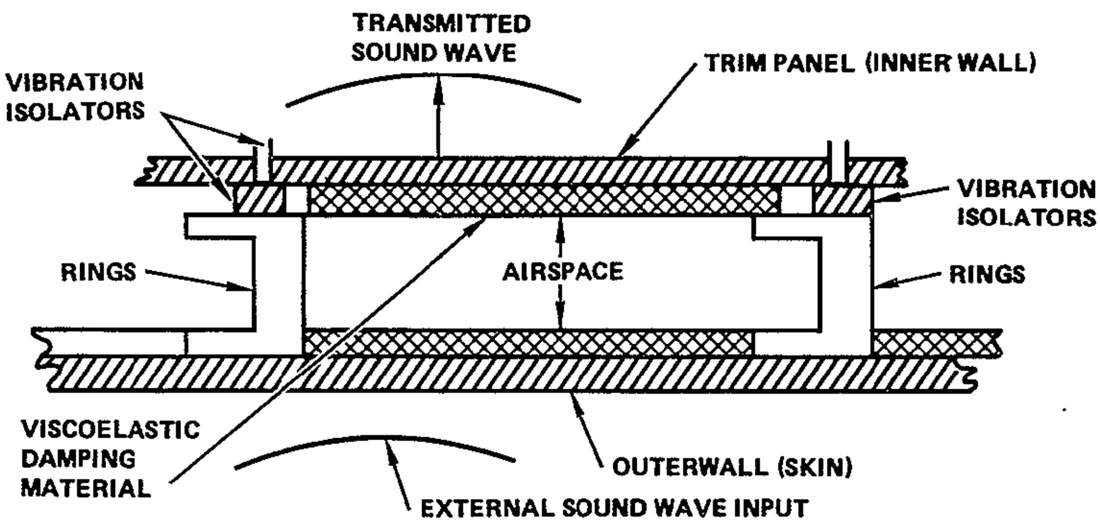

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Figure 22. Double "Limp Wall" Concept for Acoustic Treatment of Cabin Walls

In conclusion, one can say that the blade passage frequency tone will dominate the interior noise level. The selected design level 90 dB corresponds to 75 dBA at 160 Hz and 83 dBA at 320 Hz which is the upper range of blade passage frequencies for the 10-bladed propeller at 800 fps. These values compare favorably with the 80 to 85 dBA range for current turbofans. Therefore, the passenger comfort criterion selected may even be slightly conservative at the lower blade passage frequencies

3.3 PROCEDURE FOR DEFINING ACOUSTIC TREATMENT WEIGHT

The required procedure is as follows:

(1) Define the external sound pressure distribution on the cabin surface in terms of circumferential variation, and axial distance from the propeller disc plane.

(2) Define the required noise transmission loss (NTL) between the exterior SPL and the design goal interior SPL. The NTL is defined by:

$$\begin{aligned} NTL &= SPL_E\,(X, \theta) - SPL_{Design} \\ &= SPL_E - 90\ \text{dB} \end{aligned}$$

(3) Compute the total weight per unit area required (including practical design constraints) to achieve the specified NTL. The acoustic penalty is the increment above the reference turbofan weight per unit area.

(4) Integrate the excess acoustic treatment weight per unit area over the cabin wall.

The next subsection on acoustics discusses the cabin wall transmission loss aspects. The remaining acoustics subsections will (1) compare the current external near field noise data with the predictions of the previous RECAT Study (Ref. 4) and, (2) will show weight penalty results of the current study, and their comparison with previous RECAT results.

3.4 CABIN WALL TRANSMISSION LOSS PREDICTION

3.4.1 Transmission Loss Assumptions

The noise transmission loss, NTL, for the cabin wall is predicted on the basis of double "limp wall" mass law theory as described in pp 187-189 of

Ref. 4 and in Table 126, p 223 of Ref. 4, which is reproduced herein as Table 18. This theory assumes that the structural response is dominated by the sum of a large number of vibration modes at non-resonant frequencies, rather than a few resonant modes. This theory is plausible if one assumes that part of the mass on each of the walls is a suitable viscoelastic damping material. The outer wall mass consists of the outer skin plus the rings and stringers. The ring and stringer masses are added to the skin at frequencies below the ring frequency (about 288 Hz for a 19.58 ft diameter aluminum fuselage (Ref. 4, p 189)) because the flexural wave lengths are much longer than the structural bay lengths.

The double "limp wall" theory is presented in approximate form by Cremar, Heckl, and Ungar (Equation 79a, pg. 505 of Reference 3). Also shown in Reference 3 is an alternate expression for the double wall increment of noise transmission loss (NTL) due to vibrations transmitted through the vibration isolators (see Figure 22) which provide a possible "flanking path" to the interior. One limitation of double wall theory is that the lower value of NTL should be chosen (either that of the air path described in Table 18 or that through the "flanking path" afforded by the trim panel vibration isolator):

$$\Delta NTL_{isolator} = 10 \log_{10}\left[\left(\frac{V_1^2}{V_2^2}\right)\left(\frac{S\pi^3}{8_n\lambda_c^2}\right)\right]$$

In this equation a trim panel bay of area S is attached to the outer wall via n vibration isolators. The velocities, V_1 and V_2, represent the vibration velocities of the outer and inner walls at the isolator attach points. $\lambda c = C/fc$, represents the critical wave length, C is the speed of sound in the cabin air, and fc the critical frequency above which a vibrating skin panel achieves maximum acoustic radiation efficiency (Reference 3, pg. 482 and 492). For the case of air at $70^{\circ}F$ and aluminum

TABLE 18. DOUBLE WALL MASS LAW - "LIMP WALL" THEORY

$$\text{Noise Transmission Loss (NTL)} = \underbrace{20 \text{ LOG } \frac{\pi M_T f}{\rho c}}_{\substack{\text{Total Wall}\\ \text{Mass Law}\\ \text{6 dB Per Octave}}} + \underbrace{20 \text{ LOG } \left(\frac{f^2}{f_n^2} - 1\right)}_{\substack{\text{Double Wall}\\ \text{Increment}\\ \text{12 dB Per Octave}}}$$

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K_a}{\left(\frac{M_1 M_2}{M_1 + M_2}\right)}}$$

Total Increase in NTL

Per Octave is 18 dB.

When $M_1 = M_2$

$$f_n^2 \sim \frac{1}{M_T d}$$

$$\lambda_c = hw \; \frac{1.8\sqrt{(E/\rho)\ w}}{C\ air}$$

$$= hw\,\frac{(1.8)\ (16380)}{1128} = 26.13\ hw$$

where hw is the outer wall skin thickness.

For example, for hw = 0.060 inches, the critical frequency becomes

$$fc = \frac{C_{air}}{c} = \frac{C_{\ air}}{26.13\ hw}$$

$$= \frac{1128}{(26.13)\ (0.00567)} = 7618\ \text{Hz}$$

$$\text{and } \lambda_c = (26.13)\ (0.068) = 1.78 \text{ inches}$$

For well designed vibration isolators (such as those depicted in Figure 22) which could provide a velocity ratio V_2/V_1, of 1/10 or less, then the airpath would be the critical path and the mass law theory is valid. In general, the trim panel can be considered as a mass mounted on soft springs, and if the isolator spring is sufficiently softer than the air stiffness between the double wall, then the airpath dominates the noise transmission, and the isolators will not cause an undesired "short circuit" path for noise transmission.

The double wall mass law theory is convenient for preliminary design purposes; however, it does not reflect the realities of cylindrical shell dynamics. Some comparisons with Lockheed laboratory research tests on single wall cylinders show that mass law theory is too optimistic above about one-half of the ring frequency, but is somewhat conservative at lower frequencies. Also, test data show some sensitivity to incidence angle.

3.4.2 Structural Design Constraints

The double wall NTL equations (Table 18) are solved to find the total wall weight per unit area required to achieve a specified NTL. This weight is, however, increased because of a number of constraints beyond those used in the previous Study (Ref. 4). The treatment weight prediction modifications for the current study are as follows:

(1) The treatment now covers the entire circumference 61.5 sq ft of cabin length versus 16 sq. ft of side wall treatment per ft of cabin length previously used.

(2) The design NTL is decreased stepwise by 10 dB with distance from the propeller disk plane in 5 steps, according to new external SPL directivity data. The required treatment segment lengths vary with relative tip clearance according to Figures 23 and 24. An example of the longitudinal distribution of treatment material is shown in Figure 25 for a relative tip clearance $\Delta y/D = 0.8$.

Figure 22 shows plots of the required ratios of segment treatment length to prop-fan diameter for each of five segments. In the first segment the required noise transmission loss is based on the maximum exterior SPL at blade passage frequency (see Section 3.3 item (2)). Thus, for segment k = 1,

$$NTL\ (1) = SPL_{E_{max}} - 90\ dB = NTL_{max}$$

For segments k = 2 to 5 the required transmission loss is

$$NTL(k) = (SPL_{E_{max}} - 90\ dB) - (k-1) = 10\ dB$$

We define the increment of required transmission loss for each segment (k = 1 to 5) as follows

$$\Delta NTL\ (k) = NTL(k) - NTL_{max}$$

$$= (k-1) \times 10\ dB$$

It is noted that the mathematical model of $\Delta L_t/D$ is quite conservative for segment k = 2 (see remarks under item (5) below, however).

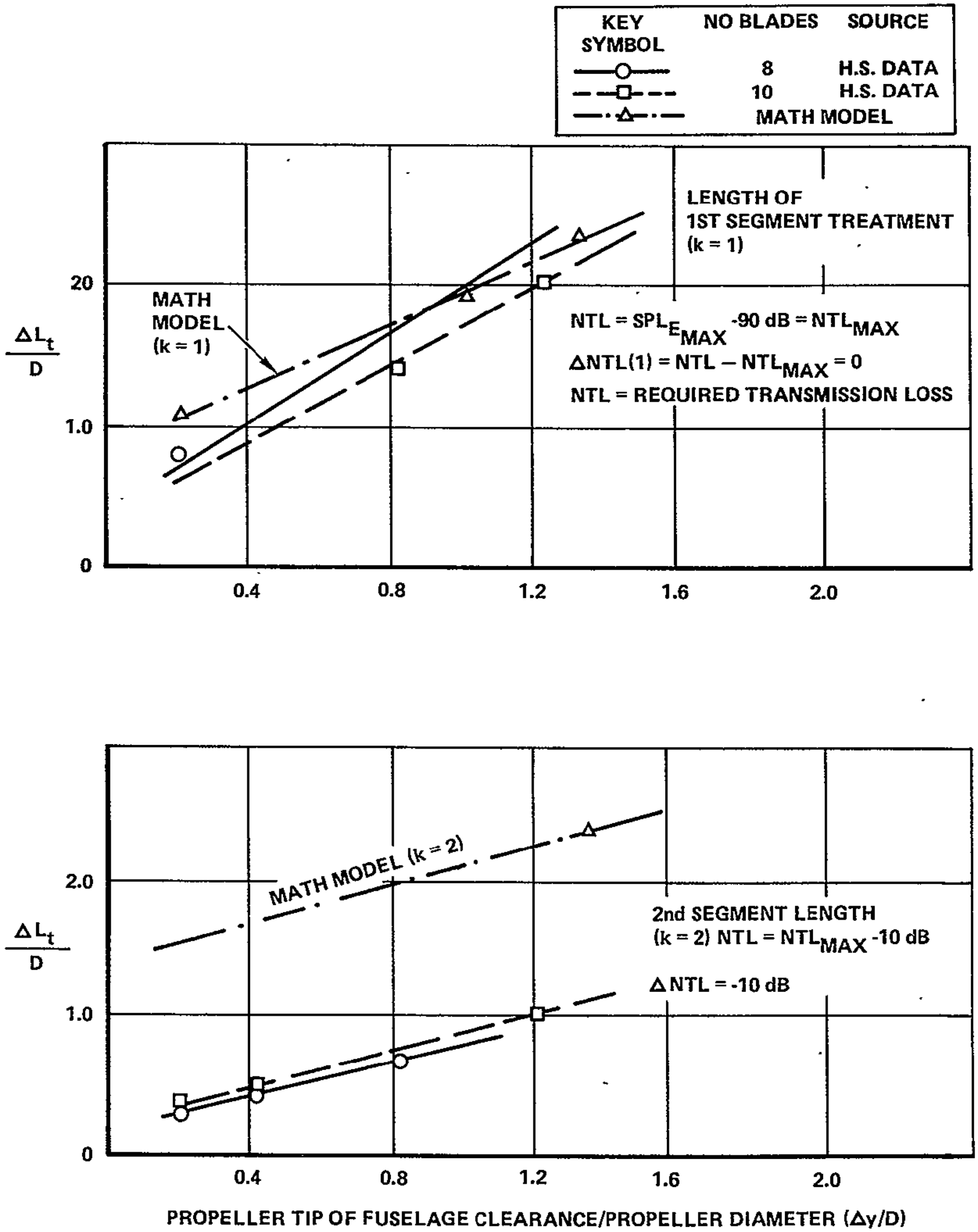

Figure 23. Required Treatment Length With Relative Tip Clearance

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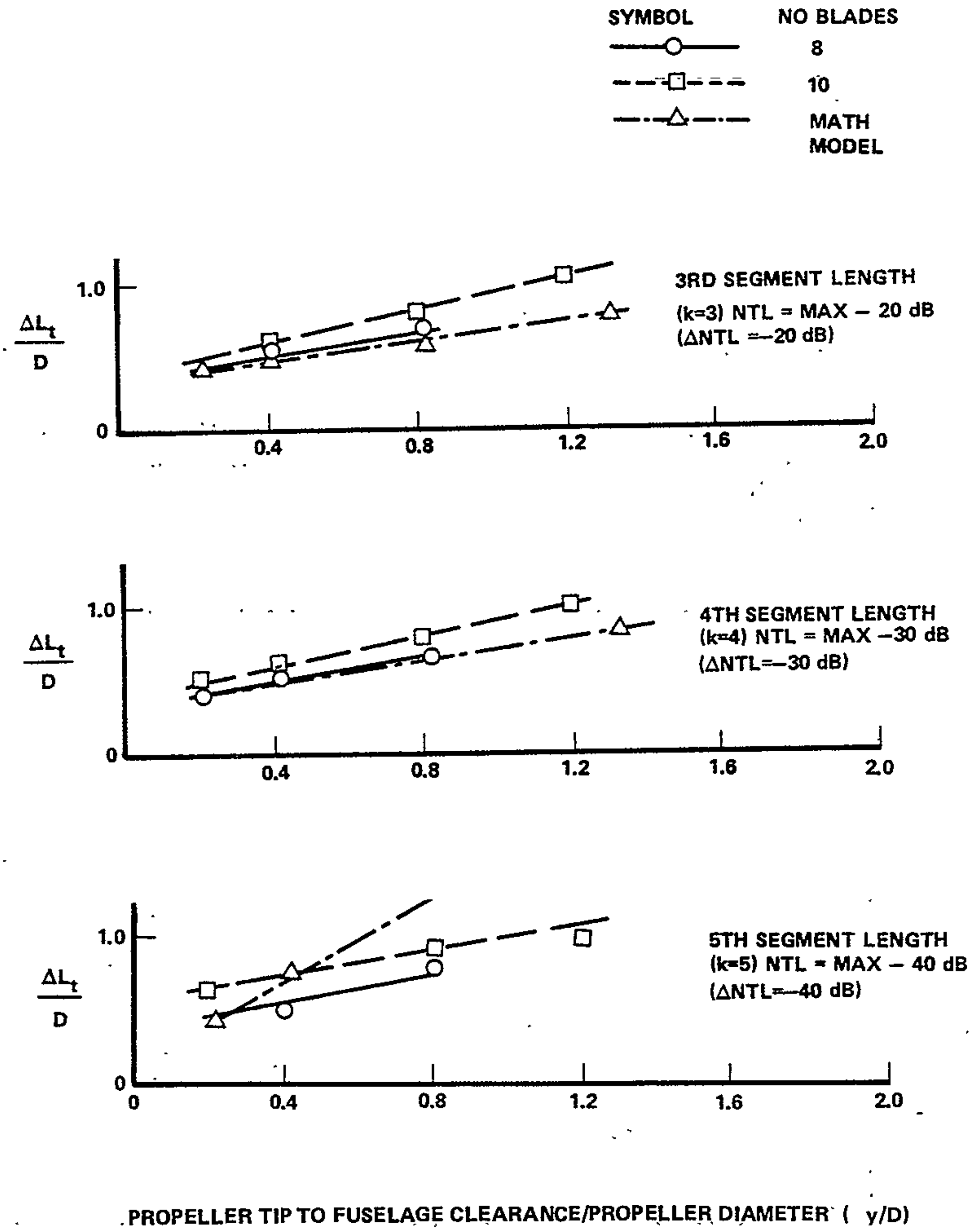

Figure 24. Required Treatment Length With Relative Tip Clearance

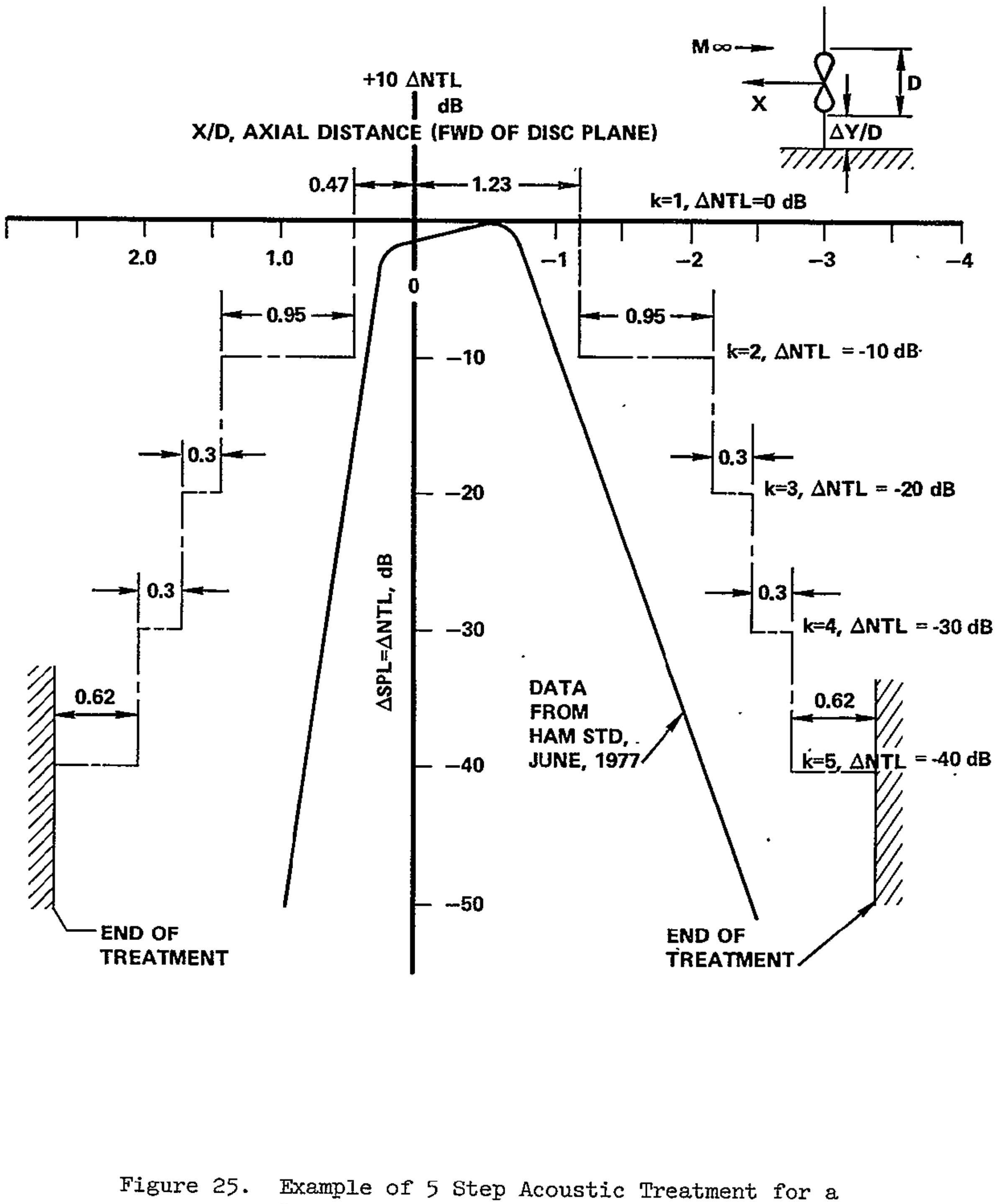

Figure 25. Example of 5 Step Acoustic Treatment for a Relative Tip Clearance of $N - \Delta_y/D = 0.8$

(3) Minimum inner and outer wall weight structural design constraints are imposed for each of the 5 treatment segments. These constraints are summarized in Table 19. The most notable feature is the choice of double the reference outer wall weight to 2.4 psf for the minimum outer wall weight for the first two segments nearest the propeller disk plane. At a relative tip clearance, $\Delta y/D$, of 0.8 these two segments cover $L_t = 3.6D$, where, D is the propeller diameter. For the segments 3 and 4 the minimum weights are increased by 25 percent (to 1.5 psf). Finally, segment 5 has a minimum increase of 10 percent to the outer wall. The minimum weight increases are provided to allow for viscoelastic damping material which will force the outer wall to behave in accordance with the limp wall mass theory.

(4) Minimum inner wall trim panel weight constraints (see Table 19) are set at 75 percent of the reference turbofan trim panel weight (0.33 psf). In some cases because of the heavy minimum values of outer wall weight (due to constraints stipulated above) the double wall theory would require even less weight for the trim panel; therefore, this constraint is considered as a structural constraint.

(5) The total treatment length now varies according to diameter and propeller tip clearance as discussed above. In the previous study (Ref. 4) the total cabin length was treated (even though confined to the side walls), because of uncertainty concerning the axial location of the maximum external SPL signature. In the present study it was decided to adopt the external SPL levels and directivity data of Appendix A (measured at M = 0.3), with the understanding that these data are subject to future revision when new external SPL is available at flight Mach numbers of 0.70 to 0.80. Lockheed believes the shockwave position uncertainty discussions of Ref. 4, pp 187-188, Figures 70 to 73 pp 207 and 208, and Table 125, p 222 are still relevant to the external SPL environment at cruise Mach numbers of 0.7 to 0.8. There it is noted that at the high flight Mach numbers, the shockwave pattern defining the external sound pressure would be moved farther aft of the disk plane than would be the case for the test data at a tunnel flight Mach number of 0.3. It is possible that the total signature length would not be greatly different, even though the axial location of peak intensity might vary from the pattern shown in Figure 25. The extra treatment length is an attempt to provide a margin of safety due to the anticipated variability of signature due to shockwave position change with flight Mach number, as discussed in Ref. 4.

(6) The current study is restricted to an airspace depth of 4.8 inches, as was used in the previous study. Increased airspace depth would be beneficial and should be considered in future design studies.

(7) In this study acoustic treatment weight variation with propeller diameter is considered during the selection of optimum propeller

TABLE 19. WALL WEIGHT CONSTRAINTS FOR 5 STEP DOUBLE WALL TREATMENT

SEGMENT	$\left(\frac{\Delta y}{D}\right)$	$\left(\frac{\Delta L_t}{D}\right)_K$	ΔNTL dB	(W_1/A) PSF	(W_2/A) PSF
1	0.2	1.1	0	2.4	0.25
	0.4	1.5			
	0.8	1.7			
	1.2	2.1			
	1.6	2.5	0	2.4	0.25
2	0.2	1.50	-10	2.4	0.25
	0.4	1.63			
	0.8	1.90			
	1.2	2.17	-10	2.4	0.25
3	0.2	0.40	-20	1.5	0.25
	0.4	0.47			
	0.8	0.60			
	1.2	0.73	-20	1.5	0.25
4	0.2	0.40	-30	1.5	0.25
	0.4	0.47			
	0.8	0.60			
	1.2	0.73	-30	1.5	0.25
5	0.2	0.40	-40	1.32	0.25
	0.4	0.68			
	0.8	1.24			
	1.2	1.80	-40	1.5	0.25

diameter, blade count, tip speed, and cruise Mach number, for a range of net thrust values appropriate to each point design aircraft (payload, range and cruise speed combination).

(8) The propeller shaft axis is held at a fixed spanwise location as propeller diameter is varied in this study. This maintains constancy of nonacoustic weight of the wing and empennage structure even though propeller tip to fuselage clearance now varies also as the propeller diameter is changed.

3.5 EXTERIOR NOISE DATA

Appendix A contains the exterior noise data supplied by Hamilton Standard. Appendix A shows OASPL data versus tip speed at cruise Mach numbers of 0.7, 0.75 and 0.8 for both eight and ten bladed propellers at 30,000 ft altitude, at various propeller efficiency values, for a relative tip clearance, $\Delta y/D$, of 0.8. Appendix A also shows the estimated directivity data for the eight and ten bladed propfan designs, taking into account the most recent test data. Also shown are the increments in SPL levels (HL's) of the blade passage frequency harmonics, relative to the OASPL. These are the data used in the present study. The acoustic data of Appendix A differs somewhat from the preliminary Lockheed predictions used in the previous study (Ref. 4, pp 187-188). Table 20 provides a comparison of data used for the previous study and this assessment.

3.5.1 Previous and Current Prediction Results

The first noticeable difference is the external SPL at blade passage frequency. Lockheed estimated the values shown in Table 21, which is a reproduction of Table 125 p 222 of Ref. 4. It is noted in Table 21 that Lockheed and Hamilton Standard prediction methods were apparently in fairly close agreement as to the blade passage frequency harmonic (n = 1) SPL value (124 dB vs 126 dB); both of these values are much lower than the current prediction of 134.5 dB. It is noted, however, that Hamilton Standard originally predicted (unpublished data, Ref. 5) an OASPL of 136 dB with a -10 dB correction for each of the first 10 harmonics. Furthermore, the altitude correction used in Ref. 5 and also, presumably, for the current data was only -4.3 dB re sea level. By contrast, the Lockheed original altitude was evaluated for 35,000 ft, and correction included in Table 20 was -12.5 dB, based on 20 Log_{10} (Pamb/P_{SL}). This represents dynamic pressure scaling at constant helical tip Mach number.

TABLE 20. COMPARISON OF PREVIOUS RECAT VS. CURRENT CABIN NOISE TREATMENT METHODOLOGY AND DATA

	PREVIOUS	CURRENT HAM STD JUNE 1977
External SPL Level		
SPL, @ BPF (M_o = 0.8, V_L = 800 D = 12.8, $\Delta y/D$ = 0.8)	124 dB	(134.5 dB @ same conditions)
Clearance, $\Delta y/D$	0.8	Varied in prop size trade
Tip Speed V_t (ft/sec)	800	800, 700, 600
Point Design Cruise Mach No, M_o	0.80	0.80, 0.75, 0.70
SHP/D^2_{ref} (HP/ft^2)	37.1	Tradeoff variable
Net Thrust (lb/engine)	3860	3860, 3000
Diameter (ft) (@ 37.1 SHP/D^2)	12.8	12.55/traded
Prop Efficiency	0.82	0.83/traded
Number of Blades	8	8, 10
Treated Areas (sq. ft.)	1568	f ($\Delta y/D$,D) per Ham Std Data June, 1977
Cabin Diameter (ft)	19.58	f ($\Delta y/D$,D) per Ham Std Data June, 1977
Cabin Length (ft)	98	f ($\Delta y/D$,D) per Ham Std Data June, 1977
Total Cabin Surface Area (sq. ft)	6028	f ($\Delta y/D$,D) per Ham Std Data June, 1977
% of Circumference Treated	26.0%	100%
Constraints	None Defined	New minimum wall weights near prop plane
Treatment Method	Damped Double wall	Damped Double Wall
Altitude	30,000 ft	30,000 ft
Blade Passage Freq (Hz) @ Ref SHP/D^2	159.2	163.2/traded

TABLE 21. EXTERNAL SPL RESULTS

$M = 0.8$ 8 Blades $D_p = 12.6$ ft $V_T = 800$ ft/s

$r_{LE}/c_b = 0.0015$ Clearance: $0.8\ D_p$ $M_H = 1.06$

HARMONIC	FREQUENCY	SPL: LOCKHEED (1)	SPL: HAM STD. (2)
Blade Passage	156 Hz	124 dB	126 dB
Second Harmonic	313 Hz	121 dB	126 dB
Third Harmonic	470 Hz	116 dB	126 dB
Fourth Harmonic	626 Hz	104 dB	126 dB

- Pulse time/blade passage period = 0.330
- Cosinusoidal pulse 

(1) Note Lockheed calculations performed for 35,000 ft, including an altitude correction of -12.5 dB. At 30,000 ft the correction is -10.5 dB.

(2) HS data includes an altitude correction of -4.3 dB at 30,000 ft altitude.

It is noted that altitude corrections used by Lockheed in Reference 4 and the current Hamilton Standard theory (Reference 6) both utilize a correction of $20 \log_{10} (P_{amb}/P_{SL})$ which corresponds to the near-field noise of a single blade or fixed blade area at fixed values of rotational and forward Mach number, and at a fixed relative blade tip clearance distance. The original Hamilton Standard altitude correction of Reference 5 is exactly equal to $10 \log_{10} (\rho/\rho_{SL})$. The method of Reference 5 is a preliminary design type method. It would represent the variation with altitude of the noise of a dipole acoustic source for a fixed value of prop-fan power loading (SHP/D^2) and for fixed values of tip speed, helical tip blade number, and relative blade tip to fuselage clearance. The "old" and "new" altitude corrections are essentially consistent because a factor of $10 \log (P_{amb}/P_{SL})$ is absorbed into the SHP/D^2 factor of the "old" (Reference 5) method.

Notice in Table 22 that Lockheed's prediction of harmonic level variation given in Ref. 4, Table 125, was more realistic than Hamilton Standard's original prediction. A larger altitude correction may be more accurate, which means the new acoustic data could be too pessimistic in this respect by 5 to

TABLE 22. COMPARISON OF HARMONIC LEVELS OF EXTERNAL SPL DATA AT 800 FT/SEC TIP SPEED, $M_{C_R} = 0.80$

Definition: HL(n) = SPL(n) MINUS OASPL, dB			
	PREVIOUS (REF. 4, TABLE 125)		CURRENT DATA APPENDIX A
SOURCE	LOCKHEED	HAM STANDARD	HAM STANDARD
n	HL(n) dB	HL(n) dB	HL(n) db
1	-2.2	-10	-1
2	-5.2	-10	-9
3	-10.2	-10	-15
4	-22.2	-10	-20

6 dB at 30,000 ft. On the other hand, the currently predicted data are based on tests at a tunnel (flight) Mach number of 0.3; this provides the wrong propeller advance angle, even if the resultant supersonic helical tip Mach number is matched, and therefore the directivity may be questioned. The Lockheed discussion of shockwave impingement in Ref. 4, pp 187-188, is considered still pertinent to this respect. It is possible that many of these differences in exterior sound pressure estimates may produce cancelling errors and lead to small differences in acoustic treatment weight penalties when all corrections are taken together.

3.5.2 Exterior Near Field Noise Prediction

Note in Table 21, that Lockheed's analysis of external SPL contained a number of blade shape oriented assumptions about what may be possible with regard especially to achieving a small leading edge radius, and the effectiveness of blade sweep in reducing the effective helical tip Mach number. These variables all affect the estimates of shockwave detachment. These estimates were made without benefit of detailed knowledge of the exact geometry of any of the fan blades which were actually tested or contemplated as a basis for the new data package contained in Appendix A. It is believed that the shockwave analysis approach used by Lockheed in Ref. 4 could lead to better blade concepts and deserves further development. There are other noise prediction methods which are reviewed here briefly.

It is noted that Hanson (Ref. 6) has recently published a more elaborate analytical scheme based on Ffowcs-Williams and Hawkings solution (Ref. 7) of the acoustic analogy equations of fluid motion. Hanson's analysis is based on linearized theory using fluid fixed coordinates, which cannot account for the shockwave effects which are present in the near geometric field. Hanson claims to have good agreement with Hubbard and Regier's static data (Ref. 8) at tip Mach numbers up to 1.0, and for clearances of 4 and 8 inches on a 4 ft diameter prop. Hanson also states that calculations of the first two harmonics were in good agreement with P-51 Mustang test data at a helical tip Mach number, $M_H = 1.07$, obtained in a dive (Ref. 9). Hanson shows agreement with results by Farassat (Ref. 10) at a distance of 5 rotor diameters. His method appears logical for far field prediction; however, it is suprising that it predicts the Hubbard-Regier data at small clearances. More test data is needed for supersonic helical speeds at high subsonic forward Mach numbers for various blade thickness distributions and for various leading edge radius to chord ratios. Blade angle of attack or loading effects appear to be secondary for the propfan designs proposed thus far, when operated near peak efficiency

3.6 ACOUSTIC TREATMENT WEIGHT PENALTY DATA

Table 20 shows a summary of parameter and methodology differences between weight penalties used for the previous and current RECAT studies. The methodology differences have been discussed in the previous subsections. What remains to be considered are parametric effects of propeller disc power loading, cruise design Mach number, design cruise thrust level, propeller tip speed, and blade count.

In evaluating the effect of propeller disk power loading, SHP/D^2, it is assumed that the propeller shaft centerline position remains constant. This means that the relative blade tip clearance, $\Delta y/D$, changes with propeller diameter. It turns out, however, that the relative clearance is still near optimum value, except for very low disk loadings (large propeller diameters). Fore these cases, a lower weight could be achieved by optimizing the relative tip clearance of the propeller.

3.6.1 Presentation of Acoustic Treatment Weight Penalty Data

Figures 26 and 27 show, for a tip speed of 800 ft/sec, the treatment weight penalties versus SHP/D^2 for an 8-bladed propeller at 30,000 ft altitude for propeller thrust levels of 3,860 lb and 3,000 lb respectively. These thrust levels bracket the thrust required at various cruise Mach numbers. Parametrically shown are curves for different point design cruise Mach numbers of 0.7, 0.75 and 0.80. Figures 28 and 29 show the same data for a propeller tip speed of 700 ft/sec. These weight penalties are clearly much worse than for 800 ft/sec tip speed. Figures 30 and 31 display the effect of propeller tip speed upon the required acoustic treatment weight and also

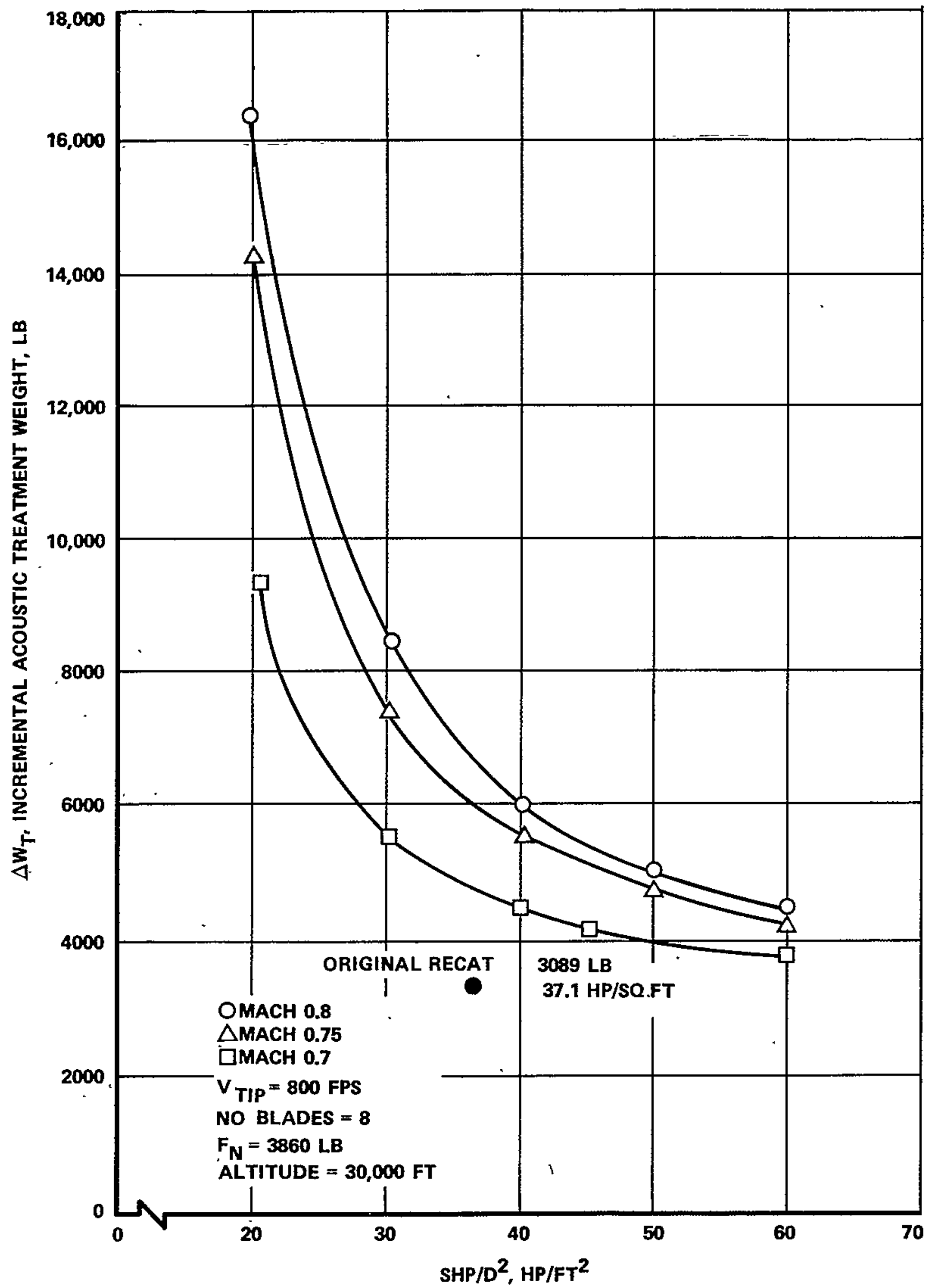

Figure 26. Acoustic Treatment Weight, 8 Blades, 800 fps, 3860 lb Thrust

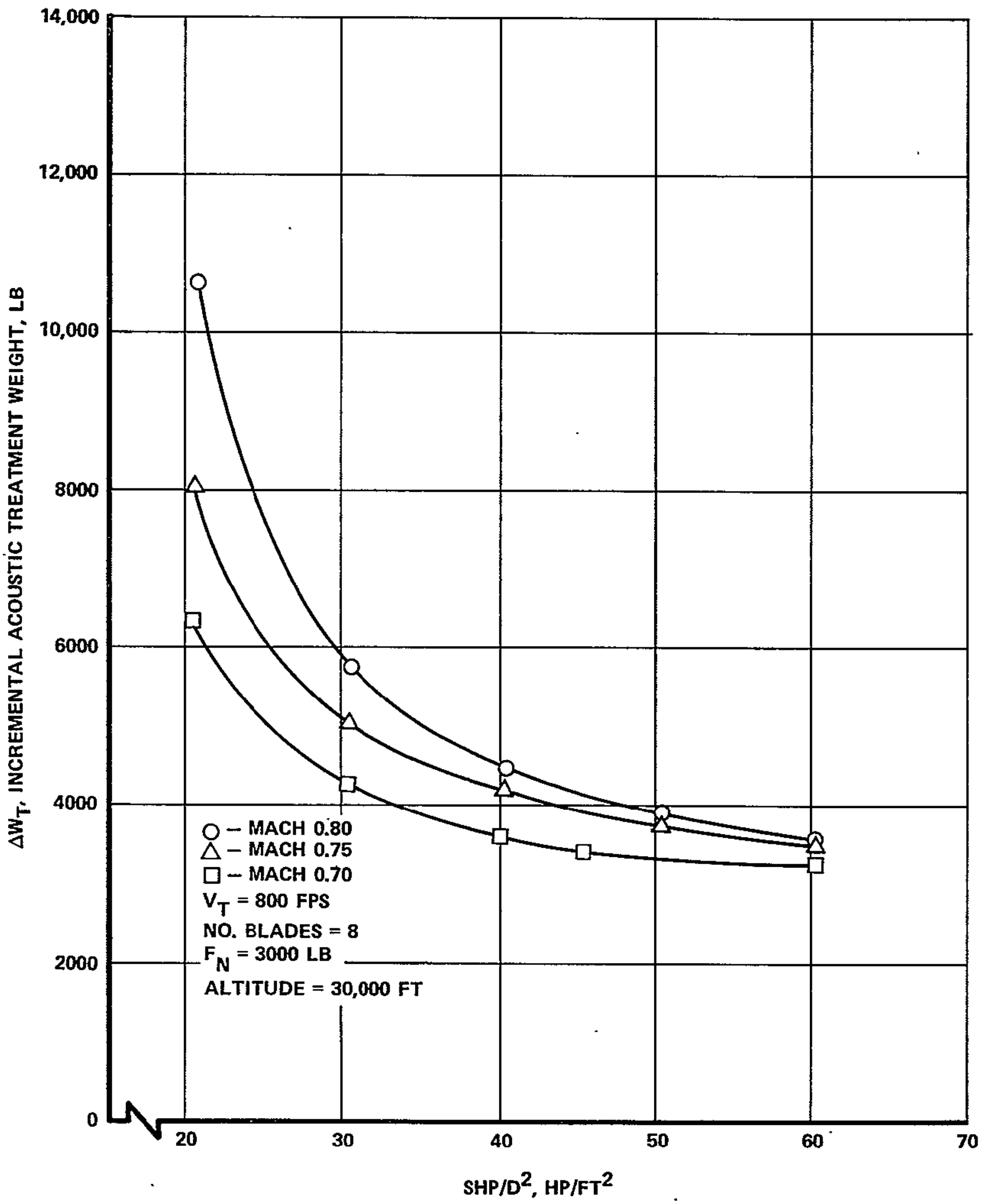

Figure 27. Acoustic Treatment Weight, 8 Blades, 800 fps, 3000 lb Thrust

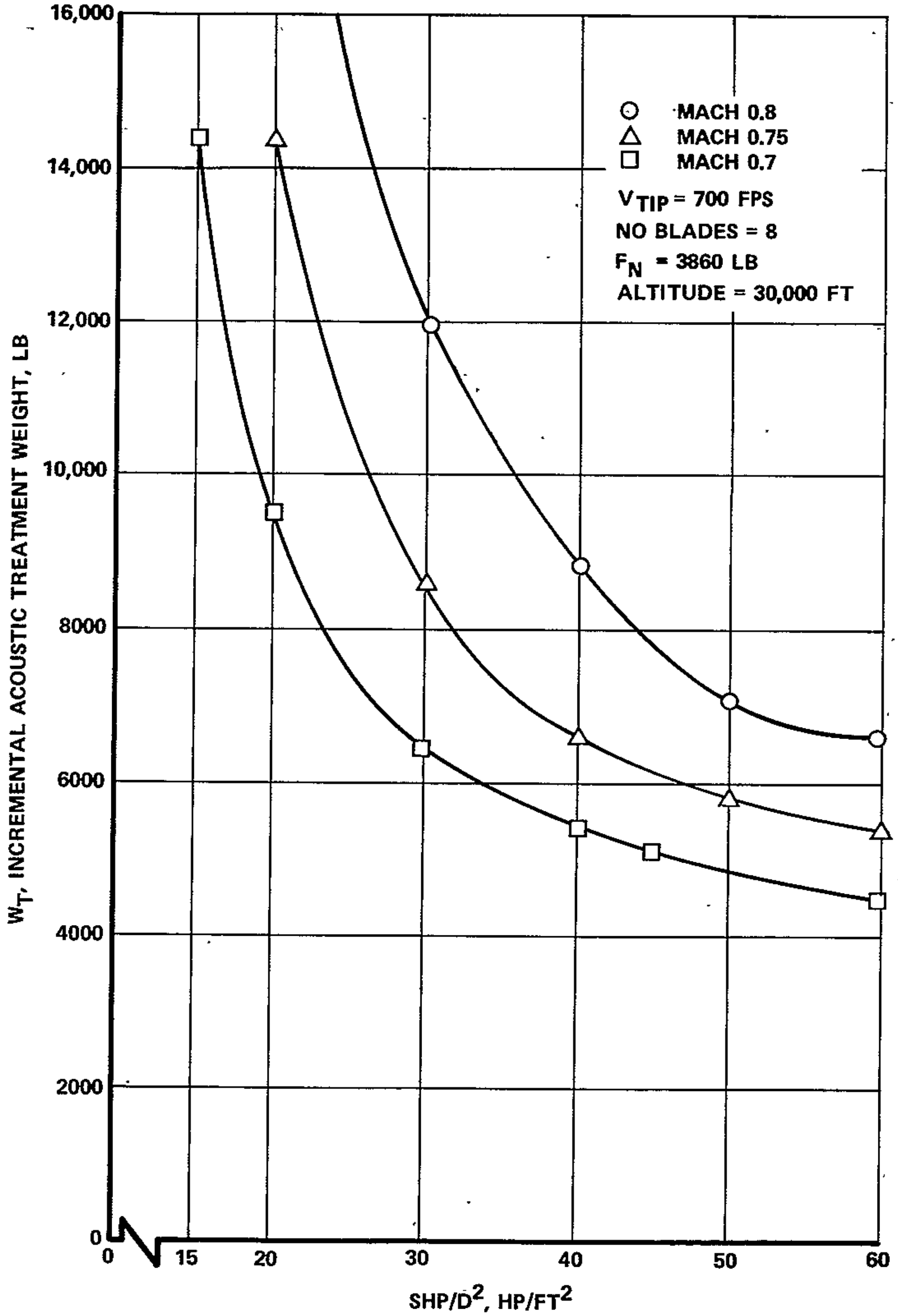

Figure 28. Acoustic Treatment Weight, 8 Blades, 700 fps, 3860 lb Thrust

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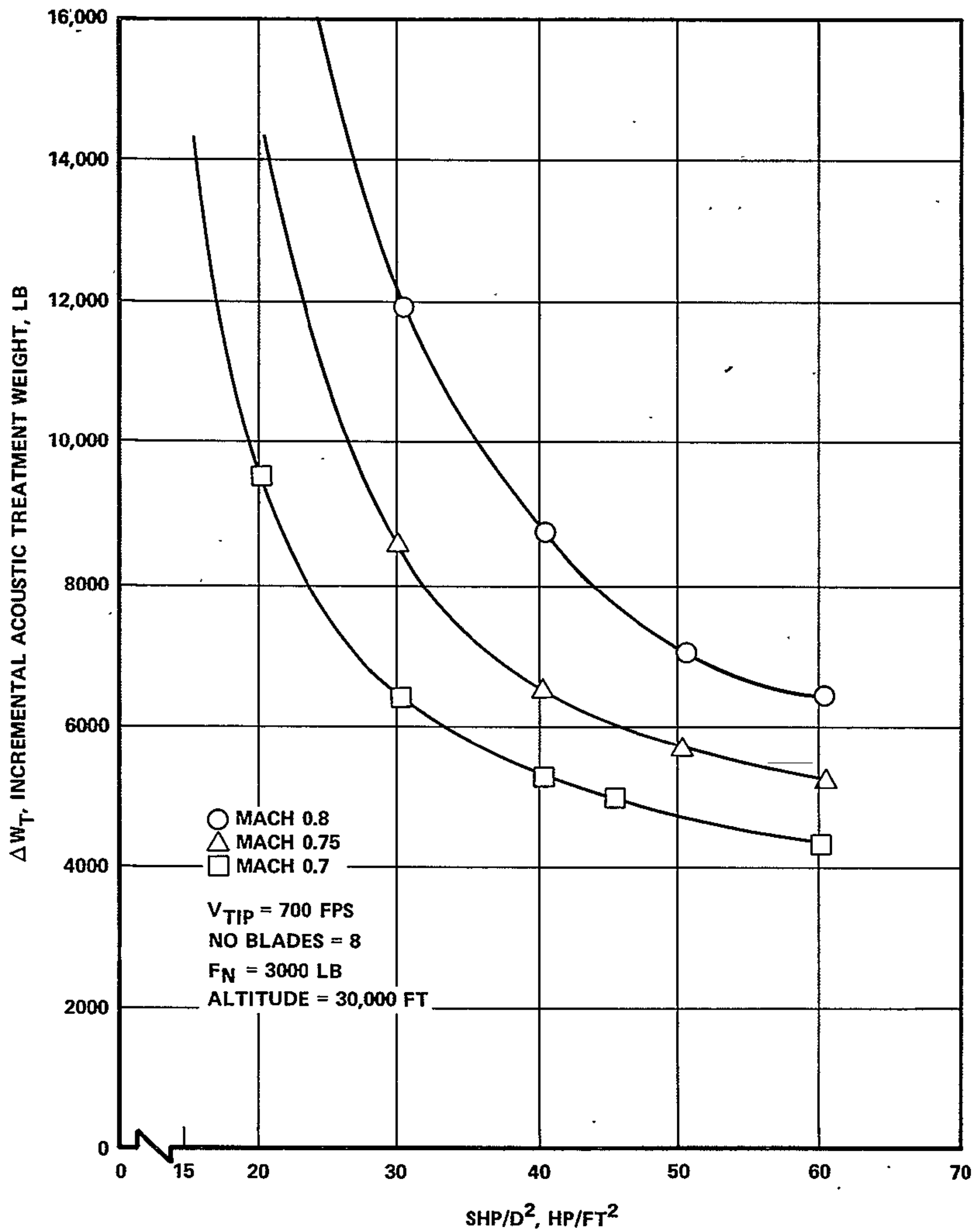

Figure 29. Acoustic Treatment Weight, 8 Blades, 700 fps, 3000 lb Thrust

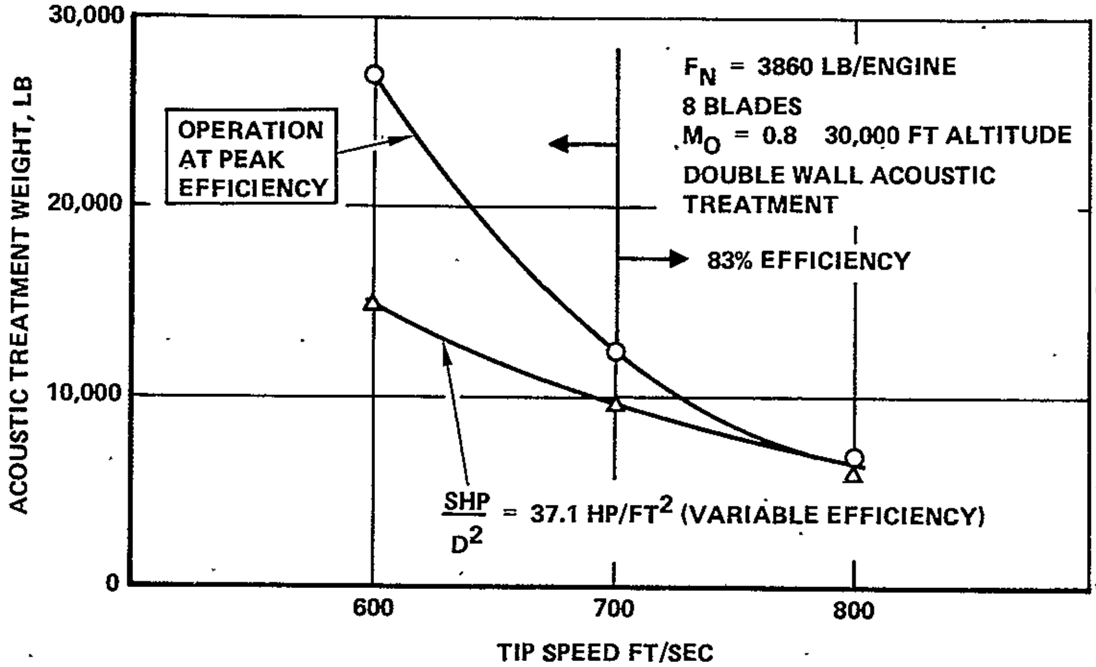

Figure 30. Acoustic Treatment Weight Required vs. Tip Speed

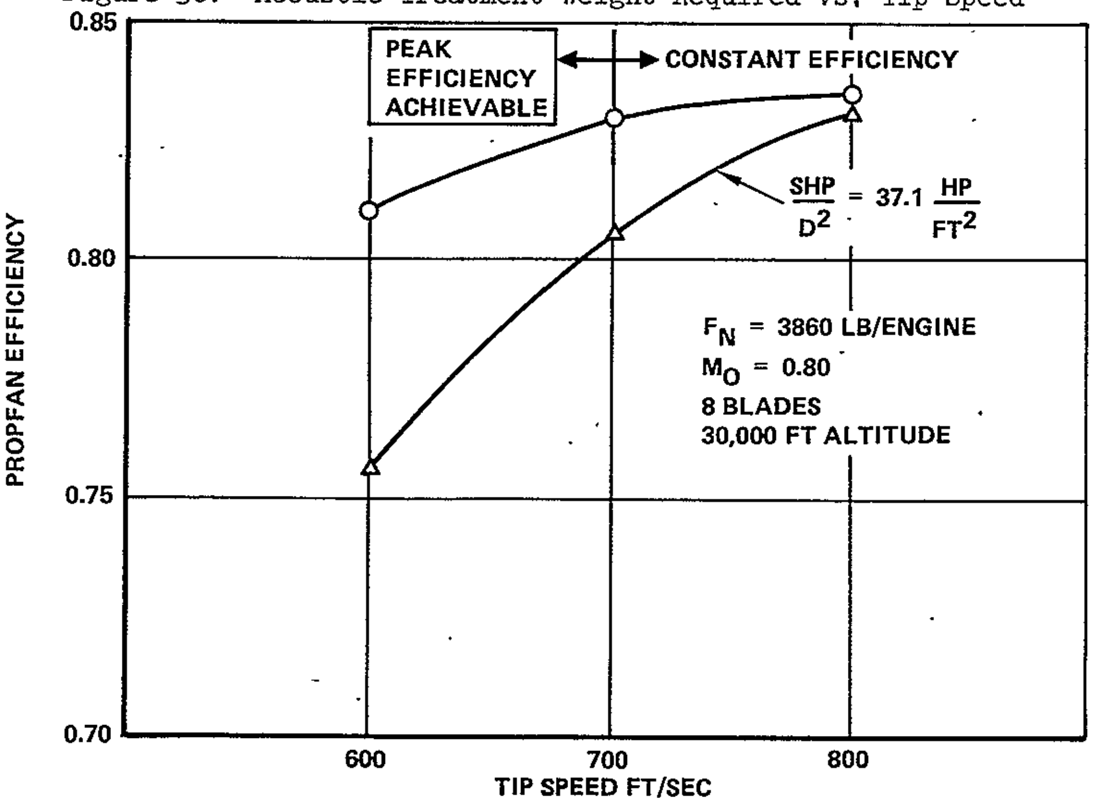

Figure 31. Propfan Efficiency vs. Tip Speed

prop-fan efficiency. The lower curve of Figure 30 shows the weight penalty if the same power loading $SPD/D^2 = 37.1$ HP/sq ft was maintained. It is seen from Figure 31, however, that a significant loss of prop-fan efficiency would occur at the low tip speeds, if the same power loading was maintained. The upper curve of Figure 31 shows the improvement in prop-fan efficiencies which could be achieved by reducing the power loading below 37.1 HP/sq ft; however, Figure 30 shows that the acoustic treatment penalty must be increased significantly to achieve these higher efficiency levels because of the much larger propeller size and the corresponding lower blade passage frequencies. It is clear from Figure 30 that the acoustic treatment penalties required for operation at a tip speed of 600 ft/sec become prohibitive, if a reasonable prop-fan efficiency is to be maintained. The absolute weight penalties must be used with some caution at these low tip speeds, since some other form of acoustic treatment may be more suitable. It is also noted that power plant weight components other than the acoustic treatment material requirements increase rapidly with prop fan diameter, and therefore, would further penalize a design based upon 600 ft/sec tip speed.

Figures 32 and 33 show results for a 10-bladed propeller at 800 ft/sec tip speed, at the same thrust levels and cruise Mach numbers. These results show a clear advantage compared to the 8-bladed prop fan.

It is evident that high disk loadings, high tip speeds, and high blade counts are desirable from the exclusive standpoint of minimum acoustic treatment weight. In the current study, however, these data were used as inputs to the aeroacoustic versus propulsion trade off studies to optimize the selection of propeller diameter. Interpolation of these data, for the selected thrust levels, results in the acoustic treatment weights reported in Section 2 of this report. The next section discusses the underlying basis of the trends presented in these figures.

3.6.2 Disk Loading Effects on Acoustic Treatment

Figure 25 shows the effect of disk loading for an 8-bladed profan at 800 ft/sec tip speed at 3860 lb thrust. Also shown is the original RECAT data point at the design disk loading, $SHP/D^2 = 37.1$ HP/sq ft for 0.8 cruise

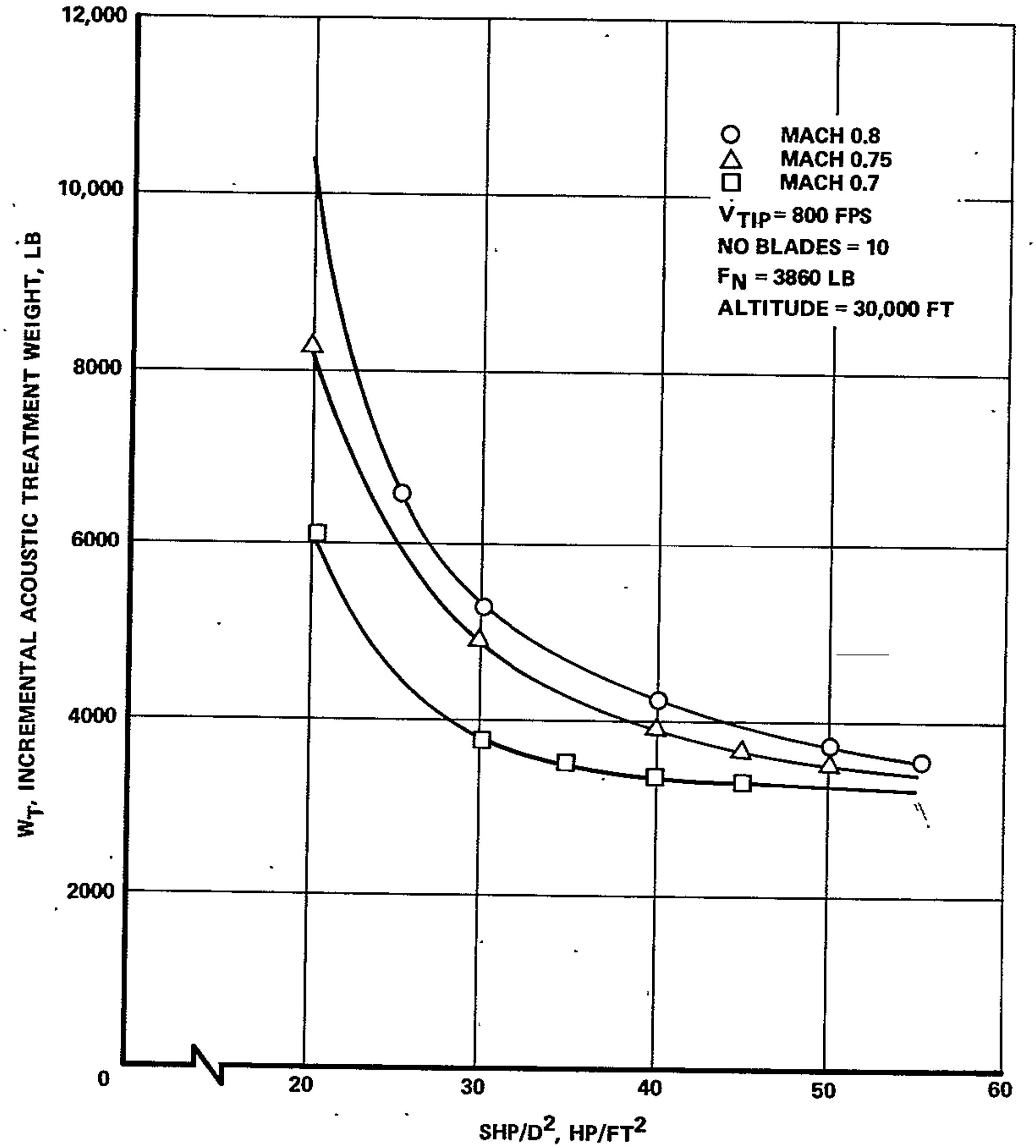

Figure 32. Acoustic Treatment Weight, 10 Blades, 800 fps, 3860 lb Thrust

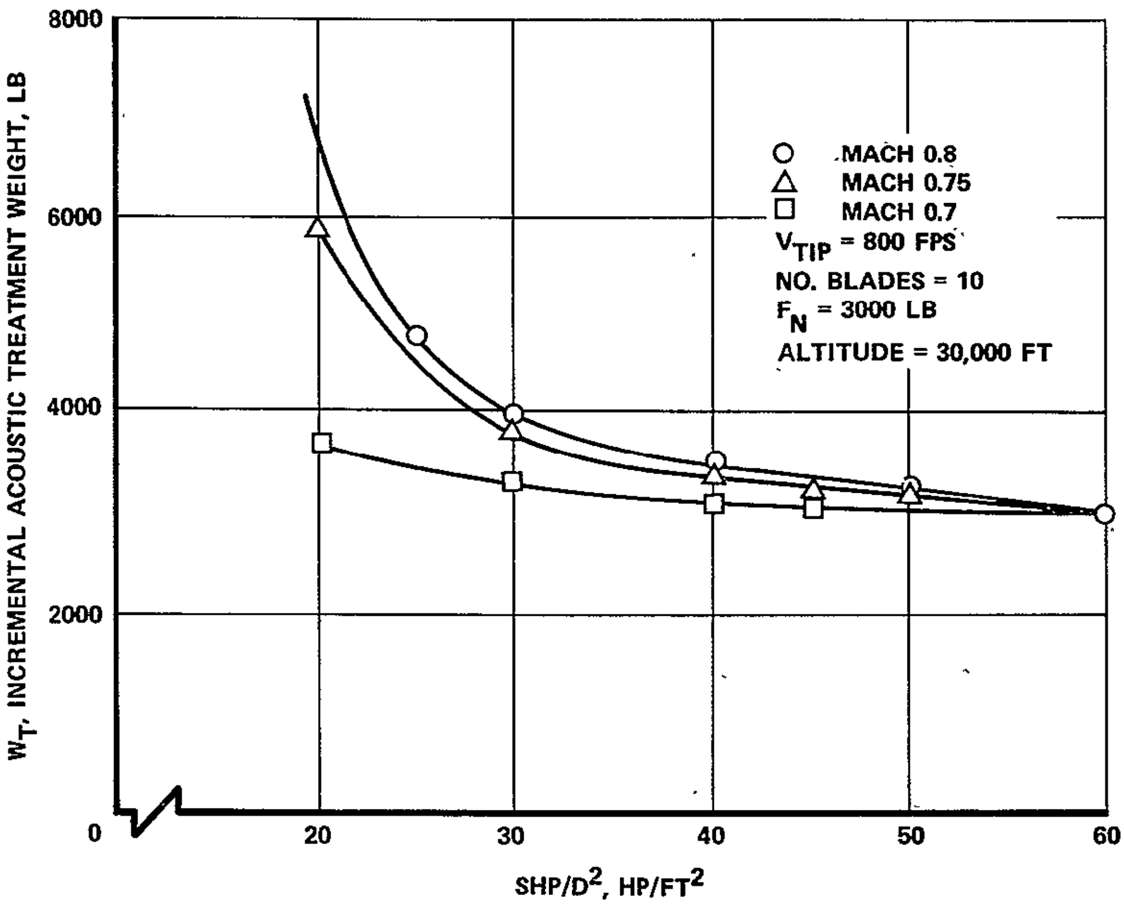

Figure 33. Acoustic Treatment Weight, 10 Blades, 800 fps, 3000 lb Thrust

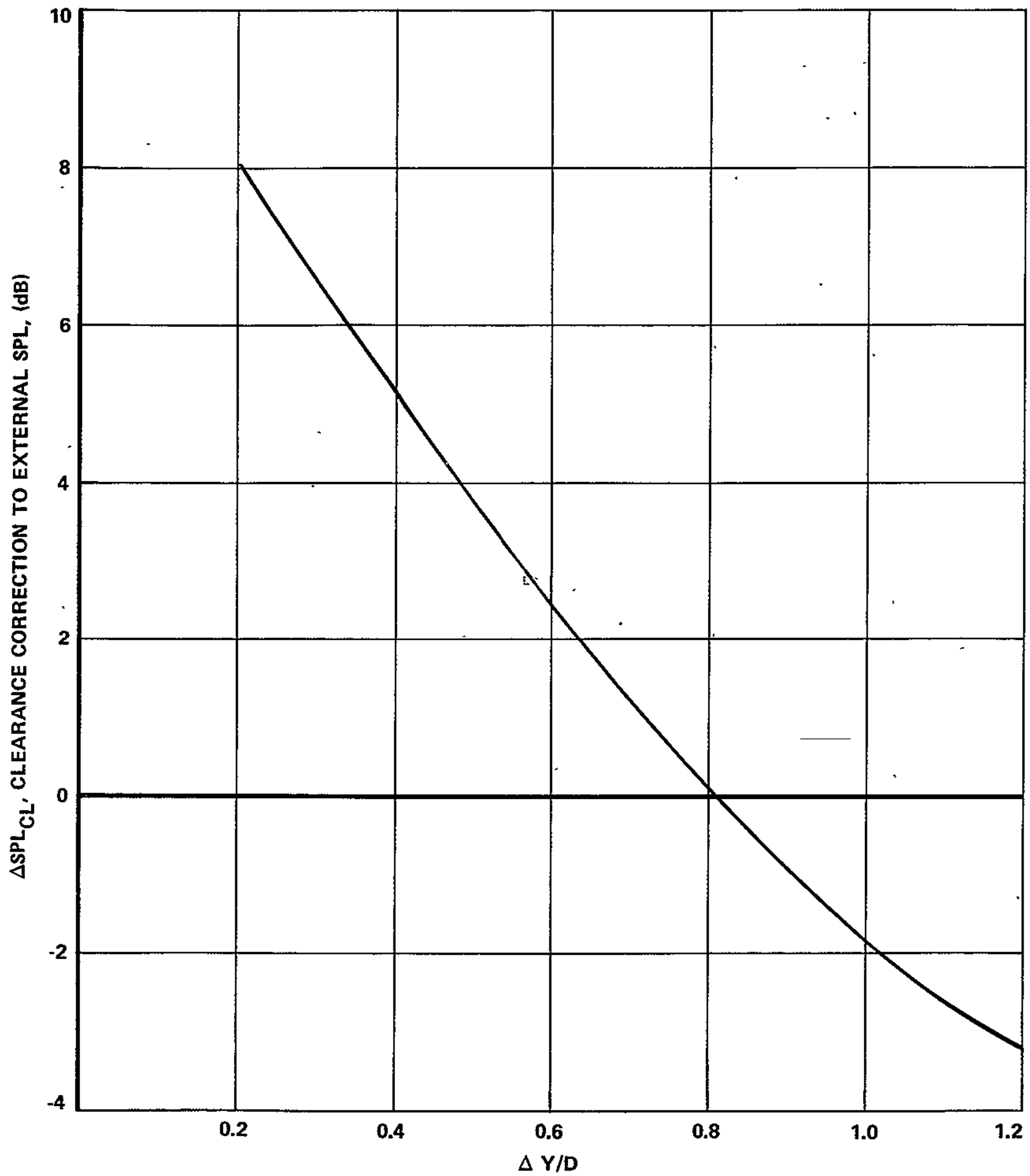

Figure 34. External SPL Correction vs. Relative Tip Clearance

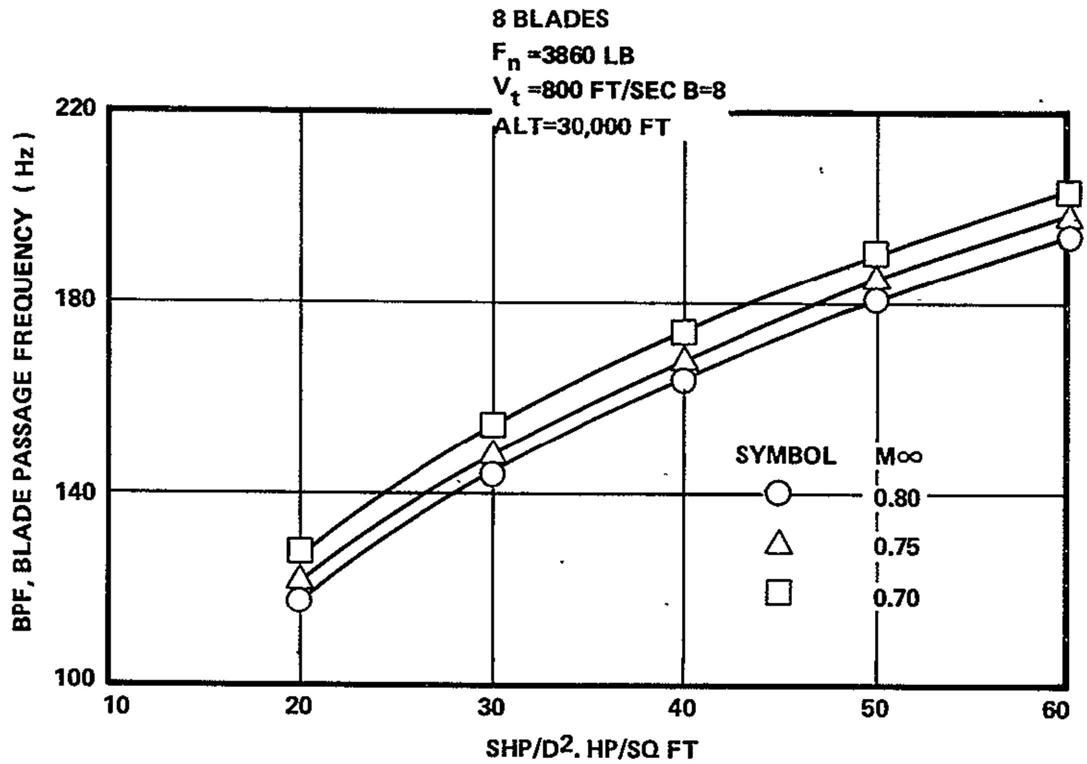

Figure 35. Blade Passage Frequency vs. Disk Power Loading

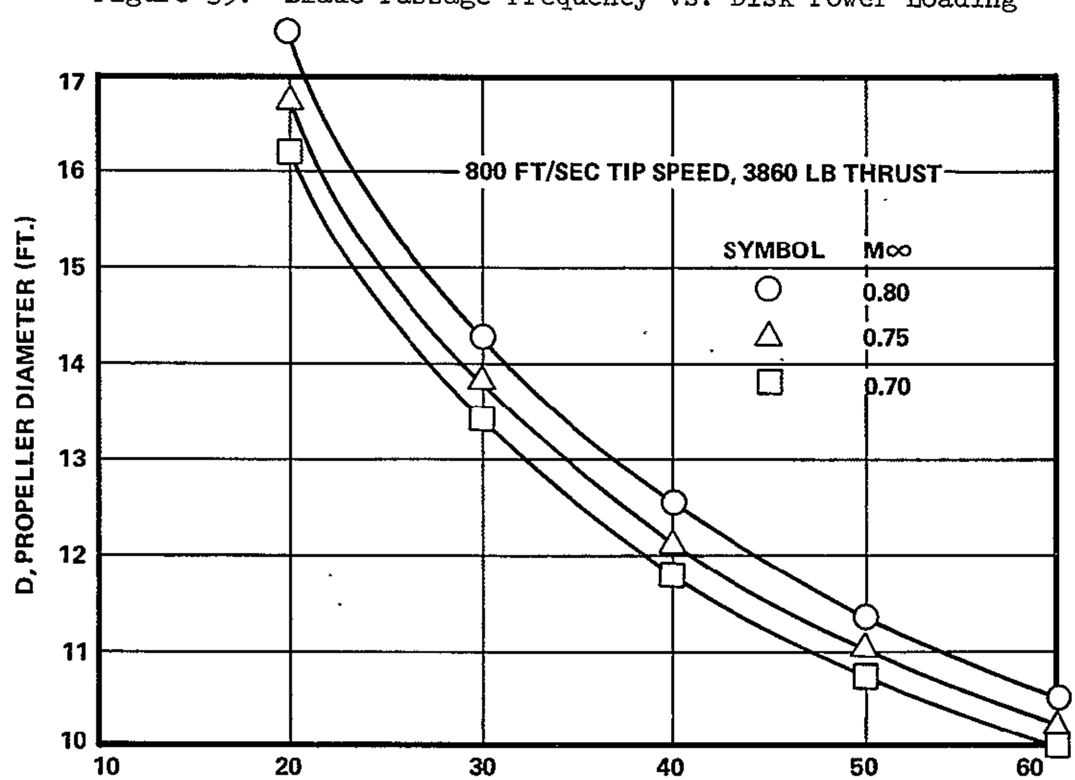

Figure 36. Propeller Diameter vs. Disk Power Loading

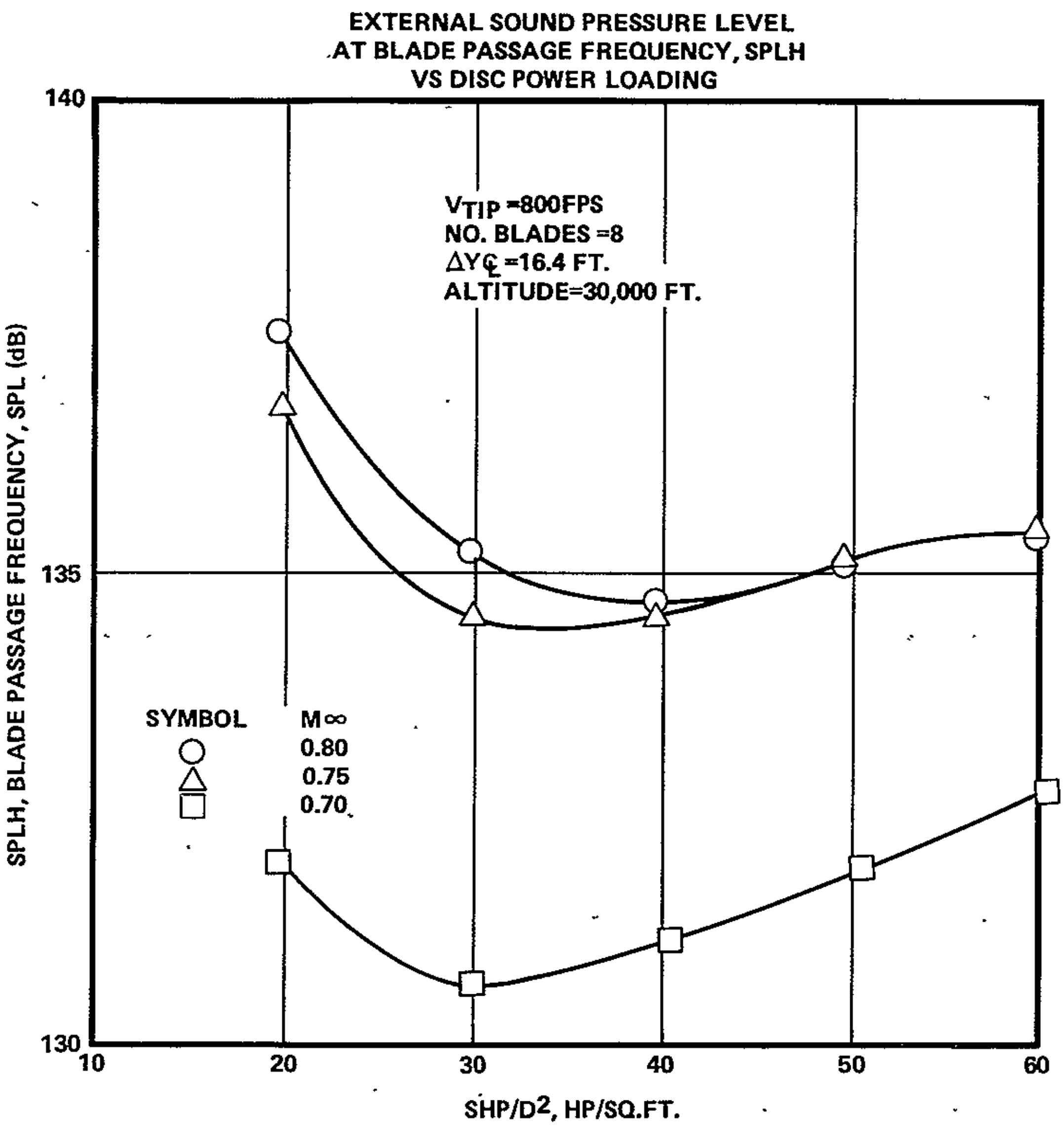

Figure 37. External SPL at Blade Passage Frequency vs. Disk Power Loading

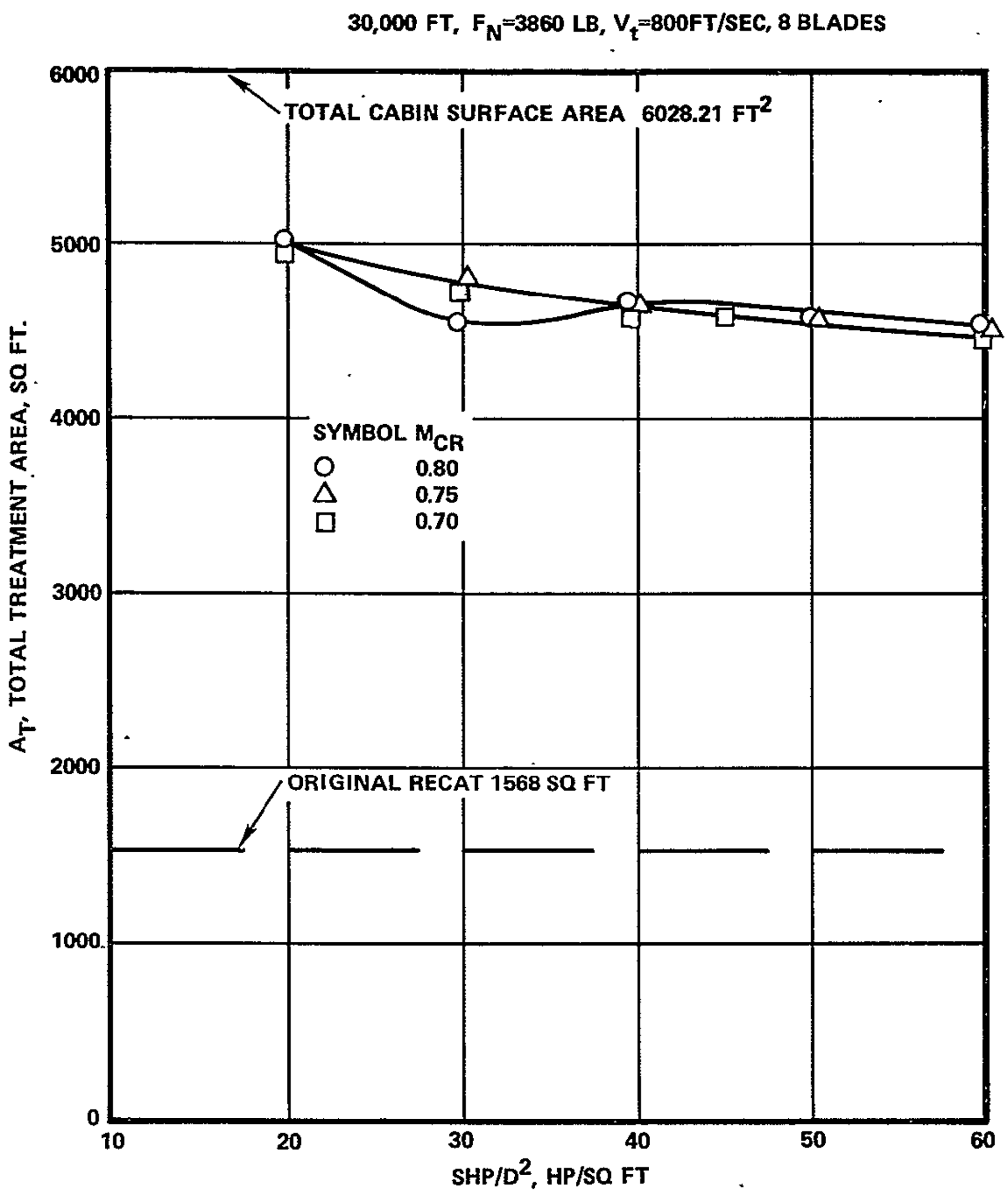

Figure 38. Total Acoustic Treatment Area Required vs. Disk Loading

Mach number. It is seen that for this study the acoustic treatment weight penalty is now 6500 lb, representing a 3400 lb increase in the weight relative to the previous study. Note also that increasing the disk loading to about 50 HP/sq ft would reduce the weight penalty by about 1500 lb to 5100 lb. This empahsizes the need to consider the acoustic treatment weight as a significant input in the selection of propeller size. Note that the required weights are further reduced if the propellers are sized for lower point design cruise Mach numbers of 0.75 or 0.70.

The external SPL data of Ref. 3 (Appendix A) show no difference between $M_{cr} = 0.8$ and $M_{cr} = 0.75$, at equal values of relative blade tip clearance. This is so, despite the reduction of helical tip Mach number by 0.08. The data in Figure 25 are affected by external SPL changes, since the relative blade tip clearance $\Delta y/D$ varies with the propeller diameter because the propeller shaft center line is maintained at $\Delta y_{C_L} = 16.4$ ft. This assumption maintains constancy of wing and empennage weight (which would change if the engines were moved spanwise to maintain a constant relative tip clearance). In the present study the relative blade tip clearance, therefore, is variable with propeller diameter, according to the following equation.

$$\Delta y/D = \left(\frac{16.4}{D} - 1/2\right)$$

Figure 34 shows the effect of relative tip clearance on the external SPL as determined from the data of Appendix A.

The strongest variable affecting the acoustic treatment weight requirement is the blade passage frequency, according to the double wall transmission loss theory. As described earlier, the transmission loss increases at 18 dB per octave increase of the blade passage frequency (Ref. 4 pp 187-189, and Table 17). Figure 35 shows the variation of the blade passage frequency with disk loading for the 800 ft/sec tip speed case. Figure 36 shows the corresponding propeller diameter requirements which are determined by the thrust and propeller efficiency data of Ref. 3, given in Appendix A. The blade passage frequency is easily calculated, given the tip speed, blade count, and propeller diameter as

$$BPF = \frac{BV_t}{\pi D}$$

Figure 37 shows the variation of external SPL with disk loading for the conditions of 8000 ft/sec tip speed, F_n = 3860 lb and M_{cr} = 0.7, .75, and 0.80. Apart from the effect of external SPL, the interior noise is governed by the blade passage frequency and propeller diameter.

Figure 38 shows the variation of total acoustic treatment area according to the 5 segment treatment scheme. This increases with propeller diameter and clearance as shown in Figure 23 and Table 17. Figure 39 shows the total treatment length versus SHP/D^2 for the same conditions (V_t = 800 ft/sec, M_{cr} = 0.80, 30,000 ft, F_n = 3850 lb/engine). Figure 40 shows the lengths of the first two treatment segments, and Figure 41 shows the total wall weight per unit area (including the reference turbofan value, 1.53 psf) versus SHP/D^2 for each of the first two segments. Figure 42 shows the treatment area for the various segments. It is noted that the total treatment areas, and even the treatment areas for the first two segments are considerably larger than the fixed value of 1568 sq ft, used for the previous RECAT study.

This is due to the decision in this study to treat the entire circumference of the cabin wall (61.5 sq ft/ft), rather than 16 sq ft/ft of side wall only. This represents the most important conservatism used in the present study to offset the risk where many technological uncertainties exist. It is anticipated that the treatment weight per unit area could be reduced near the top and bottom of the fuselage, if reliable circumferential distribution data were available for the external SPL.

The second most important conservatism in the present study is the schedule of minimum wall weights per unit area shown in Table 19. This sets minimum weight penalties above the reference weight (1.53 psf) of 1.12 for treatment segments 1 and 2, 0.22 psf for treatment segments 3 and 4, and 0.04 psf for segment 5. For the disk loading of the previous study airplane (SHP/D^2 = 37.1) a 12.8 ft diameter propeller would be required, and

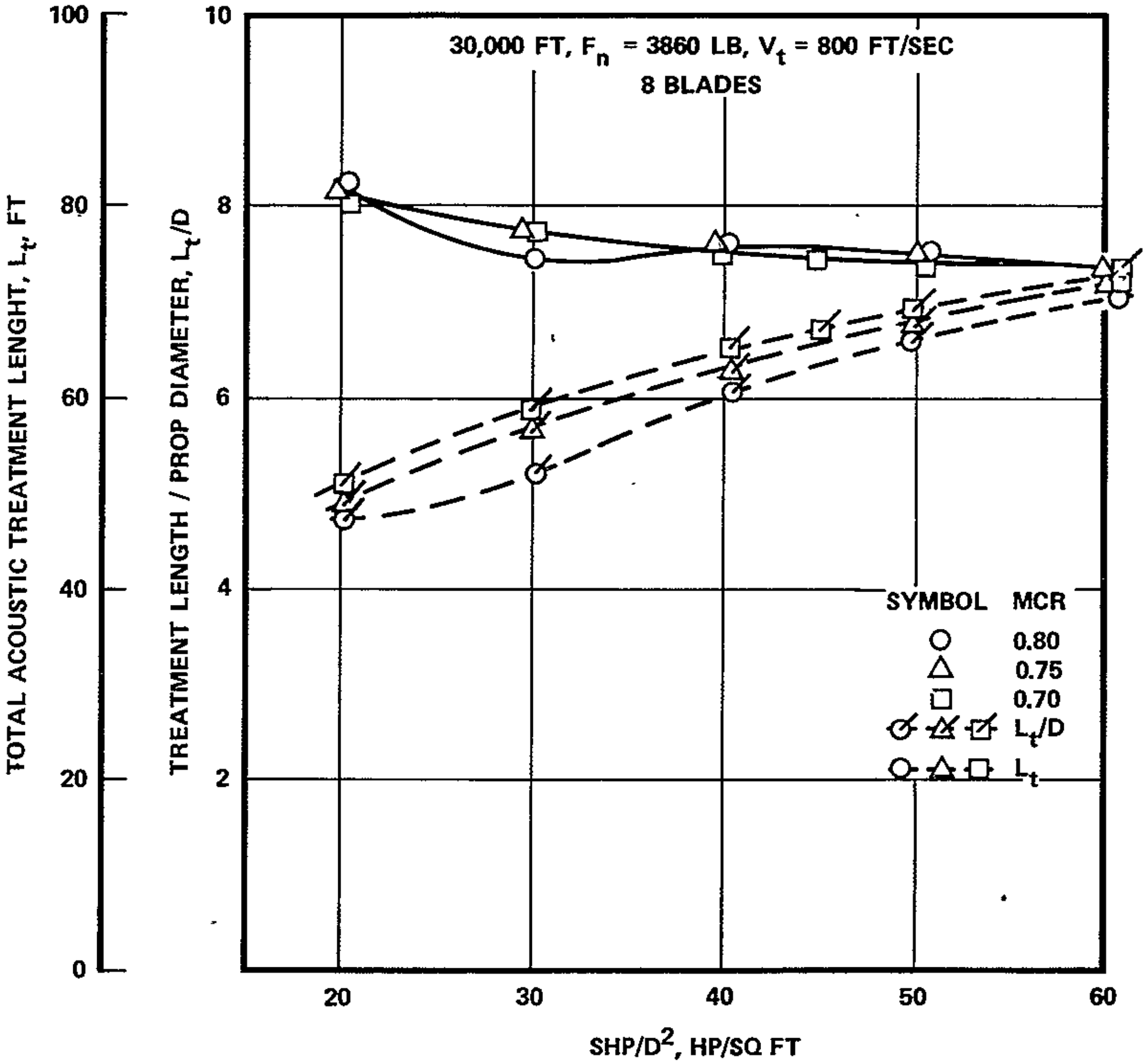

Figure 39. Total Acoustic Treatment Length vs. Disk Loading

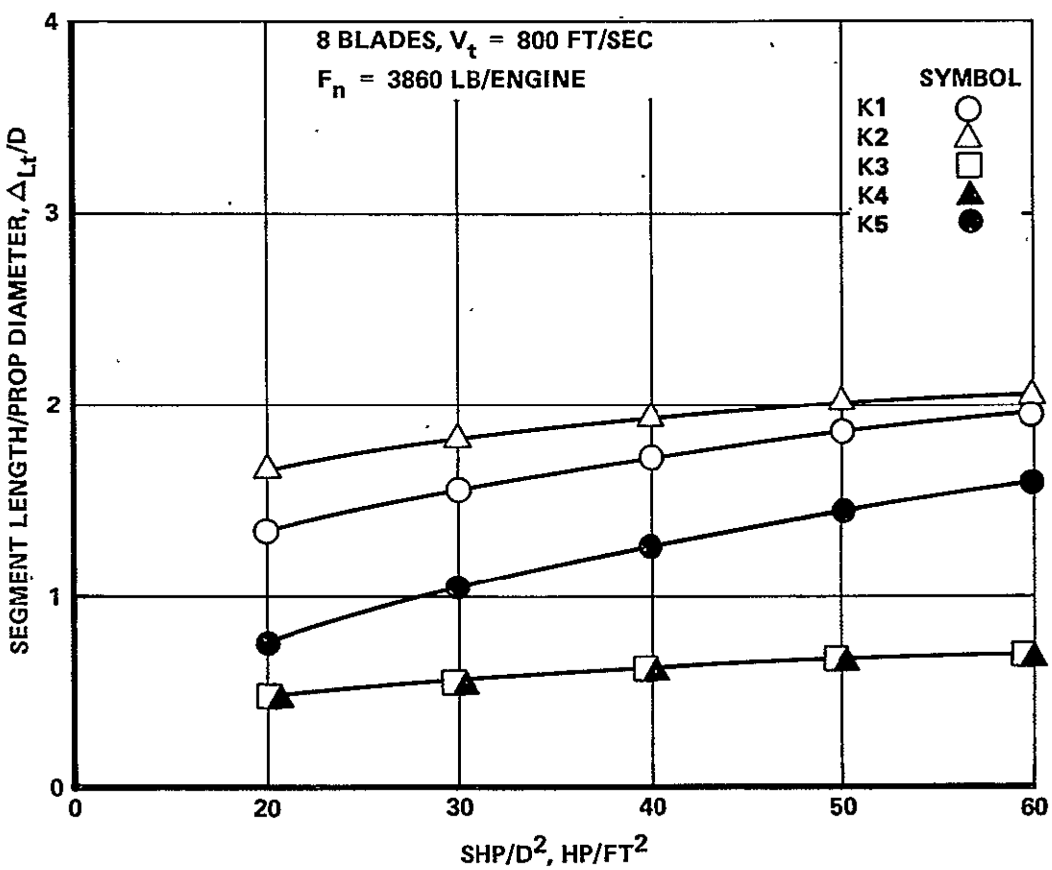

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Figure 40. Segment Length/Diameter vs. Disk Loading

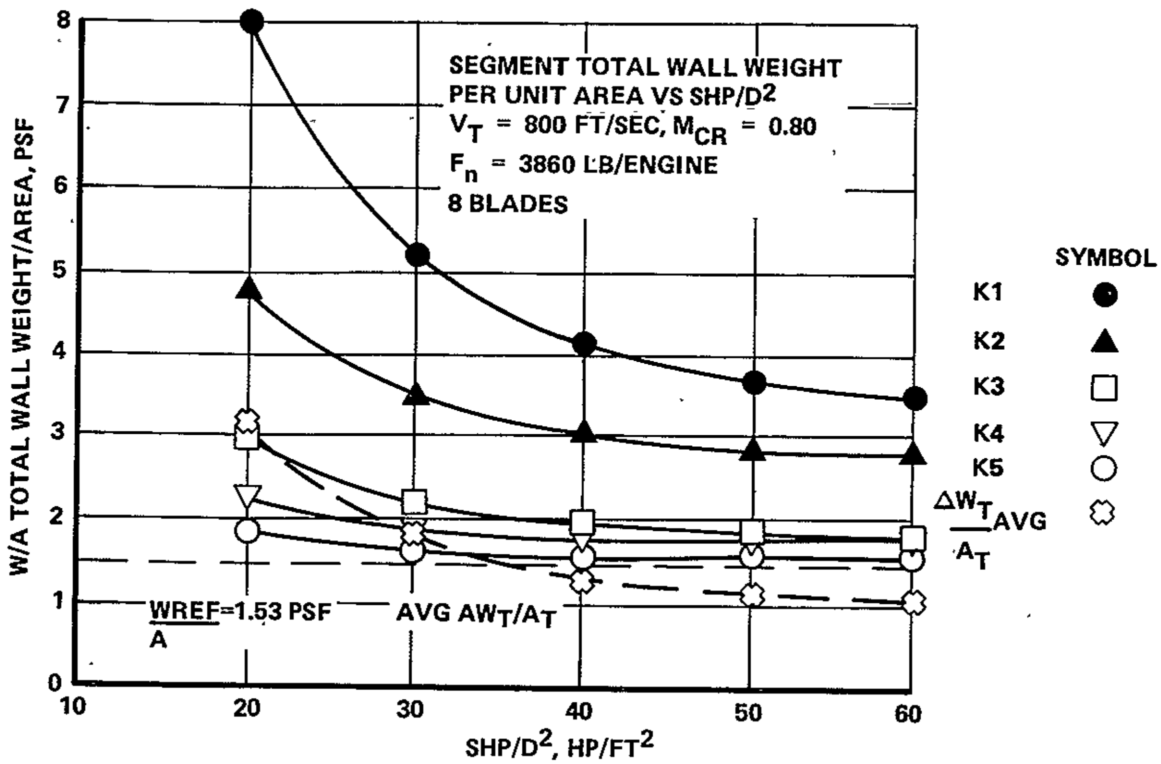

Figure 41. Segment Total Wall Weight vs. Disk Loading

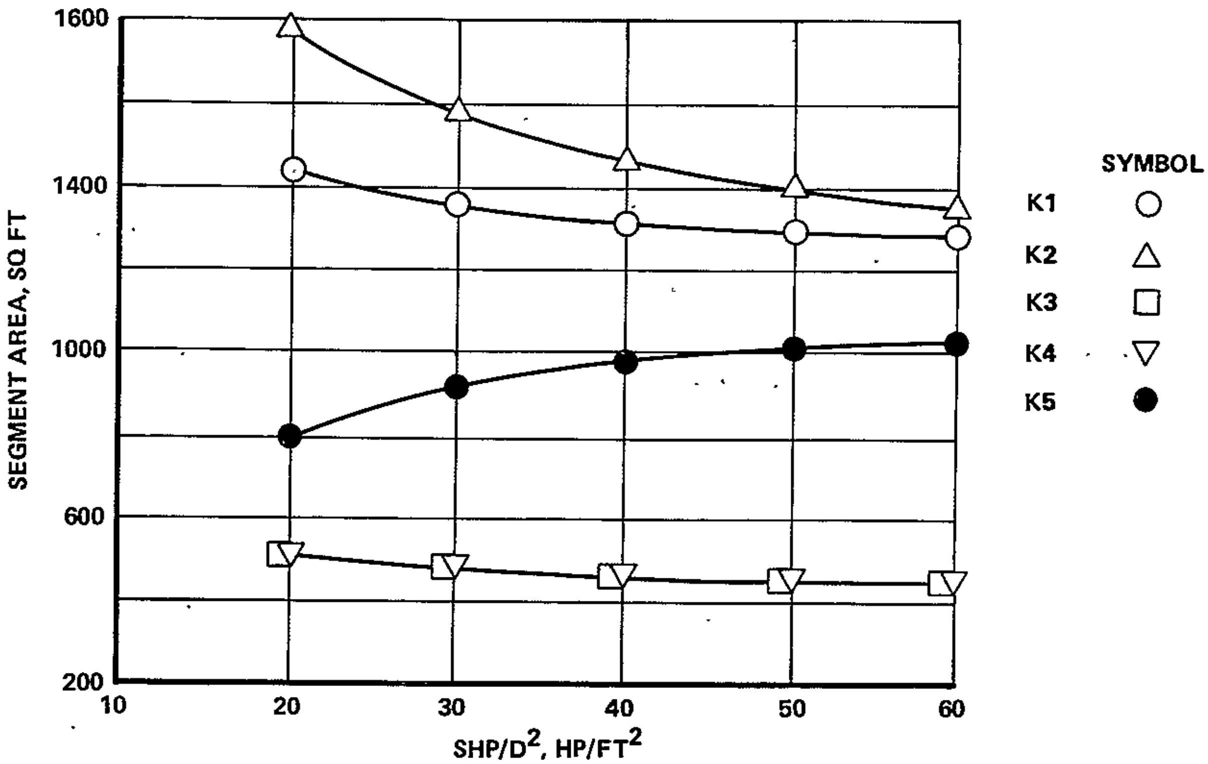

Figure 42. SHP/D^2, HP/FT^2 vs. Disk Loading

the relative tip clearance would be about 0.8D. In this case the first two segment lengths would be 3.6D = 46.08 ft, covering a treated area of 2834.5 sq ft. Applying the minimum wall weight penalty per unit area (1.12 psf) yields a penalty of 3174.6 lb, for segments 1 and 2. Segments 3 and 4 cover 1.2D = 15.36 ft and 944.83 sq ft. Applying the mandatory 0.22 psf unit area penalty yields a minimum weight increment of 207.9 lb. The fifth segment length is 1.24D = 15.87 ft covering 976.32 sq ft, and requiring a mandatory 0.04 psf unit area weight penalty adding 39.1 lb additional weight. Altogether, the minimum total weight penalty would be 3421.6 lb for the selected example 12.8 ft propeller diameter with a relative tip clearance of 0.8. The minimum weight penalty for the outer 3 segments alone is 247 lb.

The minimum weight penalty procedure described above has a tendency to diminish the weight reduction benefits of external SPL reductions and higher blade passage frequencies. Without considering the minimum unit area weight constraints, the weight penalties for the lowest cruise Mach numbers and higher disk loadings could be further reduced compared to the data of Figures 24 to 29. It is thus possible that the optimum propeller disk loading could be even higher than would be selected on the basis of the data of Figures 24 to 29. The constraint procedure does not affect the acoustic treatment weight penalty data at low SHP/D^2. This is so, because the minimum weight per unit area for each segment is well above the minimum values given in Table 19.

In order to reduce the weight penalty allowances imposed by the requirement for minimum unit area weights for each segment, it is necessary to experimentally verify the transmission loss predictions from double wall theory. This would appear to be an urgent technology development goal, since it would allow further advantage to be gained from increases in blade passage frequency and/or reductions of external near field SPL. Figure 43 shows a correlation of acoustic treatment weight penalties plotted against blade passage frequency. This data shows that at M_{cr} = 0.75 and 0.80 where the external SPL data are the same, all of the data collapse nearly into a

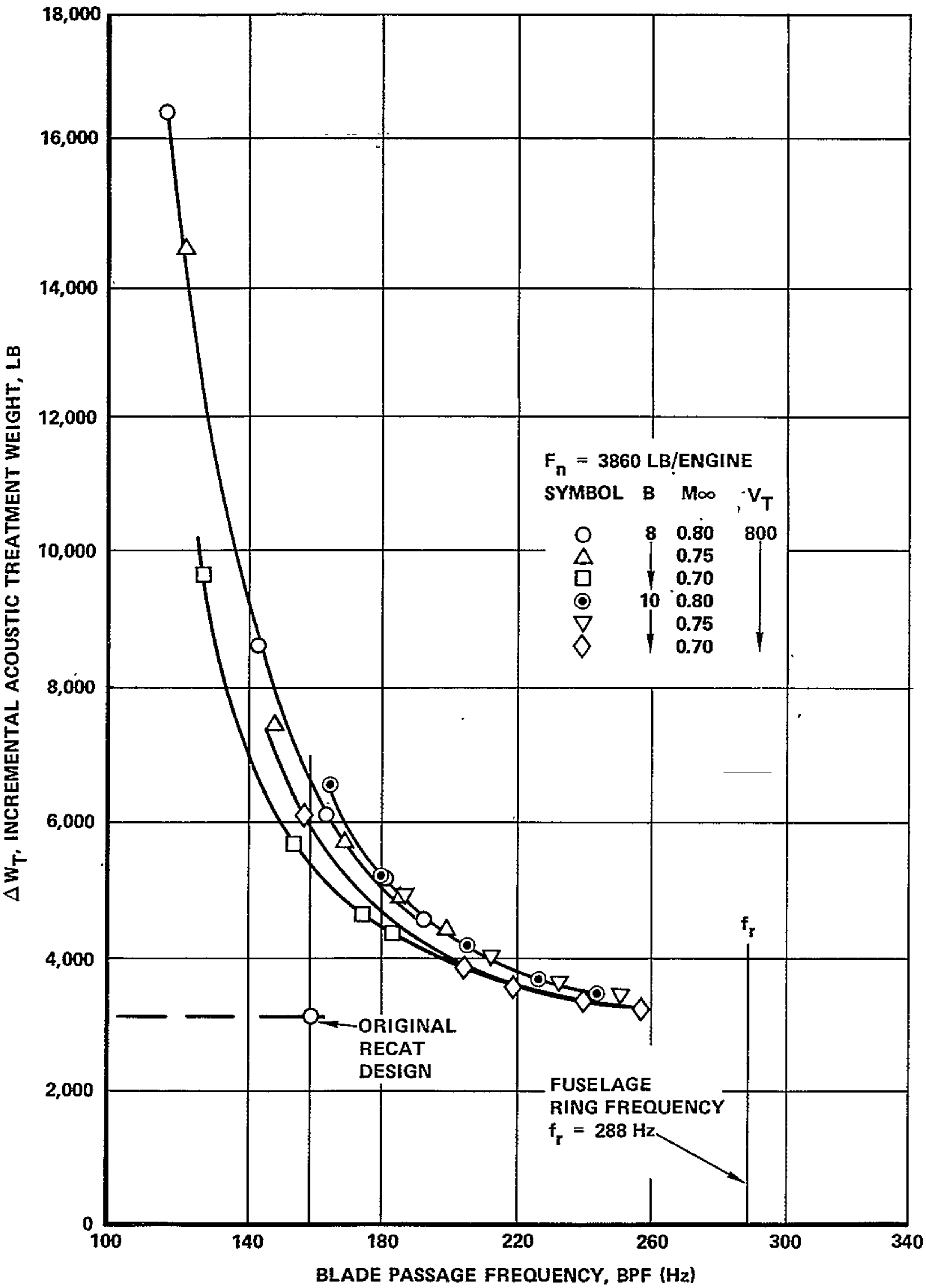

Figure 43. Acoustic Treatment Weight Increment vs. Blade Passage Frequency

single curve when plotted against blade passage frequency, for both 8 and 10 blades.

3.7 POSSIBILITIES FOR FUTURE TREATMENT WEIGHT REDUCTIONS

The trends of Figure 43 invite the development of propfans with more blades, higher tip speeds, and higher disk loadings, in order to increase blade passage frequency. The minimum constrained weight at $M_{cr} = 0.80$ for 10 blades at $SHP/D^2 = 50$, is about 3650 lb which is within 700 lb for the previous RECAT weight penalty, despite the higher exterior noise levels, and more conservative design philosophy employed in the current study. It is believed that the data of Figure 43 might be reducible by 40 percent by eliminating some of the current conservatisms with respect to the large amount of treated surface area and the mandatory minimum weight per unit area stipulated in Table 17 for the various treatment segments. These conservatisms have been injected in this study to offset uncertainties concerning the exterior SPL distribution, and the validity of the simplified double wall transmission loss theory.

With regards to the transmission loss theory, notice in Figure 43 that the structural ring frequency is 288 Hz for a 19.58 ft diameter aluminum fuselage. This value is higher by factors of 111 percent to 191 percent of the typical range of propfan blade passage frequencies (150 to 260 Hz) for 8 and 10 blades at 800 ft/sec. Figure 44 is a reproduction of Figure 74 of Ref. 4. This shows the modal density parameter for single wall cylindrical shell vibration modes which are "acoustically fast" (efficient noise radiators), as a function of the ratio of excitation frequency to ring frequency. Lockheed is working on the development of data and a theory for counterpart to this curve for the proposed double limp wall damped treatment shown schematically in Figure 22. When such a curve is available, it will be possible to correct for loss of transmission loss at frequencies near the ring frequency according to

$$\Delta NTL = A + B \log_{10} (Y_{MDP})$$

where A and B are empirical constants to be determined from transmission loss tests on Lockheed's double wall concept, and, Y_{MDP}, is the modal

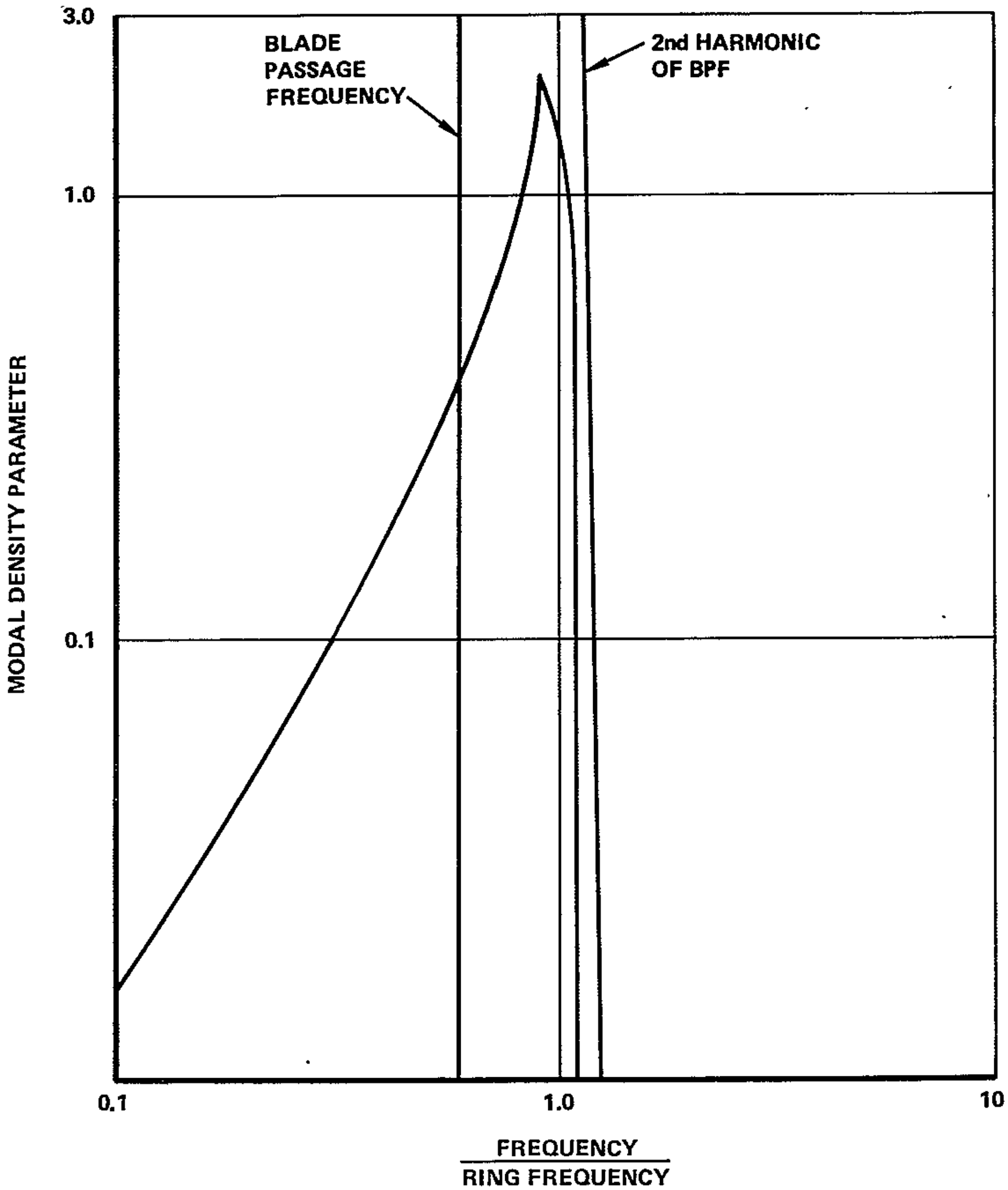

Figure 44. Modal Density for Acoustically Fast Modes

density parameter for the particular double wall construction. It is a goal of the double wall technology development to minimize the response of these acoustically fast modes to the external excitation.

3.8 CONCLUDING REMARKS CONCERNING ACOUSTIC TREATMENT WEIGHT PENALTIES

- New exterior near field SPL and propeller performance data (Ref. 3) have been evaluated with respect to acoustic treatment weight penalties. The new data are estimated to increase the weight penalty by 3400 lb to 6500 lb, compared to the 3100 lb requirement estimated for the original RECAT study (Ref. 4) at the same disk loading $SHP/D^2 = 37.1$. For this disk loading a 12.8 ft diameter propeller is required for a net thrust of 3860 lb, at a cruise point design Mach number of 0.8 at 30,000 ft. Parametric studies have been conducted of the effects, of disk loading, upon acoustic treatment weight, cruise Mach number, blade count and thrust level.

- The parametric studies include a more conservative prediction methodology which is partly responsible for the higher weight penalties. The more conservative approach has been employed to reduce the risk associated with technology uncertainties. In this sense, the attainment of the interior noise goals with the current weight estimates in this study have a higher probability of achievement through development than the estimates in the previous RECAT study.

- It appears, by increasing the blade passage frequency, that the weight penalties could still be reduced to about 3600 lb, even with the currently more conservative methodology. The range of weight penalties contained in these studies is apparently small enough to make turboprop aircraft remain attractive, based on the weight versus DOC sensitivity data of Ref. 4.

- Achievement of certain goals of technology development, outlined herein, could provide further weight penalty reductions, of the order of 40 percent, through the elimination of conservatisms which are imposed on this methodology in order to offset technological uncertainty. In particular, it is believed that the total treatment area assumptions used herein are definitely conservative, often requiring three times the 1568 sq ft treated in the original RECAT. A large part of the treatment area increase comes from the treatment of the full cabin circumference in the current study.

SECTION 4

COST/BENEFIT COMPARISONS

At the conclusion of the previous RECAT study both the turbofan and propfan powered aircraft had been designed using 1985 levels of technology and the same payload/range requirements and mission constraints. The baseline aircraft established during the previous study were competitive in terms of cruise speed, cruise altitude, block time, and passenger comfort. At the design range of 1500 nautical miles for a Mach 0.80 mission, comparison of the fuel and cost to operate these baseline aircraft showed an advantage of the propfan over the turbofan of 17.8 percent less fuel and 8.2 percent DOC savings at a 60¢/gal. fuel cost. Comparison of these baseline aircraft at a range of 475 nautical miles with a 58 percent load factor (L.F.) shows an advantage of the propfan over the turbofan of 20.4 percent less fuel and 8.5 percent savings for 60¢/gal. fuel. These comparisons are shown in Figure 45.

For this study, the competitive baseline design concept was retained so that direct comparison between the turbofan and propfan propulsion could be determined. The original baseline propfan powered aircraft was revised to reflect the latest propfan performance and acoustic data supplied by Hamilton Standard as a result of their propfan wind tunnel test program. The effect of the new propfan data, and a revised Lockheed analysis, is added weight required in the fuselage to accommodate the increase in propfan acoustic noise level. The comparisons of the revised turboprop baseline with the turbofan baseline are shown in Figure 46.

For each design/mission change investigated for the turboprop aircraft, a similar change was incorporated into the turbofan aircraft with each design

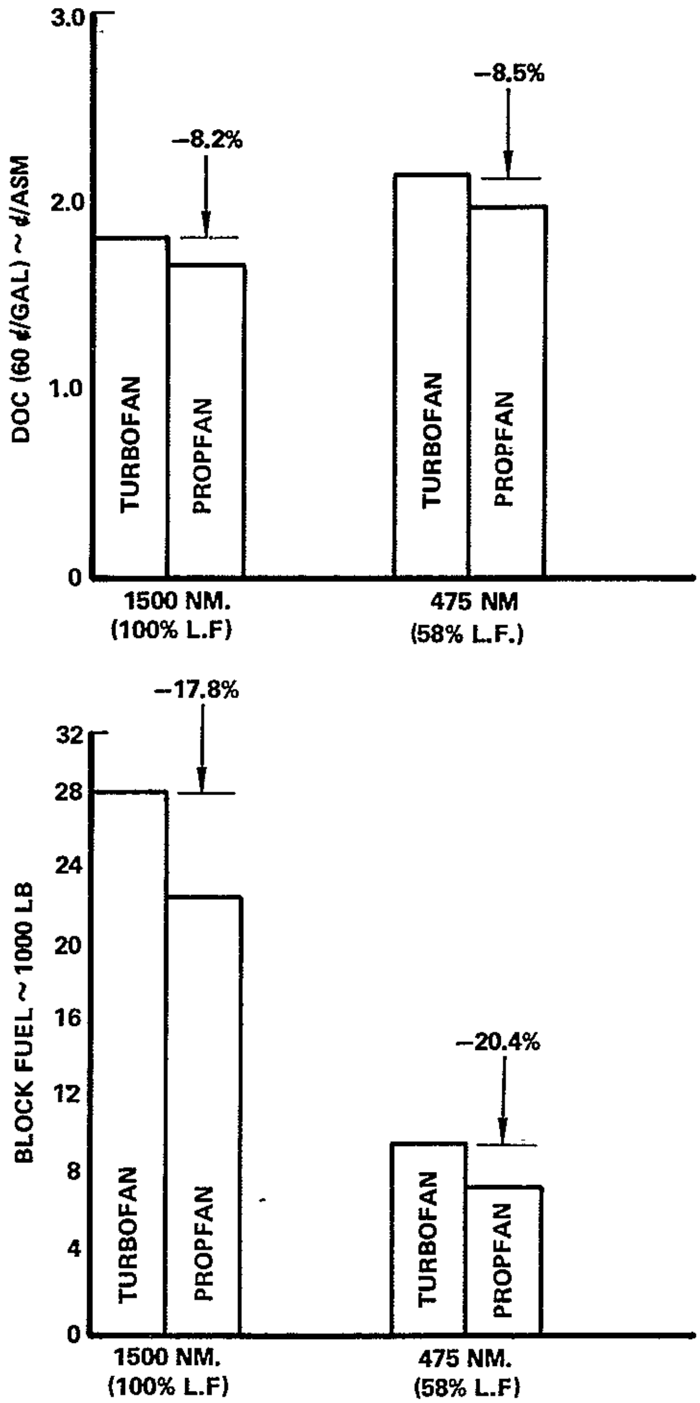

Figure 45. Fuel and Cost Comparison for Baseline Aircraft of Previous Recat Study

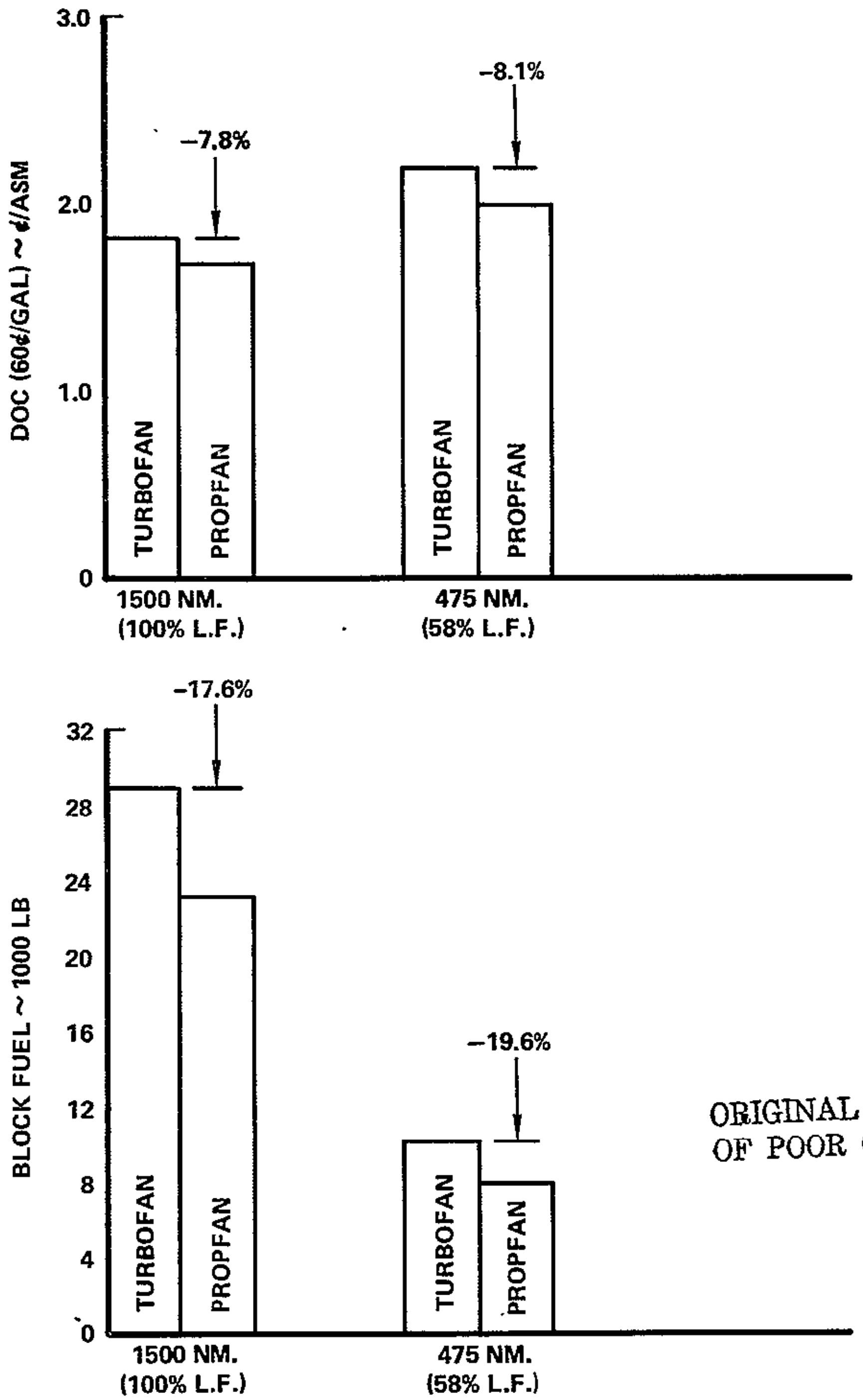

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Figure 46. Fuel and Cost Comparison for Revised Baseline Turboprop Aircraft

optimized for the desired design/mission characteristic. All subsequent comparisons of the baseline aircraft are the original turbofan baseline and the revised turboprop baseline (incorporating revised propfan data).

4.1 PERFORMANCE COMPARISON

The major differences in fuel and operating costs between the turbofan and turboprop aircraft in this study are caused by differences in engine specific fuel consumption and aircraft weight. The most significant difference in performance is in the propulsion system and its fuel consumption characteristics at the cruise condition for the 1500 nautical mile design mission. Figure 47 indicates the improvement in average cruise SFC obtained with the turboshaft engine for the design/mission conditions investigated. The turboshaft propulsion offers a 19 percent decrease in average cruise fuel consumption at the 1500 nautical mile, Mach 0.8 design mission and additionally offers another 3 percent decrease for the 1500 nautical mile, Mach 0.75 design mission.

As indicated in the previous study, the empty weight of the turboprop exceeds that of the turbofan. Figure 48 depicts the differences in aircraft empty weight between the turbofan and turboprop aircraft 1985 IOC and the 1990 IOC designs. The empty weight of the turboprop baseline design is approximately 6.4 percent greater than the turbofan baseline with the major differences being in the wing and propulsion system weight and the amount of acoustic treatment required. For the 1990 IOC aircraft, the turboprop empty weight exceeds the turbofan empty weight by approximately 3.3 percent due to decreases in the propulsion system weight (which is reflected in wing weight) and the amount of acoustic treatment required due to the reduction in induced sound level with the smaller diameter propfan. The largest single weight increment between the turboprop and turbofan aircraft is the amount of acoust treatment required to maintain the cabin interior SPL at 90 dB with the propfan. The amount of acoustic treatment required for each of the turboprop design/mission conditions is as follows:

Revised Baseline	2000 N.Mi.	0.75M	PD 370-22	STS 4E7
5220	5445	4405	4720	4390

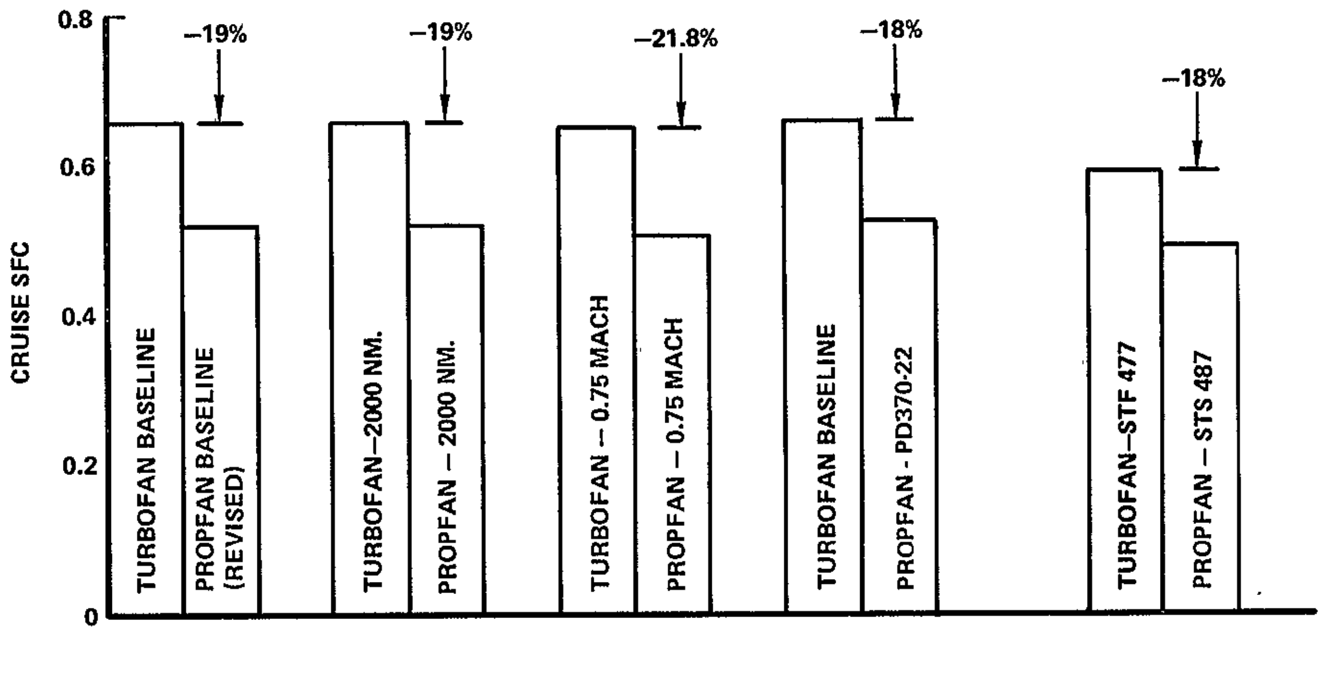

Figure 47. Effect of Design/Mission Characteristics on Aircraft Cruise SFC

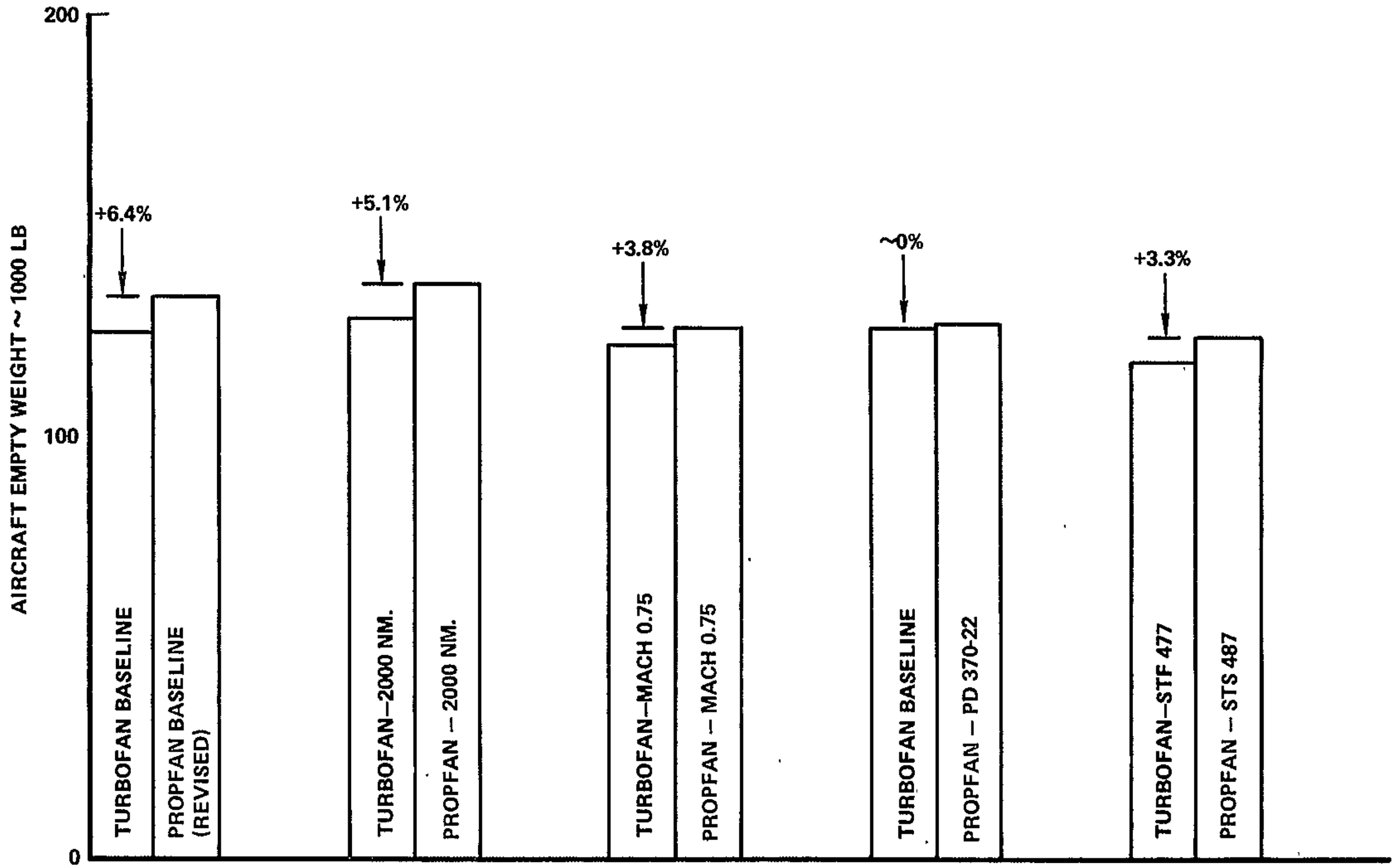

Figure 48. Effect of Design/Mission Characteristics on Aircraft Empty Weight

4.2 ECONOMIC COMPARISON

For the economic comparison of the turbofan and turboprop aircraft, all point designs were compared using the 1500 nautical mile design mission with a 100% L.F. as well as a "typical" mission of 475 nautical miles with a 58 percent L.F. DOC values for 60¢/gal. fuel cost were calculated for each mission. Figures 49 and 50 present the results of the effects of design/mission characteristics on turboprop DOC savings at the two stage lengths for 60¢/gal. fuel cost. Comparison of the 1985 IOC revised baseline propfan and turbofan aircraft indicates a 7.8 percent DOC advantage, at 60¢/gal. fuel cost, for the turboprop at the design mission of 1500 nautical miles and Mach 0.8. An additional advantage in turboprop DOC of 2.2 percent is attained by reducing the cruise speed to Mach 0.75, due to the greater advantage in fuel consumption characteristics of the turboshaft engine at reduced speed.

For the 1990 IOC aircraft, the 1990 propfan design shows an advantage in DOC, at 60¢/gal. fuel cost, of 7.8 percent over the 1990 turbofan design at the 1500 nautical mile, Mach 0.8 mission.

Incorporation of the alternate turboshaft engine, PD 370-22, results in an 10.1 percent advantage in turboprop DOC, at 60¢/gal. fuel cost, over the baseline turbofan at the 1500 nautical mile, Mach 0.8 mission. This additional decrease in DOC is due to a significant decrease in installed propulsion system weight for this engine (approximately 40 percent) and the resultant effect on aircraft weight.

4.3 MISSION FUEL COMPARISON

Figures 51 and 52 present the results of the effects of design/mission characteristics on mission fuel requirements, at both the design and "typical" (475 N.Mi.) range, for the propfan and turbofan powered aircraft. The advantage in mission fuel of the baseline propfan over the baseline turbofan is 17.6 percent. Comparison of the mission fuel requirements indicate that the largest percentage of fuel saving (21 percent) is attained by reducing the cruise speed of the turboprop to Mach 0.75. Incorporation of the 1990 engine technology in both the propfan and turbofan powered aircraft results

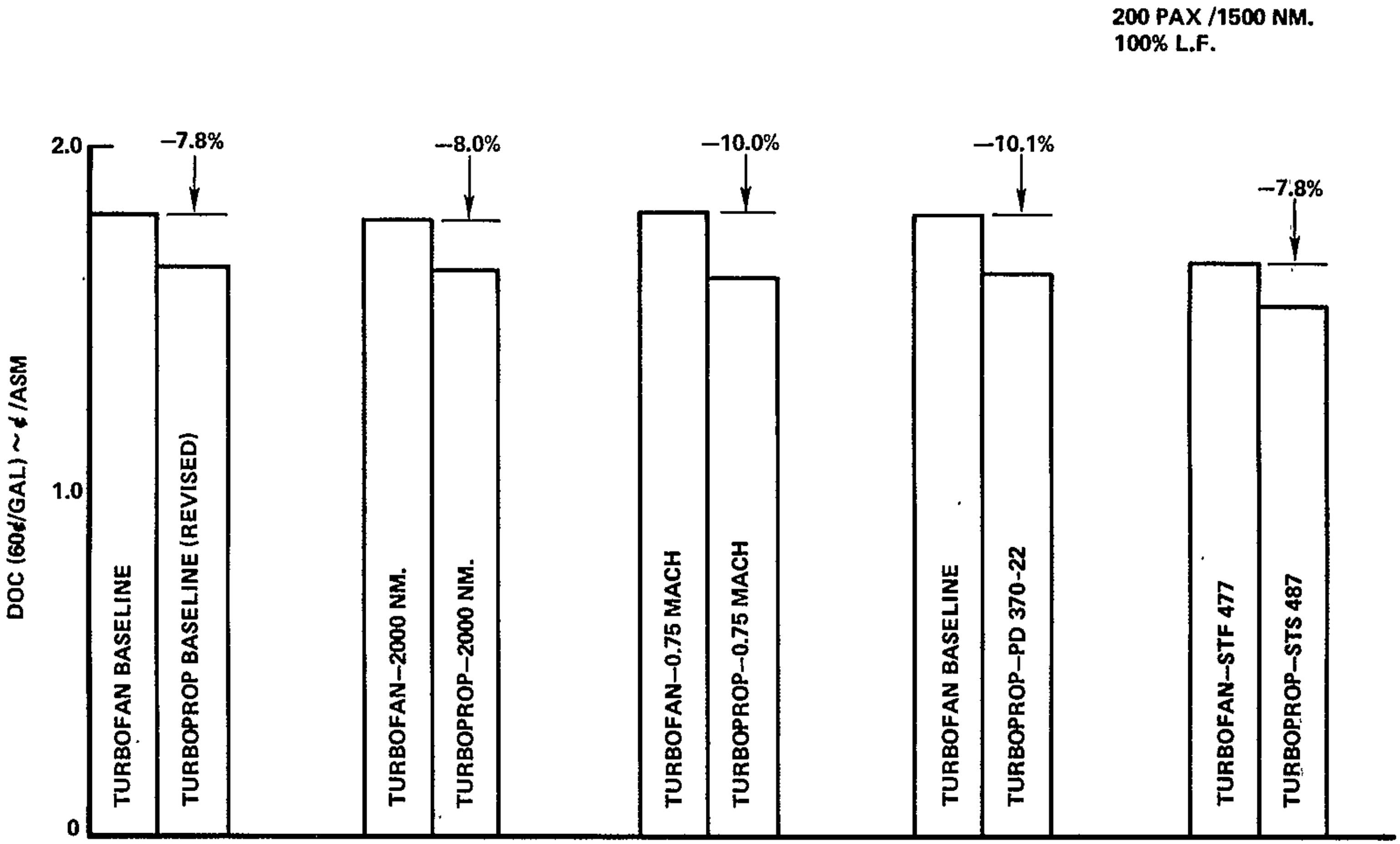

Figure 49. Effect of Design/Mission Characteristics on Aircraft DOC - 1500 NM. Mission

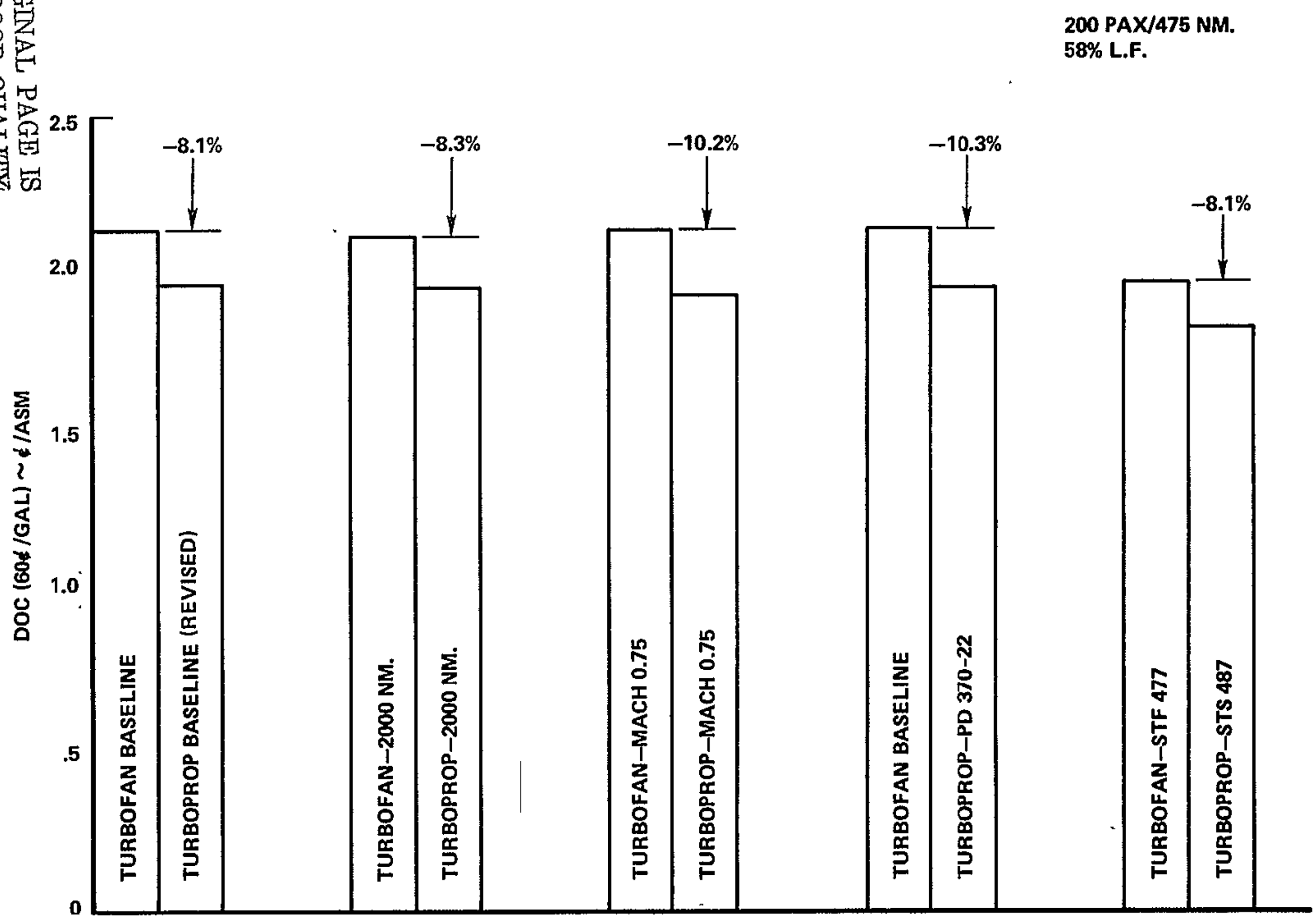

Figure 50. Effect of Design/Mission Characteristics on Aircraft DOC - 475 NM. Mission

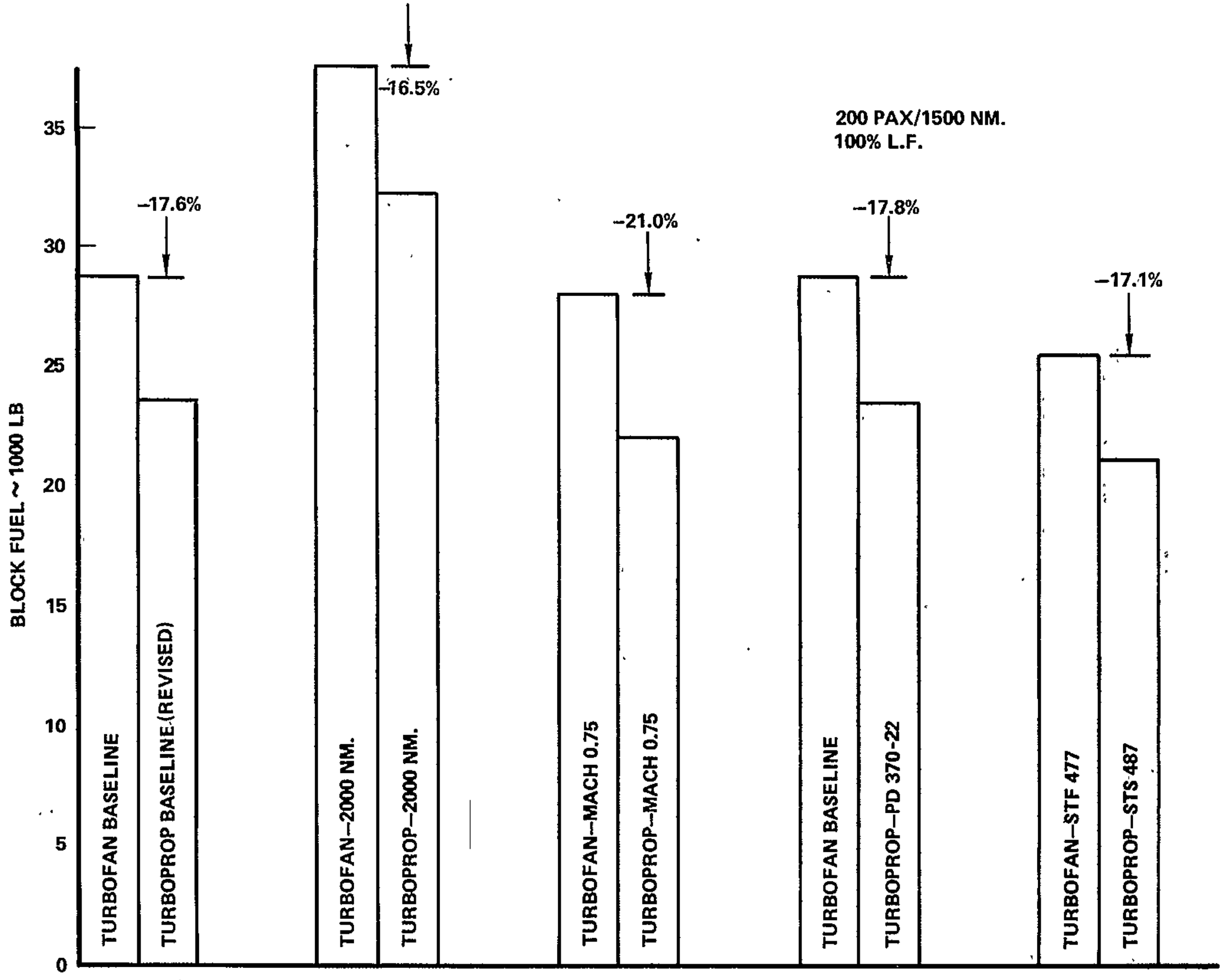

Figure 51. Effect of Design/Mission Characteristics on Block Fuel - 1500 NM. Mission

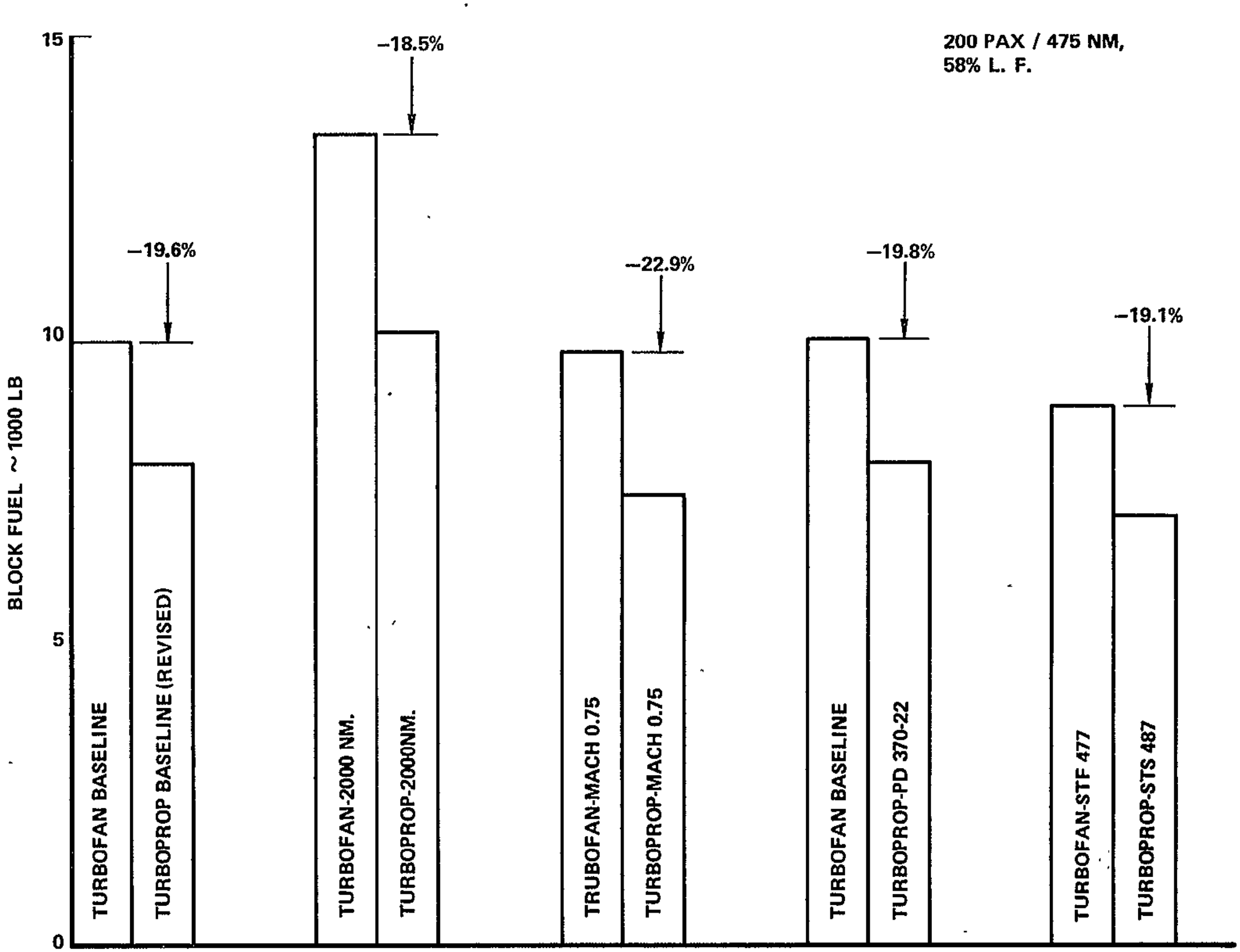

Figure 52. Effect of Design/Mission Characteristics on Block Fuel - 475 NM. Mission

in a 17.1 percent advantage in mission fuel for the turboprop since the improvement in fuel consumption characteristics is similar for both the turboshaft and turbofan engines. This advantage in fuel savings is similar to that shown for the baseline aircraft, however, the fuel savings available by incorporating the 1990 technology engine into the 1985 IOC turboprop aircraft is an additional 10.8 percent.

Incorporation of the alternate turboshaft engine, PD 370-22, into the 1985 IOC aircraft results in a additional small savings in mission fuel of approximately 0.2 percent due to the decrease in installed propulsion system weight.

Figure 53 depicts the potential fuel savings available for the turboprop aircraft, with the design/mission characteristics, investigated in this study, over the baseline 1985 IOC turbofan aircraft. A potential of approximately 32 percent fuel savings and approximately 17 percent DOC savings, shown in Figure 54, are available over the 1985 IOC turbofan aircraft by utilization of a 1990 technology turboshaft engine with the 8 bladed propfan flying at a cruise speed of Mach 0.75.

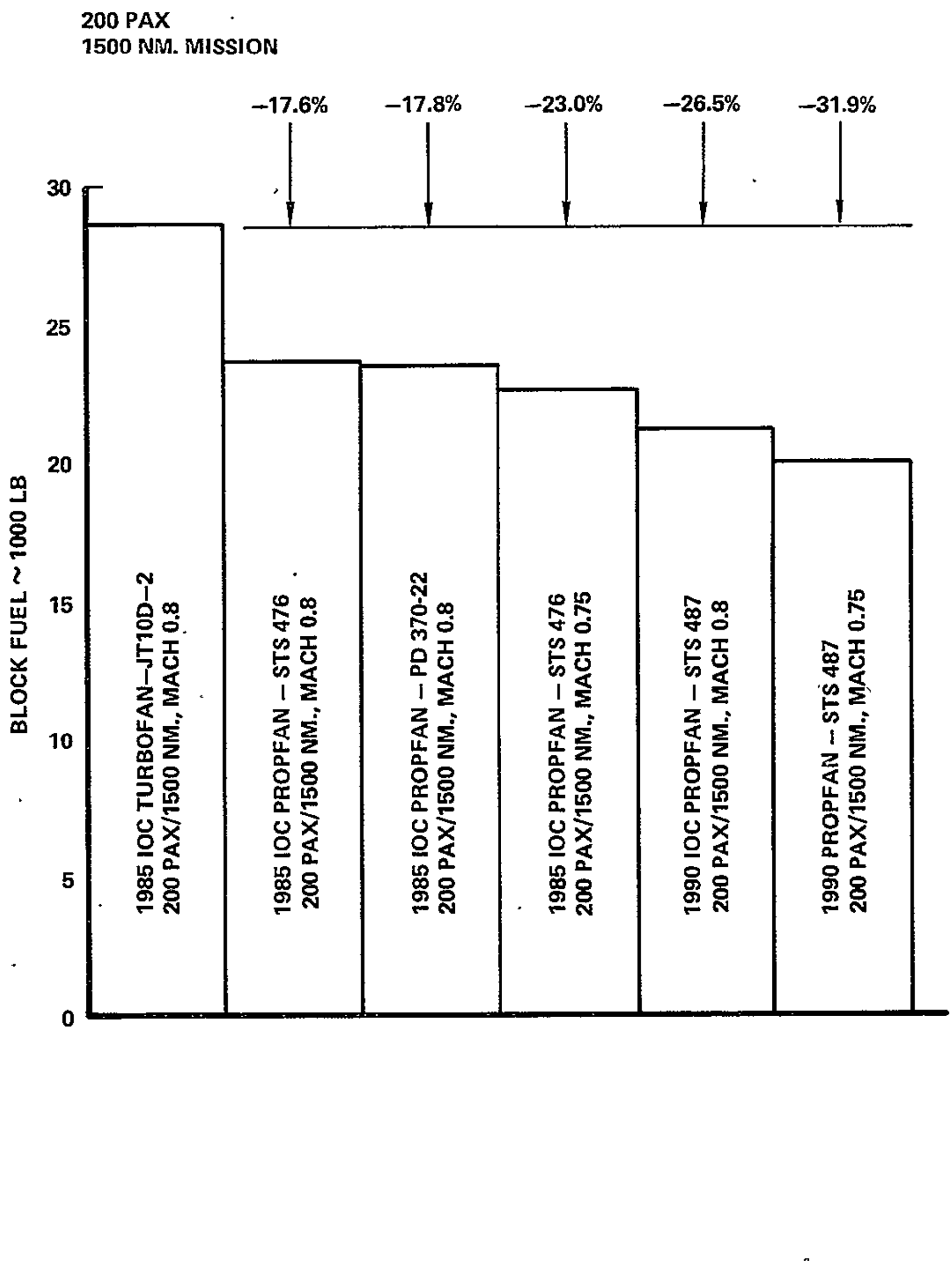

Figure 53. Fuel Savings of Propfan versus 1985 IOC Turbofan Aircraft

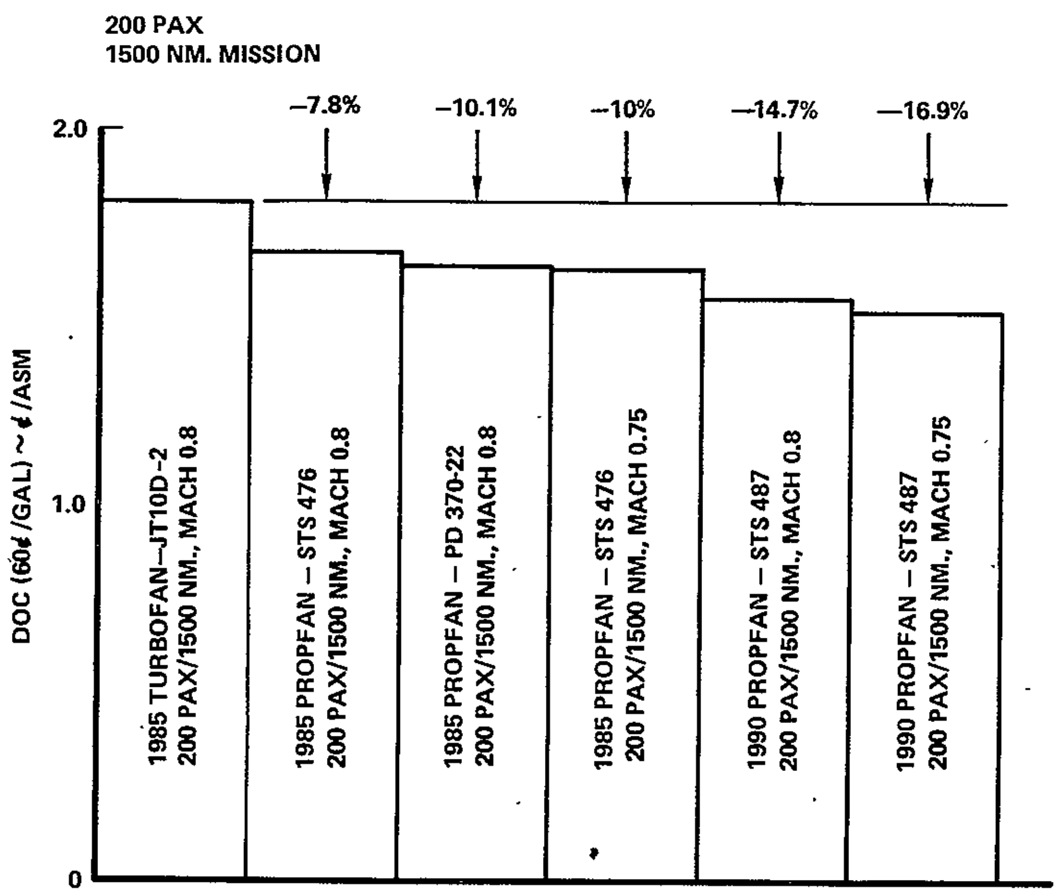

Figure 54. DOC Savings of Propfan versus 1985 IOC Turbofan Aircraft

SECTION 5

CONCLUSIONS AND RECOMMENDATIONS

The results obtained from this study show that the advanced propfan powered transport aircraft, with the 8 bladed propfan, is a viable alternative to the turbofan powered aircraft and offers significant savings in fuel and operating costs without compromising passenger comfort. The advantage in fuel and operating costs of the propfan over the turbofan continues to be significant for the 1990 IOC time frame. Additionally, further fuel and operating cost advantages are shown for the propfan aircraft at the reduced cruise speed consistent with current operator experience for the design mission range.

Propfan data supplied by Hamilton Standard, as a result of their ongoing propfan test program, shows that the performance goals are attainable. The noise generated by the propfan continues to be somewhat of a problem in that weight penalties required to damp the noise transmission into the aircraft cabin detract somewhat from fuel and operating cost savings. Estimates of the performance and acoustic characteristics of a 10 bladed propfan indicate potential for reducing the weight penalty required for the propfan aircraft.

To realize the potential fuel and operating cost advantages with the advanced turboprop aircraft, as identified during this study, the following research and technology items should be accomplished.

5.1 PROPFAN DESIGN

Data from the 8 bladed Hamilton Standard propfan, as a result of wind tunnel tests conducted on a 2 foot diameter model, indicate that propfan efficiency goals can be attained or exceeded. Acoustic measurements taken in other testing indicate that induced sound pressure levels are higher than estimated. Testing conducted at different tip speeds and Mach numbers for the 8 bladed propfan and a projection of this data to a 10 bladed configuration indicates a significant potential reduction in acoustic noise, while maintaining efficiency goals.

Further design studies are required to assess the performance, acoustics, economics, and mechanical design characteristics of 10 bladed and 12 bladed propfan configurations. These design studies should be supplemented with component development and testing to provide a viable, demonstrated propfan design for utilization in a 1990 IOC aircraft.

5.2 AIRCRAFT ACOUSTIC TREATMENT

For the advanced turboprop aircraft, one of the major design considerations is the reduction of excessive noise transmitted to the cabin interior. At the design goal of 80 percent fan efficiency and a cruise Mach number of 0.80 at 30,000 feet, the tip noise generated by an 8 bladed fan with a tip speed of 800 fps is approximately 138 dB at the fuselage wall.

Maintaining the cabin interior noise levels at a maximum of 90 dB requires a reduction in acoustic transmission of some 48 dB. Conventional wing mounted engines (as utilized in this study) requires that the burden of noise reduction be obtained by structural design of the cabin walls. The mechanism of noise transmission through the cabin walls as well as skin initiated in the fuselage by blade tip passage, is not well understood. The design of an advanced turboprop aircraft with wing mounted propfans will probably be paced by the noise transmission losses required through the fuselage walls and the acceptable sound pressure level inside the cabin.

The approach taken during this study is one of damping the noise through the cabin walls using limp wall mass treatment. Using a double wall construction with the maximum possible air space alleviates the cabin noise attenuation but results in increased fuselage diameter along with increased aircraft weight. The best potential solution appears to be the use of double wall construction providing as much structural damping in the affected areas as possible.

Design studies, in conjunction with development testing should be conducted to provide the necessary information regarding the mechanism of noise transmission and damping and structure excitation when utilizing the propfan configuration. Also, further studies should be conducted, and followed by development testing, to examine fuselage wall structural and damping concepts, optimized for reduction in noise levels, weight, producibility, maintainability, and economics.

5.3 AIRCRAFT CONFIGURATIONS

Accomplishment of this study, and the previous RECAT study, utilized a 4 engine (conventional wing mounted engines) turboprop aircraft. Locating the propfans away from the cabin area would greatly reduce the amount of noise transmitted to the cabin. To accomplish this a configuration study, including a 3 engine design, could be conducted to investigate alternate engine/aircraft installation configurations. Another purpose of a 3 engine configuration would be to enhance utilization of the propfan concept for a complete range of aircraft sizes.

The study approach would be to evaluate a series of fin positions for the third engine considering fan diameter, tip to fuselage clearance, weight and balance effects, stability and control, potential acoustic fatigue and noise transmitted to the cabin. These results could then be extended to pylon or stabilizer positions and an evaluation could be made for a variety of 2, 3, 4 wing and tail engined configurations.

5.4 ADVANCED TECHNOLOGY ENGINES

Significant design and technology studies, along with component development testing, are currently in process for advanced technology, energy efficient turbofan engines. Similar studies and component tests should be conducted for the turboshaft engine utilizing those technology areas, where applicable, which are being developed for the turbofan. The test program now in process on the propfan configuration should be supplemented with a similar program to develop an advanced technology, energy efficient, economically viable turboshaft engine.

REFERENCES

1. Schlichting, H., "Boundary Layer Theory," 4th Ed., pp 536-543, McGraw Hill, 1960

2. Peterson, A., and Bruel, P.V., "Instruments for Noise Measurements" Chapter 16 Handbook of Noise Control, McGraw Hill, 1957

3. Letter, B. Gatzen (HS) to L.K. Carson (Lockheed), June 1977

4. Hopkins, J.P., and Wharton, H.E., "Study of the Cost/Benefit Trade Offs for Reducing the Energy Consumption of the Commercial Air Transportation System," Lockheed California Company LR 27769-2, NASA CR 137926, August, 1976

5. Anon., "Preliminary Prop Fan Noise Estimation," Hamilton Standard, SP09A76 (Unpublished) March, 1976

6. Hanson, D.B., "Near Field Noise of High Tip Speed Propellers in Forward Flight," AIAA Paper 76-565 presented at 3rd AIAA Aero-acoustics Conference, Palo Alto July 20 to 22, 1976

7. Ffowcs-Williams, J.E., and Hawkings, D.L., "Sound Generated by Turbulence and Surfaces in Arbitrary Motion," Phil. Trans Roy Soc. London, Series A, Vol. 264, 1969

8. Hubbard, H.H., and Regier, A.A., "Free Space Oscillating Pressures Near the Tips of Rotating Propellers," NACA TN 1870, 1949

9. Kubjun, M.C., and Vogeley, A.W., "Measurement of Free-Space Oscillating Pressures Near Propellers at Flight Mach Numbers to 0.72," NACA Report 1377, 1958

10. Farassat, F., "Theory of Noise Generation From Wing Helicopter Blades With an Application to Helicopter Rotors," NASA TR-R-451, December, 1975

APPENDIX A

HAMILTON STANDARD PROPFAN DATA
FOR UTILIZATION IN RECAT FOLLOW-ON STUDIES

HAMILTON STANDARD

Windsor Locks, Connecticut 06096

Please address answer to
Mail Stop No. 1A-3-1

June 13, 1977

Lockheed-California Company
Lockheed Aircraft Corporation
2555 North Hollywood Way - Box 551
Burbank, California 91503

Attention: Kit Carson - Bldg. 63, Plant A-1, Dept. 75-21

Subject: Prop-Fans for RECAT II

Reference: HS/LCC technical discussions at LCC on 5-3-77

Dear Kit:

An aero/acoustic parametric study has been conducted as was agreed to in the reference discussions. Curves presenting the results are enclosed. The performance and noise data are updated by the latest test results and reflect future Prop-Fan designs. The study covers 8 and 10 blades, 600 to 800 feet per second tip speed, 0.7 to 0.8 Mach number, and a range of efficiency (SHP/D^2).

The first three curves are the generalized efficiency maps for eight blades at 0.8, 0.75, and 0.7 Mn and 30,000 feet. The fourth thru sixth curves represent Prop-Fans sized for 3860 pounds, Tnet + Tjet, for each Mn. These were generated using the efficiency maps for each respective Mn. The seventh curve provides the engine power information for each Mn. Curves eight thru thirteen provide the same information for ten blades.

Curves fourteen and fifteen provide the parametric overall SPL which complement curves one thru three and eight thru ten, respectively. Curve sixteen shows the spectrum shapes at 600, 700, and 800 feet per second. Although labeled for 0.7 Mn, it should be considered representative for the entire Mn range under consideration here. Curves seventeen and eighteen show the directivities with varying tip clearance to the fuselage for 8 and 10 blades. Again these curves can be used over the Mn range.

Both the performance and noise curves are generalized based on your need to resize for a lower thrust at 0.75 and 0.7 Mn. Using the generalized curves, LCC can accomplish the same results as shown on curves four thru seven and eleven thru thirteen for any thrust level.

HS has selected an increased number of blades in addition to the 8 LCC requested based on acoustic considerations. Increasing the number of blades while keeping total solidity about the same will lower the overall SPL (hence, the level of first blade passing frequency also reduces), will increase the frequency at which

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the tones occur, and will improve efficiency slightly. It is estimated that a 10 blade Prop-Fan will have a rotor weight which is 10% higher than the 8 blade weight provided by data package SP05A76 dated 2-27-76. Acquisition and maintenance costs for a 10 blade Prop-Fan will also increase slightly over the 8 bladed rotor. While not much change is expected in acquisition cost of the baseline 8 blade Prop-Fan, the results of the recently completed NASA funded maintenance study indicate that the maintenance cost information supplied for RECAT I is conservative. Since LCC will use the enclosed data to optimize the propulsion system, it would be best to estimate the costs (both acquisition and maintenance) after the configuration matrix has been narrowed somewhat. Please provide the selected Prop-Fan diameter, horsepower, tip speed, and number of blades when available for this task.

If any questions come up, please contact me.

Very truly yours,

HAMILTON STANDARD
Division of United Technologies Corp.

B. S. Gatzen
New Product Development

BSG/csd
Enclosures

cc: Messrs. B. Miller (NASA-Lewis)
L. Williams (NASA-Ames)
J. Dupak (LCC)

bcc: Messrs. C. Rohrbach (2)
F. Metzger
W. Adamson
R. Levintan/R. Bussolari
R. Baum (Los Angeles)
File 2.3.3

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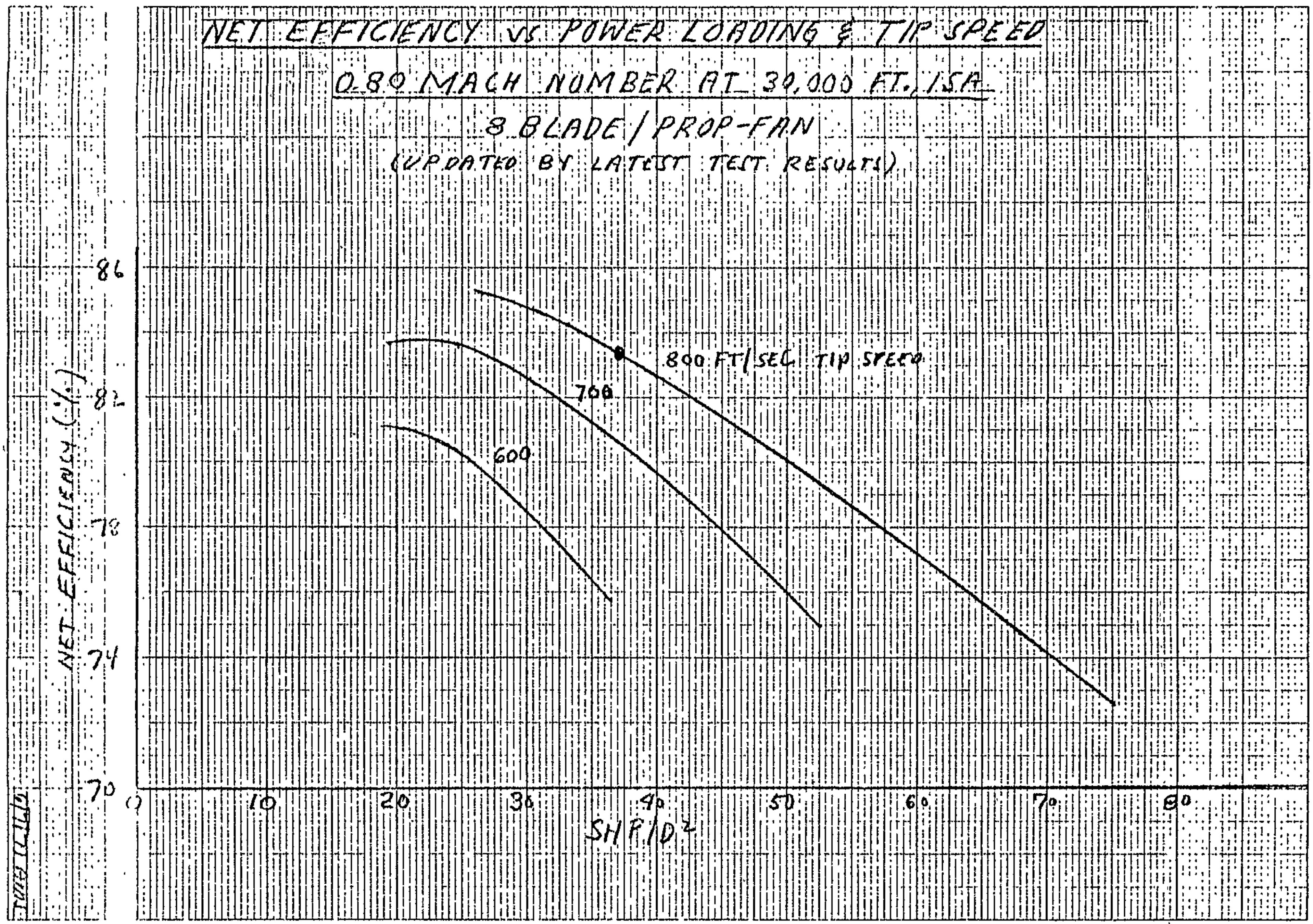

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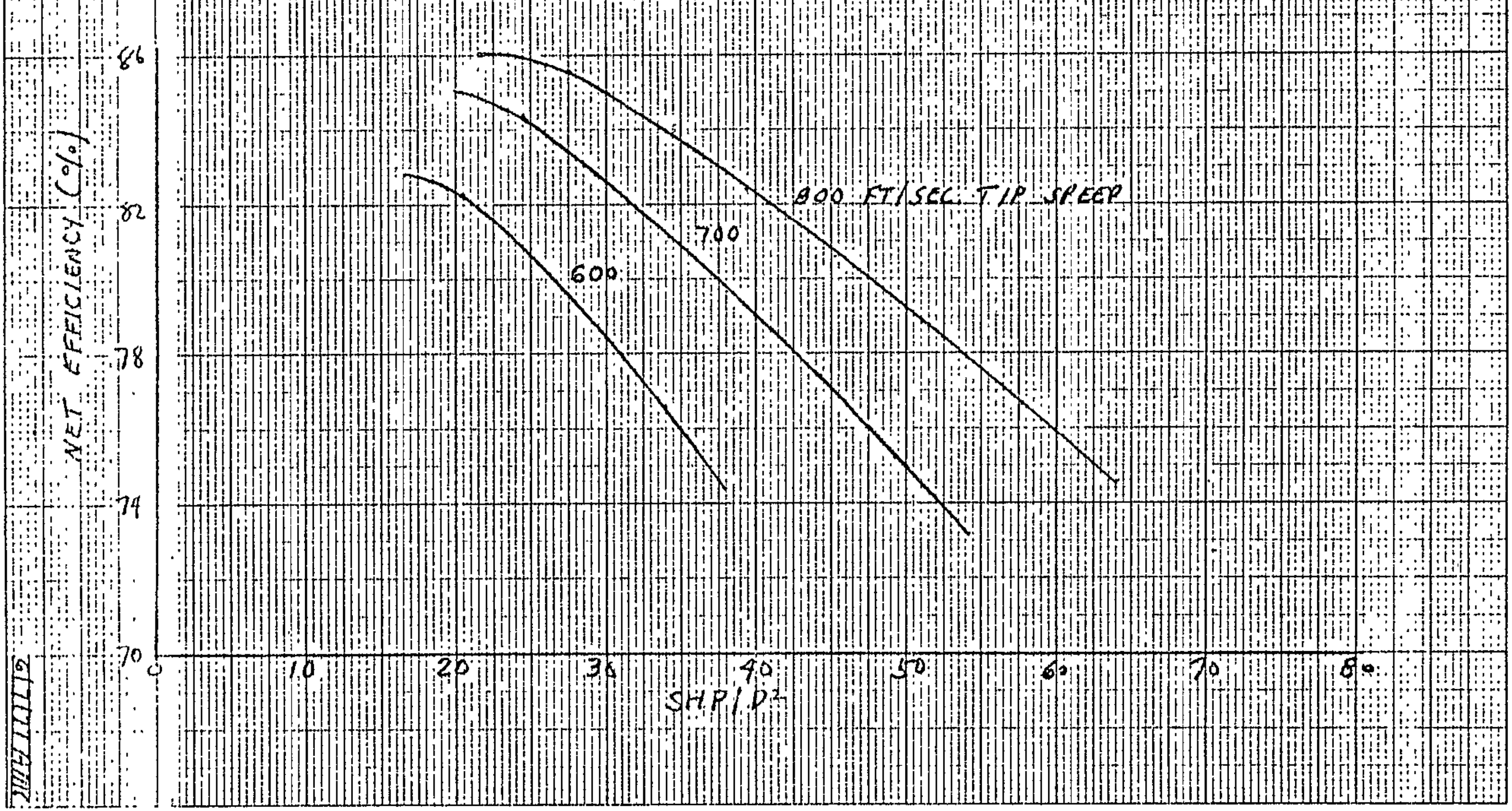
NET EFFICIENCY vs POWER LOADING & TIP SPEED

0.75 MACH NUMBER AT 30,000 FT. ISA

8 BLADE / PROP-FAN

(UPDATED BY LATEST TEST RESULTS)



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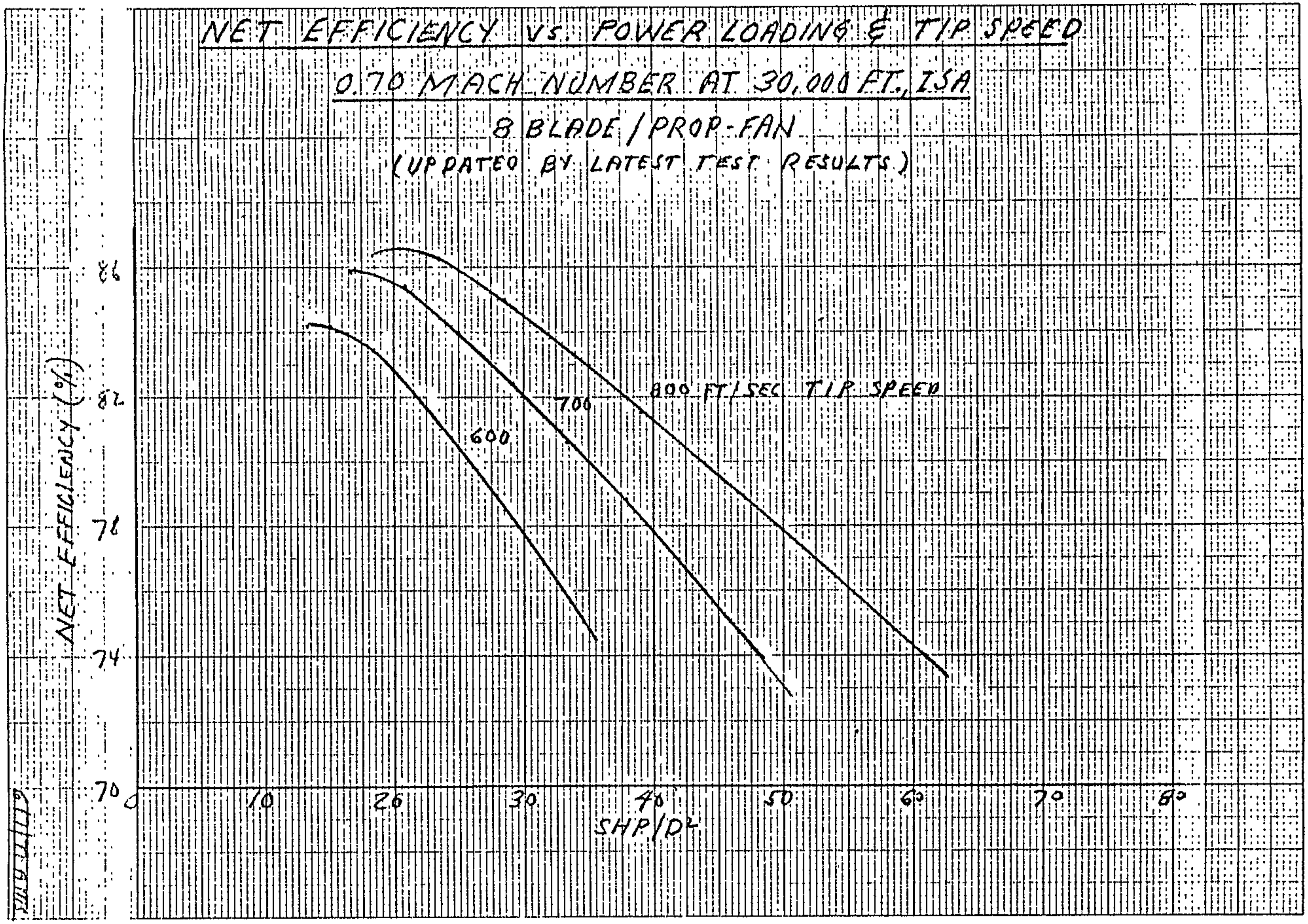

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LCC RECAT / PD 370-22 ENGINE PROP-FAN SELECTION STUDY

NET EFFICIENCY vs DIAMETER & TIP SPEED

0.80 MACH NUMBER AT 30,000 FT. ISA

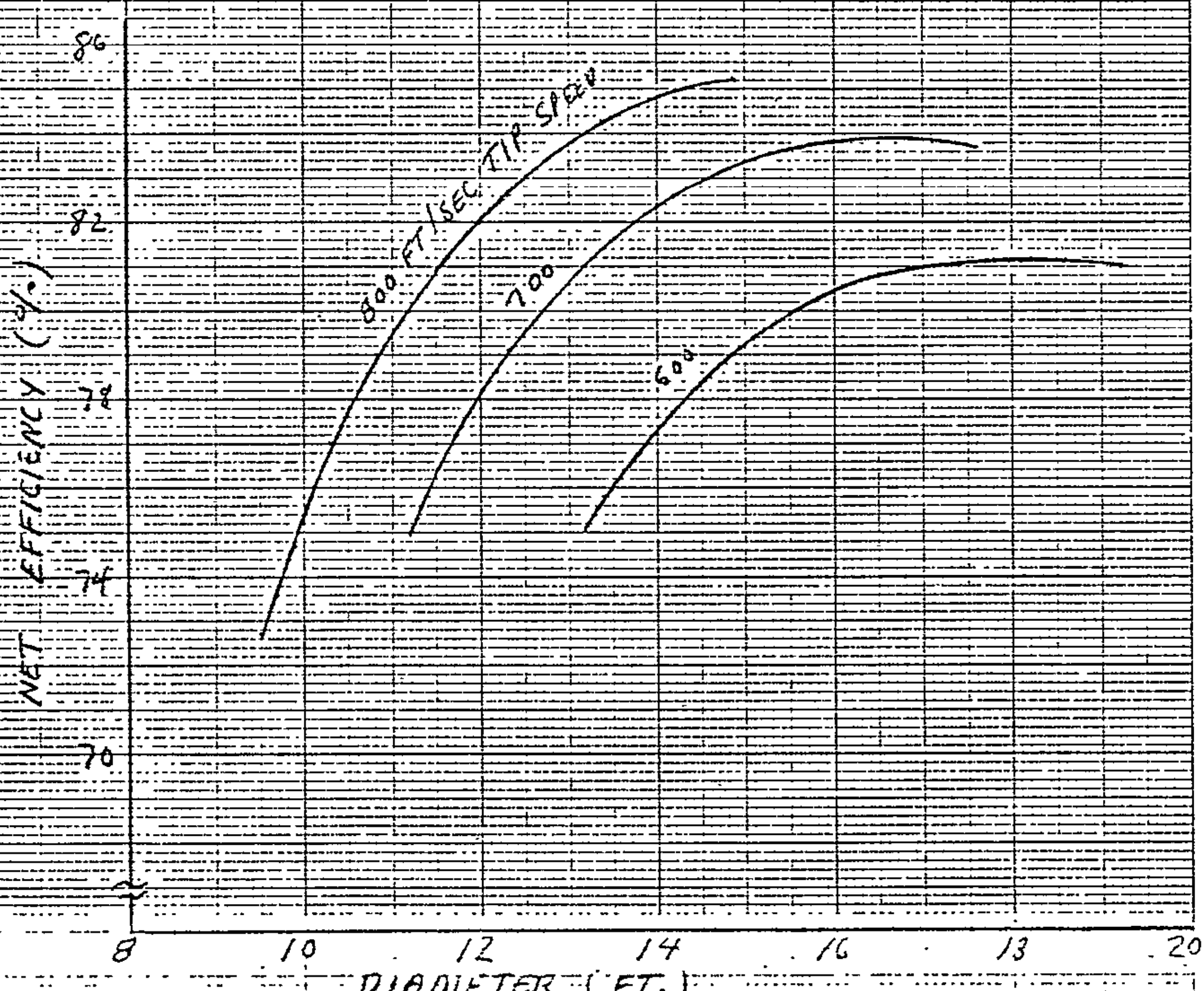
NET THRUST + FN = 3860 LBS

100% SHP = 6917

100% FN = 453.8

8 BLADE / PROP-FAN

(UPDATED BY LATEST TEST RESULTS)



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LCC RECAT / PD 370-22 ENGINE PROP-FAN SELECTION STUDY

NET EFFICIENCY vs DIAMETER & TIP SPEED

0.75 MACH NUMBER AT 30,000 FT., ISA

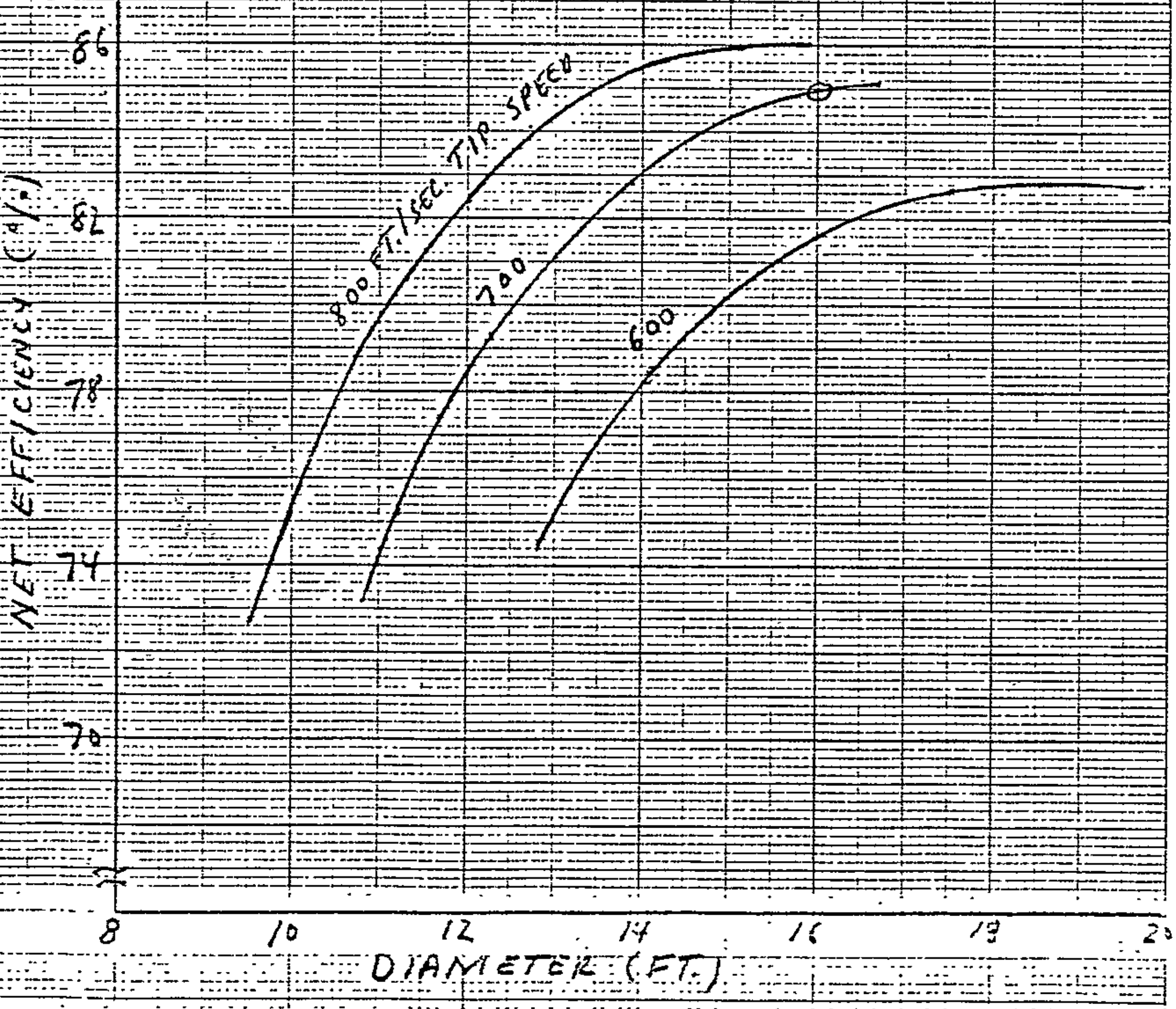
NET THRUST + FN = 3860 LBS

100% SHP = 6700

100% FN = 465 LBS

8 BLADE / PROP-FAN

(UPDATED BY LATEST TEST RESULTS)



6/7/77 AMS

LCC RECAT / PD 370-22 ENGINE PROP-FAN SELECTION STUDY

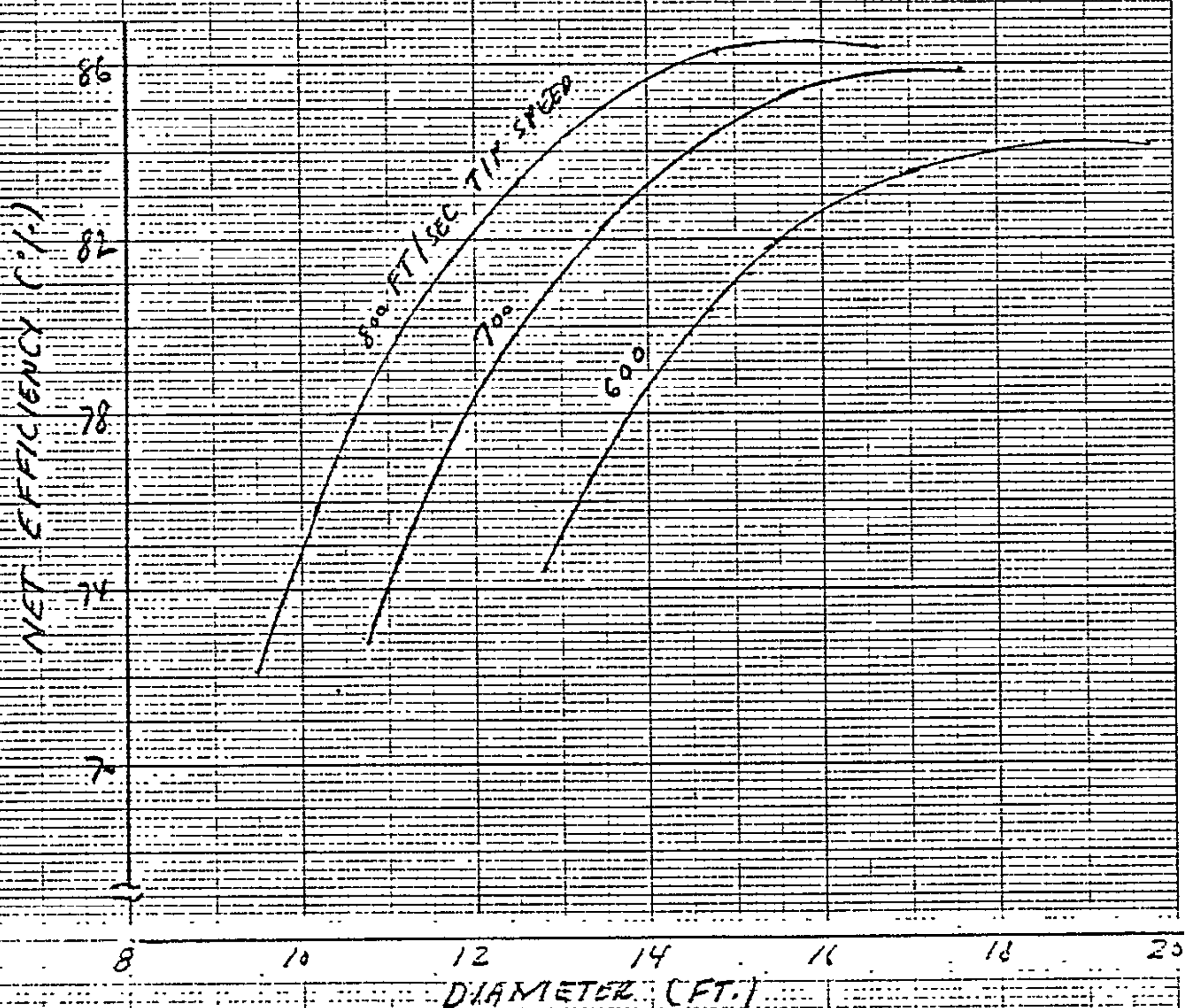
NET EFFICIENCY Vs. DIAMETER & TIP SPEED

0.70 MACH NUMBER AT 30,000 FT, ISA

NET THRUST + FN = 3860 LBS

100% SHP = 6470
100% FN = 476 LBS

8 BLADE / PROP-FAN
(UPDATED BY LATEST TEST RESULTS)



LCC RECAT / PD370-22 ENGINE PROP-FAN STUDY

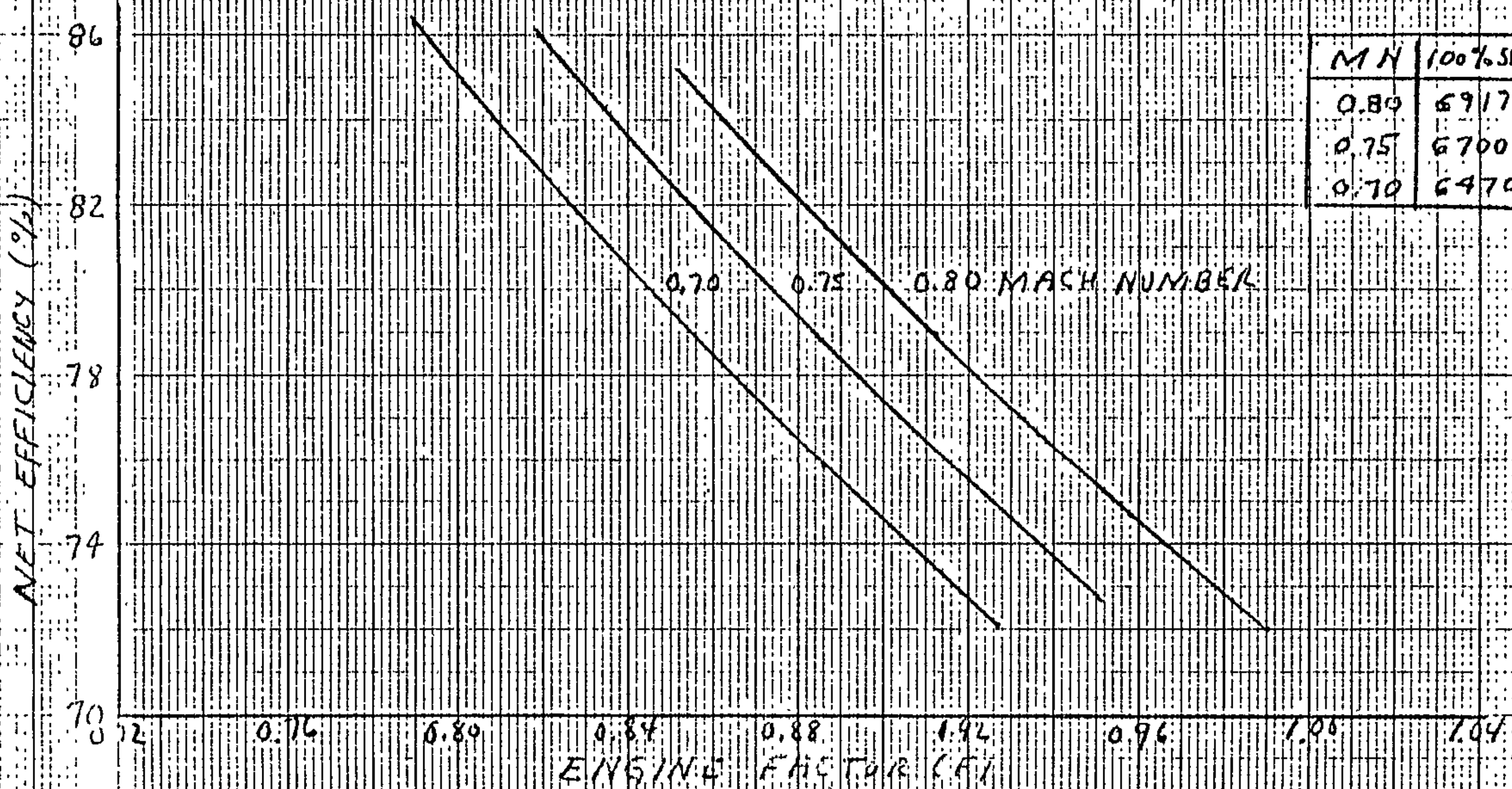
NET EFFICIENCY vs ENGINE FACTOR

30,000 FT., ISA

$$THRUST = T_{NET} + F_N = 3860 \text{ LBS}$$

$$= \frac{326\,(100\%\,SHP)(F)(\eta_{NET})}{(MN)(C_K)} + (100\%\,F_N)(F) = 3860$$

MN	100% SHP	100% FN
0.80	6917	453.8
0.75	6700	465
0.70	6470	476



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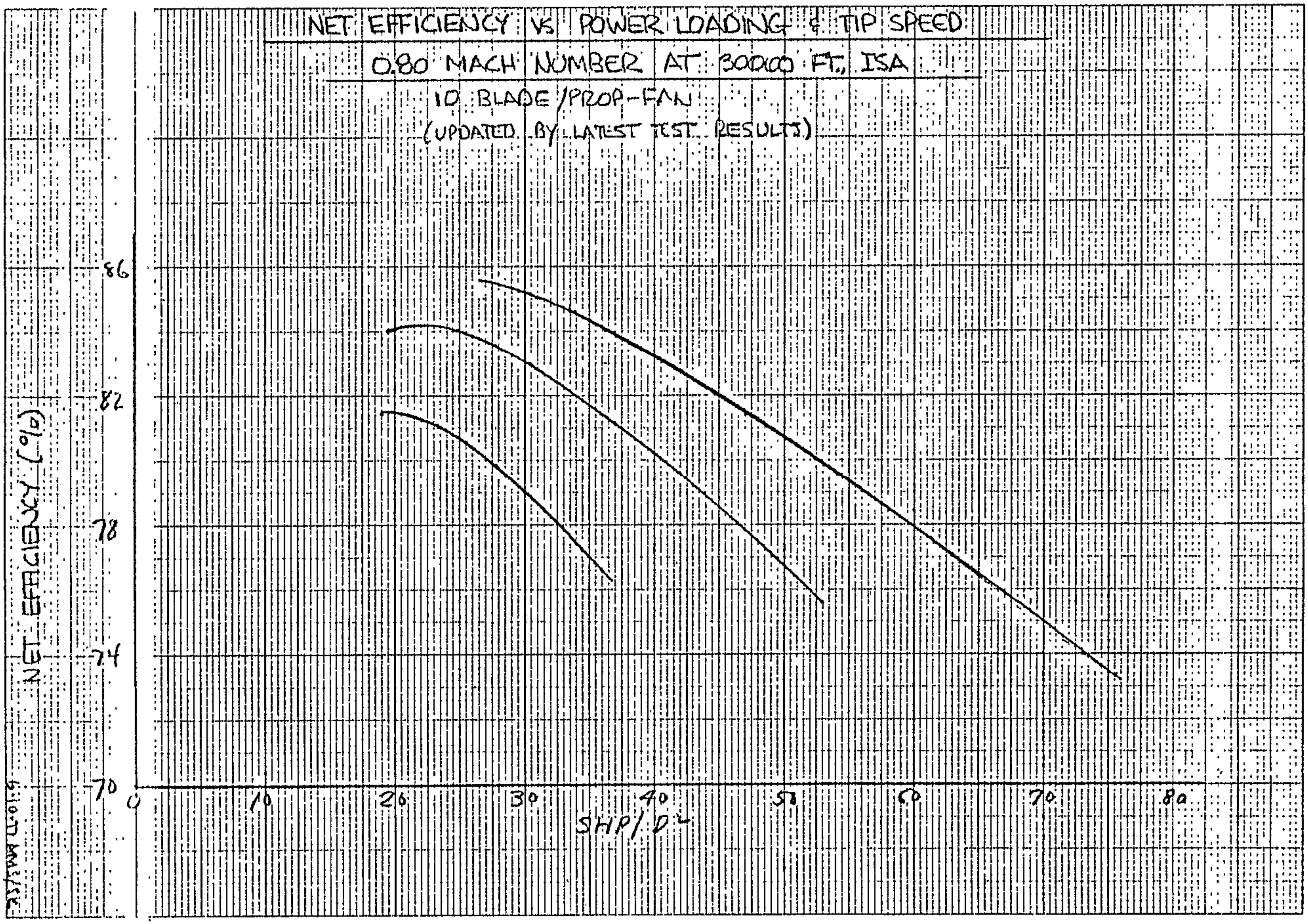
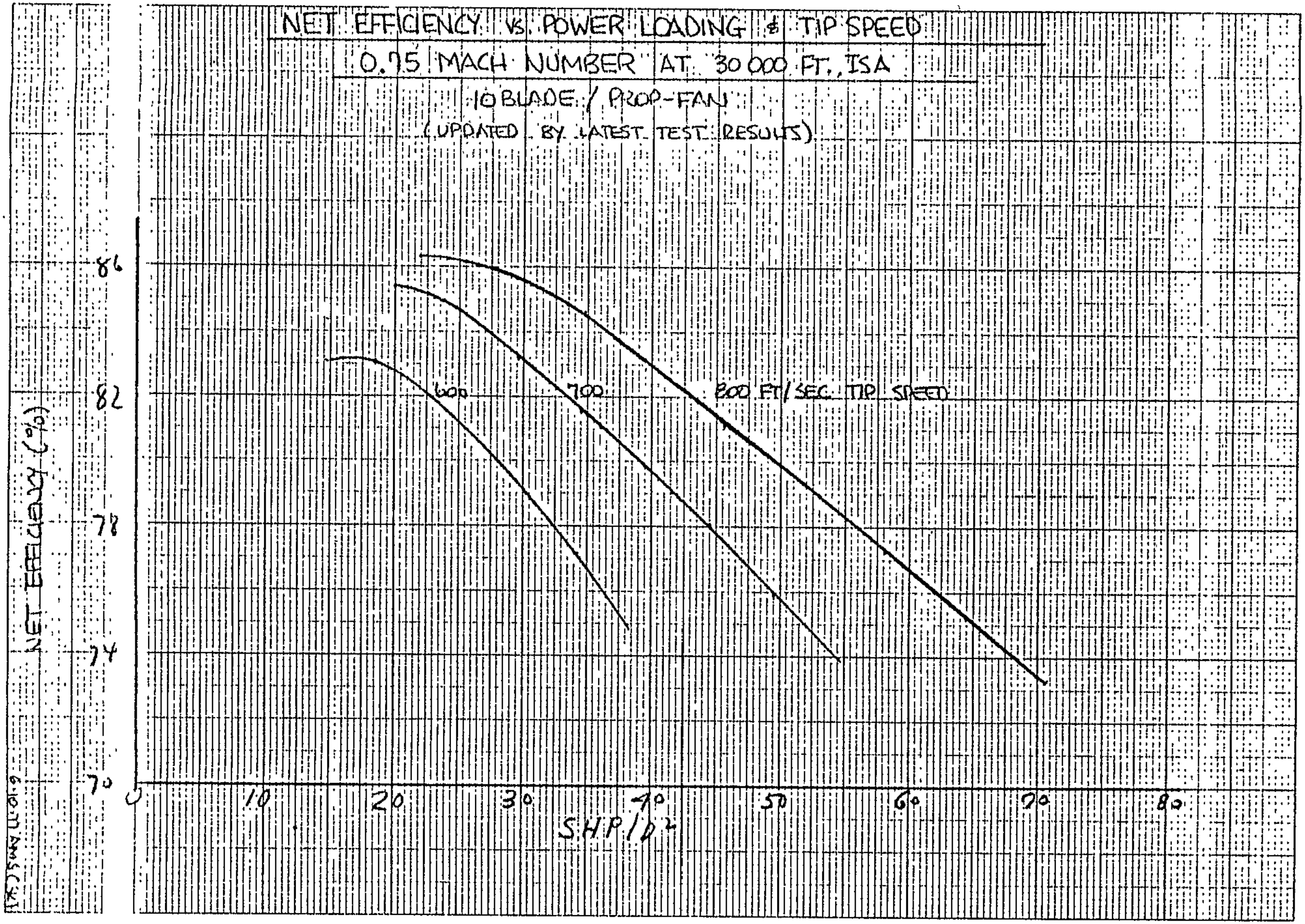

NET EFFICIENCY VS POWER LOADING & TIP SPEED
0.80 MACH NUMBER AT 30000 FT., ISA
10 BLADE PROP-FAN
(UPDATED BY LATEST TEST RESULTS)
NET EFFICIENCY (%)
86
82
78
74
70
0
10
20
30
40
50
60
70
80
SHP/D²



CALC. NO. 2837 (35)

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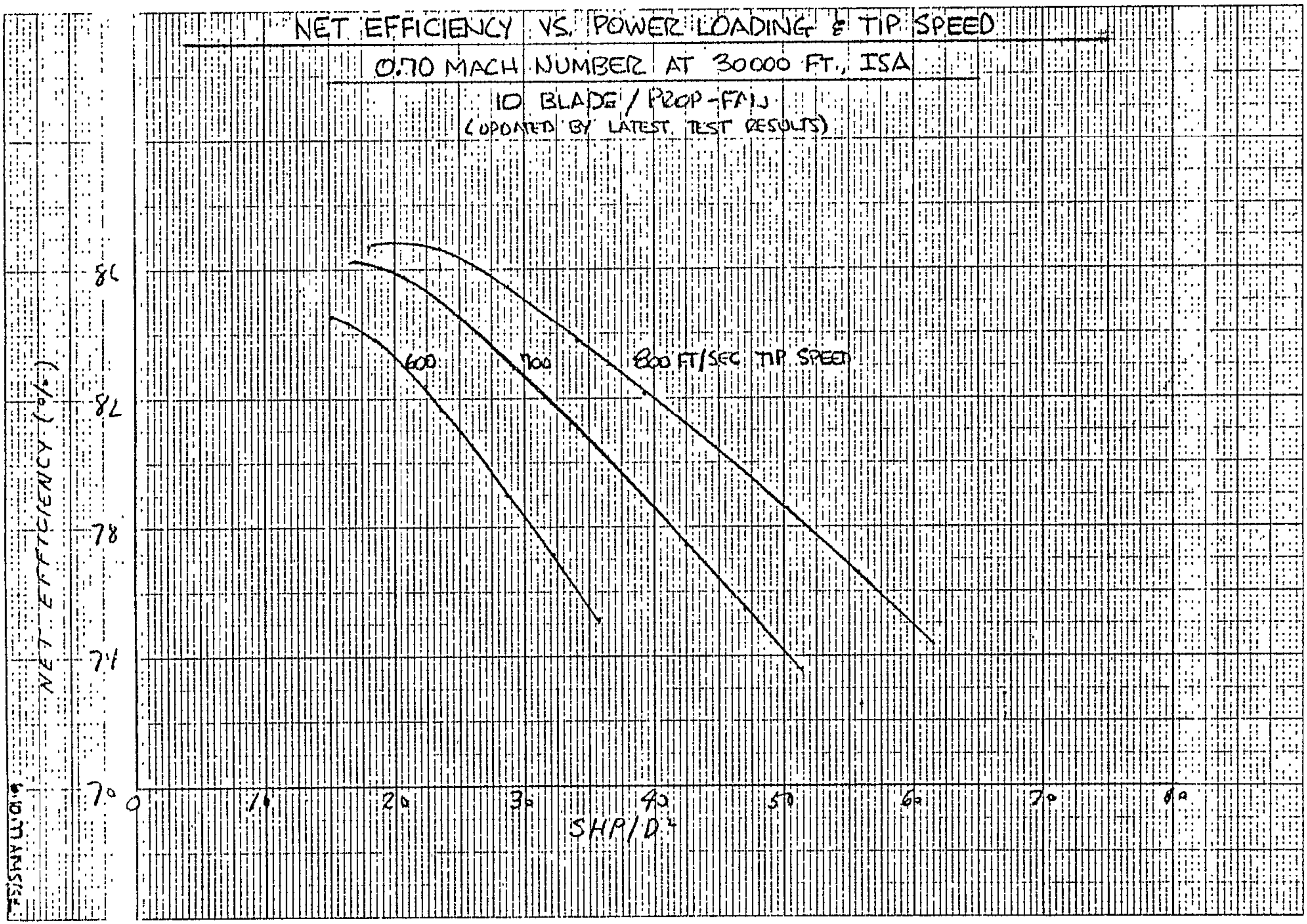


CALC NO. 2837(35)

LCC RECAT/PD 370-22 ENGINE PROP-FAN SELECTION STUDY

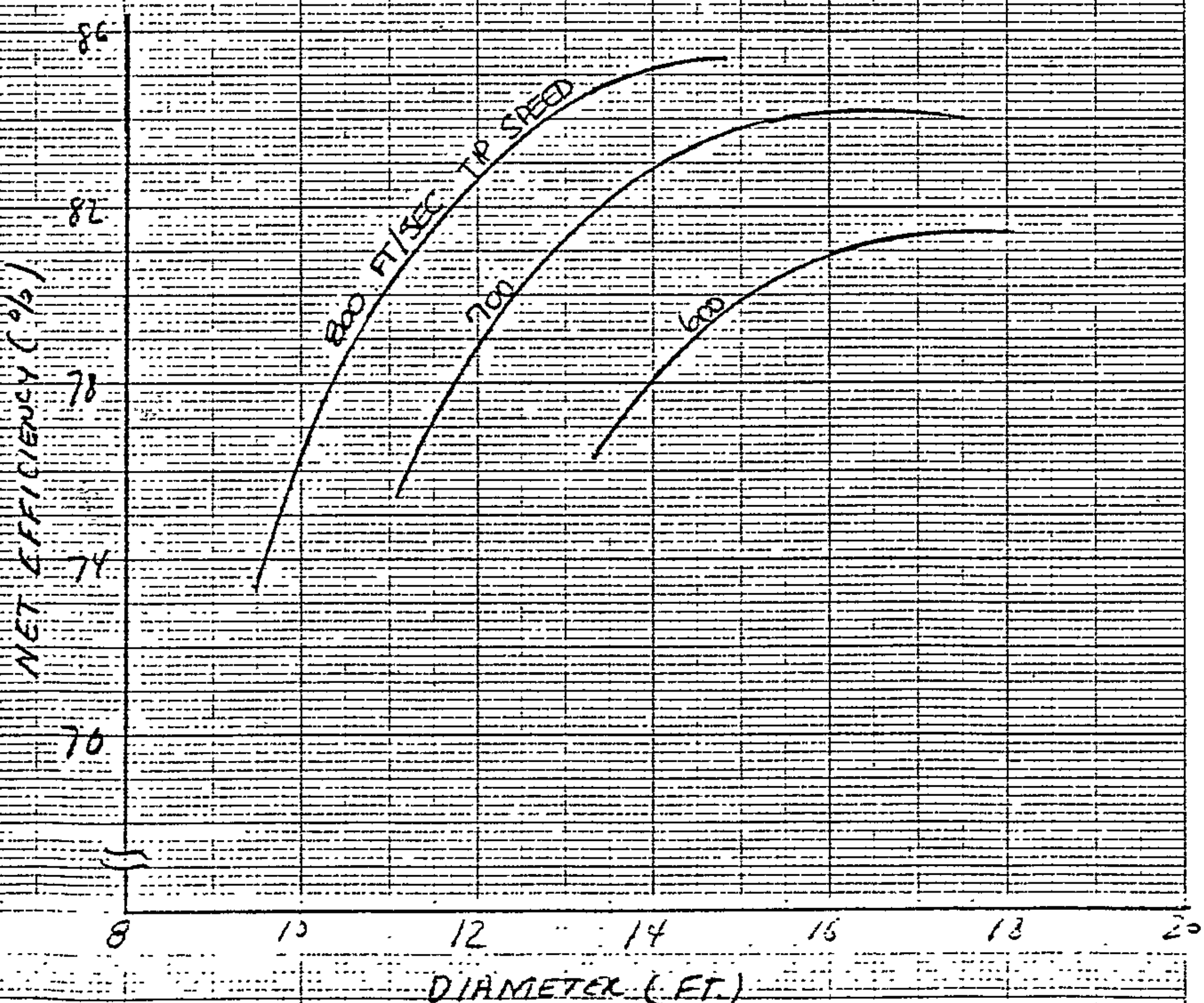
NET EFFICIENCY VS. DIAMETER & TIP SPEED
0.80 MACH NUMBER AT 30,000 FT, ISA

NET THRUST + FN = 3860 lbf

100% SHP = 6917

100% FN = 453.8

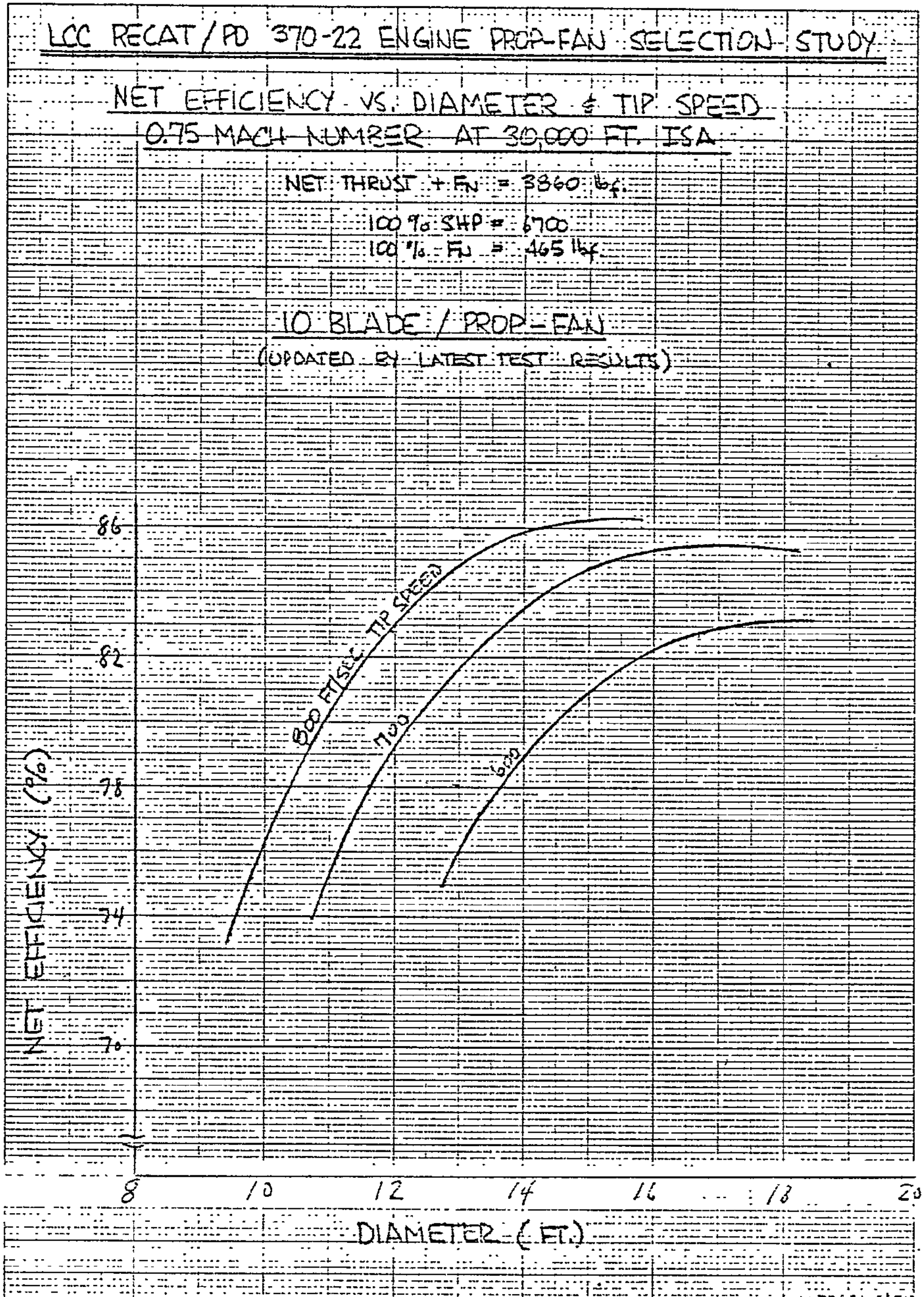
10 BLADE / PROP-FAN
(UPDATED BY LATEST TEST RESULTS)



6-16-77 EMS/SL

OF POOR QUALITY

CALC NO. 2837 (35)



(12)

LCC RECAT/PD 370-22 ENGINE PROP-FAN SECTION STUDY

NET EFFICIENCY VS. DIAMETER & TIP SPEED

0.70 MACH NUMBER AT 30,000 FT, ISA

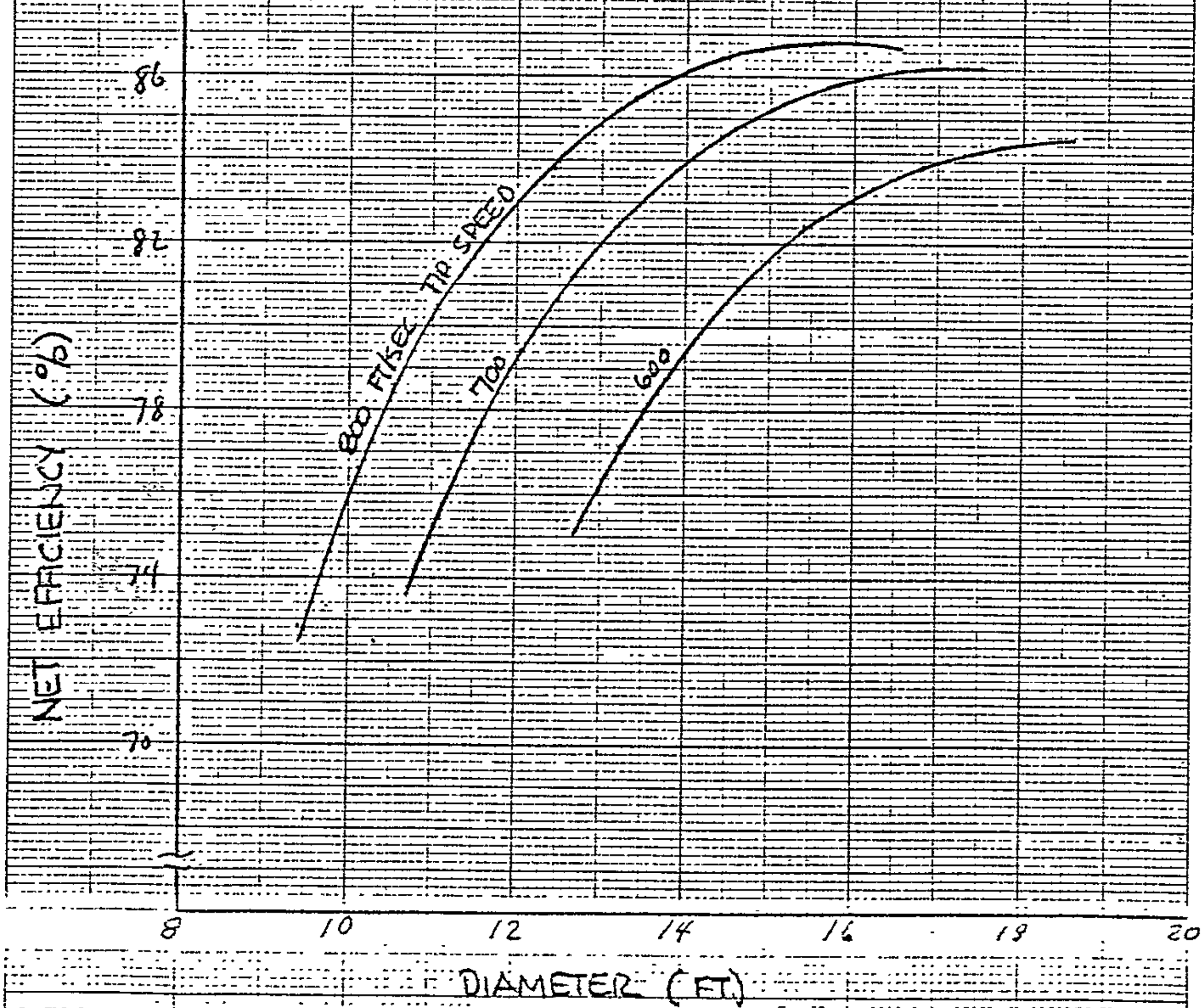
NET THRUST + FN = 3860 lbf.

100% SHP = 6470

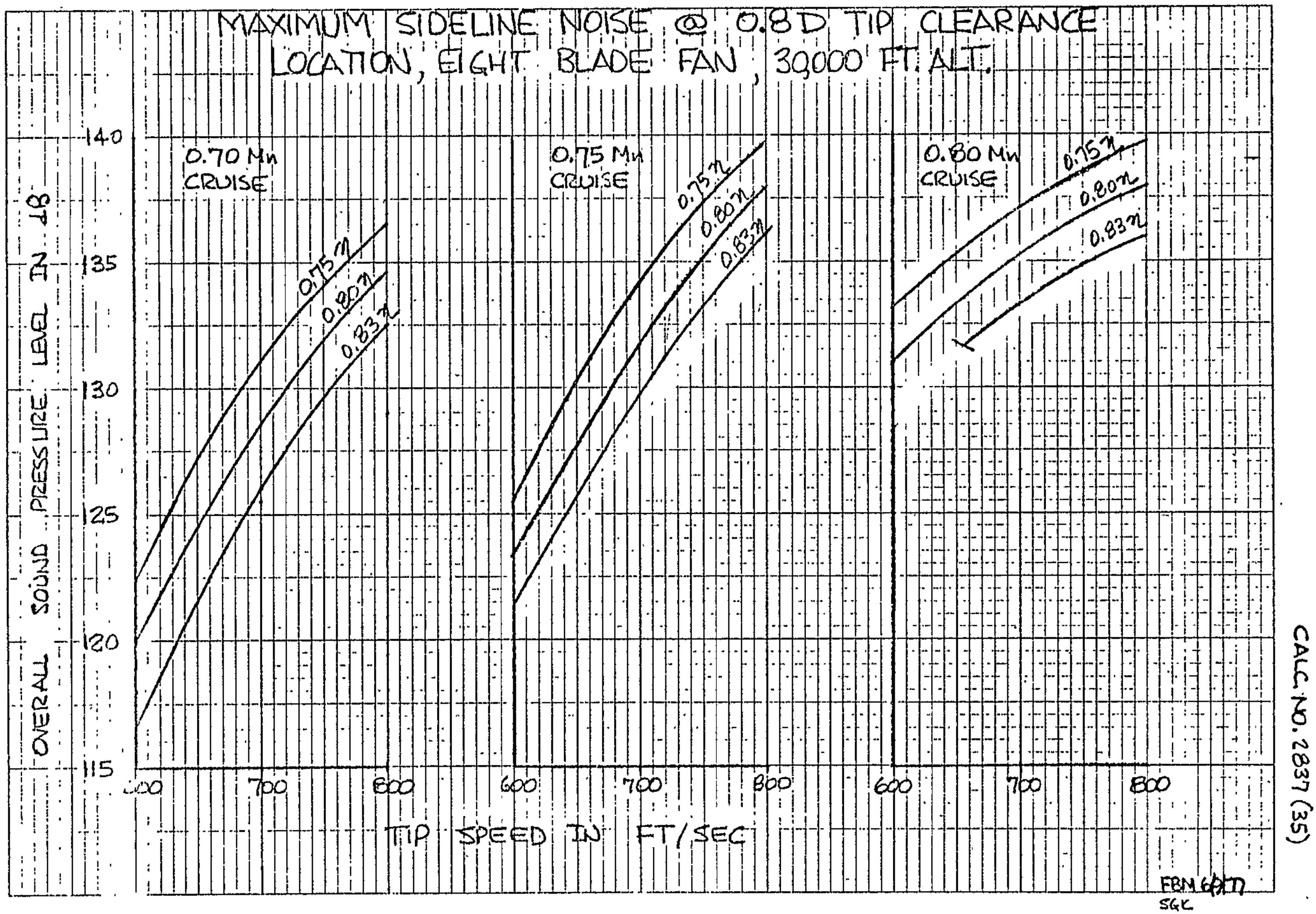
100% FN = 476 lbf.

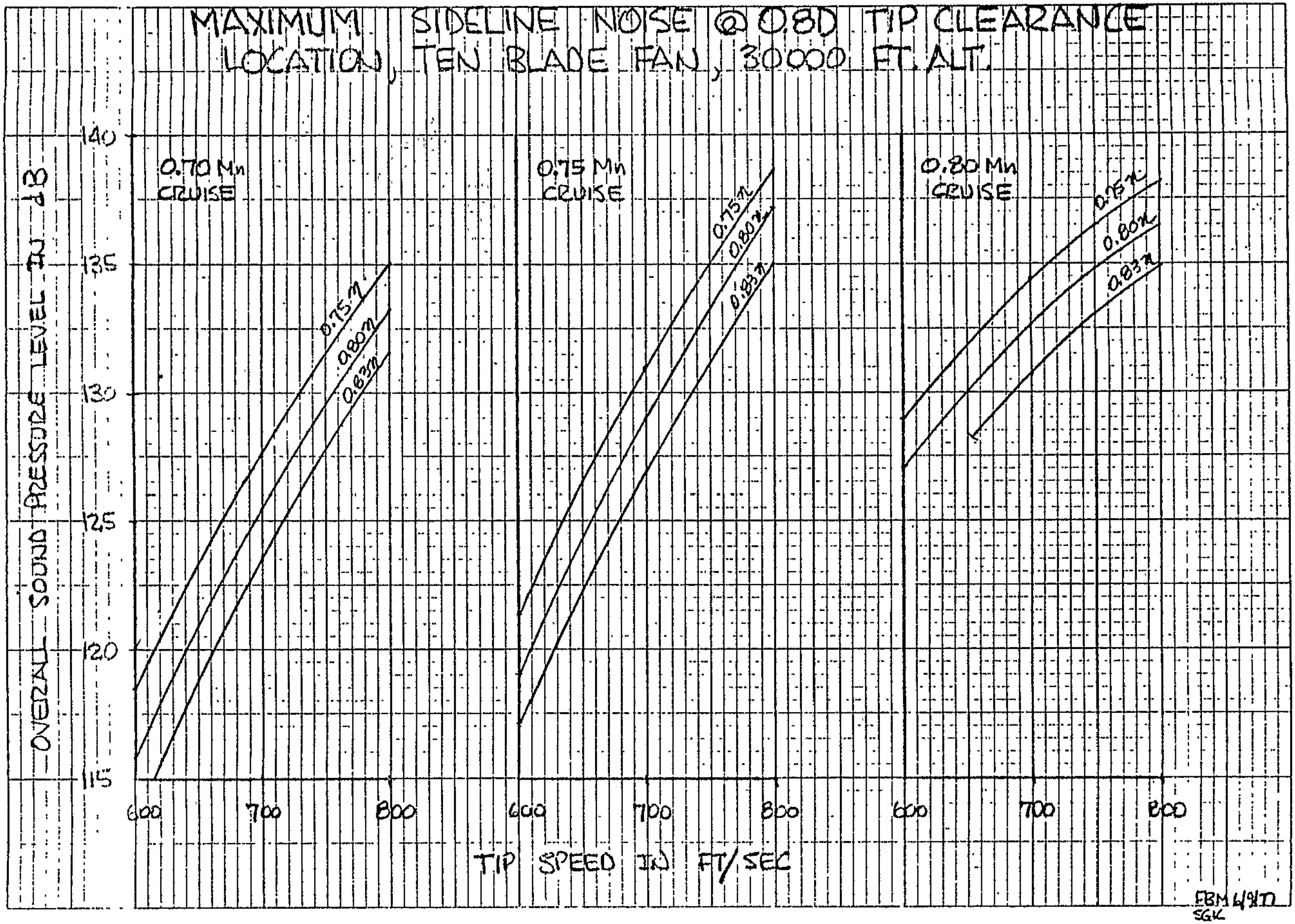
10 BLADE / PROP-FAN

(UPDATED BY LATEST TEST RESULTS)



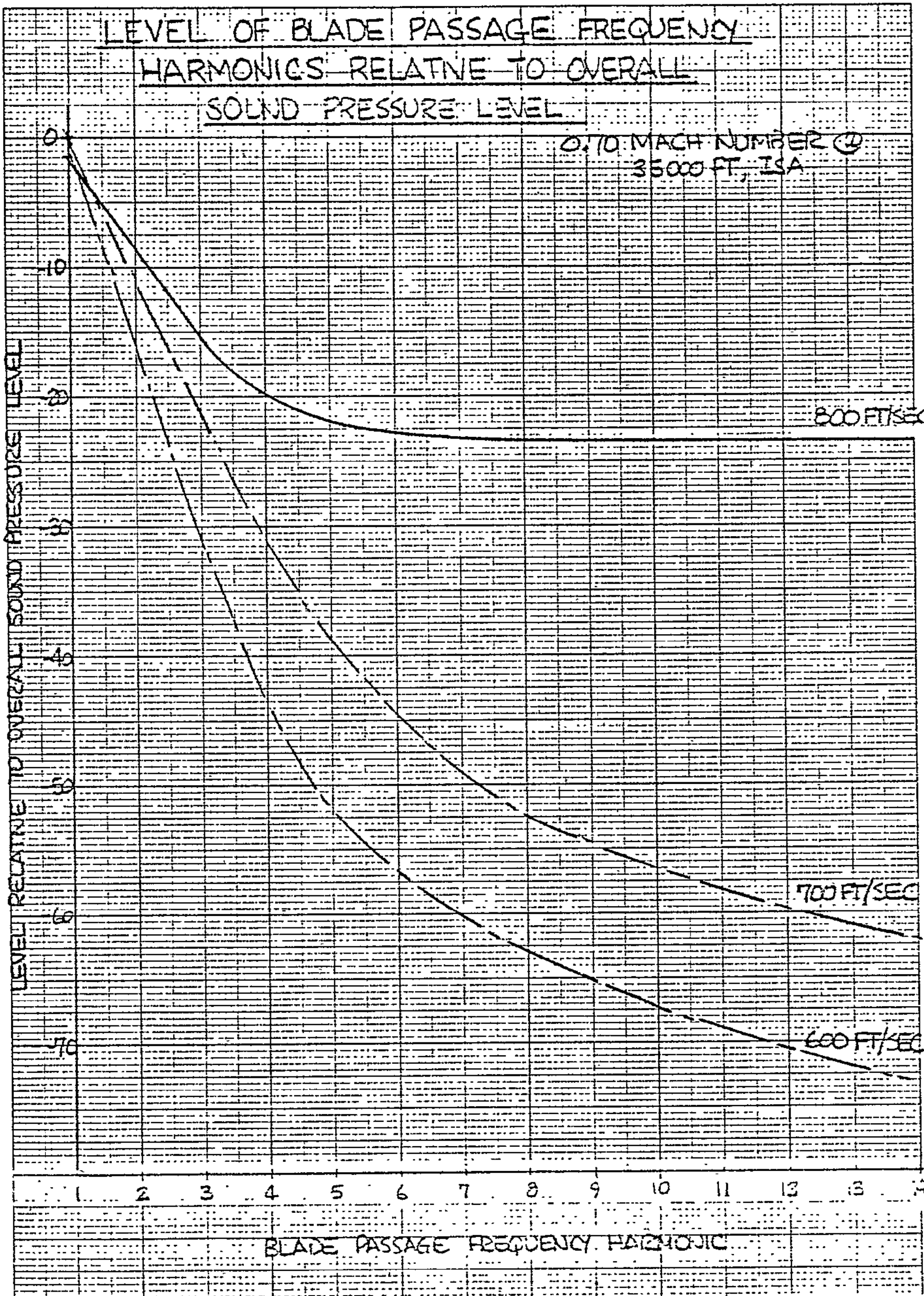
6.10.77 ANS/SK


MAXIMUM SIDELINE NOISE @ 0.8D TIP CLEARANCE
LOCATION, EIGHT BLADE FAN, 30,000 FT. ALT.
OVERALL SOUND PRESSURE LEVEL IN dB
TIP SPEED IN FT/SEC
0.70 Mn
CRUISE
0.75 Mn
CRUISE
0.80 Mn
CRUISE
0.75η
0.80η
0.83η
115
120
125
130
135
140
700
800
600
CALC. NO. 2837 (35)
FBM 6/1/77
SGK



A-18

CALC. 2837(35)



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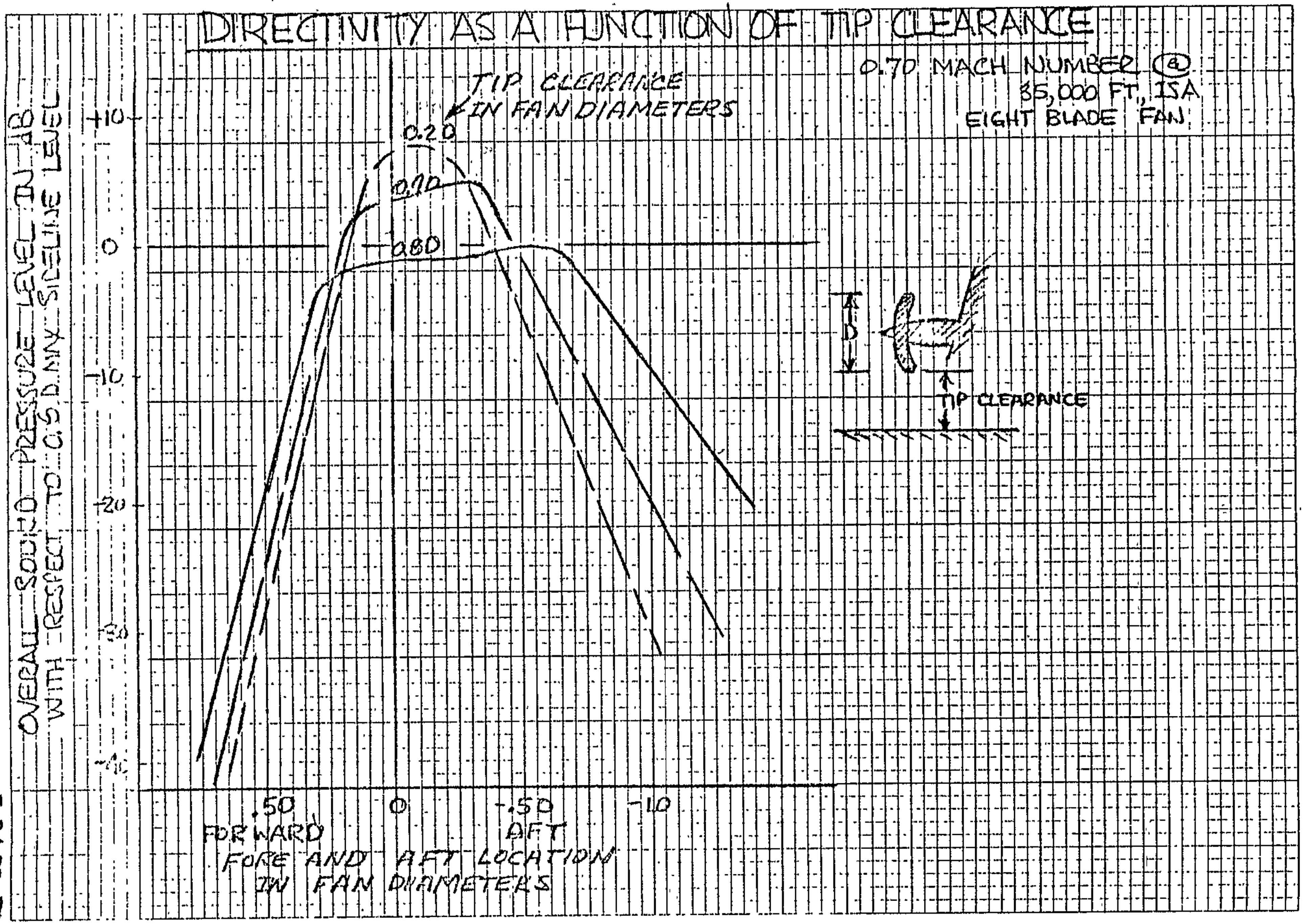
5-24-77 FBM
REVISED
6-8-77 SAK

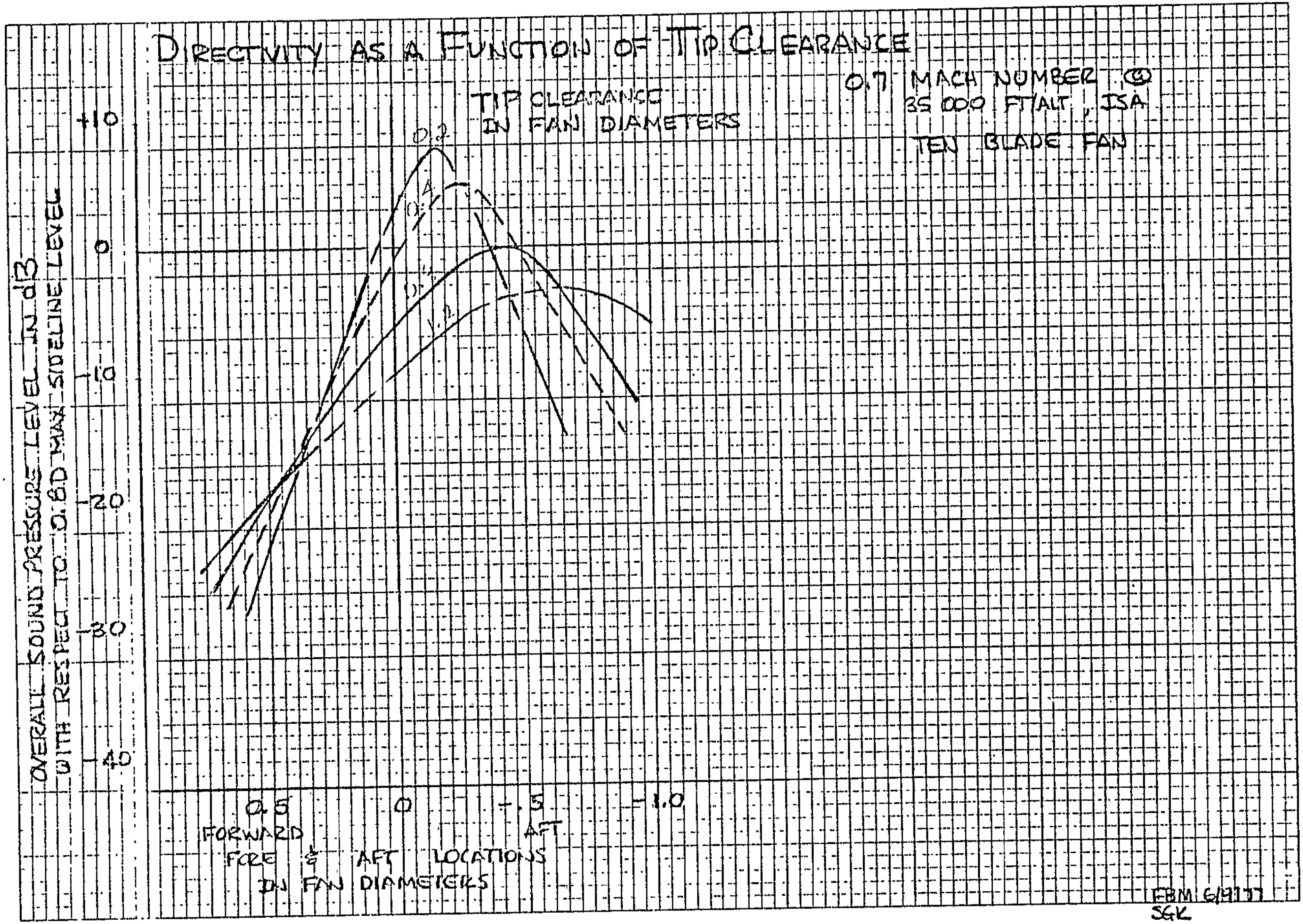
(7)



A-20

5.24.77 FBM
REVISED 6.7.77 SGK

CALC. NO. 2880(1)



CALC. NO. 2837(35)