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Simmonds Precision

INSTRUMENT SYSTEMS DIVISION

STUDY OF EFFECTS OF FUEL PROPERTIES IN TURBINE-POWERED BUSINESS AIRCRAFT

FINAL REPORT

F. D. POWELL
R. J. BIEGEN
P. G. WEITZ, JR.
A. M. DUKE

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E-2470

NASA Contractor Report 174627

Simmonds Precision
Instrument Systems Division
Vergennes, Vermont 05491

NASA - Lewis Research Center
Cleveland, Ohio 44135
Contract NAS3-22827

Simmonds Precision
INSTRUMENT SYSTEMS DIVISION
Panton Road, Vergennes, Vermont 05491 □ 802-877-2911 □ TWX 510-299-0039

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Preface

The work reported herein was conducted under NASA-Lewis Research Center Contract NAS3-22827. The NASA Technical Project Manager was Dr. Charles Baker; his guidance is acknowledged with pleasure.

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TABLE OF CONTENTS

Section	Title		Page
1.	INTRODUCTION		1-1
2.	SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS		2-1
	2.1	Summary of Economic Impacts	2-4
	2.2	Effects on Performance & Operation	2-4
	2.3	Conclusions	2-4
3.	ECONOMIC IMPACT		3-1
	3.1	Raw Data	3-1
	3.2	Total & Relative Direct Operating Costs	3-11
	3.3	The Average Mission	3-17
	3.4	Annual Costs, Relative Costs, and Fuel Break-Even Prices	3-17
	3.5	Mission and Payload Limits	3-26
	3.6	Fuel Vapor Pressure	3-29
	3.7	Overview of Economic Impact on the Fleet	3-29
4.	OPERATION		4-1
	4.1	Operational Considerations	4-1
	4.2	Effects of Varying Fuel Properties	4-6
5.	ECONOMIC IMPACT SENSITIVITY ANALYSIS		5-1
	5.1	Effect of Mission Distance	5-1
	5.2	Heavy Jet and Light Jet Mission Numbers	5-3
	5.3	The Statistics of Trip Distance and Frequency	5-3
6.	APPENDICES		6-1
	6.1	Aircraft Selection	6-1
	6.2	Data Base Extrapolation	6-3
	6.3	Atmospheric Data	6-5
	6.4	Mission Statistics and Aircraft Utilization	6-6
	6.5	Properties of Study Fuels	6-8
	6.6	Math Models	6-13
	6.7	Data Analysis Procedure	6-20
	6.8	Direct Operating Cost Data	6-25
	6.9	Economic Effects of Aromatic Content	6-27
	6.10	Tankering	6-28
	6.11	Fuel Heater and Heat Weight, and Cost	6-30
	6.12	Break-even Price of Fuel	6-31

LIST OF ILLUSTRATIONS

Number	Title	Page
3.4.1	Cost Effects of Fuel Composition on the 1990 Business Turbine-Powered Fleet in Millions of 1982 Dollars	3-27
6.2.1	Extrapolation Example, Heavy Jet-Performance Schedule	6-4
6.3.1	Atmospheric Structure	6-5
6.6.1.1	Computer Program Math Model, Aircraft & Mission Simulation (Climb & Descent)	6-14
6.6.1.2	Computer Program Math Model, Aircraft & Mission Simulation (Cruise)	6-15
6.6.1.3	Computer Program Math Model, Aircraft & Mission Simulation (Hold)	6-16
6.6.2.1	Wing Tank Fuel Temperature Model	6-18
6.7.1	Relative Cost of Aromatic Content Heavy Jet, 2700NM Mission, 0.3% Probable - Cold Day	6-22
6.7.2	Relative Cost of Heat of Combustion	6-23
6.7.3	Relative Cost of Freezing Temperature	6-24

LIST OF TABLES

Number	Title	Page
2.1	Total Cost and Relative Costs of the Average Mission	2-3
2.2	Business Fleet Total Costs of Reference Fuel and Relative Costs of the Study Fuels, 1980 and 1990, In Millions of 1983 Dollars	2-3
3.1.1	Mission Definition	3-3
3.1.2.a	Mission Raw Direct Operating Cost Data, ISO Units	3-4
3.1.2.b	Mission Raw Direct Operating Cost Data, ISO Units	3-5
3.1.2.c	Mission Raw Direct Operating Cost Data, ISO Units	3-6
3.1.2.a	Mission Raw Direct Operating Cost Data, Conventional Units	3-7
3.1.2.b	Mission Raw Direct Operating Cost Data, Conventional Units	3-8
3.1.2.c	Mission Raw Direct Operating Cost Data, Conventional Units	3-9
3.1.3	Hourly Operating Costs, 1982	3-10
3.2.1	Effect of Fuel Aromatic Content on Cost of Time	3-12
3.2.2.a	Total Costs with Reference Fuel and Relative Costs with Study Fuels	3-14
3.2.2.b	Costs with Reference Fuel and Relative Costs with Study Fuels	3-15
3.2.2.c	Costs with Reference Fuel and Relative Costs with Study Fuels	3-16
3.3.1	Fleet Class Mission Lengths & Frequency	3-17
3.3.2.a	Total Costs and Relative Costs for All Missions and for the Average Mission	3-18
3.3.2.b	Total Costs and Relative Costs for All Missions and for the Average Mission	3-19

LIST OF TABLES (CONT.)

Number	Title	Page
3.3.2.c	Total Costs and Relative Costs for All Missions and for the Average Mission	3-20
3.3.3	Total Costs and Relative Costs of the Average Mission	3-21
3.4.1	Aircraft Class & Fleet Statistics Class & Fleet Population & Missions	3-22
3.4.2	Annual Costs and Relative Costs per Vehicle in 1980 and 1990, in 1982 Dollars	3-23
3.4.3	Aircraft Class Total Costs of Reference Fuel and Relative Costs of the Study Fuels in Millions of 1982 Dollars	3-24
3.4.4	Business Fleet Total Costs of Reference Fuel and Relative Costs of the Study Fuels, 1980 and 1990, in Millions of 1982 Dollars	3-25
3.4.5	Study Fuel Break-Even Costs as a Percent of the Reference Fuel cost	3-26
3.5.1	Fuel Energy Per Unit Volume	3-28
4.1.1	CSR Relative Merit - % Change in Cruise Specific Range with Respect to the Reference Fuel	4-1
4.1.2	Holding Relative Merit - Holding Time and Delta Holding Specific Range	4-2
4.1.3	% Frozen Wing Fuel Relative Merit - General Operating Envelope	4-3
4.1.4	% Frozen Wing Fuel Relative Merit - 2% & 0.3% Probable Cold Days	4-3
4.1.5	% Range Reduction Maximum Range Trip	4-4
4.1.6	% Range Reduction Average Range Trip	4-4
4.1.7	Business Fleet Trip Frequency	4-5
4.1.8	% Range Reduction Maximum Range Trip; -10° & -20°C Cold Days High and Low Cruise Altitudes	4-6

LIST OF TABLES (CONT.)

Number	Title	Page
5.1.1	The Effect of Mission-Distance Assumptions on the Average Mission	5-2
5.2.1	Effect On Economic Analysis of an Error of ± 10% in the Relative Number of Missions for Heavy and Light Jets	5-4
6.1.1	Data: Aircraft Selection: Heavy Jets Gross Weight > 25K#	6-1
6.1.2	Data: Aircraft Selection: Light Jets Gross Weight < 25K#	6-2
6.1.3	Data: Aircraft Selection: Turboprops	6-2
6.4.1	All Fixed Wing Business Aircraft: Trip Range vs Frequency	6-6
6.4.2	Heavy Jet: Trip Range vs Frequency	6-6
6.4.3	Itinerant Flight Data	6-7
6.5.1	Fuel Properties	6-11

1. INTRODUCTION

Increased interest in research and technology concerning aviation turbine fuels and their properties has been prompted by recent changes in the supply and demand situation of these fuels. The most obvious change is the rapid increase in fuel price. For commercial airplanes, fuel costs now approach 50 percent of the direct operating costs. In addition, there have been occasional local supply disruptions and gradual shifts in delivered values of certain fuel properties. Dwindling petroleum reserves and the politically sensitive nature of the major world suppliers make the continuation of these trends likely.

Fuel usage by business aircraft is expected to increase much faster than fuel usage by commercial aircraft between now and 1990. This is particularly true for turbine-powered business aircraft. In addition, response of business aircraft to fuel property changes is not necessarily derived by scaling results for larger commercial aircraft. This study presents an analysis of the fuel-related concerns unique to turbine-powered business aircraft. Representative aircraft and missions are studied by simulation to determine the performance, operational and economic results with Jet A as a reference fuel, and with five study fuels with property variations. The various performance, operational and economic effects of the study fuels are compared with the reference fuel. The output of the study is an assessment of the economic and operational impact of fuel properties on this segment of the business aircraft fleet in the 1980 and 1990 time-frames.

The organization of the report is as follows: Section 2 presents a summary of the principal findings, and conclusions. Much of the material, especially the tables and graphs, is considered in greater detail later in the report; the redundancy which results enables this section to stand alone without repeated reference to other parts of the study. The economic analysis is concentrated in Section 3, while the examination of operational considerations appears in Section 4. Because some of the assumptions on which the economic analysis is founded are not easily verified, the sensitivity of the analysis to alternates for these assumptions is examined in Section 5. The data base on which the analyses are founded is defined in a set of appendices grouped as Section 6.

2. SUMMARY AND CONCLUSIONS

The summary of the economic impact of varying fuel properties on the business fleet in the 1980 and 1990 time-frames is followed by a summary of the performance and operational effects. The conclusions are presented at the end of this section.

2.1 Summary of Economic Impacts

The principal cost drivers are the aromatic contents of the study fuels relative to the reference fuel, their heats of combustion (energy per unit mass), and their freezing temperatures.

High aromatic content results in a smokier flame with higher radiation levels. More frequent engine overhaul and replacement, especially of the combustion and other portions of the hot sections of the engine, will be required, with a significant increment of cost.

Heat of combustion directly affects cost. If a less energetic fuel is used, more must be available as a reserve at the scheduled end of the mission, and more will be consumed during the mission. Fuel must be burned to carry the added mass of the reserve and of that consumed during the mission; this is the tankering effect. As a consequence of tankering, the obvious economic impact of fuel heat of combustion is even further magnified.

Fuel freezing temperature has a relatively minor economic impact. Fuel freezing could be precluded by use of a heater; this study shows that the costs of a fuel heater and of the energy to heat the fuel are relatively small. The fuel freezing temperature has a much more important effect on operation and performance. These effects will be examined later in the report.

Several fuel properties have relatively minor effects. Fuel density, (mass per unit volume), becomes important only for missions of maximum range; such missions, although perhaps of great importance to the passenger, appear to be relatively rare. The study did not consider the possibility that some missions might be of greater importance to the passenger than others; all missions were assumed to be equally important.

Vapor pressure has some importance in design of the engine and in its performance and operation. Vapor pressure can be economically important when the aircraft climbs extremely rapidly, as in fighter aircraft because the fuel boiling which occurs causes significant loss of fuel as vapor. However, boiling does not occur in business aircraft operation.

Table 2.1, quoted from Table 3.3.3 in Section 3, shows the cost of Time (total operating cost per flight hour excluding fuel), Fuel (cost of fuel burned exclusive of tank heating), Heater (operating cost of the tank heaters), and Heat (cost of fuel burned for tank heating) in an average mission for each of the three study aircraft with the reference fuel, and the relative costs of the study fuels. The Specification Limit Jet A, #2, and "High-Freeze", #3, show modest increases in cost, while the "Hi-Aromatic", #4, and "Special", #6, fuels show much larger increases. Fuel #5 is very similar to JP-4, while Fuel #6 is similar to the NASA ERBS Fuel, representing the properties of a possible future fuel.

Table 2.2 shows the estimated costs and relative costs for the turbine-powered business fleet in 1980 and in 1990. This table, quoted from Tables 3.4.4 and 3.4.5 in Section 3, also shows the break-even prices of the study fuels. Thus, for example, the Special Fuel #6 must have its price at 92.17% of the price of the Reference Jet A fuel to break even on total mission costs in 1990. Although the incremental cost of #6 fuel in 1990, estimated at $29.85 millions, is only 2.3% of the Reference fuel cost of $1291 million, the requirement that fuel price alone absorb the cost of the heat and heater, and especially the cost of time due to the high aromatic content, causes this fuel to be almost 8% more expensive on an equal-price basis. The "ERBS" fuel, #6, must therefore have a price about 8% less than the Reference fuel to result in equal cost to the fleet.

This table shows that in every case the "Reduced Flash " Fuel #5 is economically advantageous, so that its break-even cost is 4.2% higher than the Reference fuel cost.

Table 2.1
TOTAL COSTS AND RELATIVE COSTS OF THE AVERAGE MISSION

AIRCRAFT CLASS		TOTAL COST 1.REF FUEL TF=-44°C HOC=18574 %AROM=17.5	RELATIVE COSTS: STUDY FUELS 2.SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Heavy Jet	Average	T:$ 1222.79	T: 15.99	T: 15.99	T: 69.31	T: -61.21	T: 93.33
	Mission	F: 1616.17	F: 21.56	F: 21.56	F: 37.30	F: - 5.63	F: 37.30
		H: 0	H: 2.76	H: 2.79	H: 2.82	H: 0	H: 2.85
	Distance	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	1290 NM	S: 2838.96	S: 40.31	S: 40.34	S: 109.43	S: -66.95	S: 133.48
Light Jet	Average	T: 680.24	T: 6.15	T: 6.15	T: 26.66	T: -23.58	T: 35.88
	Mission	F: 826.21	F: 10.35	F: 10.35	F: 17.90	F: -2.70	F: 17.90
		H: 2.89	H: 0.02	H: 0.05	H: 0.06	H: -2.89	H: 0.11
	Distance	h: 0	H: 0	H: 0	H: 0	H: 0	H: 0
	1110 NM	S: 1509.34	S: 16.52	S: 16.55	S: 44.62	S: -29.17	S: 53.89
Turboprop	Average	T: 408.69	T: 4.34	T: 4.34	T: 18.82	T: -16.66	T: 25.33
	Mission	F: 345.88	F: 5.07	F: 5.07	F: 8.77	F: - 1.35	F: 8.77
		H: 2.47	H: 0.02	H: 0.05	H: 0.08	H: - 0.07	H: 0.12
	Distance	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.01
	785 NM	S: 757.04	S: 9.43	S: 9.46	S: 27.67	S: -18.08	S: 34.23

T, cost of time; F, cost of fuel; H, cost of heater; h, cost of heat; S, sum; 1982$

Table 2.2
BUSINESS FLEET TOTAL COSTS OF REFERENCE FUEL AND
RELATIVE COSTS OF THE STUDY FUELS, 1980 AND 1990, IN MILLIONS OF 1982 DOLLARS

BUSINESS FLEET	TOTAL COSTS 1. REF TF=-44°C HOC=18574 %AROM=17.5	RELATIVE COSTS OF STUDY FUELS 2.SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
1980	T:$ 516.84	T: 5.62	T: 5.62	T: 24.34	T: -21.53	T: 32.75
	F: 582.95	F: 7.78	F: 7.78	F: 13.48	F: - 2.05	F: 13.48
	H: 1.80	H: 0.40	H: 0.42	H: 0.44	H: - 0.80	H: 0.47
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.01
	S: 1109.59	S: 13.80	S: 13.82	S: 38.26	S: -24.38	S: 46.71
1990	T: 1144.80	T: 12.44	T: 12.44	T: 53.90	T: -47.70	T: 72.57
	F: 1291.59	F: 17.26	F: 17.26	F: 29.85	F: - 4.53	F: 29.85
	H: 3.97	H: 0.85	H: 0.91	H: 0.96	H: 1.77	H: 1.02
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.01
	S: 2440.36	S: 30.55	S: 30.61	S: 84.71	S: -54.00	S: 103.65
Fuel Breakeven Prices As A Percent Of The Reference Fuel Price In 1990	100.00	97.67	97.66	93.59	104.20	92.16

T, Cost of Time; F, Cost of Fuel; H, Cost of Heater, h, Cost of Heat; S, Sum, 1982$/1000000

2.2 Effects on Performance & Operation

The effect of variation of heat of combustion is to change the specific range in inverse proportion to the heat of combustion. The range of variation of heat of combustion is relatively narrow; as a result the effects on Specific-Range are comparatively small.

High freezing temperature has a very significant effect on operation if the wing-tank fuel is not heated. Thus on a cold day very large portions of the wing-tank fuel would be frozen for the high-freeze temperature fuels. Similarily, long range missions would be sharply reduced, with loss of range relative to the reference fuel. Flying at lower altitude to avoid freezing on very cold days causes a significant reduction in Specific-Range; this is not a feasible solution to the problem produced by fuels with high freezing temperatures.

The aromatic content of the fuels have some significant effects. The principal effect is due to swelling of rubber parts. In addition, such fuels have higher water solubility. The dissolved water comes out of solution when the fuel cools at altitude; this can cause significant errors in the fuel quantity gauging system.

2.3 Conclusions

1. The economic impact of high freezing temperatures for fuel are small, but the performance and operational effects are significant.

2. High aromatic content causes high engine maintenance costs.

3. The heat of combustion of a fuel has strong economic impact, but only relatively slight operational influence.

4. The statistical data to enable defining the frequency-distribution of mission distance, and of missions per year, in terms of aircraft class are deficient. Although the economic impact estimate is relatively insensitive to the range of alternate assumptions which were tested, this remains an area of uncertainty. Similarly, there are no data to indicate the relative importance of missions of various lengths. Research in this area could be of value for a number of applications.

3. ECONOMIC IMPACT

In this section the economic impact of the study fuels is considered. The method of analysis of the raw data is also discussed. However, many of the coefficients and procedures involve more complicated or theoretically difficult stages; in such cases the full derivation is presented in an appendix, to which reference will be made, in order to maintain the focus on the desired results.

The stages of analysis are outlined:

1) Raw data from the computer simulation are gathered and presented. For each mission, the primary raw data are comprised of:

a) flight time, minutes
b) weight of fuel burned
c) weight of required heater
d) weight of fuel burned to provide heat.

Details of the computer simulation are presented in subsection 6.6.1.

In addition, general quantities such as aircraft gross weight at takeoff, fuel load, tankering-factor, payload, trip-distance, and the total direct operating cost per unit of aircraft empty weight are gathered.

2) In the second stage of analysis the raw data of time, fuel-burn, etc., are converted to the form of total direct operating cost for the reference fuel and relative costs for the five study fuels. This stage requires applying a number of assumptions which are discussed wherever their need first rises.

3) The third stage involves interpolation and extrapolation of the direct operating costs and relative costs to enable definition and formation of the average mission for each aircraft and the costs for the average mission.

4) In this stage, the average mission costs are projected to enable formation of the average annual costs for each aircraft with the reference fuel, and the incremental costs with the study fuels. These costs can then be combined to form estimated costs and incremental costs for the turbine-powered business fleet.

5) In the final stage of analysis, the fleet costs are analyzed in terms of the fuel properties which lead to the components of these costs, and the required break-even fuel prices for the study fuels are determined.

3.1 Raw Data

The overall objective of the study is to form an estimate of the impact of potential changes in fuel properties on the turbine-powered business fleet. Three aircraft were selected: a heavy jet, a light jet, and a turboprop. The basis for their selection was that they should be reasonably representative of the composition of the business fleet anticipated in 1990. The selection process is discussed more fully in Section 6.1, and the extrapolation of the aircraft data bases is discussed in Section 6.2. A variety of missions was selected to span the uses of such aircraft, including especially the extremes of range, payload, and cold-weather operation. The atmospheric data are presented in Section 6.3

The missions are defined in Table 3.1.1. Each of the two long range missions was evaluated for three temperature profiles:

a) Nominal International Standard Atmosphere
b) 2% Probable Cold Day
c) 0.3% Probable Cold Day

Tables 3.1.2 a, b, c present the raw data for trip-time, fuel burn, the heater weight and the heat required for the reference fuel (#1) and the five study fuels (#2-#6). The data is presented first in the international system of units, and then each table is repeated in conventional units. The heater weight was exactly that required to keep the wing-tank fuel temperature 1.67°C above the freezing temperature for that fuel at the condition of extreme cooling-rate. The heat requirement was estimated very conservatively as the mass of fuel required to keep the fuel at the temperature specified above, when burned at 40% efficiency.

The fuel properties which have the most significant economic impact are listed at the top of these tables. Fuel properties are discussed in greater detail in Section 6.5; their operational effects are discussed in Section 4. Fuel #1 is the reference fuel; it is at the center of the specification-range for Jet-A.

Fuel #2 is at the specification-limit for Jet-A for the properties of economic importance; its freezing temperature and aromatic content are higher, while its energy-density (heat of combustion) is lower than the center of the specification. Fuel #3, arbitrarily named Hi-Freeze, has the same aromatic content and energy-density as the #2 fuel, but a higher freezing temperature. Fuel #4, named "Hi-Aromatic" has a further increase of freezing temperature and aromatic content, and a further decrease of energy-density. Fuel #5, "Reduced Flash", is similar to JP-4; it is characterized by very low freezing temperature, relatively low aromatic content, and relatively high energy-density. Fuel #6 is similar to the NASA ERBS fuel, but has a higher aromatic content than ERBS; its freezing temperature and aromatic content are at the high extremes considered, while its energy-density (together with Fuel #4) is at the low extreme considered.

The various study fuels have, of course, many other properties. These properties, which do not have significant economic impact, are discussed in Section 4.2.

Table 3.1.1
Mission Definition

Mission #	Mission Parameters	Heavy Jet	Light Jet	Turboprop
1.	Gross Weight, (lb), kg	(36675) 16670	(18300) 8318	(10375) 4716
	Trip Distance, Naut Mi	2700	2500	1600
	Fuel Load, (lb), kg	(14650) 6660	(7400) 3364	(2881) 1310
	Payload, (lb), kg	(1500) 682	(890) 405	(1361) 619
2.	Gross Weight, (lb), kg	(35800) 16273	(18300) 8318	(10375) 4716
	Trip Distance, Naut Mi	2000	1500	800
	Fuel Load, (lb), kg	(12320) 5600	(5580) 2536	(2881) 1310
	Payload, (lb), kg	(2955) 1343	(2750) 1250	(1361) 619
3.	Gross Weight,(lb), kg	(29480) 13400	(15820) 7191	(8494) 3861
	Trip Distance, Naut Mi	900	900	300
	Fuel Load, (lb), kg	(6000) 2727	(3100) 1409	(1000) 455
	Payload, (lb), kg	(2955) 1343	(2750) 1250	(1361) 619
4.	Gross Weight, (lb), kg	(26980) 12264	(14520) 6600	-
	Trip Distance, Naut Mi	400	400	-
	Fuel Load, (lb), kg	(3500) 1591	(1800) 818	-
	Payload, (lb), kg	(2955) 1343	(2750) 1250	-

Table 3.1.2.a
MISSION RAW DIRECT OPERATING COST DATA, ISO UNITS

MISSION DEFINITION		AIRCRAFT CLASS	FUELS 1. REF TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
		HEAVY JET						
Mission #	1	Median	T: 363.47	T: 363.47	T: 363.47	T: 363.47	T: 363.47	T: 363.47
Gross Weight	16670kg	Temp	F: 4944.72	F: 4988.66	F: 4998.66	F: 5038.03	F: 4930.63	F: 5038.03
Fuel Load	6660	Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
Payload #	682	Tank Factor	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
TDC/W	0.127	TF= 1.138						
Distance	2700NM							
		2%	T: 363.32	T: 363.32	T: 363.32	T: 363.32	T: 363.32	T: 363.32
		Probable	F: 4669.81	F: 4721.54	F: 4721.54	F: 4759.29	F: 4655.29	F: 4759.29
		Day	H: 0	H: 0	H: 8.85	8.93	H: 0	H: 9.03
		TF= 1.126	h: 0	h: 0	h: 0.12	h: 0.20	h: 0	h: 0.26
		0.3%	T: 363.29	T: 363.29	T: 363.29	T: 363.29	T: 363.29	T: 363.29
		Probable	F: 4569.97	F: 4670.88	F: 4670.88	F: 4721.87	F: 4588.87	F: 4721.87
		Day	H: 0	H: 8.84	H: 8.94	H: 9.03	H: 0	H: 9.14
		TF= 1.119	h: 0	h: 0.10	h: 0.20	h: 0.28	h: 0	h: 0.27
Mission #	2	Median	T: 271.35	T: 271.35	T: 271.35	T: 271.35	T: 271.35	T: 271.35
Gross Weight	16723	Temp	F: 4531.33	F: 4572.23	F: 4572.23	F: 4602.10	F: 4520.64	F: 4602.10
Fuel Load	5600	Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
Payload	1343	TF= 1.102	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
TDC/W	0.100							
Distance	2000							
		2%	T: 271.64	T: 271.64	T: 271.64	T: 271.64	T: 271.64	T: 271.64
		Probable	F: 4314.86	F: 4353.86	F: 4353.86	F: 4382.35	F: 4304.67	F: 4382.35
		Day	H: 0	H: 0	H: 0	H: 8.95	H: 0	H: 8.95
		TF= 1.093	h: 0	h: 0	h: 0	h: 0.14	h: 0	h: 0.14
		0.3%	T: 271.65	T: 271.65	T: 271.65	T: 271.65	T: 271.65	T: 271.65
		Probable	F: 4258.12	F: 4296.58	F: 4296.58	F: 4324.67	F: 4248.08	F: 4324.67
		Day	H: 0	H: 0	H: 8.87	H: 8.95	H: 0	H: 9.04
		TF= 1.088	h: 0	h: 0	h: 0.05	h: 0.16	h: 0	h: 0.21
Mission #	3	Median	T: 126.60	T: 126.60	T: 126.60	T: 126.60	T: 126.60	T: 126.60
Gross Weight	13400	Temp	F: 2052.00	F: 2066.93	F: 2066.93	F: 2077.49	F: 2048.68	F: 2077.49
Fueload	2727	Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
Payload	1343	TF= 1.032	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
TDC/W	0.055							
Distance	900							
Mission #	4	Median	T: 60.47	T: 60.47	T: 60.47	T: 60.47	T: 60.47	T: 60.47
Gross Weight	12264	Temp	F: 997.95	F: 1002.95	F: 1002.95	F: 1006.59	F: 992.10	F: 1006.59
Fuel Load	1591	Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
Payload	1343	TF= 1.010	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
TDC/W	0.0227							
Distance	400							

T: Time, Minutes, F: Fuel Burn, kg, H: Heater Weight, kg, h: Weight, kg, TF: Tankering Factor

Table 3.1.2.b
MISSION RAW DIRECT OPERATING COST DATA, ISO UNITS

MISSION DEFINITION	AIRCRAFT CLASS LIGHT JET	FUELS 1. REF TF=-44°C HOC=18574 %AROM=17.5	2.SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission # 1 Gross Weight 8318kg Fuel Load 3364 Payload 405 TDC/W 0.145 Distance 2500 NM	Median Temp Day Tank Factor TF= 1.281	T: 357.06 F: 3030.76 H: 0 h: 0	T: 357.06 F: 3056.18 H: 0 h: 0	T: 357.06 F: 3056.18 H: 0 h: 0	T: 357.06 F: 3074.71 H: 0 h: 0	T: 357.06 F: 3024.11 H: 0 h: 0	T: 357.06 F: 3074.71 H: 8.47 h: 0.05
	2% Probable Day TF= 1.256	T: 357.63 F: 2857.89 H: 8.76 h: 0.05	T: 357.63 F: 2882.08 H: 8.85 h: 0.10	T: 357.63 F: 2882.08 H: 8.92 h: 0.17	T: 357.63 F: 2895.67 H: 8.96 h: 0.23	T: 357.63 F: 2851.56 H: 0 h: 0	T: 357.63 F: 2895.67 H: 9.03 h: 0.28
	0.3% Probable Day TF= 1.249	T: 357.63 F: 2788.58 H: 8.87 h: 0.14	T: 357.63 F: 2812.23 H: 8.93 h: 0.19	T: 357.63 F: 2812.23 H: 9.00 h: 0.25	T: 357.63 F: 2829.48 H: 9.05 h: 0.30	T: 357.63 F: 2782.40 H: 0 h: 0	T: 357.63 F: 2829.48 H: 9.13 h: 0.35
Mission # 2 Gross Weight 8318 Fuel Load 2536 Payload 1250 TDC/W 0.0909 Distance 1500	Median Temp Day TF: 1.163	T: 217.53 F: 1952.74 H: 0 h: 0	T: 217.53 F: 1969.75 H: 0 h: 0	T: 217.53 F: 1969.75 H: 0 h: 0	T: 217.53 F: 1982.15 H: 0 h: 0	T: 217.53 F: 1948.30 H: 0 h: 0	T: 217.53 F: 1982.15 H: 0 h: 0
	2% Probable Day TF: 1.149	T: 218.10 F: 1843.40 H: 0 h: 0	T: 218.10 F: 1859.58 H: 0 h: 0	T: 218.10 F: 1859.58 H: 0 h: 0	T: 218.10 F: 1871.38 H: 8.85 h: 0.07	T: 218.10 F: 1839.17 H: 0 h: 0	T: 218.10 F: 1871.38 H: 8.90 h: 0.09
	0.3% Probable Day TF= 1.142	T: 218.09 F: 1800.21 H: 0 h: 0	T: 218.09 F: 1816.04 H: 0 h: 0	T: 218.09 F: 1816.04 H: 0 h: 0	T: 218.09 F: 1827.59 H: 8.92 h: 0.10	T: 218.09 F: 1796.08 H: 0 h: 0	T: 218.09 F: 1827.59 H: 8.99 h: 0.14
Mission # 3 Gross Weight 7191 Fueload 1409 Payload 1250 TDC/W 0.0545 Distance 900	Median Temp Day TF= 1.080	T: 133.35 F: 1140.30 H: 0 h: 0	T: 133.35 F: 1147.81 H: 0 h: 0	T: 133.35 F: 1147.81 H: 0 h: 0	T: 133.35 F: 1154.09 H: 0 h: 0	T: 133.35 F: 1138.21 H: 0 h: 0	T: 133.35 F: 1154.09 H: 0 h: 0
Mission # 4 Gross Weight 6600 Fuel Load 818 Payload 1250 TDC/W 0.0273 Distance 400	Median Temp Day TF= 1.024	T: 63.36 F: 550.08 H: 0 h: 0	T: 63.36 F: 552.94 H: 0 h: 0	T: 63.36 F: 552.94 H: 0 h: 0	T: 63.36 F: 555.03 H: 0 h: 0	T: 63.36 F: 549.33 H: 0 h: 0	T: 63.36 F: 555.03 H: 0 h: 0

T: Time, Minutes, F: Fuel Burn, kg, H: Heater Weight, kg, h: Weight, kg

Table 3.1.2.c
MISSION RAW DIRECT OPERATING COST DATA, ISO UNITS

MISSION DEFINITION		AIRCRAFT CLASS	FUELS: 1. REF	2. SPEC LIMIT	3. HI-FREEZE	4. HI-AROM	5. REDUCED FLASH	6. SPECIAL
		TURBOPROP	TF=-44°C	TF=-40°C	TF=-35°C	TF=-31.7°C	TF=-55°C	T=-28.9°C
			HOC=18574	HOC=18400	HOC=18400	HOC=18275	HOC=18620	HOC=18275
			%AROM=17.5	%AROM=20.0	%AROM=20.0	%AROM=30.0	%AROM=16.0	%AROM=35.0
Mission #	1	Median	T: 373.02	T: 373.02	T: 373.02	T: 373.02	T: 373.02	T: 373.02
Gross Weight	4716kg	Temp	F: 1163.46	F: 1174.12	F: 1174.12	F: 1181.90	F: 1160.68	F: 1181.90
Fuel Load	1310	Day	H: 0	H: 0	H: 8.74	H: 8.78	H: 0	H: 8.85
Payload #	619	Tank Factor	h: 0	h: 0	h: 0.01	h: 0.03	h: 0	h: 0.06
TDC/W	0.109	TF= 1.0						
Distance	1600 NM							
		2%	T: 364.72	T: 364.72	T: 364.72	T: 364.72	T: 364.72	T: 364.72
		Probable	F: 7194.11	F: 1205.06	F: 1205.06	F: 1213.05	F: 1191.25	F: 1213.05
		Day	H: 9.04	H: 9.10	H: 9.21	H: 9.35	H: 8.80	H: 9.45
			h: 0.14	h: 0.16	h: 0.21	h: 0.26	h: 0.04	h: 0.32
		TF: 1.						
		0.3%	T: 364.49	T: 364.49	T: 364.49	T: 364.49	T: 364.49	T: 364.49
		Probable	F: 1330.80	F: 1205.39	F: 1205.39	F: 1213.38	F: 1191.57	F: 1213.38
		Day	H: 9.05	H: 9.12	H: 9.25	H: 9.37	H: 8.83	H: 9.49
		TF= 1.	h: 0.15	h: 0.17	h: 0.23	h: 0.28	h: 0.05	h: 0.33
Mission #	2	Median	T: 190.17	T: 190.17	T: 190.17	T: 190.17	T: 190.17	T: 190.17
Gross Weight	4716	Temp	F: 620.43	F: 625.95	F: 625.95	F: 629.98	F: 618.99	F: 629.98
Fuel Load	1310	Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
Payload	619	TF= 1.	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
TDC/W	0.059							
Distance	800							
		2%	T: 187.06	T: 187.06	T: 187.06	T: 187.06	T: 187.06	T: 187.06
		Probable	F: 636.23	F: 641.90	F: 641.90	F: 645.82	F: 634.75	F: 645.82
		Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
		TF=1.	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
		0.3%	T: 187.03	T: 187.03	T: 187.03	T: 187.03	T: 187.03	T: 187.03
		Probable	F: 636.66	F: 642.34	F: 642.34	F: 646.48	F: 635.18	F: 646.48
		Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
		TF= 1.	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Mission #	3	Median	T: 73.34	T: 73.34	T: 73.34	T: 73.34	T: 73.34	T: 73.34
Gross Weight	3861	Temp	F: 270.65	F: 271.77	F: 271.77	F: 272.10	F: 270.31	F: 272.10
Fueload	455	Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
Payload	619	TF= 1.	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
TDC/W	0.023							
Distance	300							

T: Times, F: Fuel Burn, kg, H: Heater Weight, kg, h: Weight, kg

Table 3.1.2.a
MISSION RAW DIRECT OPERATING COST DATA, CONVENTIONAL UNITS

MISSION DEFINITION	AIRCRAFT CLASS HEAVY JET	FUELS 1. REF TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission # 1 Gross Weight (36675 lbs) Fuel Load (14650 lbs) Payload # (682 lbs) TDC/W (0.28) Distance 2700 NM	Median Temp Day Tank Factor TF= 1.138	T: 363.47 F:(10878.39) H: 0 h: 0	T: 363.47 F:(10997.06) H: 0 h: 0	T: 363.47 F:(1097.06) H: 0 h: 0	T: 363.47 F:(10997.06) H: 0 h: 0	T: 363.47 F:(11083.66) H: 0 h: 0	T: 363.47 F:(11083.66) H: 0 h: 0
	2% Probable Day TF= 1.126	T: 363.32 F:(10273.58) H: 0 h: 0	T: 363.32 F: (10373.38) H: 0 h: 0	T: 363.32 F:(10387.38) H: (19.46) h: (0.27)	T: 363.32 F:(10470.44) (19.64) h: (0.43)	T: 363.32 F:(10243.84) H: 0 h: 0	T: 363.32 F:(10470.44 H: (19.86) h: (0.58)
	0.3% Probable Day TF= 1.119	T: 363.29 F:(10113.33) H: 0 h: 0	T: 363.29 F:(10255.93) H: (19.44) h: (0.23)	T: 363.29 F:(10275.93) H: (19.66) h: (0.43)	T: 363.29 F:(10388.12) H: (19.86) h: (0.62)	T: 363.29 F:(10388.91) H: 0 h: 0	T: 363!29 F:(10388.12) H: (20.10) h: (0.81)
Mission # 2 Gross Weight (35800) Fuel Load (12320) Payload (2955) TDC/W (0.22) Distance 2000	Median Temp Day TF= 1.102	T: 271.35 F:(9968.93) H: 0 h: 0	T: 271.35 F:(10058.91) H: 0 h: 0	T: 271.35 F:(10058.91) H: 0 h: 0	T: 271.35 F:(10058.91) H: 0 h: 0	T: 271.35 F:(10124.63) H: 0 h: 0	T: 271.35 F:(10124.63) H: 0 h: 0
	2% Probable Day TF= 1.093	T: 271.64 F:(9492.69) H: 0 h: 0	T: 271.64 F:(9578.50) H: 0 h: 0	T: 271.64 F:(9578.50) H: 0 h: 0	T: 271.64 F:(9641.17) H: (19.52) h: (0.14)	T: 271.64 F:(9470.28) H: 0 h: 0	T: 271.64 F:(9641.17) H: (19.68) h: (0.14)
	0.3% Probable Day TF= 1.088	T: 271.65 F:(9367.87) H: 0 h: 0	T: 271.65 F:(9452.47) H: 0 h: 0	T: 271.65 F:(9452.47) H: (19.52) h: (0.11)	T: 271.65 F:(9452.47) H: (19.68) h: (0.35)	T: 271.65 F:(9345.77) H: 0 h: 0	T: 271.65 F:(9514.28) H: (19.88) h: (0.46)
Mission # 3 Gross Weight (29480) Fueload (6000) Payload (2955) TDC/W (0.10) Distance 900	Median Temp Day TF= 1.032	T: 126.60 F:(4515.40) H: 0 h: 0	T: 126.60 F:(4547.25) H: 0 h: 0	T: 126.60 F:(4547.25) H: 0 h: 0	T: 126.60 F:(4570.48) H: 0 h: 0	T: 126.60 F:(4507.09) H: 0 h: 0	T: 126.60 F:(4570.48) H: 0 h: 0
Mission # 4 Gross Weight (26980) Fuel Load (3500) Payload (2955) TDC/W (0.05) Distance 400	Median Temp Day TF= 1.010	T: 60.47 F:(2195.49) H: 0 h: 0	T: 60.47 F:(2206.48) H: 0 h: 0	T: 60.47 F:(2206.48) H: 0 h: 0	T: 60.47 F:(2214.50) H: 0 h: 0	T: 60.47 F:(2182.63) H: 0 h: 0	T: 60.47 F:(2214.56) H: 0 h: 0

T: Time, Minutes, F: Fuel Burn, Pounds, H: Heater Weight, Pounds, h: Weight, Pounds, TF: Tankering Factor

Table 3.1.2.b
MISSION RAW DIRECT OPERATING COST DATA, CONVENTIONAL UNITS

MISSION DEFINITION	AIRCRAFT CLASS LIGHT JET	FUELS 1. REF TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission # 1 Gross Weight (18300 lbs) Fuel Load (7440 lbs) Payload (890 lbs) TDC/W (0.32) Distance 2500 NM	Median Temp Day Tank Factor TF= 1.281	T: 357.06 F:(6667.67) H: 0 h: 0	T: 357.06 F:(6723.60) H: 0 h: 0	T: 357.06 F:(6723.60) H: 0 h: 0	T: 357.06 F:(6764.36) H: 0 h: 0	T: 357.06 F:(6653.05) H: 0 h: 0	T: 357.06 F:(6764.36) H: (19.30) h: (0.12)
	2% Probable Day TF= 1.256	T: 357.63 F:(6287.35) H: (19.28) h: (0.12)	T: 357.63 F:(6340.57) H: (19.48) h: (0.23)	T: 357.63 F:(6340.48) H: (19.62) h: (0.38)	T: 357.63 F:(6340.57) H: (19.72) h: (0.50)	T: 357.63 F:(6273.44) H: 0 h: 0	T: 357.63 F:(6370.48) H: (19.86) h: (0.62)
	0.3% Probable Day TF= 1.249	T: 357.63 F:(6134.88) H: (19.52) h: (0.31)	T: 357.63 F:(6186.91) H: (19.64) h: (0.42)	T: 357.63 F:(6186.91) H: (19.80) h: (0.56)	T: 357.63 F:(6224.85) H: (19.92) h: (0.65)	T: 357.63 F:(6121.28) H: 0 h: 0	T: 357.63 F:(6224.85) H: (20.08) h: (0.78)
Mission # 2 Gross Weight (18300) Fuel Load (5580) Payload (2750) TDC/W (0.20) Distance 1500	Median Temp Day TF: 1.163	T: 217.53 F:(4296.03) H: 0 h: 0	T: 217.53 F:(4333.45) H: 0 h: 0	T: 217.53 F:(4333.45) H: 0 h: 0	T: 217.53 F:(4360.74) H: 0 h: 0	T: 217.53 F:(4286.25) H: 0 h: 0	T: 217.53 F:(4360.74) H: 0 h: 0
	2% Probable Day TF: 1.149	T: 218.10 F:(4055.49) H: 0 h: 0	T: 218.10 F:(4091.08) H: 0 h: 0	T: 218.10 F:(4091.08) H: 0 h: 0	T: 218.10 F:(4117.04) H: (19.46) h: (0.15)	T: 218.10 F:(4046.18) H: 0 h: 0	T: 218.10 F:(4117.04) H: (19.58) h: (0.19)
	0.3% Probable Day TF= 1.142	T: 218.09 F:(3960.47) H: 0 h: 0	T: 218.09 F:(3995.29) H: 0 h: 0	T: 218.09 F:(3995.29) H: 0 h: 0	T: 218.09 F:(4020.69) H: (19.62) h: (0.23)	T: 218.09 F:(3951.37) H: 0 h: 0	T: 218.09 F:(4020.69) H: (19.78) h: 0.31
Mission # 3 Gross Weight (15820) Fueload (3100) Payload (2750) TDC/W (0.12) Distance 900	Median Temp Day TF= 1.080	T: 133.35 F:(2508.65) H: 0 h: 0	T: 133.35 F:(2525.19) H: 0 h: 0	T: 133.35 F:(2525.19) H: 0 h: 0	T: 133.35 F:(2538.99) H: 0 h: 0	T: 133.35 F:(2504.07) H: 0 h: 0	T: 133.35 F:(2538.99) H: 0 h: 0
Mission # 4 Gross Weight (4520) Fuel Load (1800) Payload (2750) TDC/W (0.06) Distance 400	Median Temp Day TF= 1.024	T: 63.36 F:(1210.18) H: 0 h: 0	T: 63.36 F:(1216.46) H: 0 h: 0	T: 63.36 F:(1216.46) H: 0 h: 0	T: 63.36 F:(1221.06) H: 0 h: 0	T: 63.36 F:(1208.53) H: 0 h: 0	T: 63.36 F:(1221.06) H: 0 h: 0

T: Time, Minutes, F: Fuel Burn, Pounds, H: Heater Weight, Pounds, h: Weight, Pounds

Table 3.1.2.c
MISSION RAW DIRECT OPERATING COST DATA, CONVENTIONAL UNITS

MISSION DEFINITION		AIRCRAFT CLASS TURBOPROP	FUELS 1. REF TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission #	1	Median	T: 373.02	T: 373.02	T: 373.02	T: 373.02	T: 373.02	T: 373.02
Gross Weight	(10375 lbs)	Temp	F:(2559.62)	F:(2583.06)	F:(2583.06)	F:(2600.18)	F:(2553.49)	F:(2600.18)
Fuel Load	(2881 lbs)	Day	H: 0	H: 0	H: (19.22)	H: (19.32)	H: 0	H: (19.46)
Payload	(1361 lbs)	Tank Factor	h: 0	h: 0	h: (0.02)	h: (0.07)	h: 0	h: 0.13
TDC/W	(0.24)	TF= 1.0						
Distance	1600 NM							
		2%	T: 364.72	T: 364.72	T: 364.72	T: 364.72	T: 364.72	T: 364.72
		Probable	F:(2627.04)	F:(2651.13)	F:(2651.13)	F:(2668.71)	F:(2620.75)	F:(2668.71)
		Day	H: (19.88)	H: (20.02)	H: (20.26)	H: (20.56)	H: (19.36)	H: (20.80)
			h: (0.30)	h: (0.36)	h: (0.46)	h: (0.58)	h: (0.09)	h: (0.70)
		TF: 1.						
		0.3%	T: 364.49	T: 364.49	T: 364.49	T: 364.49	T: 364.49	T: 364.49
		Probable	F:(2627.75)	F:(2651.85)	F:(2651.85)	F:(2669.44)	F:(2621.46)	F:(2669.44)
		Day	H: (19.92)	H: (20.06)	H: (20.36)	H: (20.62)	H: (19.42)	H: (20.88)
		TF= 1.	h: (0.32)	h: (0.38)	h: (0.51)	h: (0.62)	h: (0.11)	h: (0.73)
Mission #	2	Median	T: 190.17	T: 190.17	T: 190.17	T: 190.17	T: 190.17	T: 190.17
Gross Weight	(10375)	Temp	F:(1364.94)	F:(1377.09)	F:(1377.09)	F:(1385.96)	F:(1361.77)	F:(1385.96)
Fuel Load	(2881)	Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
Payload	(1361)	TF= 1.	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
TDC/W	(0.13)							
Distance	800							
		2%	T: 187.06	T: 187.06	T: 187.06	T: 187.06	T: 187.06	T: 187.06
		Probable	F:(1399.71)	F:(1412.18)	F:(1412.18)	F:(1420.80)	F:(1396.44)	F:(1420.80)
		Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
		TF=1.	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
		0.3%	T: 187.03	T: 187.03	T: 187.03	T: 187.03	T: 187.03	T: 187.03
		Probable	F:(1400.65)	F:(1413.14)	F:(1413.14)	F:(1422.25)	F:(1397.39)	F:(1422.25)
		Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
		TF= 1.	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Mission #	3	Median	T: 73.34	T: 73.34	T: 73.34	T: 73.34	T: 73.34	T: 73.34
Gross Weight	(8494)	Temp	F: (595.43)	F: (597.90)	F: (597.90)	F: (598.62)	F: (594.69)	F: (598.62)
Fueload	(1000)	Day	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
Payload	(1361)	TF= 1.	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
TDC/W	(0.05)							
Distance	300							

T: Times, F: Fuel Burn, Pounds, H: Heater Weight, Pounds, h: Weight, Pounds

Table 3.1.2a presents the raw data for the heavy jet; Tables 3.1.2b and 3.1.2c present similar data for the light jet and turboprop, respectively. For example, in Table 3.1.2a, consider Mission #1 for the Reference Fuel, nominal Jet A, Fuel #1, on the median day. The trip required 363.47 minutes and burned 4944.72kg (10878.39 pounds) of fuel. Fuel heating was not required. Now, consider Mission # 1 with the Specification-Limit Jet A, Fuel #2, on the 0.3% probable cold day. The trip required exactly the same time as the Reference, #1 fuel, but the fuel burn was 4648.15kg (10225.93 pounds). Further, on that cold day, the #2 fuel required a heater weighing 8.84kg (19.44 pounds) to deliver the required heat and consumed 0.10kg (0.23 pounds) of fuel in providing the heat.

The time for all fuels for any mission and temperature condition is invariant. This is consistent with the advice of the engine manufacturer that the fuel flow should be adjusted so that the thrust profile is invariant. The consequence is that the mission time is constant but the fuel burn is variable.

The cost/weight factor, total direct cost per kg (pound) of aircraft empty weight (TDC/W), has the value 0.127 (0.28) for the heavy jet. This factor enables establishing the cost of carrying the heater. This cost is based on the assumption that fuel costs 11.82 cents per kilogram (26 cents per pound). In this context, the total direct operating cost is the sum of the fuel cost for the mission and the hourly operating costs, taken from Table 3.1.3. Ideally, this factor depends on the trip time and fuel consumption and varies between fuels, since fuel consumption varies with the fuel's heat of combustion. However, the variation of this coefficient is considerably less important since the fuels' energies differ relatively little. Further, this coefficient is essentially invariant for different probable cold days, since the trip time has little variation with temperature.

Table 3.1.3: Hourly Operating Costs, 1982

Aircraft Class	Cost Per Flight Hour, Excluding Fuel	
Heavy Jet	Engine	$200
	Other	$213
	Total	$413
Light Jet	Engine	$ 84
	Other	$167
	Total	$251
Turboprop	Engine	$ 52
	Other	$ 80
	Total	$132

Tables 3.1.2 a, b, and c show a coefficient T_F, tankering coefficient. This coefficient is evaluated as

$$T_F = \dot{W}_o/\dot{W}_t$$

where $\dot{W}_o$ and $\dot{W}_t$ are the fuel burn rates at the beginning and end of cruise, respectively. This is also a raw datum; it does not vary significantly from one fuel to another but does vary with the duration of the mission and with atmospheric temperature. The tankering coefficient is used to estimate the excess fuel which must be loaded to enable landing with a specified quantity for reserve. The derivation of the tankering coefficient is presented in Section 6.10, an Appendix.

This completes the presentation of the raw data.

3.2 Total & Relative Direct Operating Costs

A variety of assumptions are required to generate costs from the raw data of time, weight of fuel burn, heater weight, and weight of fuel burned to provide the heat. These assumptions, and their rationale, are developed in this section, and the raw data of Section 3.1 are converted to total cost of the reference fuel, #1, and the relative costs of the study fuels. This conversion is carried out for each mission. One of the important steps performed in this section is the combination of the results for the various probable-cold day missions. There are four elements which must be converted; these are the conversions to cost of:

a) mission time
b) fuel burn
c) heater weight, and,
d) weight of fuel consumed in providing the heat.

These conversions are now examined.

3.2.1 Time

Engines are overhauled after some fixed number of flight hours; the overhaul cost in any mission is thus proportional to the duration of that mission. But the aromatic content of fuel affects the engine's wear and thus affects the overhaul cost per flight hour. The details of the cost increment calculation for the various fuels and aircraft are presented in Section 6.9. The conclusions stated herein are presented in Table 3.2.1.

Table 3.2.1 Effect of Fuel Aromatic Content on Cost of Time

Fuel Type & #	Aromatic Content	Aircraft Incremental Direct Operating Costs per Flt. Hr. Heavy Jet	Light Jet	Turboprop
1. Reference	17.5%	$ 0.00	0.00	0.00
2. Spec. Limit	20.0	5.40	2.27	1.40
3. Hi-Freeze	20.0	5.40	2.27	1.40
4. Hi-Aromatic	30.0	23.41	9.84	6.08
5. Reduced Flash	16.0	-20.71	-8.70	-5.38
6. Special	35.0	31.52	13.24	8.18

Note that Fuel #5, as its aromatic content is less than that of the reference fuel, has a lesser cost than the reference. Its incremental cost is therefore negative.

As flight times vary little for the various atmospheric temperature conditions, it is sufficient to calculate the fuel costs for the median temperature case only.

3.2.2 Fuel

The fuel burned in any mission is not by itself a valid measure of the cost of fuel. It is necessary that the mission have a certain reserve when the original destination is reached. But a reserve of energy is required instead of mass because of the variation between the fuels of the Heat of Combustion, or energy density. A greater mass of reserve fuel is therefore required for a less energetic fuel. But fuel must be burned to carry this increment, required to have equal reserve. The tankering factor T_F is used to estimate the excess fuel required at takeoff in order to have the same reserve at landing. The price of all fuels is assumed to be 11.82 cents per kilogram (26 cents per pound).

3.2.3 Heater

It is assumed that all missions must be performed for all fuels and for all temperature conditions. The worst case is the very long range mission (#1) at the extreme cold condition, a 0.3% probable cold day. Tables 3.1.2a, b, and c show that the heavy jet requires a heater in this case for fuels 2, 3, 4, and 6; the light jet requires a heater for fuels 1, 2, 3, 4, and 6, and the turboprop requires a heater for all the fuels. If a heater is required for any mission, it must be aboard for all missions, for that fuel. The fuel may therefore be penalized by the cost (or relative cost) of carrying the heater's weight, whether or not the heater is used in any mission. Thus, the heavy jet requires a heater weighing 9.14kg (20.10 pounds) for Mission #1, at the 0.3% cold day with fuel #6; it must carry that heater in all other missions with that fuel. As the reference fuel does not require a heater at all, that weight yields a measurable cost penalty for fuel #6. The cost penalty for this added weight is calculated from the cost/weight factor, (TDC/W). The product of heater weight and this factor yields the economic measure of the cost of requiring a heater.

3.2.4 Heat

The cost of operating the heater is directly proportional to the weight of fuel consumed in this process. The cost of operating the heater is thus relatively small; in the worst case (Heavy Jet, Mission #1, 0.3% day) this cost is $0.21.

3.2.5 Mission Costs

The consequences of the assumptions used in generating costs are discussed in this subsection. Cost of Time does not vary with the atmospheric temperature, except that as the mission time changes the relative costs of fuel vary slightly with temperature. The costs of the heater, determined by the worst-case requirement for the heater, are thus independent of temperature and depend only on the cost-ratio TDC/W. The costs of operating the heater are almost negligible. These data and assumptions are used to convert the raw data of Tables 3.1.2, a, b, and c to the cost data of Tables 3.2.2.a, b, and c.

Consider the relative costs for the various temperature cases; in Missions 1 and 2, these relative costs are almost invariant with temperature. Further, the total costs of the reference fuel do not vary greatly with temperature; the extreme variation of total fuel cost is less than 10% of the nominal case. Moreover, if the average total direct costs for the reference fuel are estimated using the given probabilities of the extreme temperature conditions, this average is within 0.2% of the median day value. It is therefore valid to omit further consideration of the extreme temperature cases of Missions 1 and 2; these cases have served their function of establishing the requirements for the fuel heater and heat which will be required in each aircraft for each of the study fuels. Table 3.2.2 reflects the cost of carrying the heater for all missions, and shows that the additional cost of providing the heat is negligible, with a value of 21 cents out of a relative cost of $275 in the worst case.

The consequences of the above observations are that:

a) the cost of the fuel burned for fuel heating in the extreme temperature conditions is trivial, and,
b) the extreme temperature conditions of Missions 1 and 2 may be neglected; only the median temperature day data need be considered further.

Table 3.2.2.a
TOTAL COSTS WITH REFERENCE FUEL AND RELATIVE COSTS WITH STUDY FUELS

MISSION DEFINITION	AIRCRAFT CLASS HEAVY JET		1. REF FUEL TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
				STUDY FUELS				
Mission # 1	Median Temp Day	T:	2501.89	32.71	32.71	141.81	-125.46	190.94
Gross Weight 16670(36675)		F:	2828.38	45.67	45.67	79.00	-11.93	79.00
Fuel Load 6660(14650)		H:	0	5.44	5.50	5.56	0	5.63
Payload 682(1500)		h:	0	0	0	0	0	0
Distance 2700 NM		S:	5330.27	83.82	83.88	226.37	-137.39	275.57
	2% Probable Day	T:	2500.85	32.71	32.71	141.81	-125.46	190.94
		F:	2671.13	45.43	45.43	78.60	- 11.87	78.60
		H:	0	5.44	5.50	5.56	0	5.63
		h:	0	0	0	0.11	0	0.15
		S:	5171.98	83.58	83.64	226.08	-137.33	275.32
	0.3% Probable Day	T:	2500.65	32.71	32.71	141.81	-125.46	190.94
		F:	2629.47	45.15	45.15	78.26	- 11.81	78.26
		H:	0	5.44	5.50	5.56	0	5.63
		h:	0	0.06	0	0.12	0	0.21
		S:	5130.12	83.36	83.36	225.75	-137.27	275.04
Mission # 2	Median Temp Day	T:	1867.79	24.42	24.42	105.87	-93.66	142.55
Gross Weight 16273(35800)		F:	2591.92	32.15	32.15	55.63	- 8.40	55.63
Fuel Load 5600(12320)		H:	0	4.28	4.33	4.37	0	4.42
Payload 1343(2955)		h:	0	0	0	0	0	0
Mission Distance 2000		S:	4459.71	60.85	60.90	165.88	-102.06	202.60
	2% Probable Day	T:	1869.69	24.45	24.45	105.98	-93.76	142.70
		F:	2468.10	32.79	32.79	56.74	- 8.56	56.74
		H:	0	4.28	4.33	4.37	0	4.42
		h:	0	0	0.06	0.06	0	0.08
		S:	4378.79	61.52	61.63	167.15	-102.32	203.94
	0.3% Probable Day	T:	1869.86	24.45	24.45	105.99	-93.76	142.71
		F:	2435.65	31.83	31.83	55.08	- 8.31	55.08
		H:	0	4.28	4.33	4.37	0	4.42
		h:	0	0	0.09	0	0	0.12
		S:	4305.51	60.56	60.70	165.53	-102.07	202.33
Mission # 3	Median Temp Day	T:	871.43	11.39	11.39	49.40	-43.70	66.51
Gross Weight 13400(29480)		F:	1174.00	14.91	14.91	25.80	- 3.90	25.80
Fueload 2727(6000)		H:	0	1.94	1.97	1.99	0	2.01
Payload 1343(2955)		h:	0	0	0	0	0	0
Distance 900		S:	2045.43	28.24	28.27	77.19	- 47.60	94.32
Mission # 4	Median Temp Day	T:	416.24	5.44	5.44	23.59	-20.87	31.77
Gross Weight 12264(26980)		F:	570.83	8.48	8.48	14.67	- 2.22	14.67
Fuel Load 1591(3500)		H:	0	0.97	0.98	0.99	0	1.01
Payload 1343(2955)		h:	0	0	0	0	0	0
Distance 400		S:	987.07	14.89	14.90	39.25	-23.09	47.45

T,F,H,h,S, :Cost (Relative Cost) of Time, Fuel, Heater, Heat, and Sum, Respectively, $

Table 3.2.2.b
COSTS WITH REFERENCE FUEL AND RELATIVE COSTS WITH STUDY FUELS

MISSION DEFINITION		AIRCRAFT CLASS	STUDY FUELS					
		LIGHT JET	1. REF FUEL TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission #	1	Median	T: $1493.70	T: 13.51	T: 13.51	T: 58.56	T: -51.77	T: 78.79
Gross Weight	8318(18300)	Temp	F: 1733.59	F: 21.06	F: 21.06	F: 36.41	F: - 5.50	F: 36.41
Fuel Load	3364(7440)	Day	H: 6.25	H: 0.03	H: 0.09	H: 0.12	H: - 6.25	H: 0.18
Payload	405(890)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.03
Distance	2500 NM		S: 3233.54	S: 34.60	S: 34.66	S: 95.09	S: -63.52	S: 115.41
		2%	T: 1469.09	T: 13.53	T: 13.53	T: 58.65	T: -51.86	T: 78.92
		Probable	F: 1634.71	F: 20.94	F: 20.94	F: 33.31	F: - 5.47	F: 33.31
		Day	H: 6.25	H: 0.03	H: 0.09	H: 0.12	H: -6.25	H: 0.18
			h: 0.03	h: 0.03	h: 0.07	h: 0.10	h: 0	h: 0.13
			S: 3137.08	S: 34.53	S: 34.63	S: 92.18	S: -63.58	S: 112.54
		0.3%	T: 1469.09	T: 13.53	T: 13.53	T: 58.65	T: -51.86	T: 78.92
		Probable	F: 1595.07	F: 20.90	F: 20.90	F: 36.15	F: - 5.46	F: 36.15
		Day	H: 6.25	H: 0.03	H: 0.09	H: 0.12	H: - 6.25	H: 0.18
			h: 0.08	h: 0.03	h: 0.07	h: 0.09	h: 0	h: 0.12
			S: 3097.09	S: 34.49	S: 34.59	S: 95.01	S: -63.57	S: 115.37
Mission #	2	Median	T: 910.00	T: 8.23	T 8.23	T: 35.67	T: -31.54	T: 48.00
Gross Weight	8318(18300)	Temp	F: 1116.97	F: 14.99	F: 14.99	F: 25.92	F: - 3.92	F: 25.92
Fuel Load	2536(5580)	Day	H: 3.90	H: 0.03	H: 0.06	H: 0.06	H: - 3.90	H: 0.12
Payload	1250(2750)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Distance	1500		S: 2030.87	S: 23.25	S: 23.28	S: 61.65	S: -39.36	S: 74.04
		2%	T: 912.38	T: 8.25	T: 8.25	T: 35.77	T: -31.62	T: 48.13
		Probable	F: 1054.43	F: 14.94	F: 14.94	F: 25.84	F: - 3.91	F: 25.84
		Day	H: 3.90	H: 0.03	H: 0.06	H: 0.08	H: - 3.90	H: 0.12
			h: 0	h: 0	h: 0.04	h: 0.04	h: 0	h: 0.05
			S: 1970.71	S: 23.22	S: 23.29	S: 61.73	S: -39.43	S: 74.14
		0.3%	T: 912.34	T: 8.25	T: 8.25	T: 35.77	T: -31.62	T: 48.13
		Probable	F: 1029.72	F: 14.89	F: 14.89	F: 25.75	F: - 3.89	F: 25.75
		Day	H: 3.90	H: 0.03	H: 0.06	H: 0.08	H: - 3.90	H: 0.12
			h: 0	h: 0	h: 0.06	h: 0.06	h: 0	h: 0.08
			S: 1945.96	S: 23.17	S: 23.26	S: 61.66	S: 39.41	S: 74.08
Mission #	3	Median	T: 557.85	T: 5.05	T: 5.05	T: 21.87	T: -19.34	T: 29.43
Gross Weight	7191(15820)	Temp	F: 652.25	F: 7.83	F: 7.83	F: 13.55	F: - 2.04	F: 13.55
Fueload	1409(3100)	Day	H: 2.34	H: 0.02	H: 0.04	H: 0.05	H: - 2.34	H: 0.07
Payload	1250(2750)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Distance	900		S: 1212.44	S: 12.90	S: 12.92	S: 35.47	S: -23.72	S: 43.05
Mission	4	Median	T: 265.06	T: 2.40	T: 2.40	T: 10.39	T: - 9.19	T: 13.98
Gross Weight	6600(14520)	Temp	F: 314.65	F: 4.31	F: 4.31	F: 7.46	F: - 1.13	F: 7.46
Fuel Load	818(1800)	Day	H: 1.17	H: 0.01	H: 0.02	H: 0.03	H: - 1.17	H: 0.03
Payload	1250(2750)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Distance	400		S: 580.88	S: 6.72	S: 6.73	S: 17.88	S: -11.49	S: 21.47

T,F,H,h,S, : Cost (Relative Cost) of Time, Fuel, Heater, Heat, and Sum, Respectively, $

Table 3.2.2.c
COSTS WITH REFERENCE FUEL AND RELATIVE COSTS WITH STUDY FUELS

MISSION DEFINITION		AIRCRAFT CLASS TURBOPROP	STUDY FUELS 1. REF FUEL TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission #	1	Median	T: 820.64	T: 8.70	T: 8.70	T: 37.80	T: -33.45	T: 50.86
Gross Weight	4716(10375)	Temp Day	F: 665.50	F: 6.88	F: 6.88	F: 11.91	F: - 1.80	F: 11.91
Fuel Load	1310(2881)		H: 4.78	H: 0.03	H: 0.11	H: 0.17	H: - 0.03	H: 0.23
Payload #	619(1361)		h: 0	h: 0	h: 0	h: 0.02	h: 0	h: 0.03
Distance	1600 NM		S: 1490.92	S: 15.61	S: 15.70	S: 49.90	S: -35.38	S: 63.03
		2%	T: 802.38	T: 8.51	T: 8.51	T: 36.96	T: -32.70	T: 49.72
		Probable	F: 683.03	F: 6.89	F: 6.89	F: 11.91	F: - 1.80	F: 11.91
		Day	H: 4.78	H: 0.03	H: 0.11	H: 0.17	H: - 0.73	H: 0.13
			h: 0.08	h: 0.01	h: 0.04	h: 0.07	h: - 0.06	h: 0.10
			S: 1490.27	S: 15.44	S: 15.55	S: 49.11	S: -34.69	S: 61.96
		0.3%	T: 801.88	T: 8.50	T: 8.50	T: 36.93	T: -32.68	T: 49.69
		Probable	F: 683.22	F: 6.89	F: 6.89	F: 11.92	F: - 1.80	F: 11.92
		Day	H: 4.78	H: 0.03	H: 0.11	H: 0.17	H: - 0.13	H: 0.23
			h: 0.08	h: 0.02	h: 0.05	h: 0.08	h: - 0.05	h: 0.11
			S: 1489.96	S: 15.44	S: 15.55	S: 49.10	S: -34.66	S: 61.95
Mission #	2	Median	T: 418.37	T: 4.44	T: 4.44	T: -19.27	T: -17.05	T: 25.93
Gross Weight	4716(10375)	Temp	F: 354.88	F: 6.89	F: 6.89	F: 11.91	F: - 1.80	F: 11.91
Fuel Load	1310(2881)	Day	H: 2.59	H: 0.02	H: 0.06	H: 0.09	H: - 0.07	H: 0.12
Payload	619(1361)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Distance	800		S: 775.84	S: 11.35	S: 11.39	S: 31.27	S: -18.92	S: 37.96
		2%	T: 411.53	T: 4.36	T: 4.36	T: 18.95	T: -16.77	T: 25.50
		Probable	F: 363.92	F: 6.88	F: 6.88	F: 11.78	F: - 1.80	F: 11.78
		Day	H: 2.59	H: 0.02	H: 0.06	H: 0.09	H: - 0.07	H: 0.12
			h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
			S: 778.04	S: 11.25	S: 11.30	S: 30.82	S: -18.64	S: 37.40
		0.3%	T: 411.47	T: 4.36	T: 4.36	T: 18.95	T: -16.77	T: 25.50
		Probable	F: 364.17	F: 6.89	F: 6.89	F: 11.91	F: - 1.80	F: 11.91
		Day	H: 2.59	H: 0.02	H: 0.06	H: 0.09	H: - 0.07	H: 0.12
			h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
			S: 778.23	S: 11.27	S: 11.31	S: 30.95	S: -18.64	S: 37.53
Mission #	3	Median	T: 161.35	T: 1.71	T: 1.71	T: 7.43	T: -6.58	T: 10.00
Gross Weight	3861(8494)	Temp	F: 154.89	F: 1.56	F: 1.56	F: 2.75	F: -0.50	F: 2.75
Fueload	455(1000)	Day	H: 1.00	H: 0.00	H: 0.02	H: 0.03	H: -0.03	H: 0.04
Payload	619(1361)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Distance	300		S: 317.24	S: 3.27	S: 3.29	S: 10.21	S: -7.11	S: 12.79

T,F,H,h,S, : Cost (Relative Cost) of Time, Fuel, Heater, Heat, and Sum, Respectively, $

3.3 The Average Mission

It is now possible to use linear interpolation and extrapolation to estimate the costs of the reference fuel and the relative costs of the study fuels for missions of arbitrary distance. Missions are thus synthesized to enable forming an estimate of the properties of the average missions for each class of aircraft.

Table 3.3.1 shows the statistical relationship between mission distance and mission frequency. This table is discussed more fully in Section 6.4; however, it should be noted here that this table is based on a variety of assumptions due to an unfortunate paucity of actual data. The sensitivity of the results in this section to the assumptions involved in Table 3.3.1 is examined in Section 5.

Table 3.3.1
Fleet Class Mission
Lengths & Frequency

Frequency, %		5	10	15	20	20	20	10
Mission	Heavy Jet	0-250	250-500	500-750	750-1000	1000-1500	1500-2000	2000+
Lengths,	Light Jet	0-250	250-500	500-750	750-1000	1000-1500	1500-2000	2000+
Naut. Mi.	Turboprop	0-200	200-400	400-600	600-800	800-1000	1000-1200	1200+

Other missions were formed, as stated, by interpolation between missions which were evaluated from simulation data earlier in this section. Thus, for example, a heavy-jet mission, named Mission #23, was formed by interpolation between missions 2 and 3. The mission distance for Mission 23, and for the other interpolated, and extrapolated missions, was selected to enable forming data for each of the seven frequency-regions shown in Table 3.3.1. In addition, a very short range mission was formed by extrapolation. These synthesized missions and the original missions are presented in Tables 3.3.2a, b, and c.

With a mission in each of the frequency-regions of Table 3.3.1, it is possible to define the average mission and its costs, which appear at the bottom of Table 3.3.2. and are shown separately in Table 3.3.3.

The distances assumed for the missions formed by interpolation affect the accuracy of the results. Similarly, some of the distances used for the basic missions fall at or near the boundaries of the frequencies in Table 3.3.1. Modest changes of the table or of the basic mission distances could cause these missions to move to a different frequency region. Sensitivity of the results to these assumptions will be examined in Section 5.

3.4 Annual Costs, Relative Costs, and Fuel Break-Even Prices

The preceding section demonstrated the formation of the various costs of the average mission for each fuel and each aircraft class. It is now possible to estimate the annual costs for each fuel and aircraft class.

Table 3.3.2a

TOTAL COSTS AND RELATIVE COSTS FOR ALL MISSIONS AND FOR THE AVERAGE MISSION

MISSION DEFINITION	AIRCRAFT CLASS HEAVY JET MISSION FREQ %		TOTAL COST 1. REF FUEL TF=-44°C HOC=18574 %AROM=17.5	RELATIVE COSTS: STUDY FUELS 2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission # 1	10%	T:	$ 2501.89	32.71	32.71	141.81	-125.46	190.94
Gross Weight 16670(36675)	(2000+NM)	F:	2828.38	45.67	45.67	79.00	- 11.93	79.00
Fuel Load 6660(14650)		H:	0	5.44	5.50	5.56	0	5.63
Payload 682(1500)		h:	0	0	0	0	0	0
Mission Distance 2700		S:	5330.27	83.82	83.88	226.37	-137.39	275.57
Mission # 2	20%	T:	1867.79	24.42	24.42	105.87	- 93.66	142.55
Gross Weight 16273(35800)	(1500-2000NM)	F:	2591.92	32.15	32.15	55.63	- 8.40	55.63
Fuel Load 5600(12320)		H:	0	4.28	4.33	4.37	0	4.42
Payload 1343(2955)		h:	0	0	0	0	0	0
Mission Distance 2000		S:	4459.71	60.85	61.00	165.87	-102.06	202.60
Mission # 23	20%	T:	1414.90	18.50	18.50	80.20	70.95	107.99
Interpolation	(1000-1500NM)	F:	1947.41	24.31	24.31	42.07	6.35	42.07
Between Missions 2&3		H:	0	3.22	3.26	3.29	0	3.32
Mission Distance 1500		h:	0	0	0	0	0	0
		S:	3362.31	46.03	46.07	125.56	77.30	153.38
Mission # 3	20%	T:	871.43	11.39	11.39	49.90	-43.70	66.51
Gross Weight 13400(29480)	(750-1000NM)	F:	1174.00	14.91	14.91	25.80	- 3.90	25.80
Fuel Load 2727(6000)		H:	0	1.94	1.97	1.99	0	2.01
Payload 1343(2955)		h:	0	0	0	0	0	0
Mission Distance 900		S:	2045.43	28.24	28.27	77.19	-47.60	94.32
Mission # 34	15%	T:	598.32	7.82	7.82	33.91	-30.00	45.67
Interpolation	(500-750NM)	F:	812.10	11.05	11.05	19.12	- 2.89	19.12
Between Mission 3&4		H:	0	1.36	1.38	1.39	0	1.41
Mission Distance 600		h:	0	0	0	0	0	0
		S:	1410.42	20.23	20.25	54.42	-32.89	66.20
Mission # 4	10%	T:	416.24	5.44	5.44	23.59	-20.87	31.77
Gross Weight 12260(26980)	(250-500)	F:	570.83	8.48	8.48	14.67	- 2.22	14.67
Fuel Load 1591(3500)		H:	0	0.97	0.98	0.99	0	1.01
Payload 1343(2955)		h:	0	0	0	0	0	0
Mission Distance 400		S:	987.07	14.89	14.90	39.25	-23.09	47.45
Mission # 4X	5%	T:	208.12	2.72	2.72	11.79	-10.44	15.89
Extrapolation	(0-250NM)	F:	235.42	4.24	4.24	7.34	- 1.11	7.34
From Mission # 4		H:	0	0.48	0.49	0.45	0	0.50
Mission Distance 200		h:	0	0	0	0	0	0
		S:	443.54	7.44	7.45	19.58	-11.55	23.73
Average Mission		T:	1222.79	15.99	15.99	69.31	-61.32	93.33
Distance 1290		F:	1616.17	21.56	21.56	37.30	- 5.63	37.30
		H:	0	2.76	2.79	2.82	0	2.85
		h:	0	0	0	0	0	0
		S:	2838.96	40.31	40.34	109.43	-66.95	133.48

T: Time, F: Fuel, H: Heater, h: Heat, S: Sum;$

Table 3.3.2b
TOTAL COSTS AND RELATIVE COSTS FOR ALL MISSIONS AND FOR THE AVERAGE MISSION

MISSION DEFINITION	AIRCRAFT CLASS LIGHT JET MISSION FREQ %	TOTAL COST 1.REF FUEL TF=-44°C HOC=18574 %AROM=17.5	RELATIVE COSTS: STUDY FUELS 2.SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission # 1	10%	T: 1493.70	T: 13.51	T: 13.51	T: 58.56	T: -51.77	T: 78.79
Gross Weight 8318(18300)	(2000+NM)	F: 1733.59	F: 21.06	F: 21.06	F: 36.41	F: - 5.50	F: 36.41
Fuel Load 3364(7440)		H: 6.25	H: 0.03	H: 0.09	H: 0.12	H: - 6.25	H: 0.18
Payload 405(890)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Mission Distance 2500		S: 3233.54	S: 34.60	S: 34.66	S: 95.09	S: -63.52	S: 115.41
Mission # 2	20%	T: 910.00	T: 8.23	T: 8.23	T: 35.67	T: -31.54	T: 48.00
Gross Weight 8318(18300)	(1500-2000NM)	F: 1167.97	F: 14.99	F: 14.99	F: 25.92	F: - 3.92	F: 25.92
Fuel Load 2536(5580)		H: 3.90	H: 0.03	H: 0.06	H: 0.06	H: - 3.90	H: 0.12
Payload 1250(2955)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Mission Distance 1500		S: 2030.87	S: 23.25	S: 23.28	S: 61.65	S: -39.36	S: 24.04
Mission # 23	20%	T: 733.93	T: 6.64	T: 6.64	T: 28.77	T: -25.44	T: 38.72
Interpolation	(1000-1500NM)	F: 910.11	F: 11.41	F: 11.41	F: 19.74	F: - 2.98	F: 19.74
Between Missions 2&3	Day	H: 3.12	H: 0.03	H: 0.05	H: 0.06	H: - 3.12	H: 0.10
Mission Distance 1200		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
		S: 1621.66	S: 18.08	S: 18.10	S: 48.57	S: -31.54	S: 58.56
Mission # 3	20%	T: 557.85	T: 5.05	T: 5.05	T: 21.87	T: -19.34	T: 29.43
Gross Weight 7191(15820)	(750-1000NM)	F: 652.25	F: 7.83	F: 7.83	F: 13.55	F: - 2.04	F: 13.55
Fuel Load 1409(3100)		H: 2.34	H: 0.02	H: 0.04	H: 0.05	H: - 2.34	H: 0.07
Payload 1250(2750)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Mission Distance 900		S: 1212.44	S: 12.90	S: 12.92	S: 35.47	s: -23.72	S: 43.05
Mission # 34	15%	T: 382.18	T: 3.46	T: 3.46	T: 14.98	T: -13.25	T: 20.16
Interpolation	(500-750NM)	F: 449.69	F: 5.72	F: 5.72	F: 9.90	F: - 1.49	F: 9.90
Between Mission 3&4		H: 1.64	H: 0.01	H: 0.03	H: 0.04	H: - 1.64	H: 0.05
Mission Distance 600		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
		S: 883.51	S: 9.19	S: 9.21	S: 20.92	S: -16.38	S: 30.11
Mission # 4	10%	T: 265.06	T: 2.40	T: 2.40	T: 10.39	T: - 9.19	T: 13.98
Gross Weight 6600(14520)	(250-500)	F: 314.65	F: 4.31	F: 4.31	F: 7.46	F: - 1.13	F: 7.46
Fuel Load 818(1800)		H: 1.17	H: 0.01	H: 0.02	H: 0.03	H: - 1.17	H: 0.03
Payload 1250(2750)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Mission Distance 400		S: 580.88	S: 6.72	S: 6.73	S: 17.88	S: -11.49	S: 21.47
Mission # 4X	5%	T: 133.53	T: 1.20	T: 1.20	T: 5.20	T: - 4.59	T: 6.99
Extrapolation	(0-250NM)	F: 157.33	F: 2.16	F: 2.16	F: 3.73	F: - 0.57	F: 3.73
From Mission # 4		H: 0.58	H: 0.00	H: 0.01	H: 0.01	H: - 0.58	H: 0.01
Mission Distance 200		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
		S: 291.44	S: 3.36	S: 3.37	S: 8.94	S: - 5.74	S: 10.73
Average Mission		T: 680.24	T: 6.15	T: 6.15	T: 26.66	T: -23.58	T: 35.88
Distance 1110		F: 826.21	F: 10.35	F: 10.35	F: 17.90	F: - 2.70	F: 17.90
		H: 2.89	H: 0.02	H: 0.05	H: 0.06	H: - 2.89	H: 0.11
		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
		1509.34	16.52	16.55	44.62	-29.17	53.89

Table 3.3.2c
TOTAL COSTS AND RELATIVE COSTS FOR ALL MISSIONS AND FOR THE AVERAGE MISSION

MISSION DEFINITION	AIRCRAFT CLASS TURBOPROP MISSION FREQ %	TOTAL COST 1. REF FUEL TF=-44°C HOC=18574 %AROM=17.5	RELATIVE COSTS: STUDY FUELS 2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Mission # 1	10%	T:$ 820.64	T: 8.70	T: 8.70	T: 37.80	T: -33.45	T: 50.86
Gross Weight 4716(10375)	(2000+NM)	F: 665.50	F: 6.88	F: 6.88	F: 11.91	F: - 1.80	F: 11.91
Fuel Load 1310(2881)		H: 4.78	H: 0.03	H: 0.11	H: 0.17	H: - 0.13	H: 0.23
Payload 619(1361)		h: 0	h: 0	h: 0.01	h: 0.02	h: 0	h: 0.03
Mission Distance 1600		S: 1490.92	S: 15.61	S: 15.70	S: 49.90	S: -35.38	S: 63.03
Mission # 12	20%	T: 619.51	T: 6.57	T: 6.57	T: 28.54	T: -25.25	T: 38.40
Interpolation	(1000-1200NM)	F: 510.19	F: 6.89	F: 6.89	F: 11.91	F: - 1.80	F: 11.91
Between Missions 1&2		H: 3.69	H: 0.03	H: 0.09	H: 0.12	H: - 0.10	H: 0.18
Mission Distance 1200		h: 0	h: 0	h: 0.01	h: 0.01	h: 0	h: 0.02
		S: 1133.39	S: 13.49	S: 13.56	S: 40.58	S: -27.15	S: 50.51
Mission # 2	20%	T: 418.37	T: 4.44	T: 4.44	T: 19.27	T: -17.05	T: 25.93
Gross Weight 4716(10375)	(800-1000NM)	F: 354.88	F: 6.89	F: 6.89	F: 11.91	F: - 1.80	F: 11.91
Fuel Load 1310(2891)		H: 2.59	H: 0.02	H: 0.06	H: 0.09	H: - 0.07	H: 0.12
Pay Load 619(1361)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Mission Distance 800		S: 775.84	S: 11.35	S: 11.39	S: 31.27	S: -18.92	S: 37.96
Mission # 231	20%	T: 315.56	T: 3.35	T: 3.35	T: 14.53	T: -12.86	T: 19.56
Interpolation	(600-800NM)	F: 274.88	F: 4.76	F: 4.76	F: 8.25	F: - 1.28	F: 8.25
Between Missions 2&3		H: 1.95	H: 0.01	H: 0.04	H: 0.07	H: - 0.05	H: 0.09
Mission Distance 600		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
		S: 592.39	S: 8.12	S: 8.15	S: 22.85	S: -14.19	S: 27.90
Mission # 232	15%	T: 238.46	T: 2.53	T: 2.53	T: 10.98	T: - 9.72	T: 14.78
Interpolation	(400-600NM)	F: 214.89	F: 3.16	F: 3.16	F: 5.50	F: -0.89	F: 5.50
Between Mission 2&3		H: 1.48	H: 0.01	H: 0.03	H: 0.05	H: -0.04	H: 0.06
Mission Distance 450		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
		S: 454.83	S: 5.70	S: 5.72	S: 16.53	S: -10.65	S: 20.34
Mission # 3	10%	T:$ 161.35	T: 1.71	T: 1.71	T: 7.43	T: -6.58	T: 10.00
Gross Weight 3861(8494)	(200-400)	F: 154.89	F: 1.56	F: 1.56	F: 2.75	F: -0.50	F: 2.75
Fuel Load 455(1000)		H: 1.00	H: 0	H: 0.02	H: 0.03	H: -0.03	H: 0.04
Payload 619(1361)		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
Mission Distance 300		S: 317.24	S: 3.27	S: 3.29	S: 10.21	S: -7.11	S: 12.79
Mission # 3X	5%	T: 80.68	T: 0.86	T: 0.86	T: 3.73	T: -3.29	T: 5.00
Extrapolation	(0-200NM)	F: 72.44	F: 0.78	F: 0.78	F: 1.37	F: -0.25	F: 1.37
From Mission # 3		H: 0.50	H: 0	H: 0.01	H: 0.01	H: -0.01	H: 0.02
Mission Distance 150		h: 0	H: 0	H: 0	H: 0	h: 0	H: 0
		S: 158.62	S: 1.64	S: 1.65	S: 5.11	S: -3.55	S: 6.39
Average Mission		T: 408.69	T: 4.34	T: 4.34	T: 18.82	T: -16.66	T: 25.33
Distance 785		F: 345.88	F: 5.07	F: 5.07	F: 8.77	F: - 1.35	F: 8.77
		H: 2.47	H: 0.02	H: 0.05	H: 0.08	H: - 0.07	H: 0.12
		h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.01
		S: 757.04	S: 9.43	S: 9.46	S: 27.67	S: -18.08	S: 34.23

Table 3.3.3
TOTAL COSTS AND RELATIVE COSTS OF THE AVERAGE MISSION

AIRCRAFT CLASS		TOTAL COST	RELATIVE COSTS: STUDY FUELS				
		1.REF FUEL TF=-44°C HOC=18574 %AROM=17.5	2.SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Heavy Jet	Average	T:$ 1222.79	T: 15.99	T: 15.99	T: 69.31	T: -61.21	T: 93.33
	Mission	F: 1616.17	F: 21.56	F: 21.56	F: 37.30	F: - 5.63	F: 37.30
		H: 0	H: 2.76	H: 2.79	H: 2.82	H: 0	H: 2.85
	Distance	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	1290 NM	S: 2838.96	S: 40.31	S: 40.34	S: 109.43	S: -66.95	S: 133.48
Light Jet	Average	T: 680.24	T: 6.15	T: 6.15	T: 26.66	T: -23.58	T: 35.88
	Mission	F: 826.21	F: 10.35	F: 10.35	F: 17.90	F: -2.70	F: 17.90
		H: 2.89	H: 0.02	H: 0.05	H: 0.06	H: -2.89	H: 0.11
	Distance	h: 0	H: 0	H: 0	H: 0	H: 0	H: 0
	1110 NM	S: 1509.34	S: 16.52	S: 16.55	S: 44.62	S: -29.17	S: 53.89
Turboprop	Average	T: 408.69	T: 4.34	T: 4.34	T: 18.82	T: -16.66	T: 25.33
	Mission	F: 345.88	F: 5.07	F: 5.07	F: 8.77	F: - 1.35	F: 8.77
		H: 2.47	H: 0.02	H: 0.05	H: 0.08	H: - 0.07	H: 0.12
	Distance	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.01
	785 NM	S: 757.04	S: 9.43	S: 9.46	S: 27.67	S: -18.08	S: 34.23

T, cost of time; F, cost of fuel; H, cost of heater; h, cost of heat; S, sum; 1982$

Determination of the annual costs and relative costs, given the mission data formed above, requires the usage-rate of each aircraft class in missions per year. These estimated data are presented in Table 3.4.1 and are more fully discussed in Section 6.4. These data come from a variety of sources and several important assumptions were required in order to reorganize the original data to this form. In particular, the original data do not segregate the light jet data from the heavy jet data. In order to achieve the required segregation, it was assumed that the annual number of missions per aircraft were equal in these two classes in 1980. The error produced by these assumptions is evaluated in Section 5.

Table 3.4.1
Aircraft Class & Fleet Statistics Class & Fleet
Population & Missions

Time-Frame	Class	No. In Class	Annual No. of Missions	Annual No. of Missions Per Vehicle	Millions of Flight Miles Per Annum
1980	Heavy Jet	1,433	135,889	95	156
	Light Jet	2,790	264,808	95	304
	Turboprop	5,014	417,949	83	326
	Fleet	9,237	818,646	-	786
1990	Heavy Jet	2,907	301,394	104	346
	Light Jet	6,448	586,237	91	673
	Turboprop	13,731	925,641	67	722
	Fleet	23,086	1,813,272	-	1,741

Multiplication of the cost elements of the average mission for each aircraft class, Table 3.3.3, by the estimated number of missions per vehicle per annum for that class, Table 3.4.1, yields the total annual costs for the reference fuel and the annual relative costs for the study fuels. These annual cost data are presented in Table 3.4.2.

Similarly, multiplication of the annual costs per aircraft for each class, Table 3.4.2, by the estimated number of aircraft in that class, Table 3.4.1, yields the annual total and relative costs for that class of aircraft in 1980 and 1990. These costs, in millions of 1982 dollars, are presented in Table 3.4.3. Summation over all classes then yields the fleet cost, presented in Table 3.4.4.

It is now possible to calculate the break-even price which the study fuels must have, relative to the reference fuel, if the increased costs of operating with one of these fuels is to be recovered by decreased price of that fuel. The analytical basis for computing the break-even price is presented in Section 6.12. The computation of fuel break-even point uses the fleet cost and

Table 3.4.2
ANNUAL COSTS AND RELATIVE COSTS PER VEHICLE IN 1980 AND 1990, IN 1982 DOLLARS

AIRCRAFT CLASS AND PERIOD	COST OF 1. REF TF=-44°C HOC=18574 %AROM=17.5	RELATIVE COSTS STUDY FUELS 2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Heavy Jet 1980	T:$ 116165	T: 1519	T: 1519	T: 6584	T: -5825	T: 8866
	F: 153536	F: 2048	F: 2048	F: 3544	F: - 535	F: 3544
	H: 0	H: 262	H: 265	H: 268	H: 0	H: 271
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 269701	S: 3829	S: 3832	S: 10396	S: -6360	S: 12681
Heavy Jet 1990	T: 127170	T: 1663	T: 1663	T: 7208	T: -6377	T: 9706
	F: 168082	F: 2242	F: 2242	F: 3879	F: - 586	F: 3879
	H: 0	H: 287	H: 290	H: 293	H: 0	H: 296
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 295252	S: 4192	S: 4195	S: 113.81	S: -6963	S: 13882
Light Jet 1980	T: 64623	T: 584	T: 584	T: 2533	T: -2240	T: 3409
	F: 78490	F: 983	F: 983	F: 1701	F: - 257	F: 1701
	H: 275	H: 2	H: 5	H: 6	H: - 275	H: 10
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 143387	S: 1569	S: 1572	S: 4239	S: -2771	S: 5120
Light Jet 1990	T: 61902	T: 560	T: 560	T: 2426	T: -2146	T: 3265
	F: 75185	F: 942	F: 942	F: 1629	F: - 246	F: 1629
	H: 263	H: 2	H: 5	H: 5	H: - 263	H: 10
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 137350	S: 1503	S: 1506	S: 4060	S: -2655	S: 4904
Turboprop 1980	T: 33921	T: 360	T: 360	T: 1562	T: -1383	T: 2102
	F: 28708	F: 421	F: 421	F: 728	F: - 112	F: 728
	H: 205	H: 2	H: 4	H: 7	H: - 6	H: 010
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 62834	S: 783	S: 785	S: 2297	S: -1501	S: 2841
Turboprop 1990	T: 27382	T: 291	T: 291	T: 1261	T: -1116	T: 1697
	F: 23174	F: 340	F: 340	F: 588	F: - 90	F: 588
	H: 165	H: 1	H: 3	H: 5	H: - 5	H: 8
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 1
	S: 50772	S: 632	S: 634	S: 1854	S: -1211	S: 2293

Table 3.4.3
AIRCRAFT CLASS TOTAL COSTS OF REFERENCE FUEL AND
RELATIVE COSTS OF THE STUDY FUELS IN MILLIONS OF 1982 DOLLARS

AIRCRAFT CLASS AND PERIOD	TOTAL COSTS 1. REF TF=-44°C HOC=18574 %AROM=17.5	RELATIVE COSTS OF STUDY FUELS 2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Heavy Jet 1980	T:$ 166.46	T: 2.18	T: 2.18	T: 9.44	T: - 8.35	T: 12.70
	F: 220.02	F: 2.93	F: 2.93	F: 5.08	F: - 0.77	F: 5.08
	h: 0	h: 0.38	h: 0.38	h: 0.38	h: 0	h: 0.39
	H: 0	H: 0	H: 0	H: 0	H: 0	H: 0
	S: 386.48	5.49	5.49	H: 14.90	H: - 9.12	S: 18.17
Heavy Jet 1990	T: 369.68	T: 4.83	T: 4.83	T: 20.95	T: -18.54	T: 28.22
	F: 488.60	F: 6.52	F: 6.52	F: 11.28	F: - 1.70	F: 11.28
	H: 0	H: 0.83	H: 0.84	H: 0.85	H: 0	H: 0.85
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 858.30	S: 12.18	S: 12.19	S: 33.08	S: -20.24	S: 40.35
Light Jet 1980	T: 180.30	T: 1.63	T: 1.63	T: 7.07	T: - 6.25	T: 9.51
	F: 218.99	F: 2.74	F: 2.74	F: 4.75	F: - 0.72	F: 4.75
	H: 0.77	H: 0.01	H: 0.02	H: 0.02	H: - 0.77	H: 0.03
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 400.06	S: 4.38	S: 4.39	S: 11.84	S: - 7.74	S: 14.29
Light Jet 1990	T: 399.14	T: 3.61	T: 3.61	T: 15.64	T: -13.84	T: 21.05
	F: 484.79	F: 6.07	F: 6.07	F: 10.50	F: - 1.59	F: 10.50
	H: 1.70	H: 0.01	H: 0.03	H: 0.04	H: - 1.70	H: 0.06
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 885.63	S: 9.69	S: 9.71	S: 26.18	S: -17.13	S: 31.61
Turboprop 1980	T: 170.08	T: 1.81	T: 1.81	T: 7.83	T: - 6.93	T: 10.54
	F: 143.94	F: 2.11	F: 2.11	F: 3.65	F: -0.56	F: 3.65
	H: 1.03	H: 0.01	H: 0.02	H: 0.04	H: -0.03	H: 0.05
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0
	S: 315.05	S: 3.93	S: 3.94	S: 11.52	S: - 7.52	S: 14.25
Turboprop 1990	T: 375.98	T: 4.00	T: 4.00	T: 17.31	T: -15.32	T: 23.30
	F: 318.20	F: 4.67	F: 4.67	F: 8.07	F: -1.24	F: 8.07
	H: 2.27	H: 0.01	H: 0.04	H: 0.07	H: -0.07	H: 0.11
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.01
	S: 696.45	S: 8.68	S: 8.71	S: 25.45	S: -16.63	S: 31.49

Table 3.4.4
BUSINESS FLEET TOTAL COSTS OF REFERENCE FUEL AND
RELATIVE COSTS OF THE STUDY FUELS, 1980 AND 1990, IN MILLIONS OF 1982 DOLLARS

BUSINESS FLEET	TOTAL COSTS	RELATIVE COSTS OF STUDY FUELS				
	1. REF TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
1980	T:$ 516.84	T: 5.62	T: 5.62	T: 24.34	T: -21.53	T: 32.75
	F: 582.95	F: 7.78	F: 7.78	F: 13.48	F: - 2.05	F: 13.48
	H: 1.80	H: 0.40	H: 0.42	H: 0.44	H: - 0.80	H: 0.47
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.01
	S: 1109.59	S: 13.80	S: 13.82	S: 38.26	S: -24.38	S: 46.71
1990	T: 1144.80	T: 12.44	T: 12.44	T: 53.90	T: -47.70	T: 72.57
	F: 1291.59	F: 17.26	F: 17.26	F: 29.85	F: - 4.53	F: 29.85
	H: 3.97	H: 0.85	H: 0.91	H: 0.96	H: 1.77	H: 1.02
	h: 0	h: 0	h: 0	h: 0	h: 0	h: 0.01
	S: 2440.36	S: 30.55	S: 30.61	S: 84.71	S: -54.00	S: 103.65

T, Cost of Time; F, Cost of Fuel; H, Cost of Heater, h, Cost of Heat; S, Sum, 1982$/1000000 relative cost data of Table 3.4.4; the resulting break-even prices of fuel as a percent of the reference fuel price are presented in Table 3.4.5. Thus, for example, fuel #4 must have a price at 93.6% of the reference fuel's price to break even over all costs.

Table 3.4.5
STUDY FUEL BREAK-EVEN COSTS AS A PERCENT OF THE REFERENCE FUEL COST

	FUELS				
	2.SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
1980	97.66	97.66	93.59	104.20	92.17
1990	97.67	97.66	93.59	104.20	92.16

The contributions of the several components of the 1990 relative costs of operating the fleet also may be deduced from Table 3.4.4; these isolated effects are shown in Figure 3.4.1. This figure shows again that the cost impact of increased aromatic content is quite severe; over the range studied, the incremental cost of high aromatic content is approximately double that of the effect of variation of heat of combustion. Similarly, the figure confirms that the economic impact of elevated freezing temperature is negligible; the impact of elevated freezing temperature and the requirement for a fuel heater are thus essentially operational problems.

3.5 Mission and Payload Limits

Missions of extreme range involve different considerations. For these missions, the aircraft carries the maximum possible volume of fuel; the extreme range is therefore determined by the fuel energy per unit volume, rather than energy per pound. The fuel energy per unit volume is the product of density and heat of combustion, and is presented in Table 3.5.1.

This table shows that all the study fuels except #4 have extreme range potential ranging from 1.7% to 2.4% greater than the reference fuel, while Fuel #5 has 1.4% less capability at extreme range. However, it should be noted that extreme range missions are also relatively rare. As a result, these two effects combine to imply that the study fuels, except for #5, are not mission-limited, and that #5 will be mission-limited only for rare events. Similarly, for missions of shorter than extreme range, there appears no reason to feel that the study fuels, with lower densities of energy per pound, will require reduced

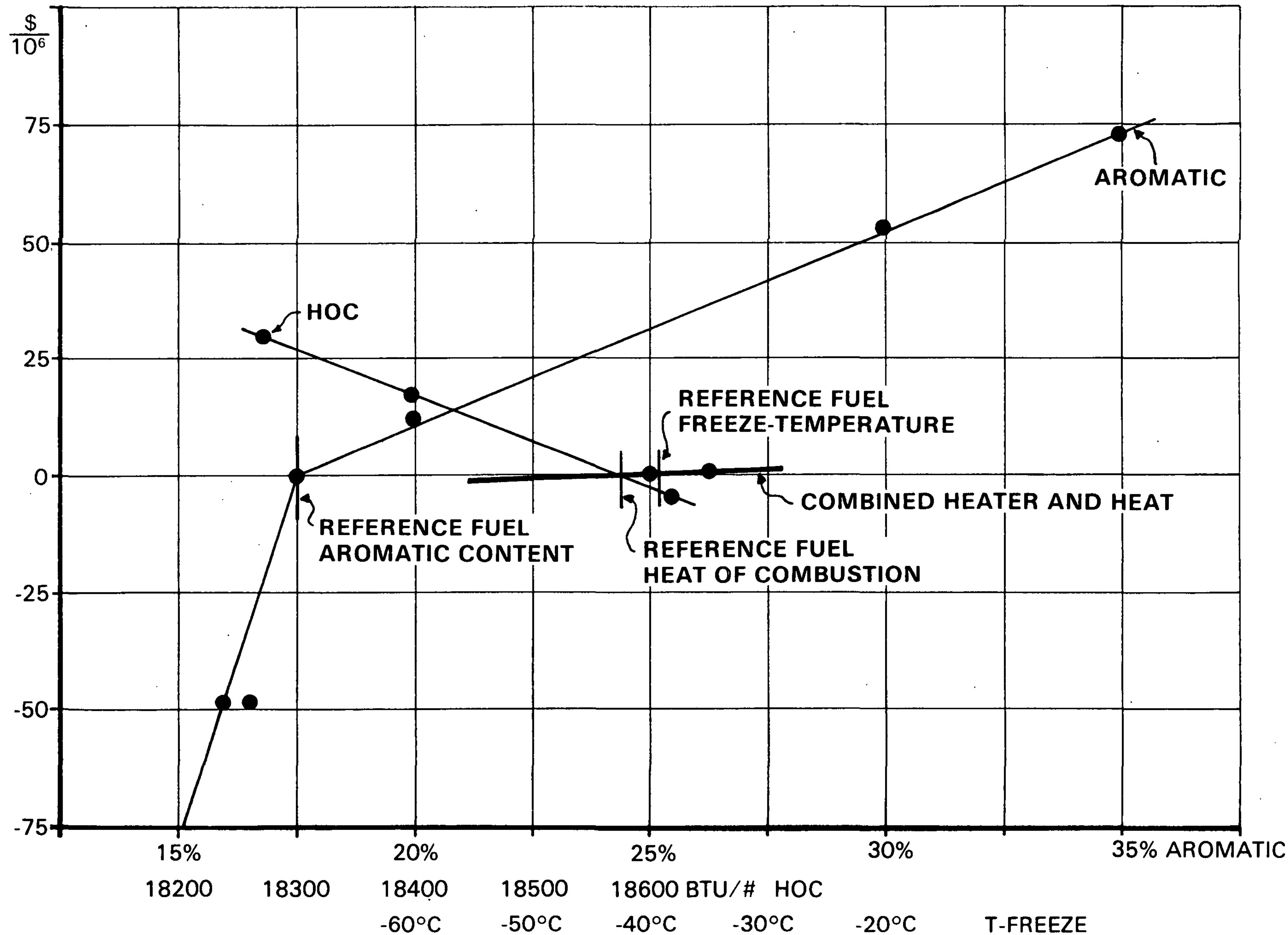

FIGURE 3.4.1
COST EFFECTS OF FUEL COMPOSITION ON THE 1990 BUSINESS TURBINE-POWERED FLEET IN MILLIONS OF 1982 DOLLARS.

Table 3.5.1
FUEL ENERGY PER UNIT VOLUME

	FUELS					
	1. REF TF=-44°C HOC=18574 %AROM=17.5	2. SPEC LIMIT TF=-40°C HOC=18400 %AROM=20.0	3. HI-FREEZE TF=-35°C HOC=18400 %AROM=20.0	4. HI-AROM TF=-31.7°C HOC=18275 %AROM=30.0	5. REDUCED FLASH TF=-55°C HOC=18620 %AROM=16.0	6. SPECIAL T=-28.9°C HOC=18275 %AROM=35.0
Density @15°C, Cubic Ft.	50.70	52.39	52.39	52.39	49.89	52.39
BTU/Cubic Ft.	941702	963976	963976	957427	928952	957427
Density Relative to Ref.	1.0000	1.024	1.024	1.017	0.986	1.017
Heat of Comb. Relative to Reference	1.00	0.991	0.991	0.984	1.002	0.984

payloads, as the least energetic fuels, 4 and 6, have energy density per unit mass only 1.6% less than the reference.

3.6 Fuel Vapor Pressure

Changes of fuel vapor pressure may have an operational impact, and may require modification of engine pumps and other components. However, the direct operational cost impact is nil, for this parameter becomes economically important only if its value is such that fuel boils during climb and is thus lost. This happens and is important in fighters, but does not happen in business aircraft operations.

3.7 Overview of Economic Impact on The Fleet

Increased aromatic content sharply increases the cost of operation of turbine aircraft as it results in significant increases in engine maintenance costs. The rate of increase of cost in 1990 is 4.15 million dollars per percent of increase of aromatic content. Decreased heat of combustion moderately increases the cost of operation. The 1990 rate of increase of cost is 1.5 million dollars per percent of decrease of heat of combustion; but it should be noted that the heat of combustion range is quite small. Fuel freezing temperature has no significant impact; its sensitivity is $73,500 per degree C.

4. OPERATION

Variations of fuel properties have a variety of effects on turbine-powered business aircraft. The quantifiable economic effects were examined in Section 3; non-quantifiable effects on operation are considered below.

The operational effects of fuel properties on turbine-powered aircraft may be subdivided into two classes. One class includes those elements which affect flight planning, such as the effects on Specific Range, or on Hold. Effects of this type are discussed in Section 4.1. A second class of effects concerns the interaction of the chemical components of the fuels on the various components of fuel system and engine, such as the effects on seals, pumps and valves. These effects are discussed in Section 4.2.

4.1 Operational Considerations

When fuels with significant property differences are used in the turbine-powered fleet, the operational envelope and performance response is affected. The following discussion will investigate the relative merit of each of the study fuels for each of the performance areas affected. These performance areas include:

- Cruise Specific Range (CSR)
- Holding Specific Range, holding time
- % frozen fuel
- % Range Reduction Fuel due to frozen fuel
- Low altitude alternative to frozen fuel

Cruise Specific Range and Holding Specific Range were evaluated with fuel heaters installed to prevent frozen fuel from biasing the results. Using the heater, the Specific Range was determined for the business fleet (three typical study aircraft) for each of the study fuels. Table 4.1.1 shows the percent change in Cruise Specific Range with respect to the reference fuel. Minimum and Maximum percent change in Cruise Specific Range, with respect to the Reference Fuel, represents the Minimum & Maximum range of these values obtained for all the study aircraft.

Table 4.1.1 - CSR Relative Merit
% Change in Cruise Specific Range with respect to the Reference Fuel

Study Fuel	% Change		Relative Fuel Merit
	Minimum	Maximum	
Reduced Flash	+0.219%	+0.249%	1
Reference Fuel	-	-	-
Spec Limit Jet A	-0.937%	-0.832%	2
High Freeze Point	-0.937%	-0.832%	2
High Aromatic	-1.611%	-1.428%	3
Special Fuel	-1.611%	-1.428%	3

As can be seen, the overall effect on Cruise Specific Range for all the study fuels is not very significant. The Relative Fuel Merit column shows that the Reduced Flash is better than the Reference Fuel while the remaining fuels are worse.

The Holding Specific Range in Table 4.1.2 shows the same Relative Fuel Merit as Table 4.1.1. Also tabulated is the change in Holding Time, since a large change would cause the flight crew to adjust the fuel reserve requirements for an alternate airport. FAA Regulations state that the fuel supply must be sufficient to reach the airport of intended landing, then proceed to the designated alternate airport, and fly thereafter for 45 minutes at normal cruise speed. For all the holding analysis the hold was assumed to be for two hours and occurred near the end of the flight. Under these conditions, the wing tanks were always empty and the hold was accomplished using fuselage fuel.

Table 4.1.2 - Holding Relative Merit
Holding Time and % Change in Hold Specific Range

Study Fuel	Relative Fuel Merit	% Change		Holding Time	
		Minimum	Maximum	Minimum	Maximum
Reduced Flash	1	+0.246%	+0.249%	+0.47	+3.23
Reference Fuel	-	-	-	-	-
Spec Limit Jet A	2	-0.938%	-0.934%	-1.77	-12.21
High Freeze Point	2	-0.938%	-0.934%	-1.77	-12.21
High Aromatic	3	-1.611%	-1.607%	-3.05	-20.99
Special Fuel	3	-1.611%	-1.607%	-3.05	-20.99

Table 4.1.2 shows a significant 20.99 minute reduction in Holding Time for both the High Aromatic & Special Fuels.

The Percent Frozen Wing Fuel and the Relative Fuel Merit are shown in Tables 4.1.3 and 4.1.4. Table 4.1.3 shows the Frozen Fuel effects within the general operating envelope specified in the flight manuals. This envelope covers from median day to 20°C colder than median day. Table 4.1.4 shows the Frozen Fuel effects for a 2% probable cold day and 0.3% probable cold day.

Table 4.1.3 - % Frozen Wing Fuel
Relative Merit - General Operating Envelope

Study Fuel	Relative Fuel Merit	Median Day		-10°C Cold Day		-20°C Cold Day	
		Min	Max	Min	Max	Min	Max
Reduced Flash	1	0%	0%	0%	0%	0%	21.35%
Reference	2	0%	0%	0%	28.30%	7.37%	80.56%
Spec Limit Jet A	3	0%	0%	0%	38.61%	18.19%	96.22%
High Freeze	4	0%	25.11%	4.57%	73.66%	29.89%	100.00%
High Aromatic	5	0%	37.92%	18.32%	98.01%	40.44%	100.00%
Special Fuel	6	0%	55.64%	29.47%	100.00%	47.13%	100.00%

Table 4.1.4 - % Frozen Wing Fuel
Relative Merit - 2% & 0.3%
Probable Cold Days

Study Fuel	Relative Fuel Merit	2% Cold Day		0.3% Cold Day	
		Min	Max	Min	Max
Reduced Flash	1	0%	39.93%	0%	42.55%
Reference	2	0%	51.63%	2.54%	91.02%
Spec Limit Jet A	3	1.86%	79.56%	8.28%	100.00%
High Freeze Point	4	10.47%	100.00%	16.81%	100.00%
High Aromatic	5	18.85%	100.00%	24.12%	100.00%
Special Fuel	6	25.49%	100.00%	30.79%	100.00%

In addition to the Relative Fuel Merit noted in Table 4.1.3, it is important to notice that the currently used reference fuel will freeze occasionally during use within the general operating envelope. Using the reference fuel as a guide, the Reduced Flash Point fuel is the only fuel that does not require a heater to maintain at least the performance of the currently used reference fuel. All the remaining study fuels will require a heater or will require a modification of their range capability to reduce the potential effects of fuel freezing.

The Percent Range Reduction for a maximum range trip and the Relative Fuel Merit are shown in Table 4.1.5. Percent Range Reduction is based on the trip range the aircraft could attain, landing with a 30 minute reserve of unfrozen fuel.

Table 4.1.5 - % Range Reduction
Maximum Range Trip

Study Fuel	General Operating Envelope Median Day to- 20° Cold Day	Relative Fuel Merit	Including 2% & 0.3% Probable Cold Day	Relative Fuel Merit
Reduced Flash	4.53%	1	17.19%	1
Reference Fuel	20.16%	2	24.00%	2
Spec Limit Jet A	27.87%	3	30.00%	3
High Freeze	30.87%	4	31.65%	4
High Aromatic	30.87%	4	32.65%	5
Special Fuel	30.87%	4	32.65%	5

Since the Percent Range Reduction is significant and the percent frozen fuels tables show the study fuels freezing in significant quantities, it becomes important to consider how often these maximum range trips occur. For an average range trip the Percent Range Reduction is considerably less, as shown in Table 4.1.6.

Table 4.1.6 - % Range Reduction
Average Range Trip

Study Fuel	Median Day	2% Probable Cold Day	0.3% Probable Cold Day	Relative Fuel Merit
Reduced Flash	0%	0%	0%	1
Reference Fuel	0%	0%	0%	1
Spec Limit Jet A	0%	0%	0%	1
High Freeze	0%	0%	0%	1
High Aromatic	0%	1.08%	5.00%	2
Special Fuel	0%	7.75%	11.68%	3

The Maximum Range Trips studied were 1600 miles for the turboprop, 2500 for the light jet and and 2700 miles for the heavy jets. The average range trips were 800, 1500, and 2000 nautical miles. These trip ranges were determined from the three study aircraft and are representative of the maximum and median range capability of these study aircraft. Table 4.1.7 shows what the typical business trip range flight actually is for the entire business fleet.

Table 4.1.7
Business Fleet Trip Frequency

Trip Frequency %	Mission Lengths Heavy & Light Jets	Turbo-Prop
5	0-250	0-200
10	250-500	200-400
15	500-750	400-600
20	750-1000	600-800
20	1000-1500	800-1000
20	1500-2000	1000-1200
10	2000+	1200+

Comparing the average range trip studied with the Table 4.1.7 frequency shows that the 800 mile or less trip for the turboprop has a frequency of 50%; the 1500 mile or less trip for the light jet has a frequency of 70%; the 2000 mile or less trip for the heavy jet has a frequency of 90%. From this frequency data, it is obvious that the % Range Reduction for the average trip in Table 4.1.6 should be given more weight than the maximum range trip in Table 4.1.5.

Since frozen fuel is undesirable, lower altitude flights were studied to determine how much the freezing effects could be reduced and to determine what other performance areas would be affected. The cruising altitude for the heavy jet was modified from 37,000 feet to 24,000 feet; the light jet from 39,000 feet to 25,000 feet; the turboprop from 30,000 feet to 19,000 feet. These lower altitudes were chosen so that the cruise speed used at the normal cruise altitude could be maintained at the lower altitude without exceeding the maximum speed capability of the aircraft. Flying these missions at lower altitude prevented the wing fuel from freezing for all the study fuels for the heavy and light jet aircraft. The turboprop aircraft wing fuel continued to freeze on a -20°C cold day using the High Aromatic and the Special Fuels. The turboprop fuels remained frozen primarily because of its high wing tank surface area, low cruise speeds and low volume. All the flights for the study aircraft and study fuels showed a significant range reduction due to the lower altitude and associated higher fuel flows. Table 4.1.8 compares the Percent Range Reduction for the high and low altitude flights for the -10° and -20° C cold days.

Table 4.1.8 - % Range Reduction
Maximum Range Trip; - 10° & -20°C Cold Days
High and Low Cruise Altitudes

Study Fuel	Relative Merit	Low Altitude		Relative Merit	High Altitude	
		Min	Max		Min	Max
Reduced Flash	1	21.23%	28.00%	1	0%	4.53%
Reference	1	21.23%	28.00%	2	0%	20.16%
Spec Limit Jet A	2	21.23%	28.92%	3	0%	27.87%
High Freeze	2	21.23%	28.92%	4	0%	30.87%
High Aromatic	3	22.79%	33.77%	5	8.13%	30.87%
Special Fuel	4	22.79%	41.58%	6	17.29%	30.87%

Table 4.1.8 shows that, by diverting to a lower altitude to avoid freezing, all the study fuels would always require approximately a 21% reduction in range while the high altitude flights show that only the High Aromatic and Special Fuels would always require range reductions of 8.13% and 17.29%, respectively.

Reviewing the Relative Merit Tables discussed above shows that, excluding economic costs and maintenance considerations due to various fuel properties, the overall relative merit of the study fuels is as follows:

Study Fuel	Overall Relative Merit
Reduced Flash Fuel	1
Reference Fuel	2
Specification Limit Jet A Fuel	3
High Freeze Point Fuel	4
High Aromatic Fuel	5
Special Fuel	6

4.2 Effects of Varying Fuel Properties

The selection of fuels and fuel properties used in the subject study may have an impact on aircraft performance and reliability that is not reflected in the computer simulations that have been performed. The following discussion attempts to describe some of these effects.

4.2.1 Reference Fuel: The properties of this fuel reflect the typical fuel being used at the present time (Reference 6). No unusual impact is indicated. The remaining fuels are discussed in comparison with this fuel.

4.2.2 Spec Limit Jet A: The reduced flash point of this fuel (100°F vs the typical 131°F) could have an impact on safety during fueling operations and under survivable crash situations.

It is quite possible for liquid fuel to be at a temperature above the 100°F flash point, making it easily ignitable if a combustion source (spark, flame, etc.) is present.

Reference 1 discusses the safety aspects of low flash point, high volatility fuels, concluding that the risk in using fuels of this type in commercial aircraft is significant.

The higher viscosity at -30°F will result in increased plumbing line losses and some reduction in ejector pump performance, but since it is within the established spec limits, no major problems should occur. Hydromechanical engine fuel control performance may also be affected by the increased viscosity (Reference 1).

Increasing the total sulfur content from the typical 0.053% to 0.3% may result in some deterioration in rubber compounds used in the fuel system as well as increased corrosion of any cadmium plated parts that are used.

The mercaptan sulfur content of 0.003% is below the 0.005% limit discussed in reference 2, so increased corrosion of cadmium plated parts should be minimal.

The increase in aromatic content from 17.5% to 20% may affect rubber parts used in the fuel system. As the fraction of aromatic hydrocarbons increases, the tendency of rubber compounds to swell increases. In addition, as the aromatic content increases the fuel hydrogen content decreases, decreasing engine combustor life. (Reference 1.3.) This result is reinforced by the napthalene content increase from 2% to 3%. More frequent engine hot section inspections may be required in addition to the use of multizone combustors (Reference 3).

4.2.3 High Freeze Point Fuel: The viscosity of this fuel at -30°F exceeds the spec limit by 13%, and is almost double that which is typical.

The comments under 4.2.2. concerning line losses, ejector pump performance, and hydromechanical fuel controls will be of greater concern with this fuel.

The comments under 4.2.2. concerning sulfur content, aromatics, and napthalenes apply with equal weight for this fuel.

4.2.4 High Aromatic Fuel: The viscosity impact of this fuel at low temperatures will be even greater than that of the high freeze point fuel.

The comments concerning the sulfur content for the Spec Limit Jet A apply with equal weight for this fuel.

The napthalene content of this fuel is three times that typically experienced and two times the spec limit. This could result in a large (on the order of 100°C) increase in combustor liner temperature compared with the typical fuel, based on Figure 16 of Reference 3.

The need for more frequent engine hot section inspections and modified combustors is greater for this fuel than it is for the Spec Limit Jet A and the High Freeze Point Fuel.

Discussion with aircraft engine manufacturers indicates that engine hot section inspections and overhauls comprise more than half of the total engine maintenance costs. Increasing the frequency of these inspections and overhauls due to increased aromatic content in the fuel would therefore have a major impact on aircraft operating cost.

The 30% aromatic content of this fuel is 50% higher than the spec limit and nearly double that typically observed. This will contribute to the high combustor liner temperature problem and also have a greater effect on the swelling of rubber parts than the Spec Limit Jet A.

The water solubility of this fuel is approximately twice that typically experienced. Fuel cooling during flight and the subsequent release of free water could result in greater volumes of liquid water being accumulated in the tanks.

Reference 1 estimates that for a typical fuel, as much as one pint of water per 1000 gallons of fuel can be released as a result of fuel cooling during aircraft ascent.

4.2.5 Reduced Flash Point Fuel: The low flash point (86°F) of this fuel is detrimental to safety during fueling and survivable crash situations. In addition, the associated higher vapor pressure could result in vapor problems in the fuel system.

Also, Reference 4 concludes that on short flights, high vapor pressure fuels have excessive boil-off losses.

The comments concerning the sulfur content for the Spec Limit Jet A apply with equal weight for this fuel.

The reduced aromatic content (10% vs 17.5% for the reference fuel) may result in reduced swell of rubber fuel system parts, which could cause inadequate sealing of O-rings, gaskets, and tank sealants. It should also result in increased engine combustor liner life.

4.2.6 Special Fuel: Comments concerning the high viscosity of the high aromatic and high freeze point fuels apply with equal weight to this fuel.

Due to the high napthalene and aromatic content of this fuel and the associated reduction in hydrogen content, high combustor liner temperature will be of more concern than that of the high aromatic fuel.

Comments on the high water solubility of the high aromatic fuel apply with greater weight to this fuel, which has an even higher water solubility.

4.2.7 Additional Comments:

Changing properties of fuels can result in many modes of interaction with aircraft fuel system operation. In addition to those discussed above are possible incompatibilities with presently used fuel additives, effects on fuel gauging systems, incompatibilities with paints and coatings, and conflict with smoke regulations.

The development of suitable freezing point depressant additives for jet aircraft fuels may lessen some of the difficulties anticipated with the high freeze point fuels.

Reference 5 indicates that flow improving additives that disperse the crystals in freezing fuel can be as effective as fuel heating techniques.

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5. ECONOMIC IMPACT SENSITIVITY ANALYSIS

In Section 3 it was noted that the results are sensitive in various ways to the assumptions used in the analysis. The effects of variations in the key assumptions are examined in this section. Three topics are considered:

1) The effect of varying assumptions of the mission distances used in Section 3, given that the statistics of trip-distance and trip frequency are valid.

2) The assumption that the number of missions of heavy and light jets are equal, and,

3) The statistics of trip-distance and trip frequency.

These topics are examined below in this sequence.

5.1 Effect of Mission Distance

Consider Table 3.3.2a; it presents the costs and relative costs for the various study missions for the heavy jet. The trip-distances, (2000 NM for Mission 2 and 1500 NM for interpolated Mission 23) are at the extreme upper end of the ranges of distances for mission-distance/mission-frequency. The effect of using mission distances nearer to the center of the ranges is considered below for the reference fuel and special fuel #6.

Table 5.1.1 shows the details of the work of evaluating this effect on the economic analysis. The first three columns of this table are directly copied from Table 3.3.2a, and present the mission definition, the costs and average cost of the reference fuel, and the relative costs for the study fuel, special fuel #6. The last three columns present redefined missions and costs with mission distances which more closely approach the centers of the distance-frequency ranges. In this group is mission (2A) with a distance of 1750 NM, in the center of the 1500-2000 NM (20%) range. There is also mission (2B) with a distance of 1200 NM, near the center of the 1000-1500 NM (20%) range. These revised missions have an average distance of 1180 NM, whereas the original set of missions has an average distance of 1290 NM. The average mission distance is decreased by 9%; the average costs are also decreased by 9%.

However, if we use the same procedure used previously to estimate the annual number of missions per aircraft, we find from the data of Table 3.4.1 that the number of missions must increase by 9% because the number of aircraft and total number of miles flown remain constant. As a result, the annual costs and relative costs for the individual aircraft and for that fleet class are completely unchanged.

TABLE 5.1.1

THE EFFECT OF MISSION-DISTANCE ASSUMPTIONS ON THE AVERAGE MISSION

MISSION DATA, COSTS, AND RELATIVE COSTS FOR FUELS # 1 & # 6, FROM TABLE 3.3.2a				MISSION DATA, COSTS, AND RELATIVE COSTS FOR FUELS # 1 & # 6 WITH MODIFIED MISSION DISTANCES			
MISSION DEFINITION	AIRCRAFT CLASS HEAVY JET MISSION FREQ %	TOTAL COSTS 1. REF FUEL TF=-44°C HOC=18574 %AROM=17.5	RELATIVE COSTS 6. SPECIAL T=28.9°C HOC=18275 %AROM=35.0	MISSION DEFINITION	MISSION FREQUENCY	TOTAL COSTS REFERENCE FUEL # 1	RELATIVE COSTS SPECIAL FUEL # 6
Mission # 1	10%	T:$ 2501.89	T: 190.94	Mission #1	10%	T: 2501.89	T: 190.94
Gross Weight 16670(36675)	(2000+NM)	F: 2828.38	F: 79.00		(2000+)	F: 2828.38	F: 79.00
Fuel Load 6660(14650)		H: 0	H: 5.63	Dist 2700		H: 0	H: 5.63
Payload 682(1500)		h: 0	h: 0			h: 0	h: 0
Mission Distance 2700		S: 5330.27	S: 275.57			S: 5330.27	S: 275.57
Mission # 2	20%	T: 1867.79	T: 142.55	Mission #2A	20%	T: 1641.35	T: 125.27
Gross Weight 16273(35800)	(1500-2000NM)	F: 2591.92	F: 55.63		(1500-2000)	F: 2269.66	F: 48.85
Fuel Load 5600(12320)		H: 0	H: 4.42	Dist 1750		H: 0	H: 3.87
Payload 1343(2955)		h: 0	h: 0			h: 0	h: 0
Mission Distance 2000		S: 4459.71	S: 202.60			S: 3911.01	S: 177.99
Mission # 23	20%	T: 1414.90	T: 107.99	Mission #2B	20%	T: 1143.17	T: 87.25
Interpolation	(1000-1500NM)	F: 1947.41	F: 42.07		(1000-1500)	F: 1560.70	F: 33.94
Between Missions 2&3		H: 0	H: 3.32	Dist 1200		H: 0	H: 2.66
Mission Distance 1500		h: 0	h: 0			h: 0	h: 0
		S: 3362.31	S: 153.38			S: 2703.87	S: 123.85
Mission # 3	20%	T: 871.43	T: 66.51	Mission # 3	20%	T: 871.43	T: 66.51
Gross Weight 13400(29800)	(750-1000NM)	F: 1174.00	F: 25.80		(750-1000)	F: 1174.00	F: 25.80
Fuel Load 2727(6000)		H: 0	H: 2.01	Dist 900		H: 0	H: 2.01
Payload 1343(2955)		h: 0	h: 0			h: 0	h: 0
Mission Distance 900		S: 2045.43	S: 94.32			S: 2045.43	S: 94.32
Mission # 34	15%	T: 598.32	T: 45.67	Mission #34	15%	T: 598.32	T: 45.67
Interpolation	(500-750NM)	F: 812.10	F: 19.12		(500-750)	F: 812.10	F: 19.12
Between Mission 3&4		H: 0	H: 1.41	Dist 600		H: 0	H: 1.41
Mission Distance 600		h: 0	h: 0			h: 0	h: 0
		S: 1410.42	S: 66.20			S: 1410.42	S: 66.20
Mission # 4	10%	T: 416.24	T: 31.77	Mission #4	10%	T: 416.24	T: 31.77
Gross Weight 12264(26980)	(250-500)	F: 570.83	F: 14.67		(250-500)	F: 570.83	F: 14.67
Fuel Load 1591(3500)		H: 0	H: 1.01	Dist 400		H: 0	H: 1.01
Payload 1343(2955)		h: 0	h: 0			h: 0	h: 0
Mission Distance 400		S: 987.07	S: 47.45			S: 987.07	S: 47.45
Mission # 4X	5%	T: 208.12	T: 15.89	Mission #4X	5%	T: 208.12	T: 15.89
Extrapolation	(0-250NM)	F: 235.42	F: 7.34		(0-250)	F: 235.42	F: 7.34
From Mission # 4		H: 0	H: 0.50	Dist 200		H: 0	H: 0.50
Mission Distance 200		h: 0	h: 0			h: 0	h: 0
		S: 443.54	S: 23.73			S: 443.54	S: 23.73
Average Mission		T: 1222.79	T: 93.33	Average		T: 1123.16	T: 85.72
Distance 1290		F: 1616.17	F: 37.30	Mission		F: 1474.38	F: 34.32
		H: 0	H: 2.85	Dist 1180		H: 0	H: 2.61
		h: 0	h: 0			h: 0	h: 0
		S: 2838.96	S: 133.48			S: 2597.54	S: 122.65

T: Time, F: Fuel, H: Heater, h: Heat, S: Sum;$

5.2 Heavy Jet and Light Jet Mission Numbers

In Section 3 it was assumed that both heavy jets and light jets fly 95 missions per year, in order to achieve a segregation of costs between the two classes. The original data, discussed further in Section 6.4, do not provide this segregation. The effect of an error of 10% in this assumption is tested below.

Assume that the number of missions per year is over-estimated by 10% for the heavy jets and underestimated by 10% for the light jets; the total number of missions remain unchanged. Total costs of the reference fuel for the two classes are estimated from the 1980 and 1990 data in Table 3.4.3. The results, which appear in Table 5.2.1, show that errors in this assumption produce very small changes of costs.

5.3 The Statistics of Trip Distance and Frequency

It was assumed in Table 3.3.2 that the average mission lengths are 1290 NM, 1100 NM, and 785 NM for the heavy jet, light jet, and turboprop classes, respectively. These data are summarized in Table 3.3.3. Similarly, in Table 3.4.1 it was estimated that the annual number of missions per aircraft in 1980 were 95, 95 and 83, for heavy jets, light jets and turboprop, respectively. Some large users of business turbine-powered aircraft assert that their experience shows the average mission to be approximately 600NM, and that the annual number of missions is in the order of 300 to 400 per aircraft; further, they suggest that this experience is true for both their large and small turbine-powered aircraft. Reducing the length of the average mission, and proportionately increasing the number of missions causes no change in the total nor relative costs. However, these data suggest that the number of missions increases more than proportionately. The total and relative costs, if these assertions are correct, would increase by 50% to 100%. The economic conclusions of Section 3 are therefore conservative, perhaps highly conservative.

Table 5.2.1

Effect On Economic Analysis of An Error of ± 10% in The Relative Number of Missions for Heavy and Light Jets

Year		Table 3.4.3 Data Total Costs; Reference Fuel Millions of 1982 $	Table 3.4.3 Data Modified Heavy Jet X0.90; Light Jet X1.10 Total Costs; Ref Fuel Millions of 1982 $	Change of Costs of Ref Fuel Due to Modified Stat. Assump. Million of 1982 $	%
1980	Heavy Jet	386.48	347.83		
	Light Jet	400.06	440.07	+ 1.36	+0.17
	Total	786.54	787.90		
1990	Heavy Jet	853.30	767.97		
	Light Jet	885.63	974.19	+ 3.23	+0.19
		1738.93	1742.16		

6. APPENDICES

A variety of analyses and data are collected here to avoid interrupting the flow of the generation and presentation of the principal results.

6.1 Aircraft Selection

In order to maximize contact with reality, three actual aircraft were selected, instead of composite aircraft. Tables 6.1.1, 6.1.2 and 6.1.3 show the range of gross properties and quantities of the several classes of aircraft. Each line represents the range of offerings of one airframe manufacturer. The bottom line on each table shows the characteristics of the specific aircraft selected, which were intended to be reasonably representative of that class through the next decade.

Table 6.1.1

DATA: AIRCRAFT SELECTION: HEAVY JETS
TURBOJET, GROSS WEIGHT > 25K#

AIRCRAFT (ALL MODELS)	MAX GROSS WT #/1000	AIRCRAFT QUANTITY 1980-1990	AREA FT^2	RANGE NM	MACH #	AIRCRAFT COST $\$/10^6$
1A	25.5	470-770	353	2420	0.75	4.1
1B	26.0-38.5	10-435	450-490	3200-4400	0.83-0.84	7.7-9.9
1C	28.7-38.8	470-1000	441-504	2520-3510	0.85	
1D	64.8-68.2	280-480	935	3760	0.85	
1E	44.5	202				
1F	38.8	270-1540	504	3510	0.83	

TABLE 6.1.2

DATA: AIRCRAFT SELECTION: LIGHT JETS
GROSS WEIGHT < 25K#

AIRCRAFT (ALL MODELS)	MAX GROSS WT #/1000	AIRCRAFT QUANTITY 1980-1990	AREA FT^2	RANGE NM	V KNOTS (M)	AIRCRAFT COST$/$10^6$
2A	13.3-19.5	790-2200	260-323	1300-3000	405-540	1.7-4.0
2B	18.7	170-280	260	1920	(0.87)	
2C	13.5-20.5	1100-2400	232-264	2100-3100	(0.81)	1.9-3.4
2D	22.8-23.5	130-400	308	2400-2900	(0.77-0.80)	3.3-3.8
2E	14.1	6-470	241	1250	(0.78)	2.2
2F	24.0	60-640	380	2800	0.83	5.7
2G	18.3	404-1137	253.3	2150-2900	460-529	3.2

TABLE 6.1.3

DATA: AIRCRAFT SELECTION: TURBOPROPS

AIRCRAFT (ALL MODELS)	MAX GROSS WT #/1000	AIRCRAFT QUANTITY 1980-1990	AREA FT^2	RANGE NM	V KNOTS	AIRCRAFT COST $/$10^6$
3A	11-12.5	2500-6200	280-303	1460-1660	256-307	0.8-1.2
3B	8.2-9.8	200-2200	225-254	1310-1650	296-327	0.8-1.2
3C	12.5	400-800	309	1370-2420	325-345	1.6-1.8
3D	10.3	640-1500	279	1000-1250	330-348	1.1-1.5
3E	7.2	1-1800	163	2000	350	1.6
3F	10.5-11.6	620-1050	178	1400-1600	340-360	1.2-1.4
3G	4.9-6.2	630-2910	229-293	1420-1650	286-333	0.7-1.22
3H	10.3	58-336	279	1247	348	1.34

6.2 Data Base Extrapolation

To accomplish the required study missions for the heavy, light jet and turboprop classes, the computer math model used baseline data from the aircraft performance manuals. This performance data consisted of Climb Time, Speed, and Fuel Burned; Cruise Fuel Flow & True Airspeed; Descent Time, Distance & Fuel Burn; Holding Fuel Flow & Indicated Airspeed. The above baseline data was presented as a function of temperature, giving data points for median day, -10° & -20°C deviation from median day. Therefore, to achieve the 2% & 0.3% probable cold day flights required for the study, considerable performance data had to be extrapolated to the required temperature regions. To extrapolate the data the following general steps were performed:

- Plotting the performance manual tabular data.

- Determining the curve trend for a constant altitude, speed, temperature or weight (whichever was appropriate for the data and the aircraft).

- Determining the trend of the family of curves for various altitudes, speeds or weights.

- Trending the data through any data that had substantial scatter.

- Maintaining reasonable curve spacing of extrapolated data between constant altitude, speed, temperature or weight curves.

- Comparing duplicate but different presentations in the performance manuals and using the most reasonable. For example, the turboprop aircraft presented cruise true airspeed variation with temperature in tabular as well as graphical form. Plotting the tabular data showed a scatter that wasn't evident in the graphical presentation. This scatter appeared to be a result of rounding off the tabular data presented.

- Avoiding flight profile missions through data regions where the validity of the baseline data and, therefore, the extrapolated data was in question. For example, the baseline cruise fuel flow data for the turboprop, from the altitudes of sea level to 15,000 ft., had a considerably different and questionable trend as compared to the fuel flow curves above 15,000 ft. Therefore, the cruise flight profiles for the turboprop were always above 15,000 ft.

A typical extrapolation example is shown in Figure 6.2.1.

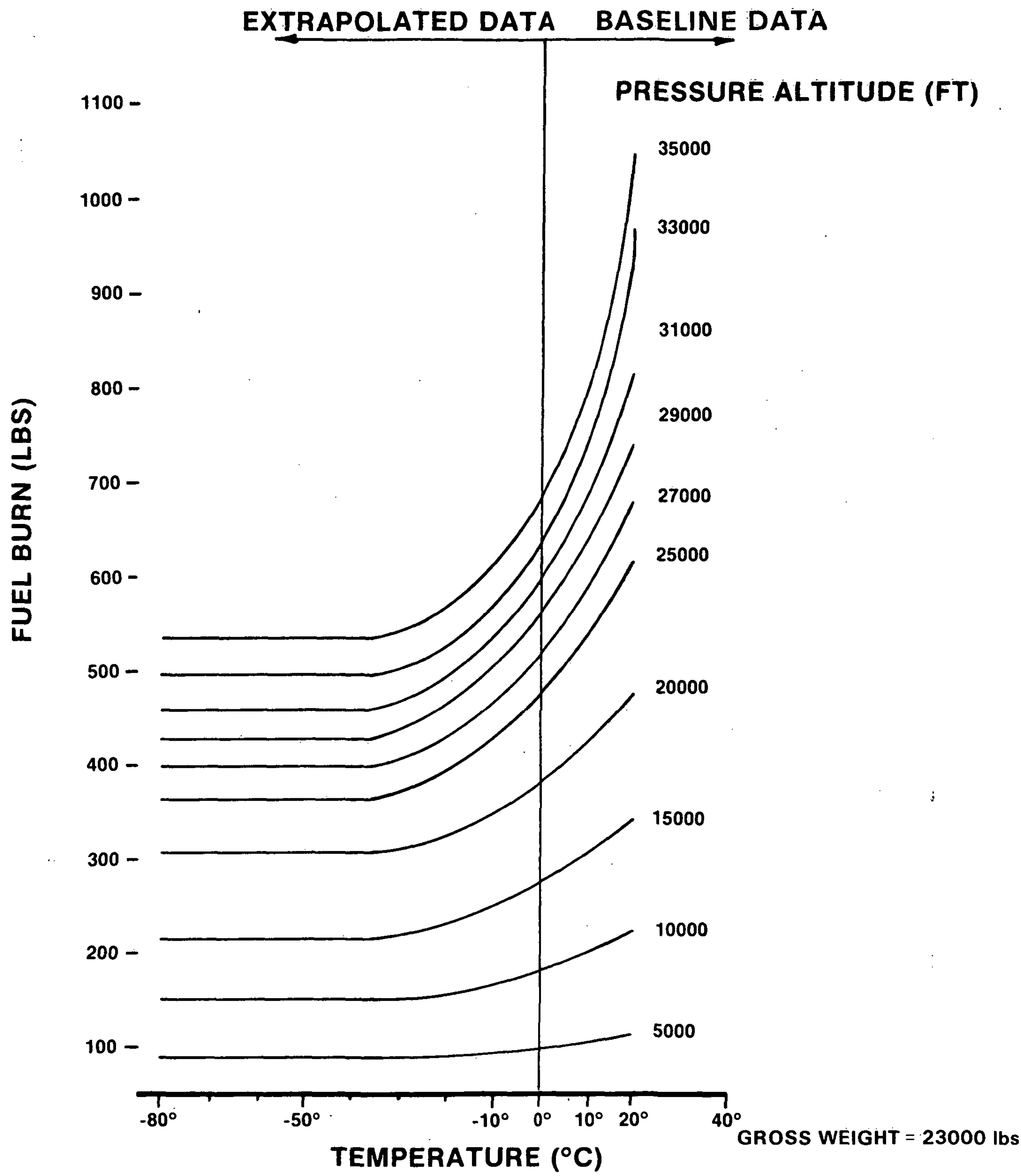


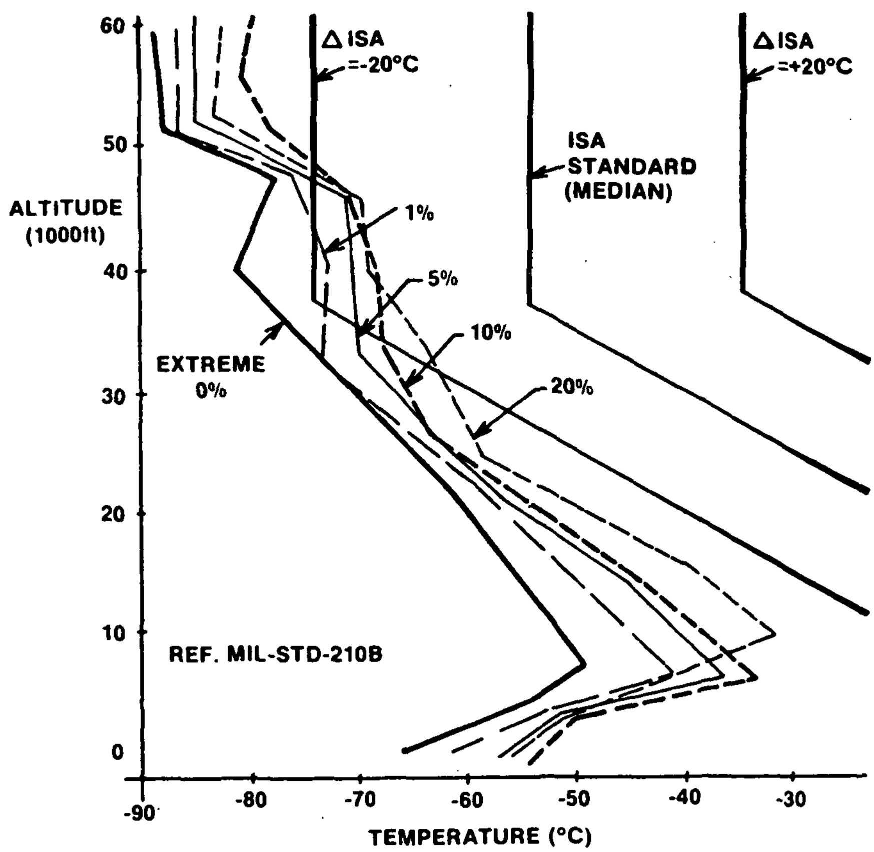
FIGURE 6.2.1.

EXTRAPOLATION EXAMPLE
HEAVY JET - PERFORMANCE SCHEDULE

6.3 Atmospheric Data

Figure 6.3.1, based on MIL-STD-210B, shows the temperature/altitude structure assumed for the atmosphere in this study. It should be noted that the International Standard Atmosphere is quite different from the experience on which these data are based.

Figure 6.3.1
ATMOSPHERIC STRUCTURE



6.4 Mission Statistics and Aircraft Utilization

The two topics considered in this section are:

1. The frequency with which turbine powered aircraft conduct missions of various lengths, and,

2. The annual number of missions per aircraft.

Reference 1 gathers data from Ref. 2 for all fixed wing aircraft, including those with reciprocating engines. These data are presented in Table 6.4.1.

Table 6.4.1

All Fixed Wing Business Aircraft : Trip Range vs. Frequency

Range, NM	0-100	100-200	200-300	300-400	400-500	500+
Frequency, %	1	9.4	20.9	21.3	15.7	29.5

The mean distance is 383 NM. The data are based on about 500 replies to a survey question.

However, it is very difficult to use these data since they are skewed by inclusion of the small non-turbine aircraft which cannot be separated out with confidence.

The sales agency for the heavy jet provided data from their customers' experience; these data are shown in Table 6.4.2

Table 6.4.2

Heavy Jet: Trip Range vs. Frequency

Range NM	0-250	250-500	500-750	750-1000	1000-1500	1500-2000	2000+
Frequency, %	5%	10%	15%	20	20	20	10

Mean Distance: 1290 NM

These data, considered more nearly representative of long-range turbine powered aircraft, were used for both the heavy and light jets. The ranges were reduced in proportion for the turboprop aircraft in this study.

The number of missions per aircraft was estimated from Table 15 of Reference 3, a portion of which is quoted as Table 6.4.3.

Table 6.4.3
Flight Data

Type of Aircraft	Number of Aircraft	Hours Flown (Thousands)	Average Speed (Naut MPH)	Miles Flown (Millions)
Turbojet	Heavy 1433, Light 2790 (total 4223)	1090	422	460
Turboprop	5014	1391	234	326

Division of the miles flown by the number of aircraft from Refs. 4 and 5 yields miles per annum per aircraft. Division of the miles per annum per aircraft by the mean trip distance yields the number of missions per annum per aircraft. In order to segregate the light and heavy jets into separate classes it was assumed that the utilizations of the two classes of aircraft are equal. This yields the data of Table 3.4.1 for 1980.

References:

1. National Business Aircraft Association, Inc., "Management Aids", Vol XII, No. 3, May 1983

2. "Corporate Aircraft, A survey of Chief Pilots", The Wall Street Journal, 1982, The Dow Jones Co., New York, New York

3. Pinciaro, Susan J., "General Aircraft Pilot and Aircraft Activity Survey", Department of Transportation, Report No. DOT-TSC-FAA-79-29, December 1979

4. "Turbine-Powered Business Aircraft, Turbofan/Turbojet Aircraft, Turboprop Aircraft", Aviation Week and Space Technology, March 9, 1981

5. "Aircraft Forecast, Military and Civil", Forecast Associates, Ridgefield, Conn., November, 1982

6.5 PROPERTIES OF STUDY FUELS

The study fuels were chosen in accordance with the guidelines given in paragraph 2.0 of RFP 3-370515. A description of each of these fuels is given below, with an explanation of the methods used to calculate some of the pertinent parameters.

A table of these parameters for all of the fuels chosen follows this discussion.

6.5.1 Reference Fuel:

All reference fuel properties were taken from DOE/BETC/PPS-81.2, Aviation Turbine Fuels, 1980 using average values of the 67 samples. Exceptions to this procedure are noted below.

- o Specific Heat: This was estimated using Fig. 18 from Reference 1.
- o Hydrogen Content: This was estimated using Fig. 3 from Reference 3.
- o Water Solubility: This was estimated using Fig. 98 in Reference 3 and Fig. 11 in Reference 1.
- o Thermal Conductivity: This was estimated using the graph on page 213 of Reference 4. Based on discussion in this reference, this value was held as a constant for all six fuels.
- o True Vapor Pressure: The Reid Vapor Pressure for this fuel is given in reference 7. Based on information in references 1 & 8, the true vapor pressure was estimated to be 4% higher.

6.5.2 Specification Limit Jet A:

Properties for this fuel were taken from the limits allowed in ASTM D1655, "Aviation Turbine Fuels", except as noted below:

- o Specific Heat: This parameter is not specified in ASTM D1655, and was obtained using Fig. 18 in Reference 1.
- o Hydrogen Content: This parameter is not specified in ASTM D1655, and was estimated using Fig. 3 from Reference 1.
- o Water Solubility: This was estimated using Fig. 98 in Reference 3.
- o Viscosity at -30°F: This was estimated using the viscosity of 8cs. at -4°F in ASTM D1655 and figure 10 in Reference 1.

- True Vapor Pressure: The true vapor pressure for this fuel was estimated using the flash point values and the methods for low volatility fuels described in Reference 7, pp. 15 - 19.

The values for sulfur content and thermal stability are specification limits but would probably not be reached in an actual fuel sample.

6.5.3 High Aromatic Content Fuel:

The aromatic content of this fuel is 30%. Properties of this fuel are similar to the Specification Limit Jet A, except as noted below:

- Water Solubility: This was estimated using Fig. 98 in Reference 3 to account for the high aromatic content.

- Hydrogen Content: This was estimated using Fig. 3 in Reference 2.

- Specific Heat: This was estimated using Fig. 148 in Reference 3 and Fig. 18 in Reference 1 to account for the high aromatic and napthalene content.

- Percent Napthalenes: This quantity was estimated at approximately half of that found in the high aromatic fuel described in Reference 5.

- Luminometer Number: This was held at the spec limit due to the high aromatic and napthalene content.

- Flash Point: This was estimated to fall between the reference fuel value and the 140°F value for the fuel in Reference 5.

- Freezing Point: The freezing point was estimated to be slightly lower than that of the high aromatic fuel in Reference 5.

- True Vapor Pressure: The true vapor pressure for this fuel was estimated using the flash point values and the methods for low volatility fuels described in reference 7, pp. 15 - 19.

6.5.4 High Freeze Point Fuel:

The freezing point of this fuel is -31°F. The properties of this fuel are similar to the Specification Limit Jet A, except as noted below:

- Viscosity @ -30°F: This was estimated to be 17 cs based on the -31°F freeze point and Fig. 10 in Reference 1, falling between JP-5 and No. 1 fuel oil.

- Specific Heat: This was estimated using Fig. 18 from Reference 1.

- Water Solubility: This was estimated from Fig. 98 in Reference 3.

- Flash Point: The flash point was estimated using Fig. 124 in Reference 3.

- True Vapor Pressure: The true vapor pressure for this fuel was estimated using the flash point values and the methods for low volatility fuels described in Reference 7, pp. 15 - 19.

6.5.5 Reduced Flash Point Fuel:

The flash point of this fuel is 86°F. The properties of this fuel are similar to the Specification Limit Jet A, except as noted below:

- 10% Distillation Temperature: This was estimated using Fig. 124 in Reference 3.

- Freezing Point: This was estimated using the 10% distillation temperature and Reference 6. The average 10% distillation temperature for the JP-4 and JP-5 samples was 300°F, close to the 311°F point estimated for the low flash point fuel.

The average freezing point for these samples was -67°F, and this value was used.

- Gravity: Based on Reference 6 the Jet A specific gravity range of 0.775 to 0.830, and the low flash point indicating a greater quantity of light hydrocarbons, the API gravity was estimated to be 45.4.

- True Vapor Pressure: The true vapor pressure for this fuel was estimated using the flash point values and the methods for low volatility fuels described in Reference 7, pp. 15 - 19.

- Viscosity: The viscosity was estimated using Fig. 10 in Reference 1.

- Heat of Combustion: This was estimated using Fig. 122 in Reference 3.

- True Vapor Pressure: The true vapor pressure for this fuel was estimated using the flash point values and the methods for low volatility fuels described in Reference 7, pp. 15 - 19.

6.5.6 Special Fuel:

- The proposed special fuel is similar to the "ERBS" fuel described in Reference 5, and the properties listed for this fuel are taken from that document, with the exception that the aromatic content was assumed to be 35% instead of 30%.

- The true vapor pressure for this fuel was calculated using the flash point temperature and the ASTM distillation curve slope with the method described in Reference 7, p. 19.

Table 6.5.1
FUEL PROPERTIES

	REFERENCE FUEL	SPEC LIMIT JET A	HIGH FREEZE PT	HIGH AROMATICS	REDUCED FLASH PT	*SPECIAL FUEL
Gravity S.G. 60/60	.813	.840	.840	.840	.80	.840
Gravity °A.P.I.	42.6	37	37	37	45.4	37.1
Distillation °F						
IBP	342					324
10%	375	400	370	380	311	370
50%	417					419
90%	473					
E.Pt.	514	572	572	608	500	622
Flash Point °F	131	100	140	136	86	140
Freeze Point °F	-48	-40	-31	-25	-67	-20
Viscosity @ -30°F cs	8.78	15	17	-	7	-
Total Sulfur %	.053	0.3	0.3	0.3	0.3	.085
Mercaptan Sulfur %	.0008	.003	.003	.003	.003	.0005
Naphthalenes %	1.99	3	.3	6	3	13.2
% Aromatics	17.5	20.0	20.0	30.0	15.0	35
% Olefins	1.2	2.0	2.0	2.0	2.0	0
Smoke Point	22.5	20	20	-	20	-
Heat of Combustion BTU/LB	18,574	18,400	18,400	18,275	18,620	18,275
Specific Heat @ 60°F	.419	.408	.408	.381	.421	.376
-30°F BTU/LB-°F	.463	.452	.452	.425	.465	.420
Thermal Conductivity 60°F	.0789	.0789	.0789	.0789	.0789	.0789
BTU/FT2/HR/(°F Per FT) -30°F	.0821	.0821	.0821	.082	.0821	.0821
Water Solubility % @ 20°C	.007	.008	.008	.015	.008	.020
Hydrogen Content %	14	13.8	13.8	13.2	14.4	12.9
Luminometer Number	-	-	-	45	-	45
Vapor Pressure psi True @ 100°F	.208	.407	.0895	.116	1.02	.100

* Properties listed for this fuel were obtained from Reference 5.

REFERENCES

1. Barnett, H.G., and Hibbard, R.R., "Properties of Aircraft Fuels", NACA Technical Note TN 3276, 1956.

2. Longwell, J.P., "Alternative Aircraft Fuels", NASA Technical Memorandum TM-73836, 1978.

3. Smith, M., "Aviation Fuels", G.T. Foulis & Co., 1970.

4. Maxwell, J.B., "Data Book On Hydrocarbons", 2nd Edition, D. VanNostrand, 1968.

5. Prok, G.M., and Seng, G.T., "Initial Characterization of an Experimental Referee Broadened Specification (ERBS) Aviation Turbine Fuel", NASA Technical Memorandum TM-81440, 1980.

6. Shelton, E.M., "Aviation Turbine Fuels, 1978, BETC/PPS-79/2, Bartlesville Energy Technology Center, Department of Energy, Bartlesville, Oklahoma, 1979.

7. Shelton, E.M., "Aviation Turbine Fuels 1980, DOE/BETC/PPS-81/2, Bartlesville Energy Technology Center, U.S. Dept. of Energy, Bartlesville, Oklahoma, 1981.

8. Nelson, W.L., "Petroleum Refinery Engineering", McGraw-Hill Book Co. 1958.

6.6 Math Models

The math models for the aircraft, mission, and fuel heating are discussed in this section.

6.6.1 Aircraft and Missions Simulation Math Model

For each of the study aircraft, performance manuals were obtained from the aircraft manufacturer, and the following data tables were extracted to generate the required missions:

- Climb Time and Fuel Burned as functions of aircraft weight, speed, altitude and temperature deviation from standard day.

- Cruise Fuel Flow and True Airspeed as functions of aircraft weight, altitude, and temperature deviation from standard day.

- Descent Time, Distance and Fuel Burned as functions of aircraft weight, speed and altitude.

- Holding Fuel Flow and Indicated Airspeed as functions of aircraft weight and altitude.

These data tables were then extrapolated and expanded as described in Section 6.2. The Mission Simulation Math Model is functionally divided into three parts:

- Climb and Descent

- Cruise

- Hold

The Climb and Descent Math Model uses altitude increments selected by the operator, and computes delta time and delta range to climb or descend through this altitude increment until the desired altitude is obtained. Initially, the Climb/Descent Math Model takes the current altitude, adds the altitude increment and uses this new altitude to determine rate of climb, fuel burn and speed from the stored performance data tables. It also determines what the delta fuel burn would be, dependent on the study fuel chosen and based on the ratio of the heat of combustion of the study fuel to the heat of combustion of the reference fuel. A thrust-minus-drag function for the reference fuel is then computed based on weight, fuel burn, air speed, rate of climb and acceleration. Using this function and the delta fuel burn due to the study fuels, the model determines the rate of climb for the study fuels, and the time and range intervals between the altitude increments. Figure 6.6.1.1 shows the basic model flow. The Cruise Math Model uses range increments selected by the operator and computes delta time and fuel burned to cruise this range increment. Figure 6.6.1.2 shows the cruise computational flow. The Holding Math Model uses operator inputs of fixed holding fuel and fixed holding time to compute additional Holding Fuel due to fuel properties for a fixed time interval and to compute additional holding time for a fixed amount of fuel. Figure 6.6.1.3 shows the hold computational flow. The fuel temperature subroutine is exercised in each computation cycle until the wing-tanks are empty.

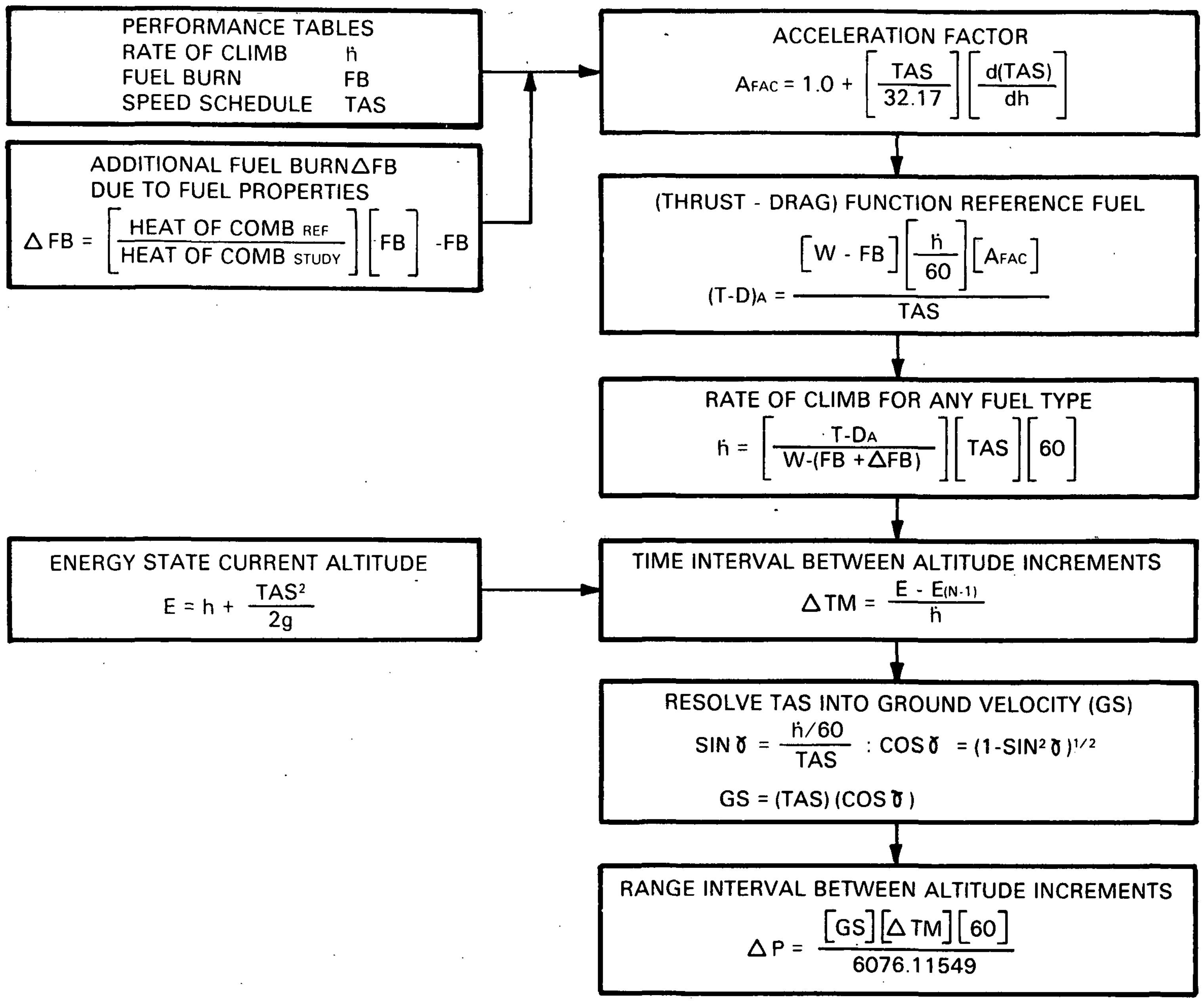


FIGURE 6.6.1.1
COMPUTER PROGRAM MATH MODEL
AIRCRAFT & MISSION SIMULATION (CLIMB & DESCENT)

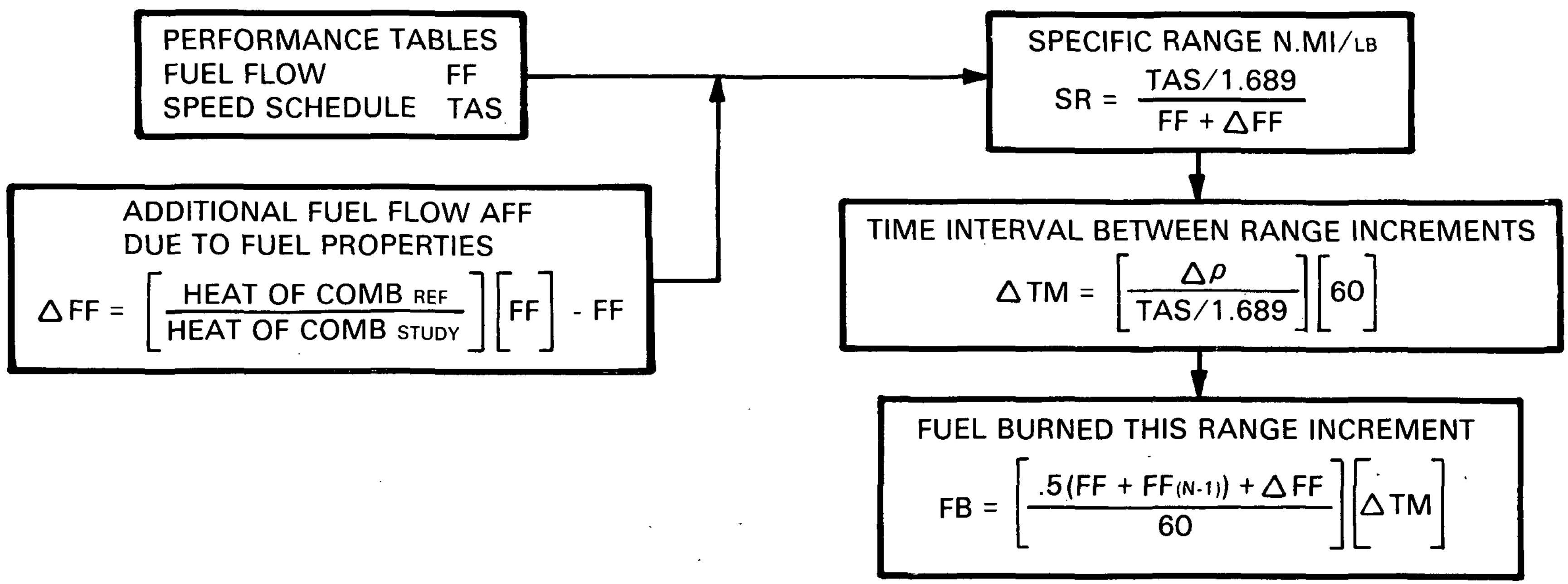


FIGURE 6.6.1.2
COMPUTER PROGRAM MATH MODEL
AIRCRAFT & MISSION SIMULATION (CRUISE)

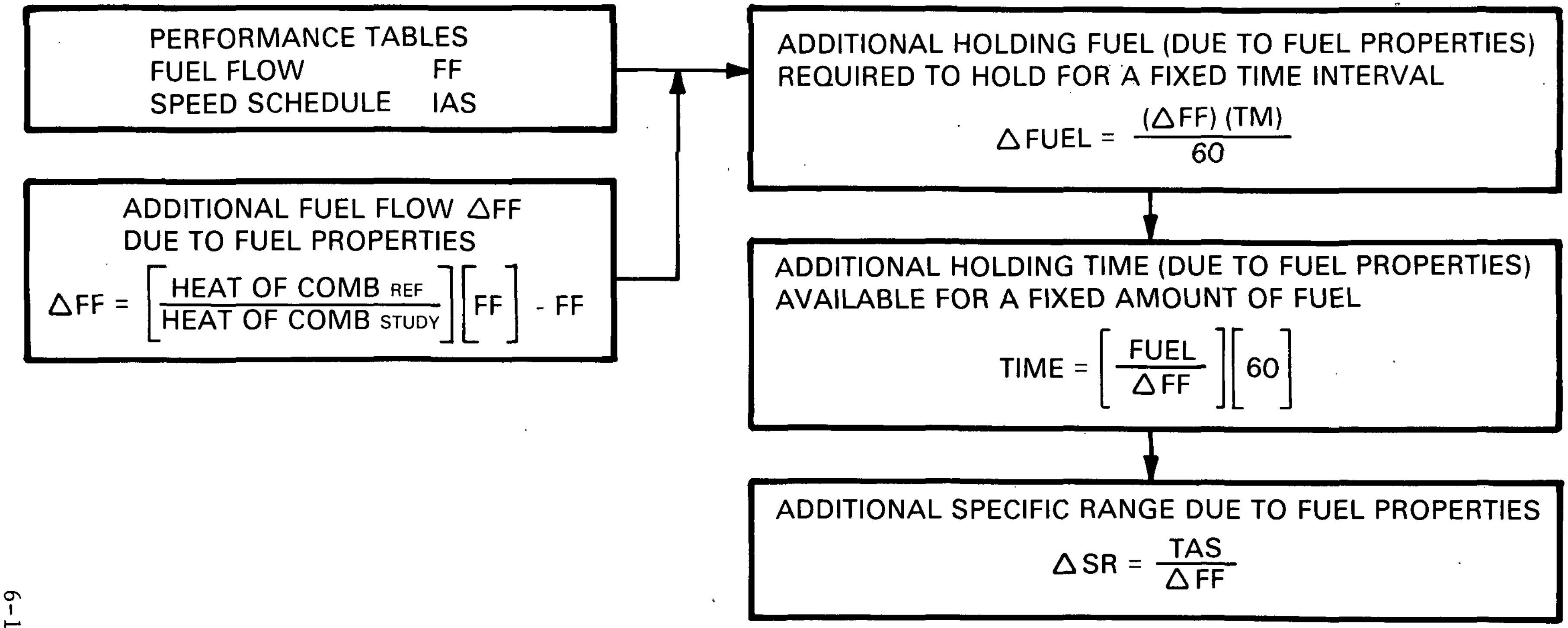


FIGURE 6.6.1.3.
COMPUTER PROGRAM MATH MODEL
AIRCRAFT & MISSION SIMULATION (HOLD)

6.6.2 Wing Tank Fuel Temperature Model (The Key Assumptions are Listed)

- o Fuel isothermal.

- o Aerodynamic heat transfer coefficient calculated using Eckert's "Reference Temperature" method.

- o Fuel - wall heat transfer coefficients calculated for top and bottom wetted surfaces using flat plate natural convection equations.

- o Upper and lower wetted surfaces are analyzed separately for natural convection coefficients.

- o Analysis is "Quasi-Steady-State", i.e. new temperatures are calculated from energy and mass balances over short time intervals using steady state heat transfer coefficients that are recalculated at each time step.

A high-level flow diagram of this model is shown in Figure 6.6.2.1 This Fuel Temperature Math Model was based upon a math model described in Reference 1.

References

1. Barr, N. M., Hayes, G.E., Pasion, A. J. and Schmidt, J. E., "Boeing Airplane Fuel Systems at Low Temperatures", Boeing Document D6-42386, 1975

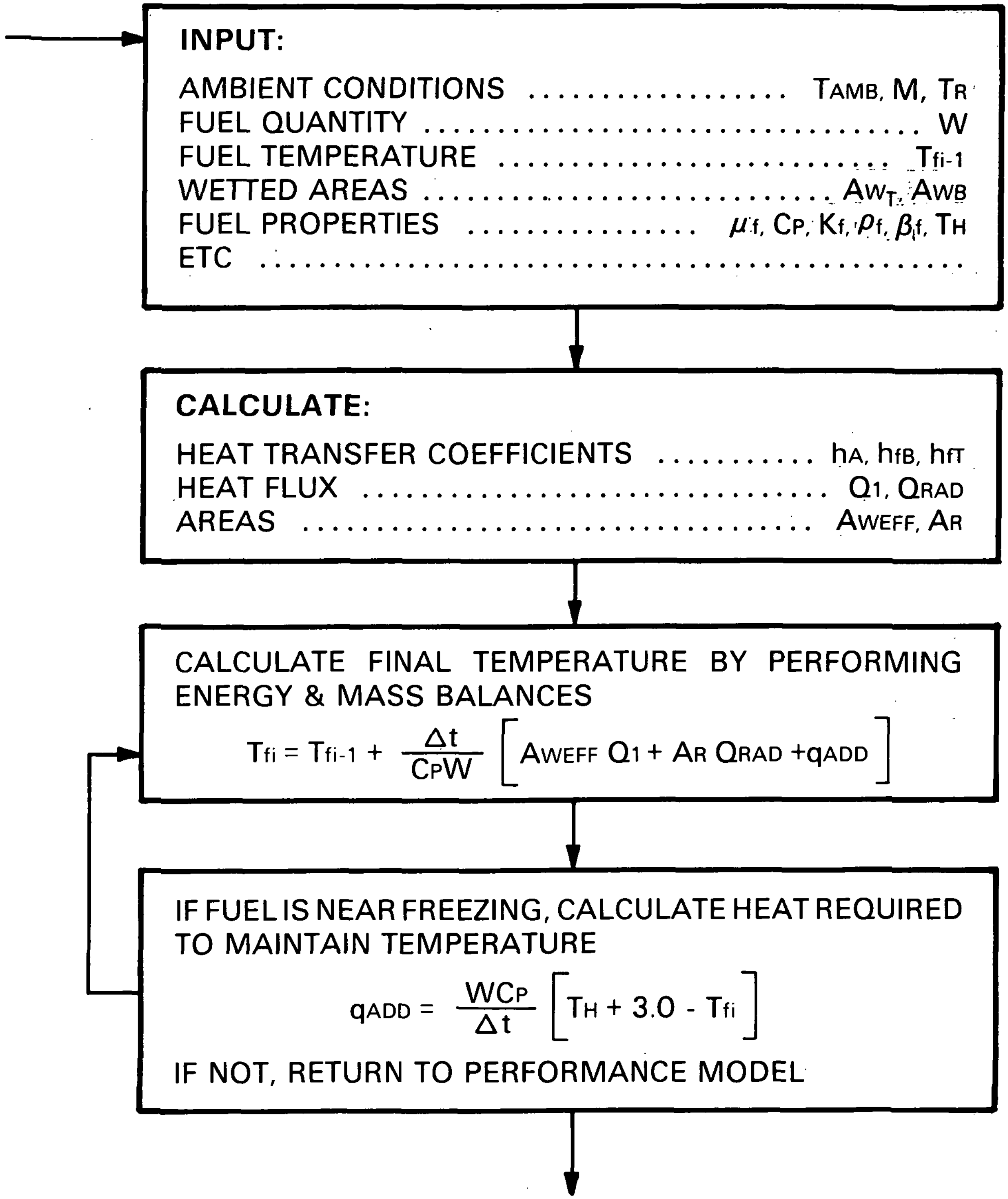


FIGURE 6.6.2.1.
WING TANK FUEL TEMPERATURE MODEL

NOMENCLATURE LIST

SYMBOL	DEFINITION	UNITS
A_r	Free surface area of fuel radiating to tank walls	Ft^2
A_{weff}	Effective aerodynamic heat transfer area wetted by fuel	Ft^2
C_p	Heat capacity of fuel	Btu/Lb. °R
h_A	Aerodynamic heat transfer coefficient	Btu/Min-Ft^2°R
k	Thermal conductivity	(Btu/Min-Ft^2°R)/FT
M	Mach number	Dimensionless
Q_1	Heat flux between fuel tank wall and ambient	Btu/Min Ft^2
A_{wt}	Aerodynamically exposed fuel wetted area that is on the top of the tank	Ft^2
A_{wb}	Aerodynamically exposed fuel wetted area that is on the bottom of the tank	Ft^2
h_{ft} & h_{fb}	Fuel to tank wall convection coefficient for top and bottom of tank	$\frac{Btu}{Min\text{-}Ft^2\text{-}°F}$
T_h	Holdup or freezing temperature of fuel	°R
q_{add}	Heat added directly to fuel	Btu/Min
μ_f	Absolute viscosity	Lb/Ft-sec
β_f	Coefficient of volumetric expansion for fuel	°R^{-1}
Q_{rad}	Radiant heat flux between fuel surface and tank walls	Btu/Min. Ft
T	Temperature	°R
t	Time into flight	Minutes
w	Mass of fuel in a tank	Lbs.
Δ	Indicates an increment in the succeeding variable	Dimensionless
ρ_f	Density of fuel in tank	Lbs/Ft^3
f	Relevant to fuel in tank	
i	Evaluated for the fuel in a tank at the end of the time increment involved	
i-1	Evaluated for the fuel in a tank at the beginning of the time increment involved	

6.7 Data Analysis Procedure

This section outlines the procedure for converting the trajectory data to relative costs for each aircraft mission. Combining the mission data to yield cost data for the average mission for each class, weighting of the costs for the average mission by the composition of the business fleet and projection of the relative direct operating costs of the anticipated 1990 fleet were discussed in Section 3.

The analysis procedure discussed here consists of estimation of the incremental costs for each aircraft and mission. The aircraft and mission cost analyses are discussed below. The significant cost drivers, aromatic content, heat of combustion, and fuel freezing temperature, are considered separately. It is assumed that all fuels have the same cost.

Figure 6.7.1 shows the procedure for analysis of the incremental cost of aromatic content for the specific mission:

Heavy jet; 2700 NM mission; Fuel load, 6695kg; payload, 680kg; Atmosphere; 0.3% probable cold day.

The judgment of the engine manufacturer was that all fuels should be flown at the same speed/altitude profile; therefore, the flight duration of 6.055 hours is the same for the two fuels, Jet A, and Spec-Limit Jet A, with aromatic contents of 17.5% and 20% respectively. Entering the curve, relative loss of life as a function of aromatic content, at the lower-left corner of this figure, the aromatic content of 20% shows a 6% loss of engine hot-section life (Reference 1) due to the increased flame radiation temperature associated with increased aromatic content. The hot-section overhaul cost is approximately 45% of the total overhaul cost of the engine. The product, (0.06))(0.45) = 0.027, shows that the operating cost is increased by 2.7% of the engine operating cost of $200 per flight hour, or 0.027 (200) = $ 5.40 per flight hour. As the flight duration is 6.055 hours, the cost increment is $32.70. The data on engine hot-section overhaul costs are based on conversations with engine manufacturers. The cost per hour increment appears in Table 3.1.3.

Figure 6.7.2 shows, in a block-diagram form, the procedure for determining the relative costs of varying heat of combustion in the same mission. The initial fuel load is compared to the fuel-burn for the two fuels to determine the reserve fuel. As a reserve is essential, an increment of the study fuel is required so that the energy reserves of the study and reference fuels are equal This increment of 19.50kg is added to the excess burn of the study fuel of 51.36kg. The excess consumption is therefore 70.86kg. In order to land with 70.86kg more of the #2 fuel than it did, the aircraft must take off with 79.36kg more fuel, as some of the extra fuel loaded must be burned in order to carry the remainder; this is the tankering factor used in Figure 6.7.2. Tankering is fully discussed in Section 6.10.

Tankering was assumed to be restricted to cruise; this tends slightly to underestimate the effect. The relative cost is then determined by multiplying the required excess initial fuel weight by the cost of fuel, assumed to be approximately 57 cents per kilogram to determine the relative cost of fuel, $45.40, for the mission.

The cost of the heater plus heat is now considered; see Fig. 6.7.3. The weight of the heater required to keep the wing tank fuel temperature at 1.67 degrees C above its freezing temperature was determined. As most of the weight of the heater is due to the required pipes, pumps, and brackets, and relatively little is due to the heat exchanger, the weight is relatively insensitive to the fuel freezing temperature. The weight of the heater required for each study fuel was compared to the heater required for the reference fuel, if any. The difference was multiplied by the factor (Direct Operating Cost/Dry Weight) to generate the relative cost. In this computation, direct operating cost is the total cost of time plus the cost of fuel. The heater is assumed to be heated by burning fuel at 40% efficiency; the cost of heat is therefore the cost of the fuel burned for this purpose. This cost is very small. In this analysis it was assumed that the aircraft must be able to complete every assigned mission. The weight of the heater for the aircraft is thus determined for all missions by the long-range 0.3% probable cold day mission, which imposes the most severe requirements on the heater.

References:

1. Grobman, J., and Reck, G. M., "The Impact of Fuels on Aircraft Technology Through the Year 2000", NASA Technical Memorandum 81492, 1980

#	FUEL TYPE	TRIP TIME HOURS	FUEL BURN, KG	HEATER WEIGHT, KG	HEAT WEIGHT, KG	RELATIVE COST OF TIME
1	REFERENCE FUEL - 17.5% AROMATIC	6.055	4596.97	0.00	0.00	
2	JET - A SPEC. LIM. 20.0% AROMATIC	6.055	4648.33	8.84	0.105	$32.70

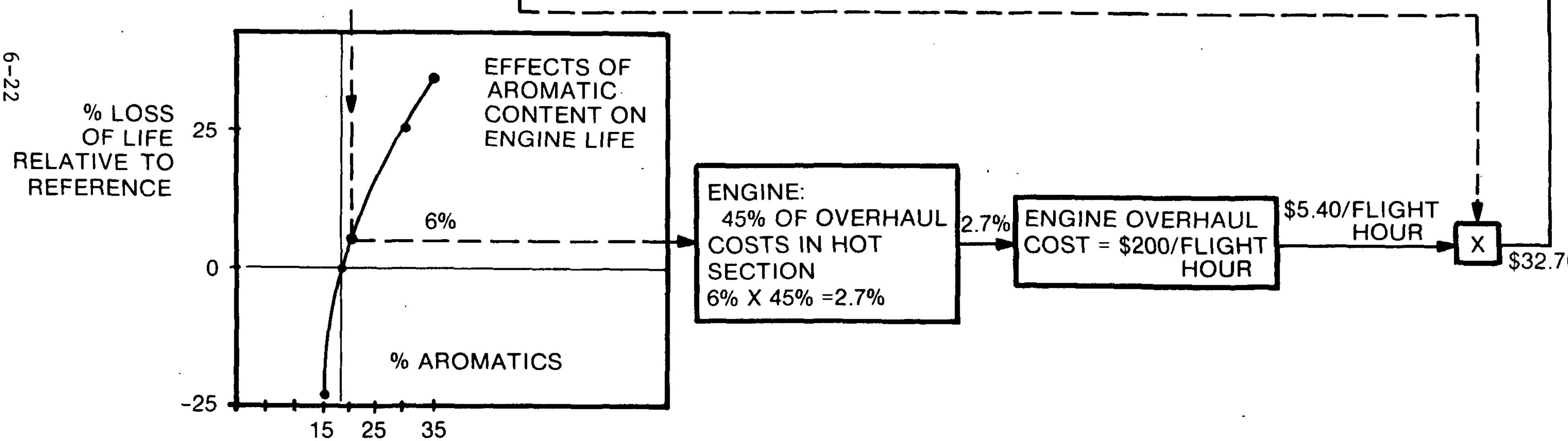


FIGURE 6.7.1.
RELATIVE COST OF AROMATIC CONTENT
HEAVY JET, 2700NM MISSION, 0.3% PROBABLE — COLD DAY.

HEAVY JET, 2700 NM MISSION, 0.3% PROBABLE - COLD DAY, FUEL LOAD 6659.1 KG

FUEL #	FUEL TYPE	TRIP TIME HOURS	FUEL BURN, KG	HEATER WEIGHT, KG	HEAT WEIGHT, KG	
1	REFERENCE HOC = 18574 BTU/LB	6.055	4596.97	0.00	0.00	RELATIVE DIRECT COST OF FUEL $45.40
2	SPEC - LIMIT JET A HOC = 18400 BTU/LB	6.055	4648.33	8.84	0.105	

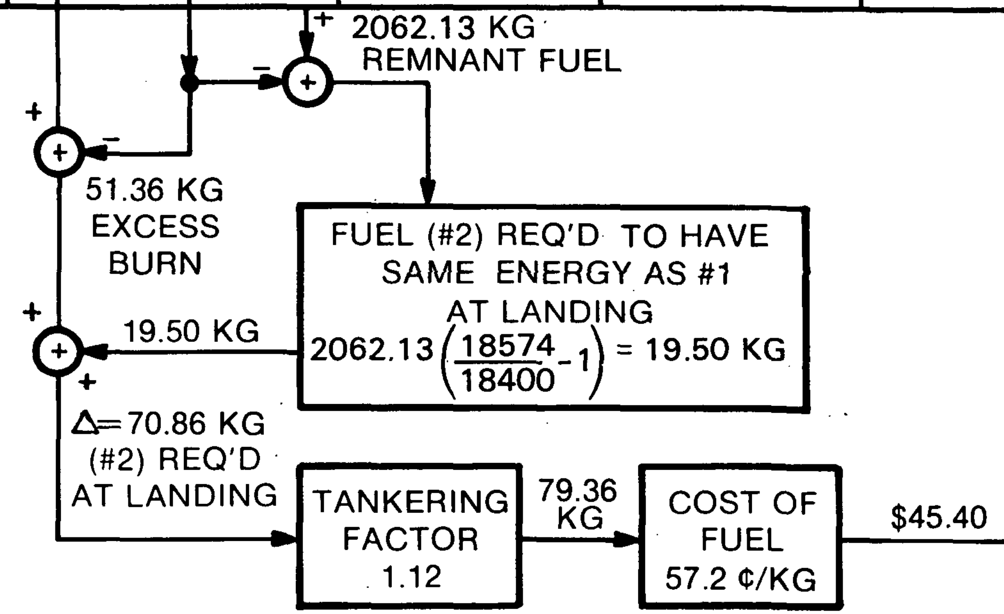


FIGURE 6.7.2.
RELATIVE COST OF HEAT OF COMBUSTION

HEAVY JET, 2700 NM TRIP, 0.3% COLD DAY

#	FUEL TYPE	TRIP TIME HOURS	FUEL BURN, KG	HEATER WEIGHT, KG	HEAT-FUEL KG	RELATIVE COSTS HEATER	RELATIVE COSTS HEAT
1	REFERENCE JET A FREEZE = ⁻44° C	6.055	4596.97	0.00	0.00		
2	SPEC LIMIT JET A FREEZE = ⁻40° C	6.055	4648.33	8.84	0.105	$5.45	$0.06

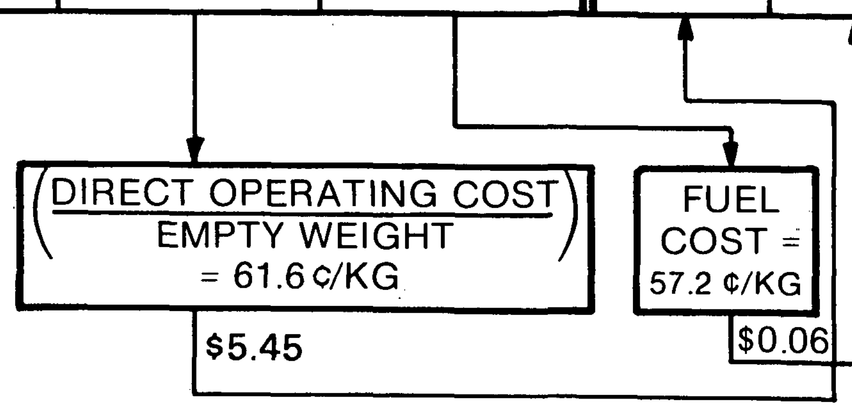


FIGURE 6.7.3.
RELATIVE COST OF FREEZING TEMPERATURE

6.8 Direct Operating Cost Data

Direct non-fuel operating costs for the three study aircraft are presented. Fuel costs are treated separately. The data in the following paragraphs for the non-fuel operating costs were provided by the manufacturers of the three study aircraft.

6.8.1.1 Heavy Jet (3 Engines)

Maintenance per hour	
Labor (2.8 Man hours/flight hour at $35.00 per hour)	$ 98.00
Parts	89.54
Engine Reserves, Maintenance Service Plan	200.10
Miscellaneous Expenses	25.00
Total Per Flight Hour Excluding Fuel	$412.64

6.8.1.2 Light Jet (2 Engines)

Maintenance per hour	
Airframe and Engine Scheduled Replace (Labor $29.48, Material $9.07)	38.55
Airframe Unscheduled Maintenance (Labor $27.00, Material $19.04)	46.04
Tires, Brakes and Batteries (Labor $4.97, Material $22.90)	27.87
Avionics and Instrumentation (Labor $15.00, Material $11.20)	26.20
Engine Reserves, Maintenance Service Plan	84.06
Miscellaneous Expenses (Oil, Crew Travel, Landing, Parking, Cabin Supplies)	28.00
Total Direct Cost Per Hour Excluding Fuel	$250.72

6.8.1.3 Turboprop (2 Engines)

Maintenance per hour	
Labor (@ $35.00/hour)	$ 38.50
Parts	21.75
Engine Reserves	51.94
Miscellaneous Expenses	
Landing and Parking Fees	2.00
Crew Expenses	15.00
Small Supplies	3.00
Total Direct Costs Per Hour Excluding Fuel	$132.19

6.8.2. Fuel: Heavy Jet, $1.70/gal; Light Jet, $1.75/gal; Turboprop, $1.75/gal; average 1982 fuel cost of $1.73/gal, 26 cents per pound, was used.

These direct operating costs were rounded off for use in the economic analysis of Section 3.

6.9 Economic Effects of Aromatic Content

High concentration of aromatic hydrocarbons in some of the study fuels will result in increased temperatures in the hot section of the aircraft jet engines. This increase in temperature will cause a reduction in life for combustors and turbine components.

Based on Figure 13 in Reference 1, the reduction in hydrogen content from 14% for the Reference fuel #1 to 12.9% for the Special fuel #6 will result in a combustor life decrease of approximately 35%.

Conversely, the increase in hydrogen content of 14.4% for the Reduced Flash point fuel will result in a combustor life increase for this fuel of approximately 23%.

Discussion with aircraft engine manufacturers indicates that engine hot section inspections and overhauls comprise approximately half of the total engine maintenance costs. Increasing the frequency of these inspections and overhauls due to increased aromatic content in the fuel would therefore have a major impact on aircraft operating cost. The figure 0.45 was used instead of one-half to avoid over-estimating this effect.

References

1. Grobman, J., and Reck, G. M. "The Impact of Fuels on Aircraft Technology Through the Year 2000", NASA Technical Memorandum 81492, 1980

6.10 Tankering

The theoretical basis for the tankering problem is developed in this subsection. The tankering problem is defined, and the analysis follows.

The tankering problem considered below responds to this question: If the aircraft operator requires a certain reserve of fuel at the end of the flight (at the planned destination), how much added fuel must he load? It is obvious that it is necessary to burn fuel in order to carry the reserve; the tankering analysis enables quantizing the excess load and consequent burn.

Assume that fuel burn-rate at cruise is related to aircraft weight according to

$$F = a \exp(bw) \tag{6.10.1}$$

where F Fuel burn rate
w Aircraft gross weight
a,b Parameters to be determined.
But $\dot{w} = -F$
where $\dot{w}$ rate of change of gross weight,
therefore

$$\dot{w} = -a \exp(bw) \tag{6.10.2}$$

Upon separating variables,

$$\exp(-bw)\, dw = -a dt$$

and on integrating subject to the initial condition $w = w_0$ when $t=0$
where w_0 is the gross weight at start of cruise and
t = time during cruise

we have

$$\exp(-bw) - \exp(-bw_0) = abt \tag{6.10.3}$$

At the end of cruise, $t=T$, and $w=w_T$
where T duration of cruise and
w_T gross weight at end of cruise,
so that

$$\exp(-bw_T) - \exp(-bw_0) = abT \tag{6.10.4}$$

Then, as T is a constant for each mission/fuel case, the rate of change of weight at the beginning of cruise with respect to the rate of change of weight at the end of cruise is

$$\partial w_0/\partial w_T = (\exp(-bw_T))/(\exp(-bw_0)) = T_F \tag{6.10.5}$$

which is the tankering coefficient.

It is now necessary to evaluate the right of (6.10.5). From (6.10.2) at t=0 and at t=T we have

$$w_0 = -a \exp(bw_0) \text{ and } w_T = -a \exp(bw_T) \tag{6.10.6}$$

hence $$w_0 / w_T = \exp(bw_0 - bw_T) \tag{6.10.7}$$

and substitution into (6.10.5) yields the final result

$$T_F = w_0/w_T \tag{6.10.8}$$

The fuel burned to carry the reserve during climb and decent is neglected; this result is therefore somewhat conservative.

The parameters a and b may be evaluated; from (6.10.7)

$$(w_0/w_T)\exp(-bw_0) = \exp(-bw_T)$$

so that $bw_0 - \ln(w_0/w_T) = bw_T$

hence $$b = (\ln(w_0/w_T))/(w_0 - w_T) \tag{6.10.9}$$

Substitution into (6.10.6) enables evaluating a. This model yields a gross weight which is in excellent agreement with the computer simulation.

6.11 Fuel Heater and Heat Weight, and Cost

The procedures for determining the weight and cost of the wing-tank fuel heaters, and the cost of the fuel burned to provide the heat, are discussed.

The fuel is assumed to be heated by a double closed loop system with water in one loop and fuel in the other. Water is heated by an electric resistance heater in a separate heat exchanger. This heater will occupy approximately one cubic foot of space. To determine the weight of the heater in pounds, this model uses:

$$\text{WEIGHT} = .0422\ \text{Capacity}\left(\frac{\text{BTU}}{\text{MIN}}\right) + 9.578$$

Therefore, if a 100 BTU/MIN capacity is required, the heater weight would be 13.8 lbs and for a 10 BTU/MIN capacity, the heater weight would be 10 lbs. Two heaters are assumed. The required heater capacity was determined to meet the worst case within that mission. This weight is converted to cost by multiplying the heater weight by the factor (mission total cost)/(aircraft empty weight). As most of the heater weight is in pumps and pipes, and very little is in the heat exchanger the heater weight is insensitive to the required heating capacity.

The heat is assumed to be provided by burning fuel (reference or study) at the maximum heating rate (BTU/minute) from takeoff until the wing-tank is empty. The efficiency is assumed to be 40%. These assumptions are very conservative.

6.12 Break-even Price of Fuel

This subsection presents the analytical basis for computing the break-even prices of the study fuels relative to the reference fuel. Throughout the main portion of Section 3 it was assumed that all fuels have the same price; the relative costs are therefore based on the same fuel cost. In the final section the question and viewpoint are reversed so that it is possible to answer the question: what must the study fuels' prices be so that the fleet total costs becomes equal for all fuels? Thus, for a fuel such as #4, which has high operating costs due to its high aromatic content and low heat of combustion, the fuel price must be low enough to compensate for these other higher-cost components.

The total cost for fuel #i is

$$C_i = T_i + F_i + H_i + h_i \qquad (6.12.1)$$

where

- i fuel index number
- C_i total cost for fuel i
- T_i cost of time
- F_i cost of fuel
- H_i cost of heater
- h_i cost of heat

The break-even concept requires that $C_i = C_1$, i.e., the total cost for any fuel must equal the total cost for the reference fuel. But the cost of fuel is the product of the price of fuel and the fuel burned, so that

$$F_i = P_i B_i \qquad (6.12.2)$$

where

- P_i price of fuel i
- B_i fuel burned for fuel i

Substitution of these two relationships into (6.12.1) yields

$$C_1 = T_1+P_1B_1+H_1+h_1=T_i+P_iB_i+H_i+h_i=C_i \qquad (6.12.3)$$

Solving for P_i yields

$$P_i = [(T_1-T_i)+(H_1-H_i)+(h_1-h_i)+P_1B_1]/B_i \qquad (6.12.4)$$

Now dividing by P_1 and adding and subtracting P_1B_1 to the denominator and P_iB_i to the numerator yields

$$\frac{P_i}{P_1} = \frac{[(P_1B_1 - P_iB_i) + (T_1-T_i) + (H_1-H_i) + (h_1-h_i)] + P_iB_i}{P_1B_1 + (P_1B_i - P_1B_1)} \qquad (6.12.5)$$

where:

(T_1-T_i)	=	incremental cost of time for fuel i
(H_1-H_i)	=	incremental cost of heater for fuel i
(h_1-h_i)	=	incremental cost of heat for fuel i
$(P_1B_1-P_iB_i)$	=	incremental cost of fuel for fuel i
$(P_1B_i-P_1B_1)$	=	incremental cost of fuel for fuel i at fuel #1 or the reference fuel price
P_1B_1	=	cost of fuel for the reference fuel

The square bracket in the numerator is the negative of the total relative cost using fuel i, presented in all the total cost tables in Section 3. Define the relative cost as ΔC_i, then

$$\frac{P_i}{P_1} = \frac{-\Delta C_i + P_1B_i}{P_1B_1 + (P_1B_i-P_1B_1)} \qquad (6.12.6)$$

Now add and subtract P_1B_1 to the numerator again, to yield

$$\frac{P_i}{P_1} = \frac{-\Delta C_i + (P_1B_i-P_1B_1)+P_1B_1}{P_1B_1 + (P_1B_i-P_1B_1)} = 1- \frac{\Delta C_i}{P_1B_1+(P_1B_i-P_1B_1)} \qquad (6.12.7)$$

This result permits physical interpretation, for the numerator on the right is the total relative cost for fuel i, while the denominator is the fuel cost for the reference fuel plus the relative cost of fuel for fuel i when both fuels are at the price of the reference fuel, #1.

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15. Supplementary Notes

Program Manager, C.E. Baker, NASA

16. Abstract

This study is an analysis of the fuel-related concerns unique to business aircraft. Representative aircraft and mission models were selected to yield performance, operational, and economic differences between the currently used reference fuel and five study fuels. The representative aircraft were based on the published characteristics of modern aircraft in three classes: heavy jet, light jet, and turboprop. Missions for these aircraft were computer simulated to include several range, payload, and temperature combinations. The five study fuels included a specification limit fuel, a high freeze point fuel, a high aromatics fuel, a reduced flash point fuel, and a special fuel similar to the NASA ERBS fuel. All of these fuels varied in aromatic content, heat of combustion, freezing temperature, density, and several other properties of lesser importance. The simulation included extreme cold day missions outside the current operational envelope of the aircraft, and included a math model of the wing tank fuel temperature based on heat transfer and outside air temperature conditions. This study estimated the 1980 direct operating costs and the 1990 costs for the turbine-powered business fleet and determined the break-even prices of the study fuels. Also discussed are the performance and operational effects of aromatic content, heat of combustion, fuel freezing, fuel heater requirements, required range reductions due to fuel freezing, specific range and various other chemical property effects.

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