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Aircraft Fuel Weight Penalty Due to Air Conditioning

RATIONALE

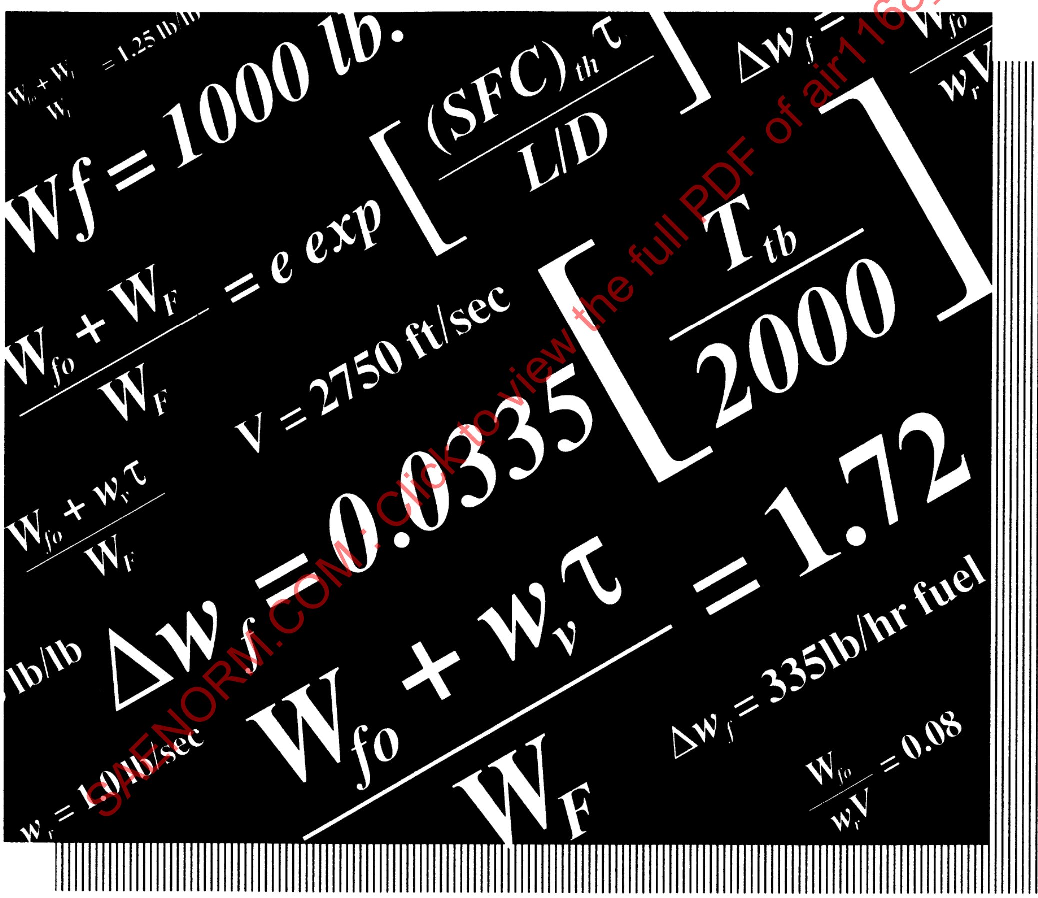
This document has been determined to contain basic and stable technology which is not dynamic in nature

STABILIZED NOTICE

This document has been declared "Stabilized" by the AC-9 Technical Committee and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

Aircraft Fuel Weight Penalty Due to Air Conditioning

AIR 1168/8



SAE Aerospace Applied Thermodynamics Manual

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PREFACE

This document is one of 14 Aerospace Information Reports (AIR) of the Third Edition of the SAE Aerospace Applied Thermodynamics Manual. The manual provides a reference source for thermodynamics, aerodynamics, fluid dynamics, heat transfer, and properties of materials for the aerospace industry. Procedures and equations commonly used for aerospace applications of these technologies are included.

In the Third Edition, no attempt was made to update material from the Second Edition nor were SI units added. However, all identified errata were corrected and incorporated and original figure numbering was retained, insofar as possible.

The SAE AC-9B Subcommittee originally created the SAE Aerospace Applied Thermodynamics Manual and, for the Third Edition, used a new format consisting of AIR1168/1 through AIR1168/10. AIR1168/11 through AIR1168/14 were created by the SAE SC-9 Committee.

The AIRs making up the Third Edition are shown below. Applicable sections of the Second Edition are shown parenthetically in the third column.

AIR1168/1	Thermodynamics of Incompressible and Compressible Fluid Flow	(1A,1B)
AIR1168/2	Heat and Mass Transfer and Air-Water Mixtures	(1C,1D,1E)
AIR1168/3	Aerothermodynamic Systems Engineering and Design	(3A,3B,3C,3D)
AIR1168/4	Ice, Rain, Fog, and Frost Protection	(3F)

AIR1168/5	Aerothermodynamic Test Instrumentation and Measurement	(3G)
AIR1168/6	Characteristics of Equipment Components, Equipment Cooling System Design, and Temperature Control System Design	(3H,3J,3K)
AIR1168/7	Aerospace Pressurization System Design	(3E)
AIR1168/8	Aircraft Fuel Weight Penalty Due to Air Conditioning	(3I)
AIR1168/9	Thermophysical Properties of the Natural Environment, Gases, Liquids, and Solids	(2A,2B,2C,2D)
AIR1168/10	Thermophysical Characteristics of Working Fluids and Heat Transfer Fluids	(2E,2F)
AIR1168/11	Spacecraft Boost and Entry Heat Transfer	(4A,4B)
AIR1168/12	Spacecraft Thermal Balance	(4C)
AIR1168/13	Spacecraft Equipment Environmental Control	(4D)
AIR1168/14	Spacecraft Life Support Systems	(4E)

F.R. Weiner, formerly of Rockwell International and past chairman of the SAE AC-9B Subcommittee, is commended for his dedication and effort in preparing the errata lists that were used in creating the Third Edition.

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1. INTRODUCTION

1.1 Scope

The purpose of this section is to provide methods and a set of convenient working charts to estimate penalty values in terms of take-off fuel weight for any given airplane mission. The curves are for a range of specific fuel consumption (*SFC*) and lift/drag ratio (*L/D*) compatible with the jet engines and supersonic aircraft currently being developed. A typical example showing use of the charts for an air conditioning system is given.

Evaluation of the penalty imposed on aircraft performance characteristics by the installation of an air conditioning system is important for two reasons:

1. It provides a common denominator for comparing systems in the preliminary design stage, thus aiding in the choice of system to be used.

2. It aids in pinpointing portions of existing systems where design improvements can be most readily achieved.

All factors that influence the flight performance of an aircraft can be expressed in terms of weight, external and momentum drags, and changes in powerplant performance due to bleed air or shaft power extraction, or both. These factors lend themselves to numerical analysis, and the purpose of this chapter is to present and discuss methods that permit their evaluation.

The methods of evaluating performance penalties to an aircraft in flight employ such parameters as flight range, aircraft gross weight, fuel load, payload, speed-altitude characteristics (Refs. 1-3), and the effects of power, landing, and take-off field length limiting cases.

Two major criteria need to be considered in arriving at system take-off weight penalties:

1. Air vehicle weight is assumed fixed, and degradation in range occurs as a result of weight displacing fuel.

2. Range is assumed fixed, and the resultant take-off weight penalty is added to the total airplane weight.

The latter method will be discussed in this section, and is based, in part, on Ref. 4. The former method (degradation in range) can be found, in detail, in Ref. 5.

The optimization process consists of calculating specific penalty numbers for system fixed weight, variable weight, power consumption, ram air, and bleed air consumption, in terms of take-off weight and selecting the system that results in greater payload or range.

1.2 Nomenclature

D	=	Drag, lb
e	=	Base of the Napierian (natural) logarithm, 2.718...
exp	=	Exponent
g	=	Gravitational acceleration, ft/sec^2
P	=	Power being consumed, hp

L	=	Lift, lb
R	=	Range, miles
$(SFC)_p$	=	Specific fuel consumption for power, lb/hr-hp
$(SFC)_{th}$	=	Specific fuel consumption for thrust, lb/hr-lb
T_{tb}	=	Turbine inlet temperature, °R
V	=	Cruise velocity, ft/sec
Δw_f	=	Change in fuel flow rate, lb/hr
w_b	=	Bleed air flow rate, lb/hr
w_r	=	Ram air flow rate, lb/sec
W_F	=	Fixed weight of system, lb
W_{fo}	=	Take-off fuel weight required to carry fixed or variable weight, lb
w_v	=	Rate of consumption of variable weight, lb/hr
τ	=	Mission time duration under evaluation, hr

1.3 Common Abbreviations

ASME	— American Society of Mechanical Engineers
Calif.	— California
Eq.	— Equation
exp	— Exponent
Fig.	— Figure
Figs.	— Figures
fps	— Feet per second
ft	— Feet
ft/sec	— feet per second
hp	— Horsepower
hr	— Hour
L/D	— Lift/drag ratio
lb	— Pound
lb/hr	— Pounds per hour
Min	— Minute
NAVWEPS	— Naval Weapon System
Par.	— Paragraph
°R	— Degrees Rankine
Ref.	— Reference
Refs.	— References
SAE	— Society of Automotive Engineers
sec	— Second
SFC	— Specific fuel consumption
WADC TR	— Wright Air Development Center Technical Report

2. THE TOTAL SYSTEM TAKE-OFF WEIGHT METHOD

The total system take-off weight penalty can be estimated by breaking down the overall flight mission into segments. During each of these the L/D ratio and the engine SFC can be considered to be essentially constant.

For each such flight segment, the fuel penalty due to system fixed weight, expendable media weight, ram air flow, bleed air flow, shaft horsepower, and the fuel required to carry this extra penalty fuel can be determined in terms of total take-off fuel weight.

The sum of the penalties for each segment represents the take-off weight penalty for the whole mission due to the design being evaluated. The accuracy of results can be increased by taking smaller time segments consistent with the objectives of the analysis.

The following data are required prior to any penalty evaluation:

1. Specific mission profile in terms of altitude, speed, and duration.
2. Bleed air flow, ram air flow, and shaft horsepower extraction data corresponding to the mission profile.
3. Estimated *L/D* and *SFC* at start of each segment of the mission being evaluated.

2.1 Fixed Weight Penalty

Fuel is required to carry the system fixed weight and the dead weight of fuel up to the point where it is expended. The total take-off weight penalty for fixed weight consists of the system fixed weight plus the weight of the fuel required to carry it, and is given by

$$\frac{W_{fo} + W_F}{W_F} = \text{e exp}\left[\frac{(SFC)_{th}\tau}{L/D}\right] \tag{3I-1}$$

Figs. 3I-1 through 3I-6 show the takeoff weight penalty per pound of fixed weight as a function of mission duration, *L/D*, and *SFC*.

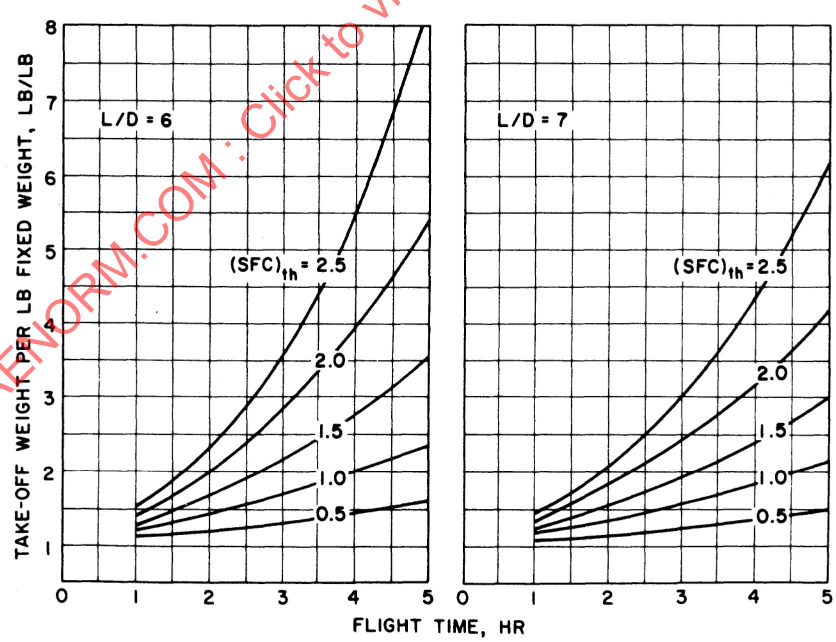

Figure 3I-1 - Fixed Weight Penalty as a Function of Time Carried, L/D = 6, 7

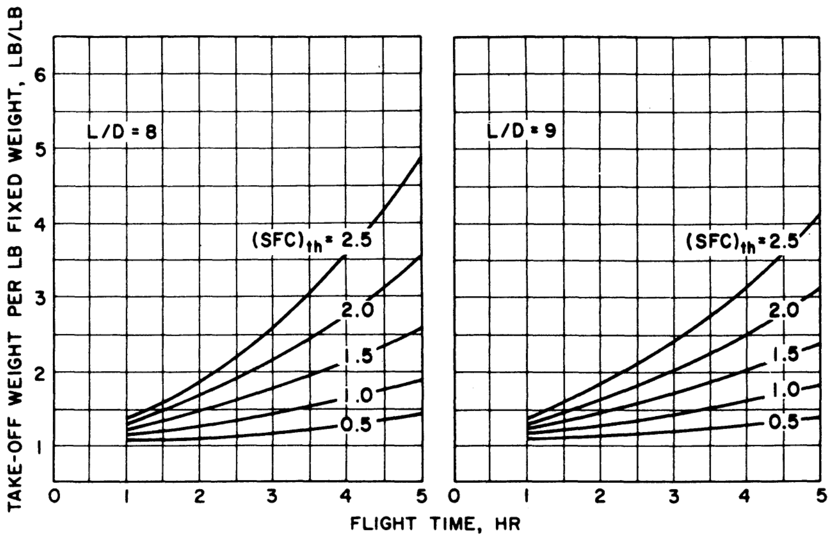

Figure 3I-2 - Fixed Weight Penalty as a Function of Time Carried, L/D = 8, 9

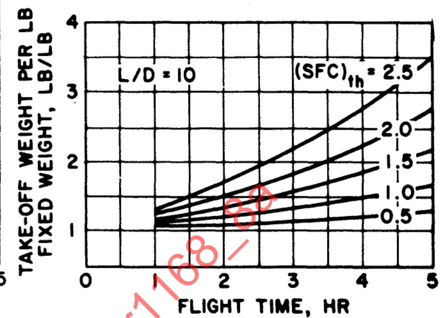

Figure 3I-3 - Fixed Weight Penalty as a Function of Time Carried, L/D = 10

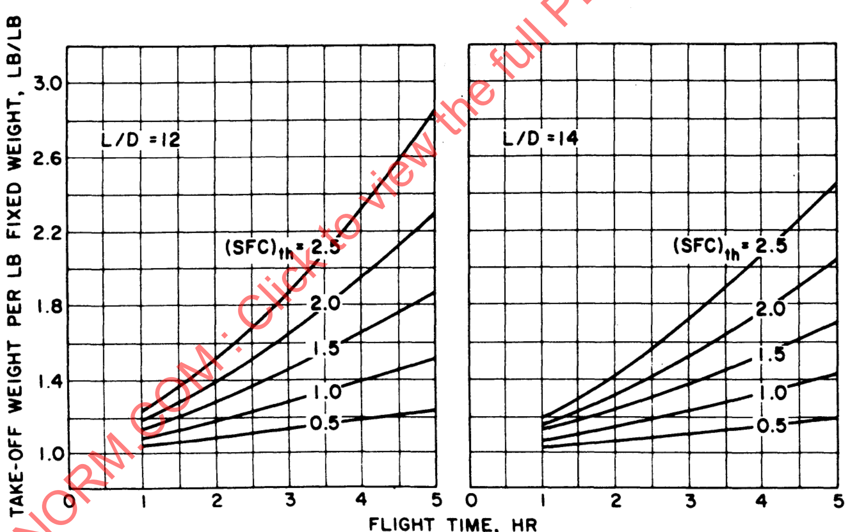

Figure 3I-4 - Fixed Weight Penalty as a Function of Time Carried, L/D = 12, 14

2.2 Variable Weight (Expendable Material) Penalty

Expendable material (such as water for use in water boilers) may be carried aboard the airplane and used during any portion of the flight. If it is assumed that the rate of consumption of the expendable material is constant during the time segment under evaluation, then the take-off fuel weight required for carrying the decreasing weight of expendable material, and also of fuel, is given by

$$\frac{W_{fo} + w_v \tau}{w_v} = \frac{L/D}{(SFC)_{th}} \left[\left(e \ \exp \frac{(SFC)_{th} \tau}{L/D} \right) - 1 \right] \qquad (3I\text{-}2)$$

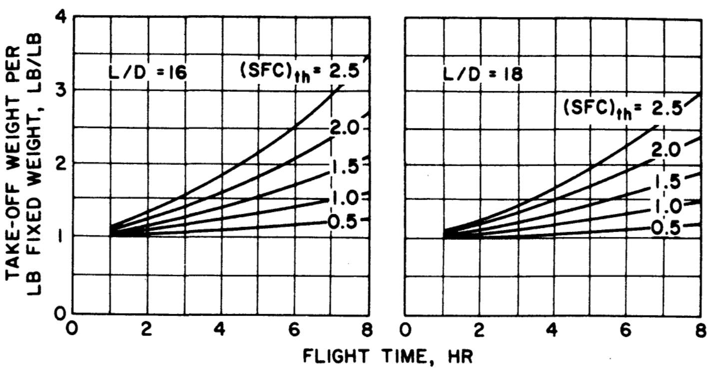

Figure 3I-5 - Fixed Weight Penalty as a Function of Time Carried, L/D = 16, 18

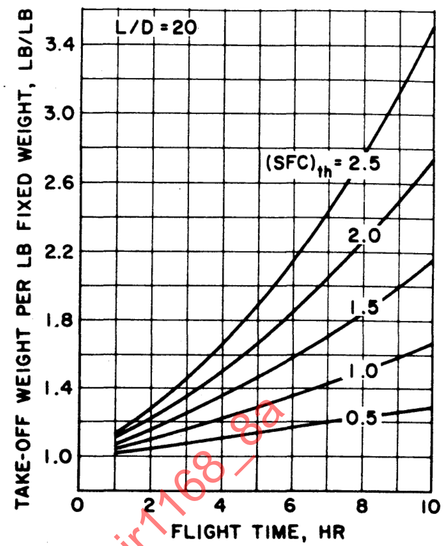

Figure 3I-6 - Fixed Weight Penalty as a Function of Time Carried, L/D = 20

It may be pointed out that the expendable material weight imposes a fixed weight penalty until the time its consumption starts, and should be evaluated by the method given in Par. 2.1.

Figs. 3I-7 through 3I-12 show the take-off weight penalty per lb/hr of expendable material consumed as a function of mission duration, *L/D*, and *SFC*.

2.3 Ram Air Penalty

Assuming complete momentum loss, the ram air penalty in terms of take-off fuel weight is given by

$$\frac{W_{fo}}{w_r V} = \frac{L/D}{g}\left[\left(e\ \exp\frac{(SFC)_{th}\tau}{L/D}\right) - 1\right] \qquad \text{(3I-3)}$$

where the units are expressed as lb/ [(lb/sec)(ft/sec)].

As in the case of expendable material, the weight of fuel at the beginning of the mission segment must be carried as fixed weight throughout the previous mission segments.

Figs. 3I-13 through 3I-18 show the variable weight penalty for use of ram air.

2.4 Bleed Air Penalty

If bleed air is extracted from the compressor of the turbojet engine, the penalty can be evaluated on the basis of increased fuel flow required to maintain constant thrust. As a first approximation only, the increase in fuel flow rate due to bleed air extraction is given by:

$$\Delta w_f = 0.0335\left[\frac{T_{tb}}{2000}\right] w_b \qquad \text{(3I-4)}$$

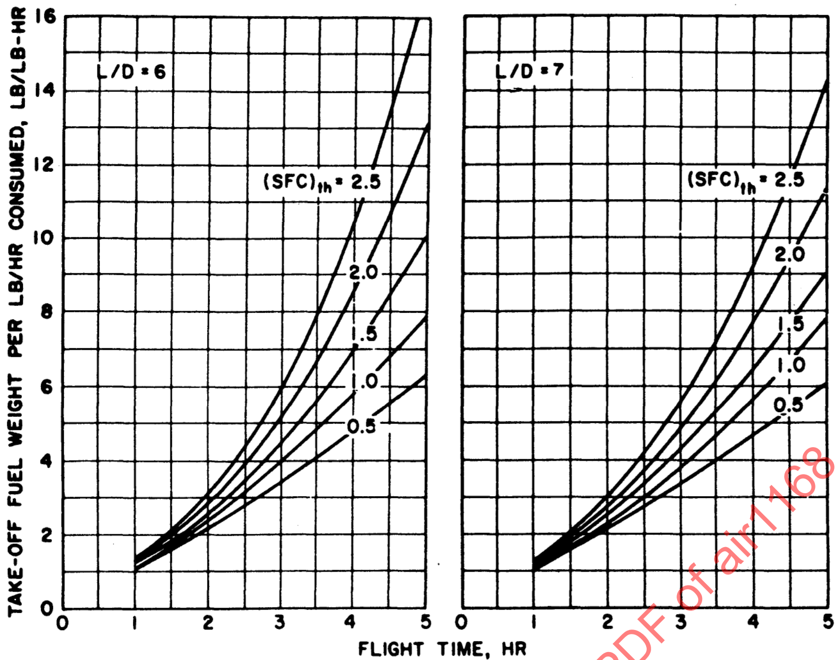

Figure 3I-7 - Variable Weight Penalty as a Function of Flight Time, L/D = 6, 7

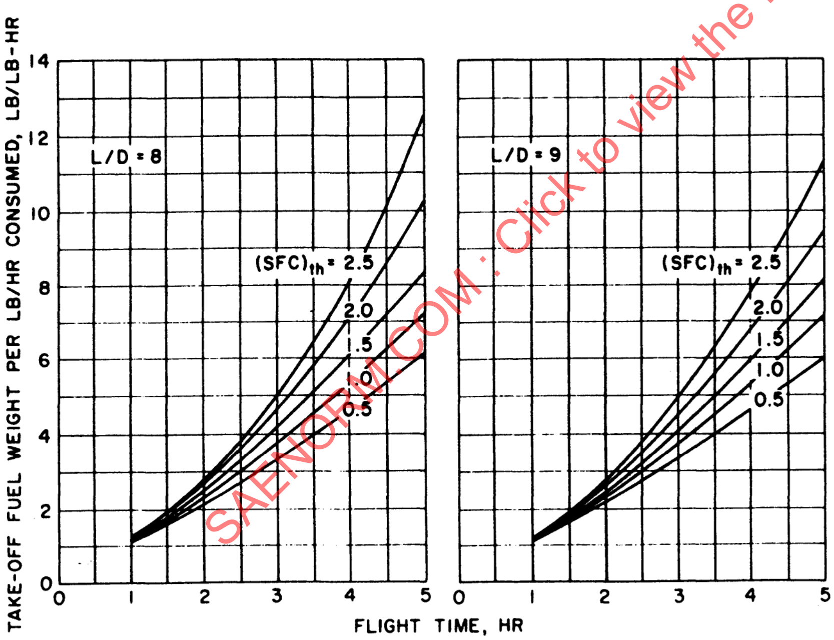

Figure 3I-8 - Variable Weight Penalty as a Function of Flight Time, L/D = 8, 9

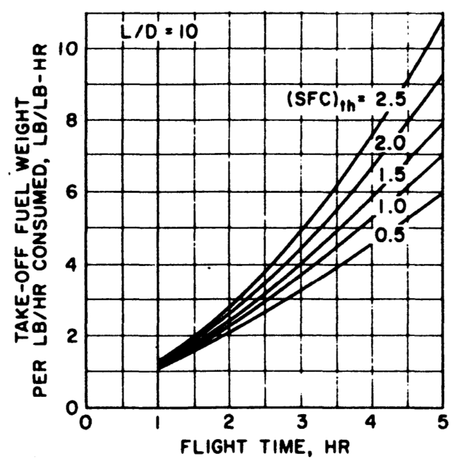

Figure 3I-9 - Variable Weight Penalty as a Function of Flight Time, L/D = 10

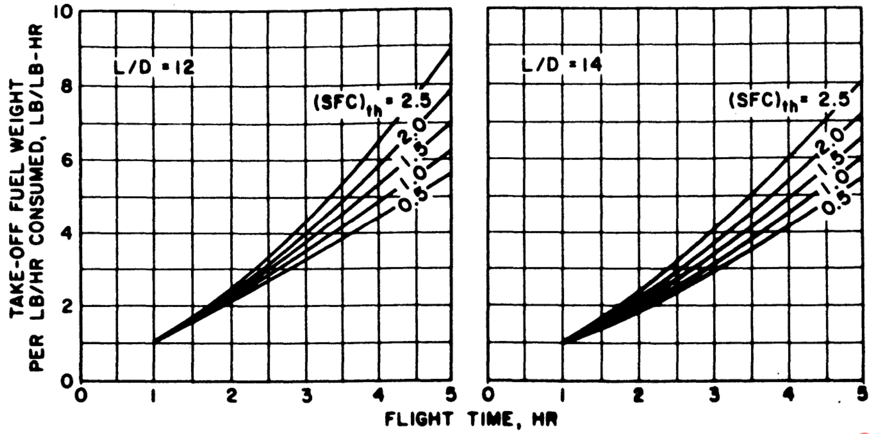

Figure 3I-10 - Variable Weight Penalty as a Function of Flight Time, L/D = 12, 14

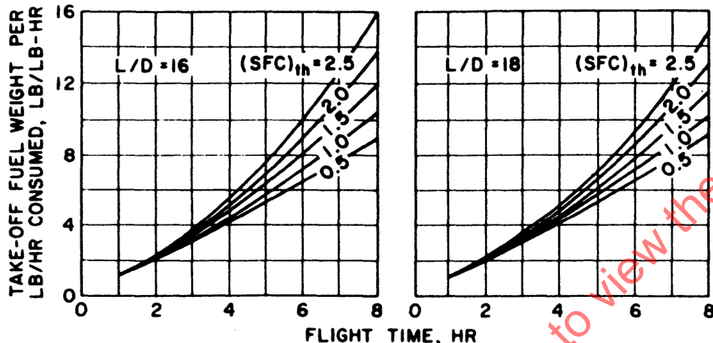

Figure 3I-11 - Variable Weight Penalty as a Function of Flight Time, L/D = 16, 18

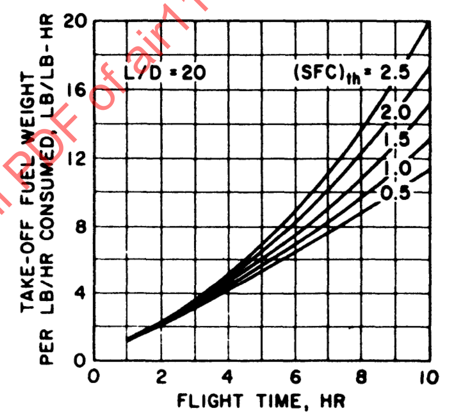

Figure 3I-12 - Variable Weight Penalty as a Function of Flight Time, L/D = 20

For more accurate estimates of bleed air penalty, it is necessary to obtain performance data for the specific engine being considered and the compressor stage being bled.

Fig. 3I-19 is a plot of increase in fuel flow rate for different bleed air flow rates based on Eq. 3I-4.

The bleed air penalty in terms of take-off fuel weight can also be expressed as:

$$\frac{W_{fo}}{w_b} = 0.0335\left[\frac{L/D}{(SFC)_{th}}\right]\left[\frac{T_{tb}}{2000}\right]\left[\left(e\ \exp\frac{(SFC)_{th}\tau}{L/D}\right) - 1\right] \tag{3I-5}$$

Since Eq. 3I-5 is based on the empirical relation given by Eq. 3I-4, it must be considered to have the same limitations as Eq. 3I-4. The penalty for carrying bleed air penalty fuel as an expendable material is obtainable from Figs. 3I-7 through 3I-12.

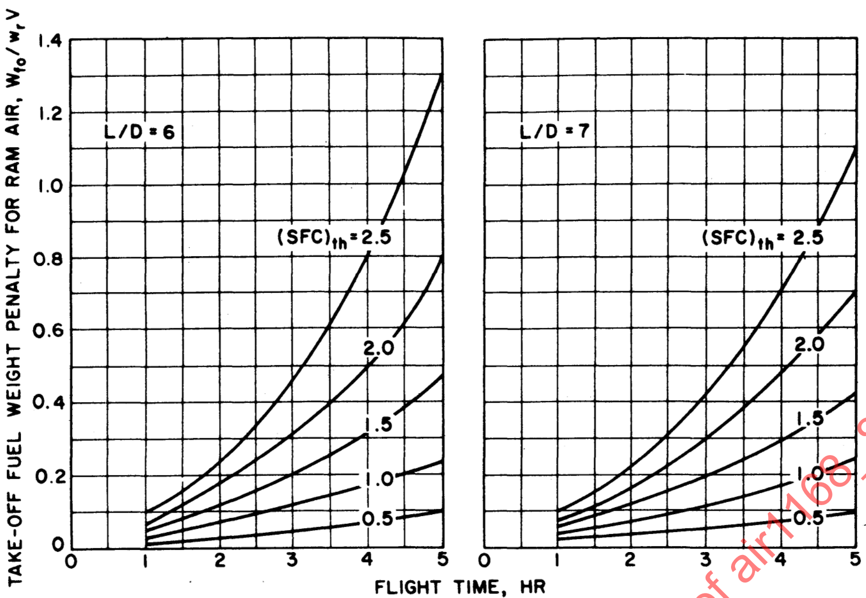

Figure 3I-13 - Variable Weight Penalty for Ram Air as a Function of Flight Time, L/D = 6, 7

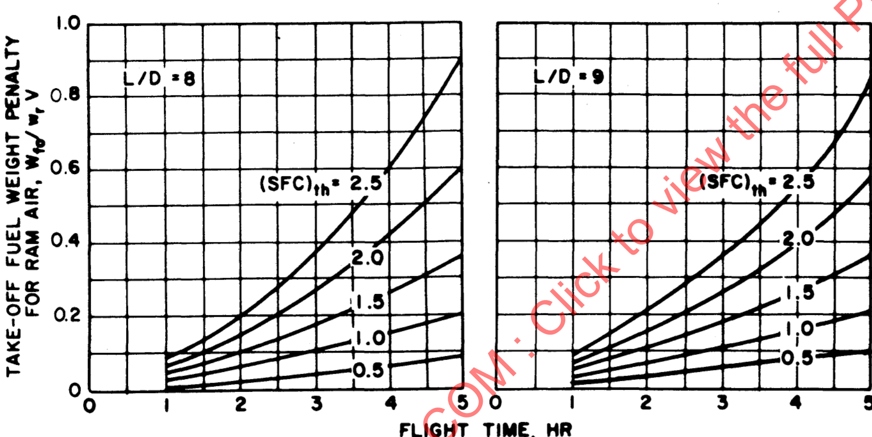

Figure 3I-14 - Variable Weight Penalty for Ram Air as a Function of Flight Time, L/D = 8, 9

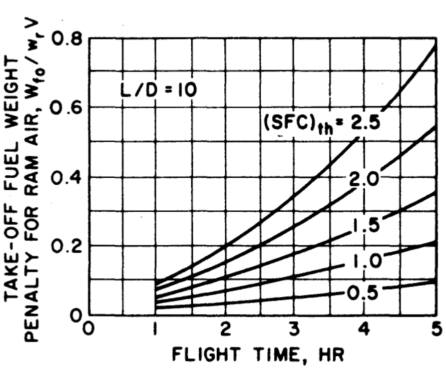

Figure 3I-15 - Variable Weight Penalty for Ram Air as a Function of Flight Time, L/D = 10

2.5 Shaft Horsepower Extraction Penalty

To maintain constant net thrust from the engine, the shaft power extracted must be compensated by an increase in fuel flow rate to the engine. Assuming power is consumed at a constant rate during the portion of mission being evaluated, the take-off fuel weight penalty is given by

$$\frac{W_{fo}}{P(SFC)_p} = \frac{L/D}{(SFC)_{th}}\left[\left(e\ \exp\frac{(SFC)_{th}\tau}{L/D}\right) - 1\right] \tag{3I-6}$$

where units are expressed as (lb/hp) / (lb/hp-hr).

Figs. 3I-20 through 3I-25 show the variable weight penalty for extraction of shaft power.

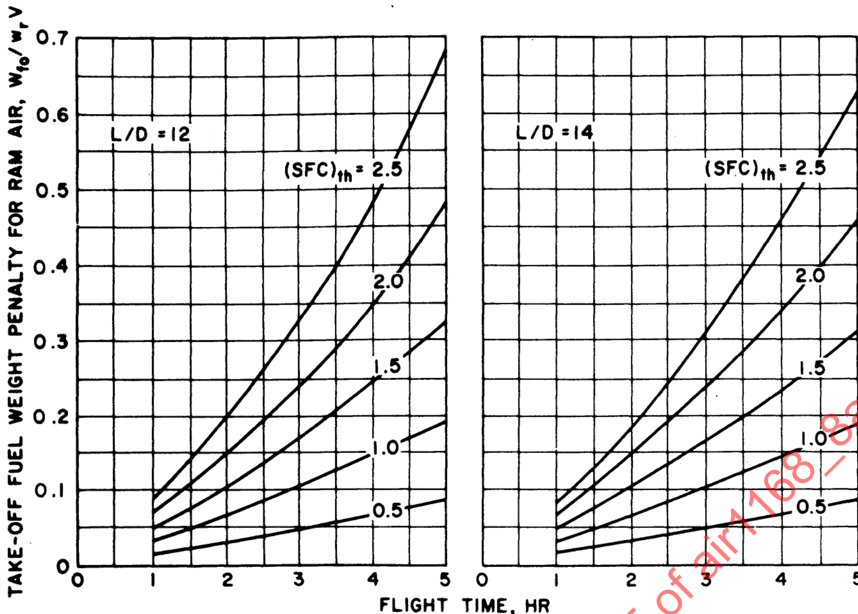

Figure 3I-16 - Variable Weight Penalty for Ram Air as a Function of Flight Time, L/D = 12, 14

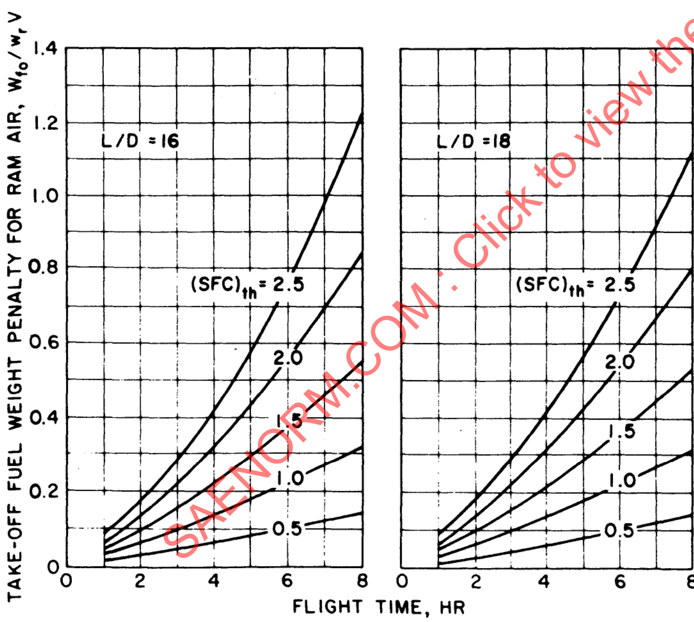

Figure 3I-17 - Variable Weight Penalty for Ram Air as a Function of Flight Time, L/D = 16, 18

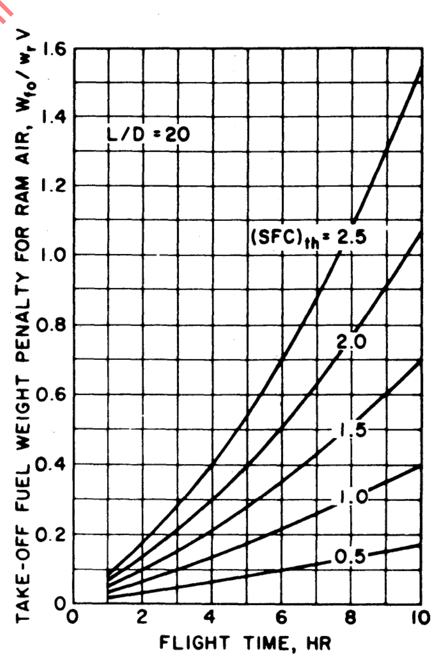

Figure 3I-18 - Variable Weight Penalty for Ram Air as a Function of Flight Time, L/D = 20

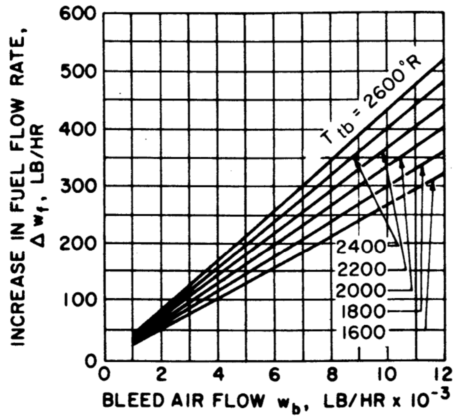

Figure 3I-19 - Increase in Fuel Consumption as a Function of Bleed Air Flow

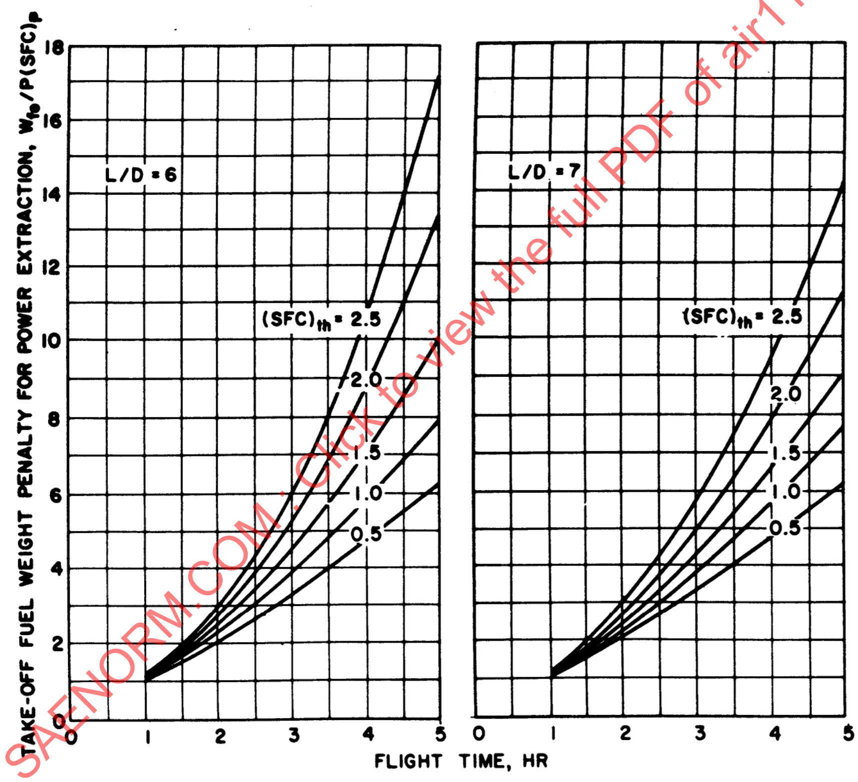

Figure 3I-20 - Variable Weight Penalty for Shaft Power Extraction as a Function of Flight Time, L/D = 6, 7