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A METHODOLOGY FOR HYPERSONIC TRANSPORT TECHNOLOGY PLANNING

by E. M. Repic, G. A. Olson, and R. J. Milliken

Prepared by
ROCKWELL INTERNATIONAL, SPACE DIVISION
Downey, Calif. 90241
for Langley Research Center

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16. Abstract

This document provides a systematic procedure by which the relative economic value of technology factors affecting design, configuration, and operation of a hypersonic cruise transport can be evaluated. Use of the methodology results in identification of first-order economic gains potentially achievable by projected advances in each of the definable, hypersonic technologies. Starting with a baseline vehicle, the formulas, procedures and forms which are integral parts of this methodology are developed. A demonstration of the methodology is presented for one specific hypersonic vehicle system.

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FOREWORD

The methodology and practices contained in this report were developed by North American Rockwell during the time period 11 September 1972 to 22 January 1973. The study was funded under Langley Research Center Contract NAS1-6024 through a work order (L.S. 2935 A3) from McDonnell Douglas Astronautics Company. Mr. H. P. Adam of McDonnell Douglas acted as liaison between NASA and North American Rockwell.

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SYMBOLS

A_C	total cowl inlet area, ramjet (or scramjet) engines, m^2 (ft^2)
C_D	drag coefficient (drag/qS)
C_D/C_{TRJ}	ratio of drag coefficient to ramjet thrust coefficient at cruise
C_{D_i}/C_L^2	induced drag factor
C_{D_o}	zero-lift drag coefficient
C_L	lift coefficient (lift/qS)
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)
C_{AF}	cost of HST airplane less engines and avionics, \$
C_{AV}	cost of avionics equipment per aircraft, \$
C_f	cost of fuel per unit weight, \$/kg, (\$/lb)
C_{HST}	cost of HST airplane (total), \$
C_{RJ}	cost of ramjet engine set per aircraft, \$
C_{TJ}	cost of turbojet engine set per aircraft, \$
DOC	direct operating cost, \$ per ton mile (or ¢ per ton-mile)
E	modulus of elasticity, N/m^2 ($lb/in.^2$)
F	design factor
f_{cy}	compressive yield stress, N/m^2 ($lb/in.^2$)
f_{ty}	tensile yield stress, N/m^2 ($lb/in.^2$)
FMP	fuselage material properties parameter

IR	annual insurance rate, %/100
K_{CL}	climb fuel fraction (ratio of climb to main fuel)
K_D	descent fuel fraction (ratio of descent to main fuel)
K_{LRJ}	ratio, maintenance labor for ramjet engines to present subsonic turbojet engines
K_{LTJ}	ratio, maintenance labor for HST turbojet engines to present subsonic turbojet engines
K_{MRJ}	ratio, maintenance material for ramjet engines to present subsonic turbojet engines
K_{MTJ}	ratio, maintenance material for HST turbojet engines to present subsonic turbojet engines
K_R	reserve fuel fraction (ratio of reserve to main fuel)
L_d	depreciation life of aircraft, years
L/D	cruise lift-drag ratio
LF	average load factor (ratio of average payload carried to normal maximum capability), %/100
M	cruise Mach number
N_{RJ}	number of ramjet engine modules per aircraft
N_{TJ}	number of turbojet engines per aircraft
q	free stream dynamic pressure, N/m^2 (lb/ft^2)
R_{CR}	Breguet cruise range, km (statute miles)
R_{CL}	range covered during climb, km (statute miles)
R_D	range covered during descent, km (statute miles)
r_L	average maintenance labor rate, all personnel, $/manhour

R_T	operational range, km (statute miles)
S	reference area, m^2 (ft^2)
sfc	specific fuel consumption at cruise, (kg/N-hr lb_m/lb_f-hr)
t_B	block time, hr
t_F	time of flight, hr
T_{TJ}	turbojet thrust (sea level static) per engine, N (lb)
$(T/W)_{GTO}$	maximum thrust to weight ratio at take-off
U	aircraft utilization, block hr/yr
V_B	block velocity (operational range/elapsed time from engines-on to engines-off), km/hr (miles/hr)
V_B/V_{CR}	ratio of block velocity to cruise velocity
$\left(\frac{W}{A_C}\right)_{RJ}$	ramjet specific weight, kg/m^2 (lb/ft^2)
W_{AF}	weight of HST aircraft excluding main fuel, propulsion, avionics, payload, and wet airframe items, $\left(W_{GTO} - W_{f_T} - W_{TJ} - W_{RJ} - W_{AV} - W_{PL} - W_{Misc}\right)$, kg (lb)
W_{AV}	weight of avionics equipment per aircraft, kg (lb)
W_{CR_i}	weight at end cruise, kg (lb)
W_{CR_o}	weight at begin cruise, kg (lb)
W_e	empty weight $\left(W_e = W_{GTO} - W_{f_T} - W_{Misc} - W_{PL}\right)$, kg (lb)
$W_{f_{CL}}$	fuel consumed in climb, kg (lb)
$W_{f_{CR}}$	fuel consumed in cruise, kg (lb)

W_{f_D}	fuel consumed during descent, kg (lb)
W_{f_R}	reserve fuel, kg (lb)
W_{f_T}	weight of main fuel, kg (lb)
W'_F	total fuselage structural weight minus the fuselage fixed weight $\left(W_F - W_{F,F}\right)$, kg (lb)
$W_{F,F}$	fuselage fixed structural weight (weight of all fuselage elements not designed by primary loads), kg (lb)
W_{GTO}	gross take-off weight, kg (lb)
W_{Misc}	weight of crew, residuals, power reserve and in-flight losses, kg (lb)
WMP	wing material properties parameter
W_{PL}	weight of normal maximum payload, kg (lb)
W_{RJ}	installed weight of ramjet engines per aircraft, kg (lb)
$W_{RJ}/A_C C_{TRJ}$	ramjet sizing parameter, kg/m^2 (lb/ft^2)
$(W/S)_{GTO}$	reference wing loading at take-off kg/m^2 (lb/ft^2)
$(W/T)_{TJ}$	turbojet propulsion specific weight $\left(\frac{W_{TJ}/N_{TJ}}{T_{TJ}}\right)$
W_{TJ}	installed weight of turbojet engines and ducts per aircraft, kg (lb)
W'_W	total wing weight minus the wing fixed weight $\left(W_W - W_{W,F}\right)$, kg (lb)
$W_{W,F}$	wing fixed weight (weight of all wing elements not designed by primary loads), kg (lb)

η_K	ramjet inlet kinetic energy efficiency
η_C	ramjet combustion efficiency
η_{KN}	ramjet nozzle kinetic energy efficiency
ρ	material density, kg/m^3 (lb/ft^3)

DEFINITIONS

Driver	A parameter in the DOC formula which significantly impacts DOC and which is directly relatable to hypersonic technology
Technology Parameter	A parameter which relates Drivers to specific areas of hypersonic research

INTRODUCTION AND SUMMARY

The objective of the study reported on herein was to develop a systematic procedure for evaluating the relative value of technology factors affecting design, configuration, and operation of a hypersonic cruise transport (HST), including the potential economic gains achievable through projected advances in hypersonic technologies.

In this context, the "systematic procedure" is a "tool" intended for NASA's use - by which the potential payoff from alternative hypersonic research objectives may be quantitatively evaluated. As such, this "tool" is intended to complement the existing practices and procedures which NASA uses in its technology planning process.

The logic of the subject method is illustrated in figure 1. The method begins with the definition of a baseline HST. The baseline may be any cruise system/configuration for which it be desired to determine the relative values of potential technology improvements in support of technology planning. The present method calls for the baseline to be obtained from an independent study or to be synthesized from independent data sources. The output of this first step is vehicle and mission data which are specifically required to initiate the succeeding steps.

The second step in the method is to use formulas for the computation of Direct Operating Costs (DOC) for the baseline. These formulas comply with Air Transport Association of America conventions, but are modified to reflect projected hypersonic factors. This step also identifies the DOC "Drivers"; i.e., parameters of the DOC formulas which are directly relatable to hypersonic technology and which have significant impact on the DOC.

The third step in the method is to compute the impact upon the DOC Drivers of variations in Technology Parameters (TP's). By definition, TP's are parameters which are lower-tier to the Drivers and which are relatable to specific areas of hypersonic research. The baseline TP's will have been specified within the data obtained from the first step.

The fourth step involves projections of technology advances beyond the state-of-the-art incorporated in the baseline HST. The projections are made at the level of the Technology Parameters referenced above. These projections, made by the appropriate technology specialists, are prime inputs to the following step.

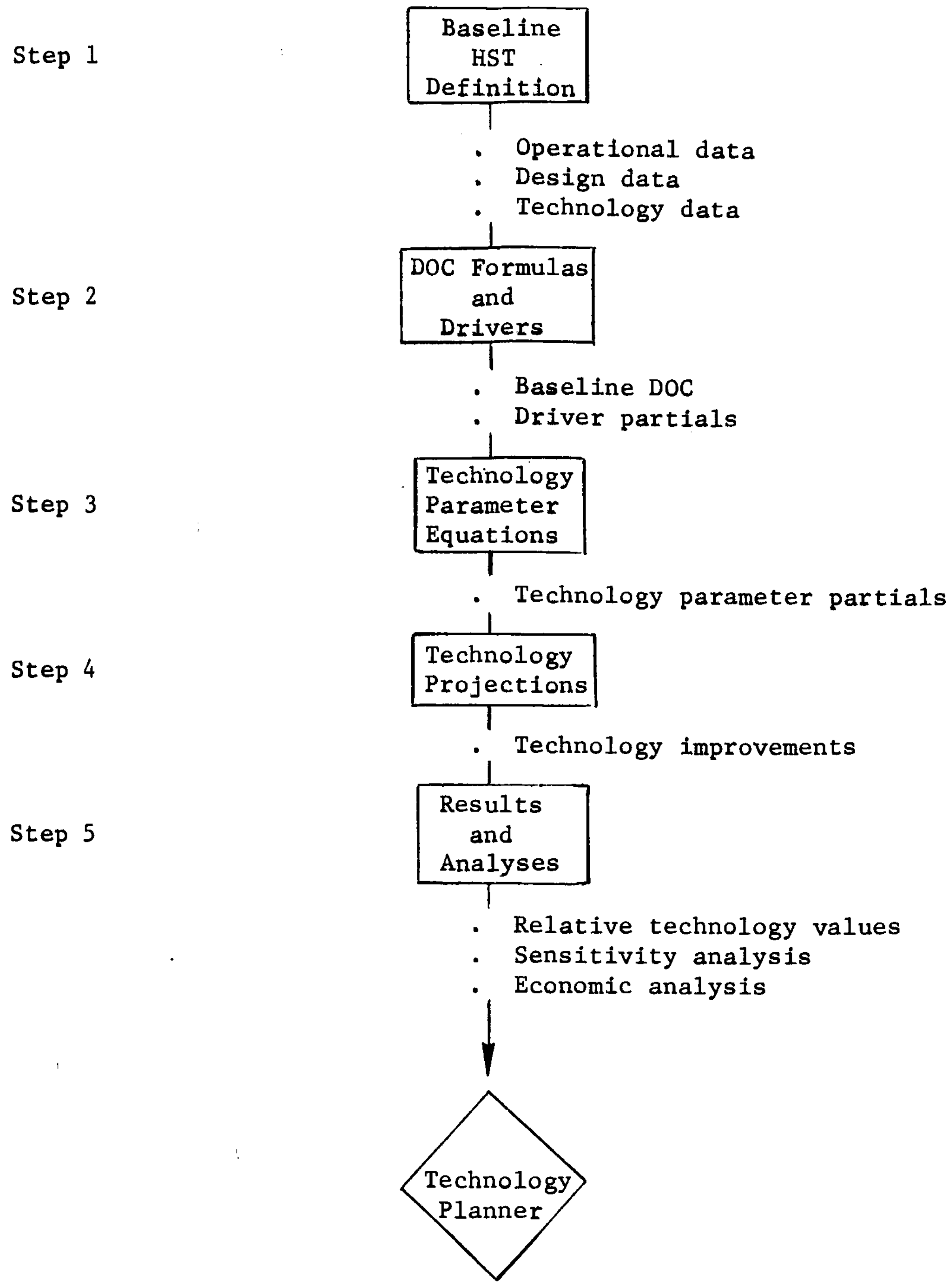

Figure 1.- Method Logic

The fifth step integrates the preceding data to produce estimates of the potential DOC savings afforded by advances in the hypersonic technologies. The relative DOC savings per technology area is the major product of the subject method. To qualify the product, step five includes sensitivity and economics analyses. The sensitivity analysis examines the impact of uncertainties upon the relative economic values of the technologies. The uncertainties apply to the semiempirical constants contained in the DOC formulas and to the projected technology improvements. If the sensitivity and economic analyses qualify the results to be valid and meaningful, the product is appropriately packaged to be transmitted to the person(s) or organization(s) who are responsible for technology planning.

Demonstration

The methodology and procedures discussed above were applied to an example case during the study to illustrate their use. The baseline HST chosen (step 2), along with its principal characteristics, are shown in figure 2. This HST was assumed to have an operational range of about 7400 km (4600 statute miles), a cruise Mach number of 6 and a nominal payload of about 22 700 kg (50 000 lb). The propulsion system used included 4 liquid hydrogen burning turbojets of 260 000 N (58 000 lb) thrust each to accelerate the HST to Mach 3 at which point the 9 scramjets, having a total thrust of 698 000 N (157 000 lb), take over.

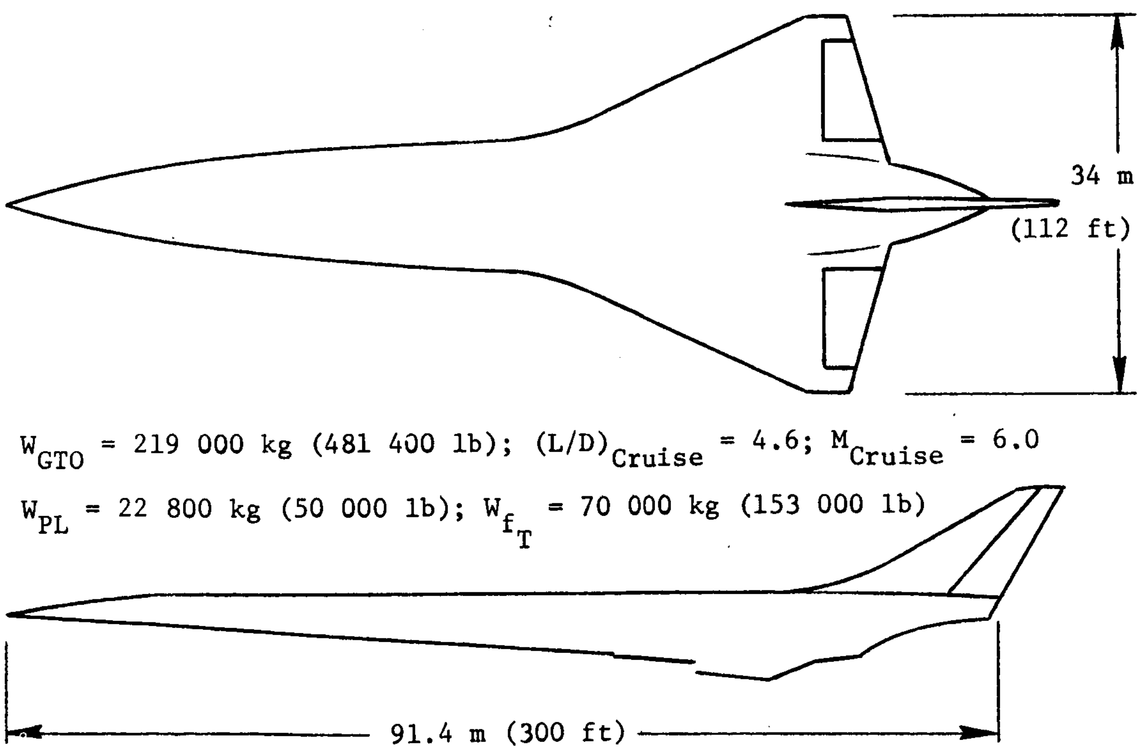

Figure 2.- Baseline HST

The baseline Direct Operating Costs (DOC) computed for this baseline HST, using the equations developed in the study (step 2), are shown in Table I. These values are used as the base values from which the effects of Technology improvements are computed.

TABLE I.- BASELINE DIRECT OPERATING COSTS

DOC Element	DOC - ¢/ton-mile
Fuel	25.7
Depreciation	12.0
Maintenance	6.0
Insurance	2.1
Crew	1.0
Total	46.8 ¢/ton-mile

Table II lists the principal vehicle parameters (i.e., "Driver" Parameters) and the corresponding "Technology" Parameters.

Figure 3 shows the sensitivity of the baseline DOC to changes in the Driver Parameters which is step 3 in the method.

Table III shows the sensitivity of the Driver Parameters to projected improvements in the Technology Parameters.

During the study, potential improvements in the Technology Parameters were projected by a combination of NASA and North American Rockwell Specialists. This is step 4 in the procedure described earlier. These projected improvements are also shown on Table II. Using this information, along with the sensitivity shown earlier, the final results relating the projected improvements to changes in the DOC were computed and are shown in figure 4. For the example case chosen, the results indicate that the net effect of all the projected improvements in hypersonic technology is to lower the HST direct operating cost by over 60% which would bring it near the level of current subsonic transports.

TABLE II.- DRIVER PARAMETERS AND TECHNOLOGY PARAMETERS

W_{AF}/W_{GTO} Airframe Weight Fraction	L/D Lift-to-Drag Ratio	sfc Specific Fuel Consumption	$\frac{W_{RJ}}{A_C C_{TRJ}}$ Ramjet Sizing Parameter	$(W/T)_{TJ}$ Turbojet Specific Weight
F_{MP} - fuselage material parameter (-10%)	C_{D_o} - zero lift drag coeff. (-10%)	η_K - inlet efficiency (+1%)	$\frac{W_{RJ}}{A_C}$ - ramjet specific weight (-10%)	$\left(\frac{W}{T}\right)_{Eng}$ - engine specific weight (-6%)
W_{MP} - wing material parameter (-10%)	C_{D_i}/C_L^2 - induced drag factor (-2.5%)	η_C - combustion efficiency (+1%)	C_{TRJ} - ramjet thrust coefficient (+10%)	
F_W - wing design factor (+10%)		η_{KN} - nozzle efficiency (+1%)		
F_F - fuselage design factor (+10%)				
F_i - other element design factors (+10%)				

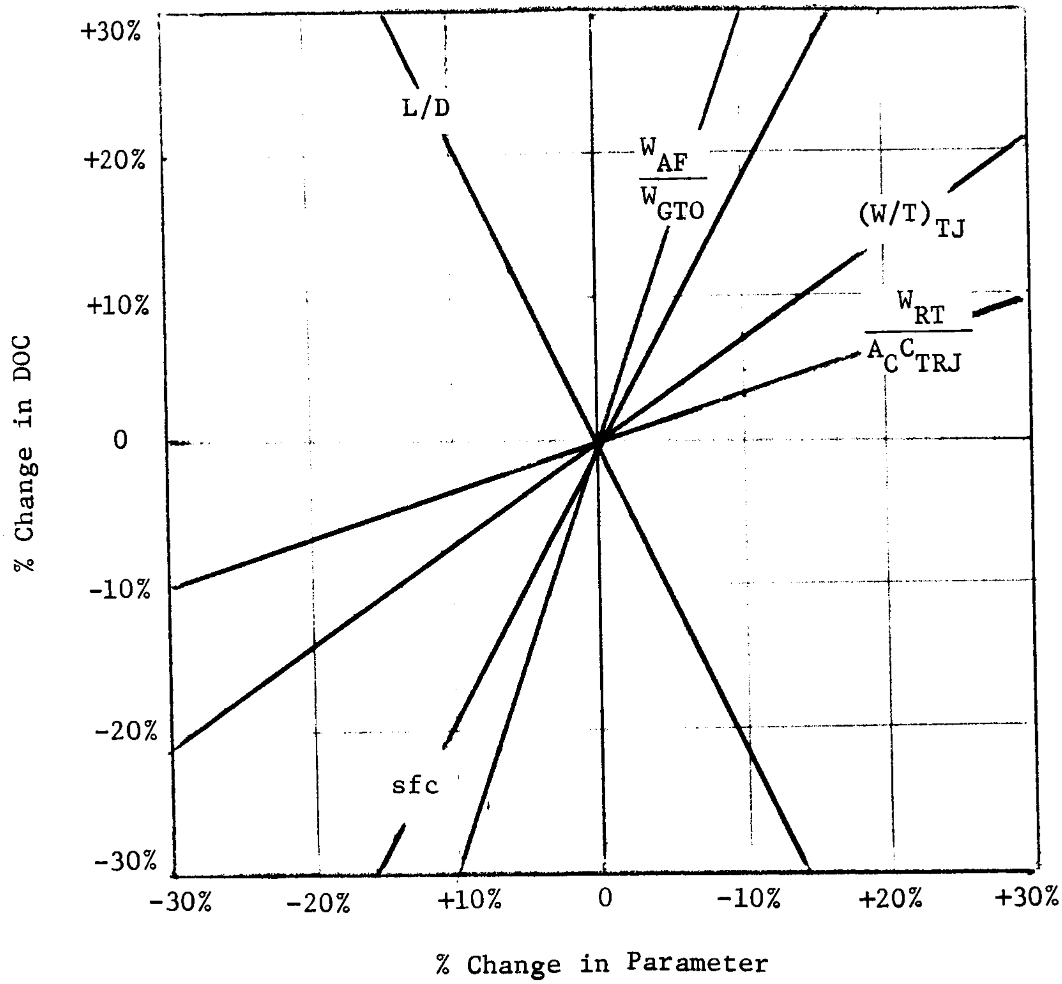

Figure 3.- Driver Parameter Sensitivities

TABLE III.- TECHNOLOGY PARAMETER SENSITIVITIES

Technology Parameter		ΔDOC for a 10% Increase (¢/ton-mile)
F_{MP}	- fuselage material parameter	+1.5
W_{MP}	- wing material parameter	+1.8
F_F	- fuselage design factor	-4.3
F_W	- wing design factor	-4.1
C_{D_o}	- zero lift drag coefficient	+8.1
$C_{D_i}/C_L{}^2$	- induced drag factor	+4.8
η_K	- inlet efficiency (1% increase)	-0.2
η_C	- combustion efficiency (1% increase)	-0.8
η_{KN}	- nozzle efficiency (1% increase)	-3.6
W_{RJ}/A_C	- ramjet specific weight	+1.4
C_{TRJ}	- ramjet thrust coefficient	-1.4
$(W/T)_{Eng}$	- turbojet specific weight	+3.7

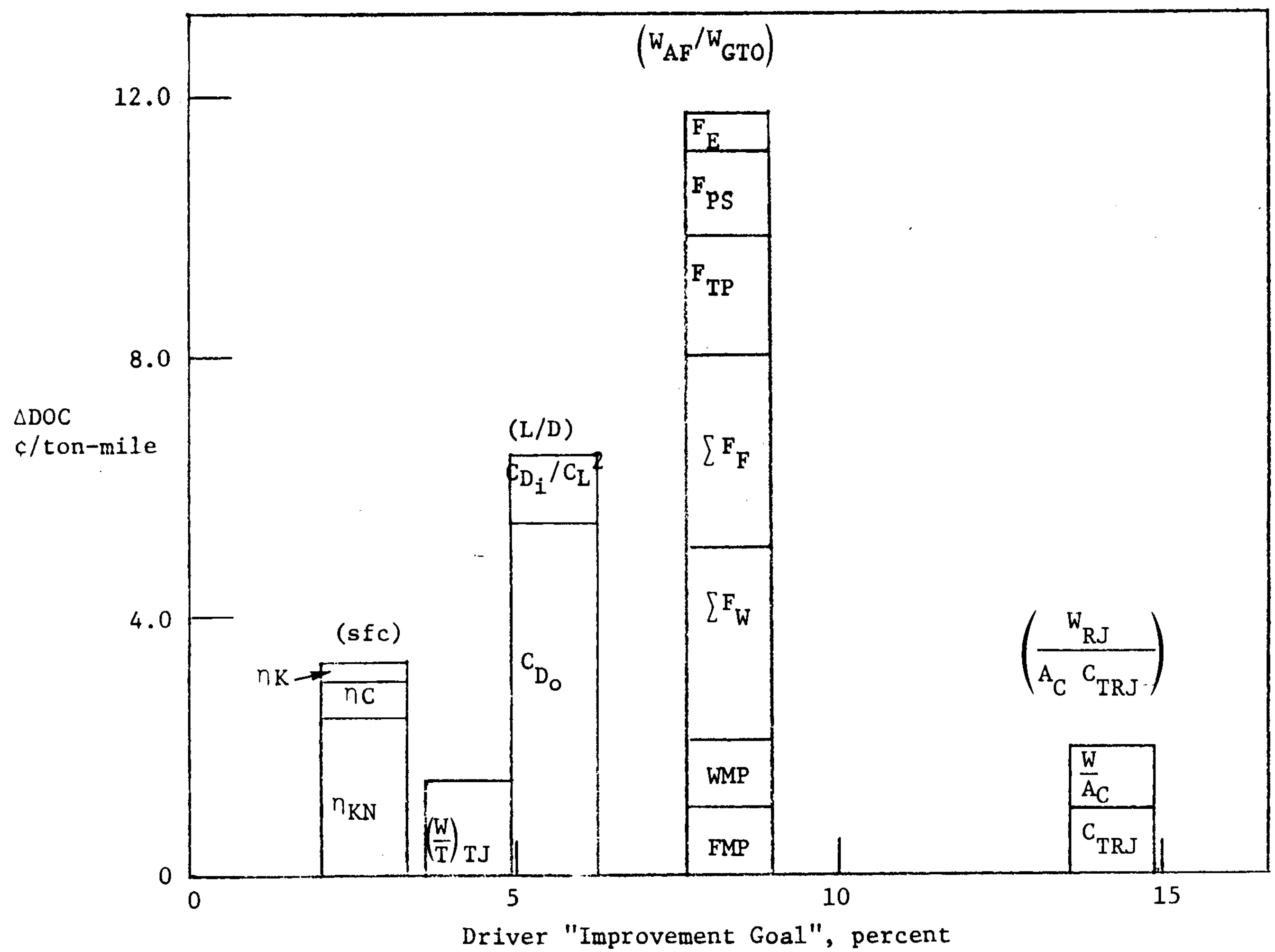

Figure 4.- Results Summary Chart

Scope and Qualifications

The subject method has been designed to provide a quantitative rationale which will support NASA's planning and resource allocation for hypersonic vehicle technology. The depth of analysis and the accuracy requirements imposed on the method are appropriate to this objective. The final step in the method is particularly designed to eliminate spurious information.

In general, the method applies to any passenger or cargo-carrying hypersonic cruise mission where the aircraft is of the horizontal take-off, horizontal landing type, and utilizes air-breathing engines for propulsion.

The user of the method is cautioned, however, to limit its application to its intended objective: to support technology planning. The results of the method are not intended to evaluate the economics of hypersonic flight, nor to evaluate aircraft design or operational features. For such purposes, independent studies would be performed.

Organization of Report

The method is modularized to permit ease of communication and data handling between the various personnel who would participate in its application. In total, there are six method modules - five corresponding to the five steps discussed earlier and a sixth which provides project direction and integration for the total activity. These six method modules are listed below by title:

MM No. 1 - Method Integration

MM No. 2 - Baseline HST Definition

MM No. 3 - DOC Formulas and Drivers

MM No. 4 - Technology Parameter Equations

MM No. 5 - Technology Projections

MM No. 6 - Results and Analyses

Each method module is essentially a set of instructions and procedures to be applied by the user in developing the output required of his particular module. Each module contains detailed instructions and procedures, a statement of the input data required, the output data to be produced, and an example demonstration of the method.

METHOD MODULE 1

METHOD INTEGRATION

METHOD MODULE 1 - METHOD INTEGRATION

Logic

The subsequent modules of this six-module set present data, equations, and procedures to establish the relative economic value of technology factors as an aid in planning future technology programs for a hypersonic transport. Each of the modules covers a single facet of the problem and, when taken individually, contributes only a part of the overall answer. This module provides the procedures, instructions, and explanatory material required to initiate, monitor, and integrate the work defined in the other five modules.

In all that follows, it is assumed that the user of the overall methodology, generally the technology planner, will have available to him the services of appropriate technologists and system specialists as required. The user, hereafter called the Project Office, is expected to act as coordinator, and it is recommended (although not required) that he also personally perform the calculations described in Module 6 to establish the relative technology values for the baseline vehicle being considered. This recommendation is made based on exploratory use of the methodology by the authors in which it was found that personal participation in the final calculations was of great help in fully understanding the results.

The interaction of the Project Office and the five modules comprising the basic methodology is shown in figure 1-1. A basic function of the Project Office is to monitor the outputs of the modules and assure the availability of required input data to each module. This means that all module outputs should be reviewed by the Project Office prior to being distributed to other participants. If the material is incomplete or questionable, the Project Office must supplement or change the data prior to passing it on. In order to accomplish these tasks efficiently, the Project Office should develop, publish, and maintain a schedule of these tasks to assure coordination between modules and participants. Specific instructions and recommendations on achieving the above goals are presented in this module.

Conditions and Qualifications

Consistent with the overall methodology and practices, the HST baseline definition method applies specifically to hypersonic cruise aircraft utilizing air-breathing engines and employing horizontal take-off and landing.

Within these limitations the baseline definition method has the flexibility to accommodate broad mission and design variables, as summaried in Table 1-I.

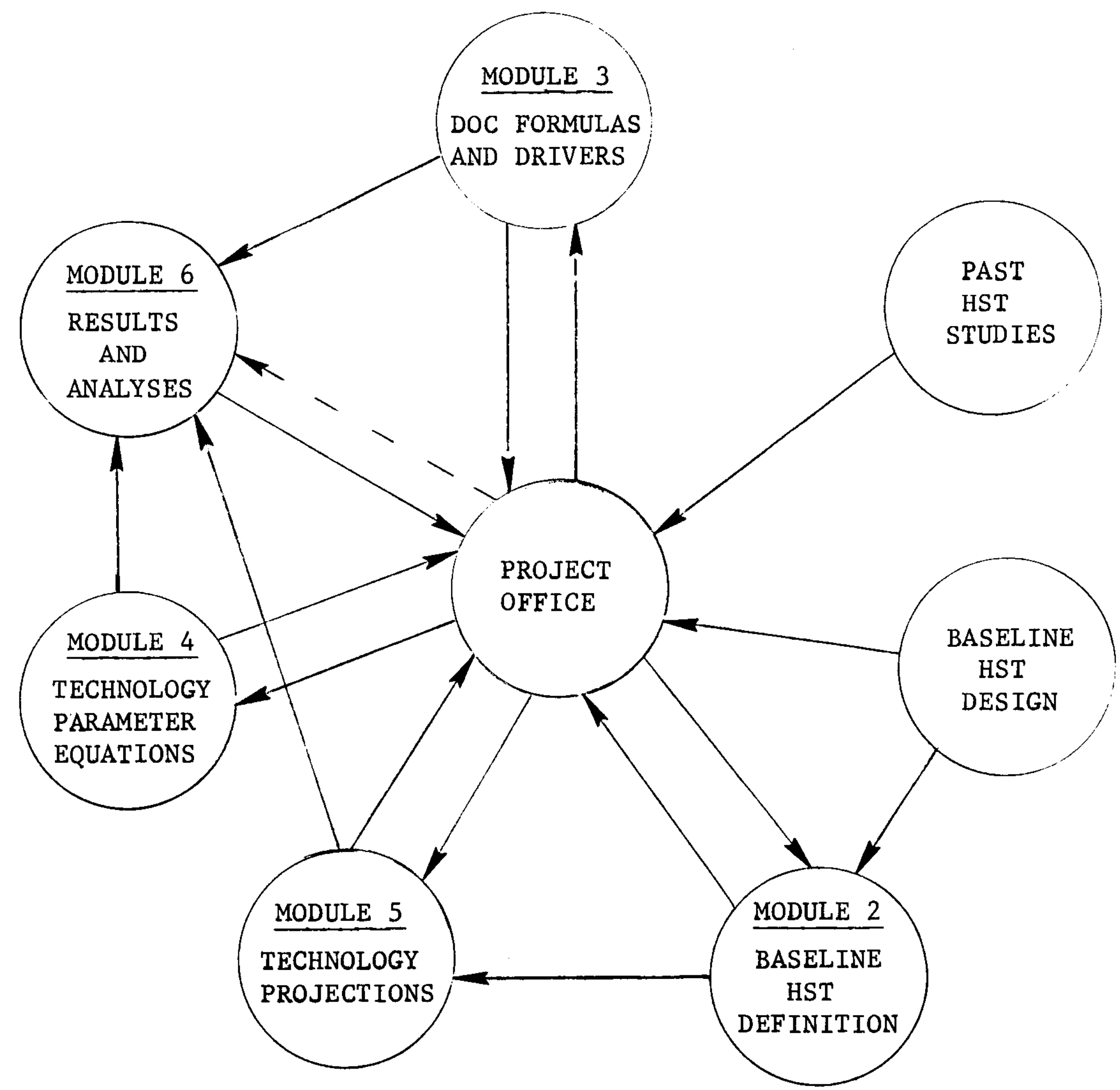

Figure 1-1.- Method Integration Logic

TABLE 1-I.- RANGE OF FEASIBLE BASELINE MISSION AND DESIGN VARIABLES

Variable Category	Major Alternatives Accommodated
Payload	Cargo, passengers or combination
Cruise Mach number	5-12
Fuel type	Liquid hydrogen, jet fuels, methane, etc., and combinations
Structure	Actively cooled, uncooled, or combination; integral or non-integral fuel tanks
Aero configuration	Blended wing-body, all-body or conventional
Propulsion	Separate turbojets and ramjets or integrated propulsion systems; supersonic or subsonic combustion, or dual-mode ramjets

Variations in payload type have minimal effect in baseline development because the density of an airplane passenger compartment is comparable with the density required to accommodate most potential cargos. In the case of a liquid hydrogen-fueled airplane, where the fuel density is similar to cargo or passenger compartment densities, payload weight variations may be traded for fuel, with subsequent range changes.

The parameters and relationships in this method are generally applicable to the hypersonic Mach number range of 5 to 12. Mach numbers beyond this range should not be treated without a prior assessment of suitability.

Although the baseline HST design and performance are strongly dependent on fuel type, the basic methodology is not. Means for accommodating different fuel types are discussed in the Baseline HST Definition module.

The output of the structures definition is expressed in weight fractions, associated technology parameter values, and supporting descriptions and conditions. Parameters in the method accommodate either or both cooled and uncooled structures. For example, the demonstration included later in the Baseline HST Definition module describes an HST which has an actively cooled wing and fuselage and an uncooled tail.

Procedures in subsequent modules will further explain the means for adapting this method to other combinations.

A final condition which must be observed is concerned with the technology base associated with the baseline design. The baseline must be predicated on the use of presently postulated and immediately foreseeable technology. This is important in that the technology projections will be made from this base. If the baseline has already incorporated projected technology advances, then the methodology developed here will not properly show the relative value of technology improvements.

Input Data

Effective use of the methodology described here is predicated on the use of an existing baseline hypersonic transport design such as that described in Reference 1. A consistent set of mission, design, and operational parameters must be specified and sufficient supporting detail must be available to provide the technology specialists with a design definition. If an adequate level of detail is not available, then the Project Office must either arrange to have the material generated or must establish by ground rule, the values to be used.

The last input data requirement is the Project Objectives. The user must clearly understand the objective he is striving for so that he can properly inform and lead those he will ask to participate. The objective of this methodology is to provide a quantitative rationale to support the planning and allocation of resources for HST technology. The results of the methodology are not intended to evaluate the economics of hypersonic flight nor to evaluate aircraft and operational procedures.

Procedures

This section presents the specific procedures to be followed by the Project Office in achieving the objective of the technology planning exercise. Each user will find some advantage in modifying these basic procedures to more exactly conform with his own view of the overall technology planning problem. The basic procedures are written so that a user with no prior experience in this area can easily use the methodology. Figure 1-2 is a flow chart of the various steps in the Procedures. Each step shown in figure 1-2 is explained in the following subsections.

Technological scenario.- The first step in the procedure is for the Project Office to prepare a "Technological Scenario." This scenario is to present a framework of perspectives and conditions within which the HST technological developments may be assumed to occur. The specialists who will make the technology projections requested in Module 5 will need this background to put their projections in the proper context. An example of such a Technological Scenario is given as follows:

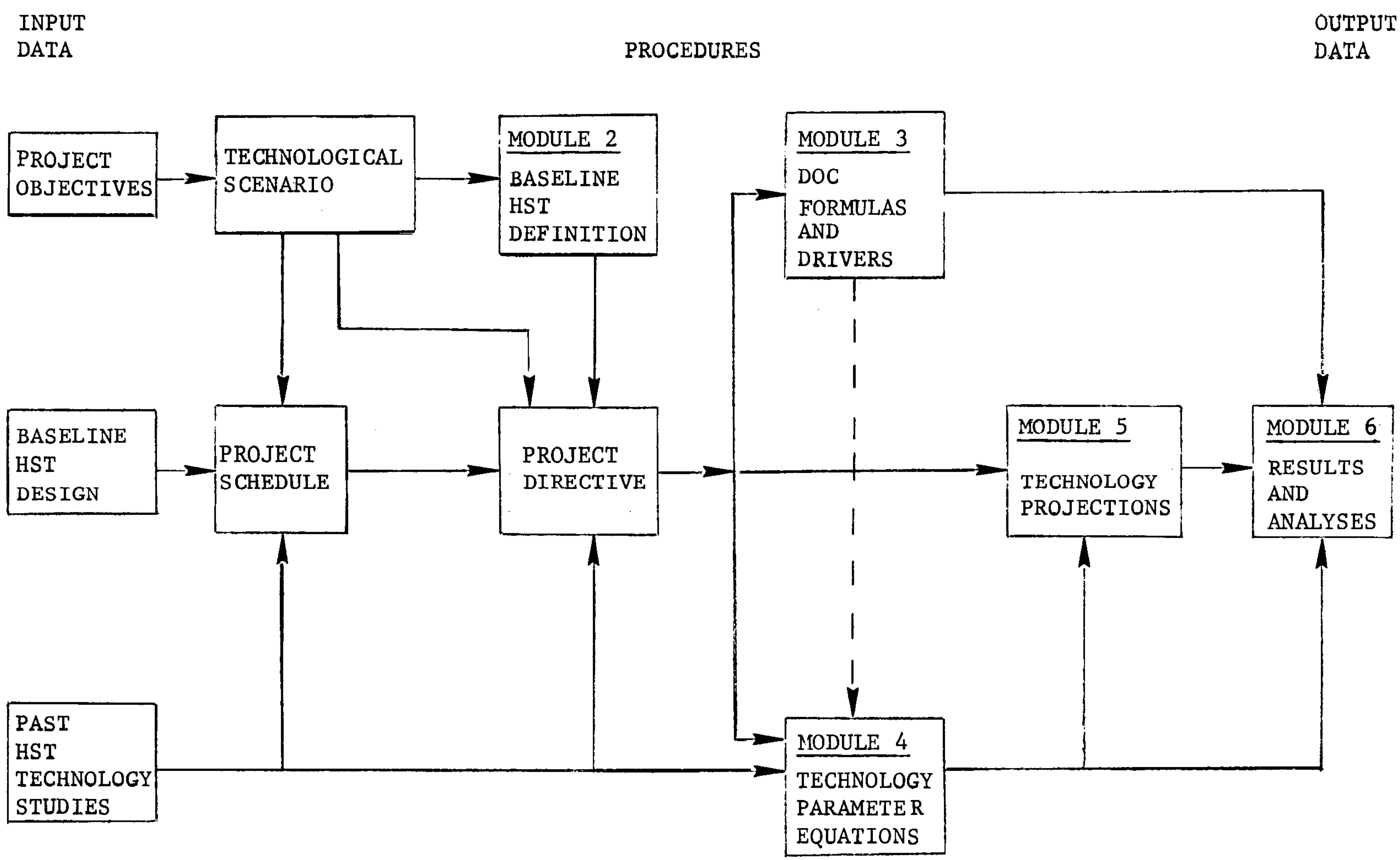

Figure 1-2.- Method Integration Flow Chart

Technological Scenario (Example):

During the period of the late 70's, exploratory flights of the Hypersonic Research Aircraft (HRA) will commence. Over the next several years the flights will prove the technological feasibility of sustained cruise at Mach 6.0 using LH_2 propellants in an advanced scramjet engine. Various types of thermal protection and conditioning systems will be shown to be practical - including active cooling of the airframe. The long-life reusability and maintainability of advanced components and materials will be demonstrated. Cruise efficiencies of the aircraft will be shown to support the economic potential of a hypersonic cruise transport aircraft.

During the same period, the competition of foreign aircraft manufacturers and airlines will begin to erode the traditional lead of the U.S. Support will grow for a new aircraft which will recapture the U.S. advantage. The successes of the HRA will augment this support.

In the early 80's, the government will initiate a long-range program to achieve an economic hypersonic transport capability by the year 2000. Research and early study activity will be accelerated to support the objective. By 1985, the government will initiate the development of the baseline aircraft with the objective of first flight by 1995.

Project schedule.- The Project Schedule relates the work to be done to the time period allotted and sets limits on each individual task. Figure 1-3 is an example Project Schedule with the recommended time periods for each task shown. Figure 1-3 can be used as is or modified by the Project Office for a particular schedule constraint. Generally, ten to twelve working days will be required to complete the method because of the need to transmit and receive written material between nonadjacent groups of people.

Baseline HST definition.- As soon as the scenario and schedule are available, the Project Office will initiate work on Module 2, Baseline HST Definition. Again, it is assumed that a consistent baseline HST design, well documented, is available. Unless the Project Office is going to complete Module 2, it is recommended that this task be given to a systems analyst as opposed to a functional specialist. In any case, this module must be completed quickly since the output is required input for all the remaining modules. Information required to initiate the work of Module 2 includes identification of the HST design to be the subject of the HST baseline definition, identification of reference documents from which data are to be extracted, and identification of any special depth and technology emphasis desired.

Project directive.- The Project Directive contains all the required instructions, schedules, data, and background required by the participants to do their jobs. It is the major output of the Method Integration module and should be started as soon as the schedule is established. An example Project Directive Outline is given in Appendix 1-A.

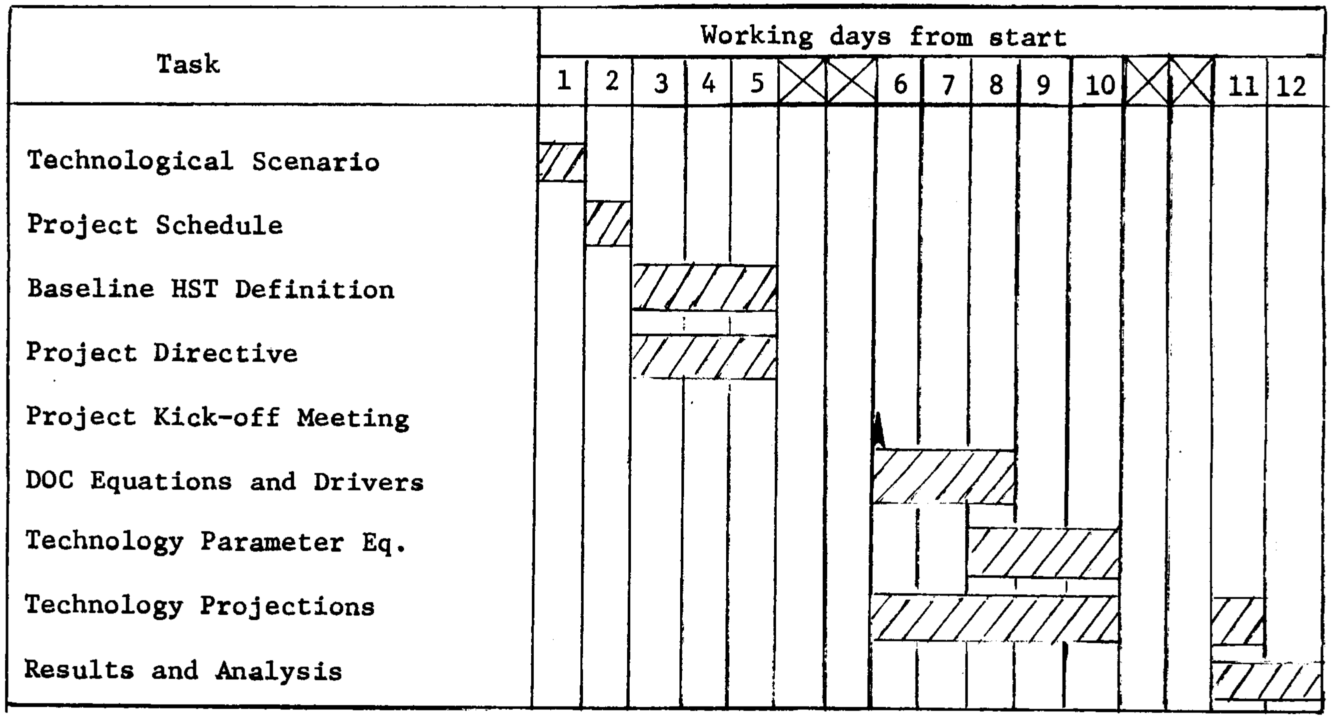

Figure 1-3.- Project Schedule

The Project Directive should be distributed by the Project Office at a project kick-off meeting held on the sixth working day. The meeting would give all the participants a chance to ask questions and to assure schedule coordination. The participants must be chosen by the Project Office within the first few days and should include the analysts who will actually complete the modules as well as the technology specialists who will be responsible for the Technology Projections (Module 5).

DOC equations and drivers.- This is Module 3 which can be initiated immediately after the kick-off meeting by giving the responsible analyst a copy of Module 3 and the Projective Directive. The output of this module should be reviewed by the Project Office and should be coordinated with the analyst working with Module 4, Technology Parameter Equations.

Technology parameter equations.- This is Module 4, and again, this module can be initiated immediately after the kick-off meeting. As before, the output should be reviewed by the Project Office and coordinated with Module 3.

Technology projections.- This is Module 5 and has potentially the longest time requirement. This module must be initiated immediately after the meeting. If possible, the Project Office should try to get the inputs earlier than shown in the schedule to allow some time for review and possible rework. Also, the specialists involved may not be in close proximity to the Project Office so some time delay in data transmittal must be expected.

Results and analyses.- The final module should be completed by the Project Office or at least closely monitored by the Project Office. The output of Module 6 is essentially the output of the methodology.

Summary

The methodology embodied in the six modules of this report can be a valuable tool if used together with the technology planner's normal data sources. The user is cautioned, however, not to use the results to make broad generalizations about the feasibility or economic viability of an HST. The method must be applied judiciously and the results must be interpreted in the context of overall technology planning.

REFERENCE

1. Helenbrook, R.G., McConarty, W.A., and Anthony, F.M.: Evaluation of Active Cooling Systems for a Mach 6 Hypersonic Transport Airframe, NASA CR-1917, December 1971.

APPENDIX 1-A

EXAMPLE PROJECT DIRECTIVE OUTLINE

INTRODUCTION

This section should discuss the background and objectives of the project.

PROJECT SCHEDULE

Include the actual schedule and discuss the key dates for coordination, reproduction, distribution, etc. Include actual calendar dates on the schedule.

TECHNOLOGICAL SCENARIO

This section should give the reader an understanding of the projected environment for the HST and for technology. It should be in brief, narrative form as in the example given earlier.

BASELINE HST DEFINITION

This section is the output section of Module 2, Baseline HST Definition.

GROUND RULES AND GUIDELINES

This section is optional and would include any additional parameters or constraints which the Project Office might impose.

BIBLIOGRAPHY

The Project Office should establish a recommended bibliography.

METHOD MODULE 2

BASELINE HST DEFINITION

METHOD MODULE 2 - BASELINE HST DEFINITION

Logic

The relative economic payoff of technology improvements is dependent upon the requirements and characteristics of the reference HST baseline, e.g. - its mission, configuration, design features and technology state-of-the-art.

This module presents a mechanism for identifying and documenting the characteristics of HST aircraft to form baselines for use in relative technology valuations.

The fundamental purpose of the "Baseline HST Definition" module is to organize relevant data into a form useful to the DOC and technology modules of the overall procedure. In accomplishing this purpose the module utilizes information from previously or separately conducted studies. The process responds to ground rules and constraints which are a part of the initial input to this module.

The logic to be employed in the definition of HST baselines is shown schematically in figure 2-1.

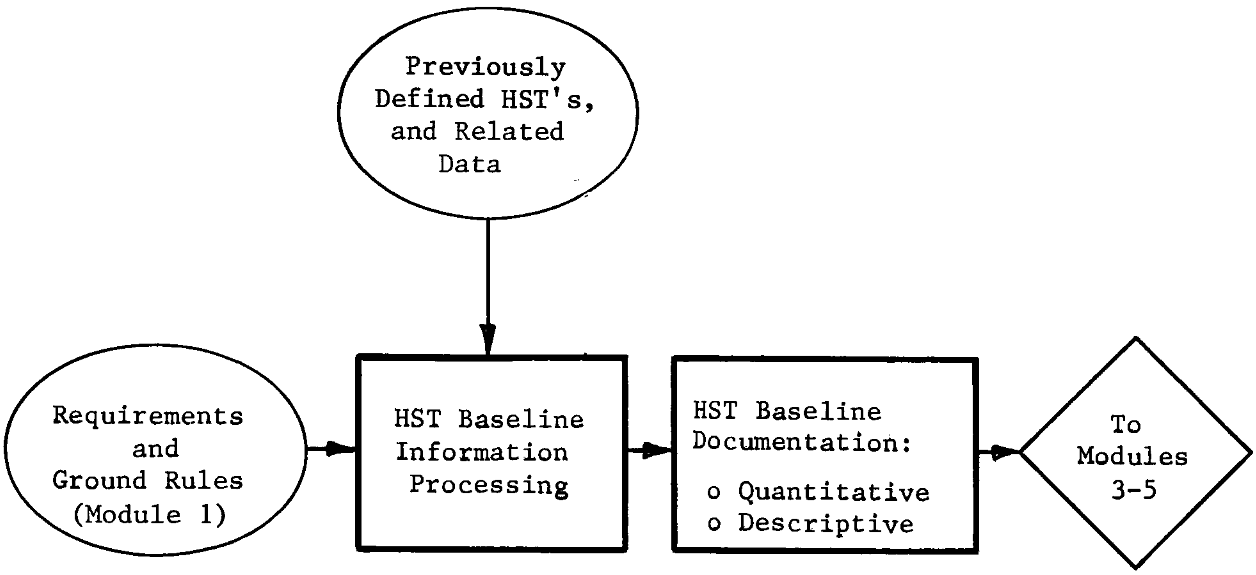

Figure 2-1.- Baseline Definition Logic Diagram

The baseline definition method is seen to consist of two major parts: information processing and documentation.

The purpose of the first part, information processing, is to form a complete, consistent package of data for use in the subsequent documentation. Basic steps are:

- o Acquisition of all relevant HST data.
- o Screening to locate data applicable to the definition.
- o Collation of screened data for visibility and access.

(In preparing the illustrative HST definition which appears in the documentation section, information deficiencies were encountered. Actions taken to overcome these deficiencies are reviewed in the Appendix to this module for background information only. These corrective actions are outside the scope of this method module.)

The purpose of the second part, documentation, it to prepare the baseline HST definition output. The documentation consists of mission, operations, performance, design, weights and technology data. These data include:

- o Quantitative tabular data for use in the DOC and Technology Parameter equations, and technology projections.
- o Descriptive and quantitative data to fulfill other data needs and to provide an adequate understanding of the baseline HST and its technology state-of-the-art.

Formats and guidelines for preparing the HST definition are included in the output data section. The formats for the quantitative tabular data give precisely the scope and depth of that portion of the information output. The descriptive summary of the baseline in the Demonstration section is an example of the scope and depth suggested for that portion of this module's information output.

Conditions and Qualifications

Consistent with the overall methodology and practices, the HST baseline definition method applies specifically to hypersonic cruise aircraft utilizing air-breathing engines and employing horizontal take-off and landing.

Within these limitations the baseline definition method has the flexibility to accommodate broad mission and design variables, as summarized in the following table:

Variable category	Major alternatives accommodated
Payload	Cargo, passengers or combination
Cruise Mach no.	5-12
Fuel type	Liquid hydrogen, jet fuels, methane, etc., and combinations
Structure	Actively cooled, uncooled, or combination Integral or non-integral fuel tanks
Aero configuration	Blended wing-body, all-body or conventional.
Propulsion	Separate turbojets and ramjets or integrated propulsion systems; supersonic or subsonic combustion, or dual-mode ramjets

Variations in payload type have minimal effect on baseline development because the density of an airplane passenger compartment is comparable with the density required to accommodate most potential cargos. In the case of a liquid hydrogen-fueled airplane, where the fuel density is similar to cargo or passenger compartment densities, payload weight variations may be traded for fuel, with subsequent range changes.

The parameters and relationships in this method are generally applicable to the hypersonic Mach number range of 5 to 12. Mach numbers beyond this range should not be treated without a prior assessment of suitability.

Although the baseline HST design and performance are strongly dependent on fuel type, the basic methodology is not. Means for accommodating different fuel types are discussed in the "Procedures" section.

The output of the structures definition is expressed in weight fractions, associated Technology Parameter values, and supporting descriptions and conditions. Parameters in the method accommodate either or both cooled and uncooled structures, and integral or non-integral tanks. For example, the demonstration included later in this method module describes an HST which has an actively cooled wing and fuselage and an uncooled tail.

Instructions for accommodating major variations in aerodynamic configuration and propulsion types are included later in this section under "Procedures."

Procedures in subsequent modules will further explain the means for adapting this method to other combinations.

Input Data

As illustrated in the previous "Baseline Definition Logic Diagram," figure 2-1, two types of input data are required by this method module. One type, requirements and ground rules, is instructional; the other, HST data, is informational.

Requirements and ground rules.- The requirements and ground rules, in conjunction with information in the referenced document(s), constrain the process in this module to the information processing and documentation activities. These instructional items, which are received by this module from module 1, shall have the following general content.

(1) identification of the HST design to be the subject of this baseline definition,

(2) identification of the reference document(s) from which the data required by this module should be extracted,

(3) any special depth and technology emphasis desired of descriptive data.

A sample requirements and groundrules input appears in the "Demonstration" section of this module.

Table 2-I identifies additional governing characteristics of HST airplane designs. Should any of the options in the table be available in the reference document(s), the ground rules should specify which of the options are to be part of the baseline.

HST reference information.- As noted previously, the baseline HST definition methodology operates upon existing information in preparing the HST technical definition output. The information is required to support quantitative definition of the HST airplane, associated technology parameters and other qualifying characteristics.

TABLE 2-I.- HST GOVERNING CHARACTERISTICS

Information type	Governing characteristics
Mission	Cruise Mach number Options { Payload weight and volume, or... Operational range, or... Payload weight and volume, and operational range
Performance	Fuel type
Operations	Flight cycles
Vehicle	Aero configuration (external geometry), General arrangement of major elements, Option: Wing reference area and fuselage length, Accelerator/descent engines, Cruise/accelerator engines
Design and structures	Airframe structural configuration: cooled or uncooled, governing design concepts, temperatures and materials for... wing and empennage, fuselage and tanks, air induction and ramjet structure Thermal management system approach: coolants/operating temperatures, heat shields and insulation
Weight	Options { Take-off gross weight constraint only, or selected specific component weights only (others to be determined), or... weight statement (for case of previously defined HST)
Technology	General technological state of the art, Option: Specific technology constraints

Input data types required to support preparation of the module outputs include: mission, performance, operations, aerodynamics and propulsion, design and structures, weights and related technologies. Within these information categories, Table II lists specific information items needed to quantify and subjects to qualify the HST baseline definition.

Procedures

The procedures for defining and describing a baseline HST are in two parts, (1) information processing and (2) documentation, consistent with the logic design, figure 2-1.

Information processing.- As noted earlier, the purpose of the information processing activities is to form a complete consistent package of readily retrievable data adequate for the needs of the subsequent documentation activities.

Acquisition, screening and collating of relevant HST data: Information acquisition shall provide reasonable assurance that all HST data relevant to the description of the desired baseline are available for use in this methodology. Information screening shall locate those HST data within the acquired data base which support the baseline HST definition needs. The screening criteria to be employed are: input data requirements as introduced in Table 2-II and expanded later under "Output Data," Tables 2-III, 2-IV, and 2-V; and the descriptive information guidelines associated with Table 2-V. (Tables 2-III, 2-IV and 2-V may be used to document the location of relevant screened data by noting the appropriate references and page numbers across the value columns of Tables 2-III and 2-IV and the open right portion ot Table 2-V.) The degree of collation to be employed is at the discretion of the user of this method module since needs are dependent on the diversity of information sources encountered.

HST baseline documentation.- The procedure for preparing the baseline documentation includes, as a first requisite, flexibility to accommodate major baseline variables. Next, the procedure provides for confirmation and/or adjustment of baseline values. Completion of the module outputs is the final step.

Accommodation of major variables: Flexibility built into the baseline definition method for accommodating mission and design variables has been summarized under "Conditions and Qualifications." Procedures for implementing this accommodation are included here in conjunction with discussion as to how the method handles many major variables automatically.

Alternate fuels The type of fuel to be employed provides an example of a variable which can exert a profound effect on the size, weight, and technology of the baseline and yet is readily accommodated by the baseline

TABLE 2-II.- SPECIFIC DEFINITION ITEMS REQUIRING INFORMATION BASE

Input Information Types	Typical Definition Items Requiring Information Inputs
Mission definition	W_{PL}, M, R_T Mission profile
Performance characteristics	L/D, sfc, W_{f_T}/W_{GTO}
Operational characteristics	t_F, U, L_d
Vehicle characteristics	Configuration; general arrangement $(W/S)_{GTO}$, C_D, C_L N_{TJ}, T_{TJ}, $(T/W)_{GTO}$ A_C, N_{RJ}, $W_{RJ}/A_C C_{TRJ}$
Weight characteristics	Weight statement W_{AF}/W_{GTO}
Design and structures description	Wing structure, materials Empennage structure, materials Fuselage structure, materials Tankage structure, material Thermal management Propulsion systems installation Turbojet description Ramjet description Avionics Equipment
Technology parameters	ρ, f_{ty}, f_{cy}, E, F, $(W/A_C)_{RJ}$ η_K, η_c, η_{KN}, C_{TRJ} C_{D_o}, C_{D_i}/C_L^2

definition methodology. A review of the baseline definition items in Table 2-III, Technology Parameters in Table 2-IV and information subjects listed in Table 2-V reveals that all items and subjects are applicable to the definition whether the fuel is liquid hydrogen, liquid methane or others. For example, major changes in fuel heating value are reflected in the reference document's value of cruise specific fuel consumption sfc, the fuel weight fraction W_{f_T}/W_{GTO} and gross takeoff weight W_{GTO}. Major changes in density are reflected primarily in airframe weight fraction W_{AF}/W_{GTO}, and others secondarily.

The method in this module also can be applied to a design which employs liquid hydrogen basically but carries a denser, high-temperature fuel as its reserve. In this case the source information would include an altered reserve fuel fraction K_R primarily as required for reserve range or duration, and altered definition items such as W_{AF}/W_{GTO} secondarily. For this example, the user of the method should include the weight of the reserve tank separately in the HST airplane weight statement and identify associated technology requirements in the description.

Aerodynamic configuration Lift-drag ratio L/D is the descriptor of aerodynamic performance in this method. Airplane cruise drag coefficient C_D is the key aerodynamic design characteristic, since it is directly relatable to cruise propulsion requirements. Zero-lift drag coefficient C_{D_O} and induced drag factor C_{D_i}/C_L^2 are the aerodynamic technology parameters. All of the above definition items and parameters remain applicable whether the configuration be a blended wing-body, all body or conventional. The user of this method should identify reference areas and governing dimensions, and include these values in a table of airplane configuration characteristics in the descriptive portion of the HST documentation.

Propulsion systems There are numerous candidate propulsion system types and combinations for potential application to the HST. Consequently, it is important that the baseline definition method be adaptable to inclusion of these candidates. Basically, this method is formulated to describe two types of engines, accelerator/descent and cruise/accelerator types, in a baseline HST. The accelerator/descent engines may be afterburning or non-afterburning turbojets, or others such as turboramjets. Ramjet cruise/accelerator engines may be designed for supersonic combustion (scramjets) or subsonic combustion. A ramjet which burns supersonically at cruise condition may have a subsonic combustion mode when operating in the supersonic accelerator flight regime, as is the case in the demonstration of this method.

Integrated or shared inlets as for a turbojet-ramjet propulsion system, reference 1, shall be accommodated, in part, by subdividing and allocating air induction system weights to the two engine types. The turbojet air induction system shall include the inlet and ducting leading to the engine; the ramjet shall include the variable geometry internal flow divider and the duct portion from the divider to the ramjet engines.

To include the case of a single compound engine type for acceleration, cruise, descent and loiter, the user of the baseline definition method should define cruise performance and parameters using the terms in the ramjet equations and the acceleration/descent-related parameters using the turbojet terms. The user also should subdivide the engine weight into the gas generator and bypass portions. Seventy percent of the air induction weight may be charged to the "turbojet" portion of the compound engine and thirty-percent to the "ramjet" portion. Terms which apply to the turbojet portion are: $(T/W)_{GTO}$, T_{TJ}, N_{TJ}, $(W/T)_{TJ}$, W_{TJ}/W_{GTO}. Terms which apply to the ramjet portion of the compound engine are: sfc, N_{RJ}, A_C, $W_{RJ}/A_C C_{TRJ}$ and W_{RJ}/W_{GTO}; and the ramjet technology parameters: C_{TRJ}, $(W/A_C)_{RJ}$, η_K, η_C and η_{KN}. All ramjet terms are to be expressed for the cruise condition.

Confirmation or adjustment of baseline values: This step in the procedure includes the following:

- o Check input values, including range, to assure compatibility with methods for later determination of partials and sensitivities.
- o Reconstitute weight statement, as required, to support the quantifying of weight parameters. (See Tables 2-XII and 2-XIII in Demonstration section.)
- o Calculate dependent parameters, as required, e.g., - weight fractions from weight statement.

In confirming range, the cruise component may be determined from the equation,

$$R_{CR} = \frac{1000\ M}{9} \frac{L/D}{sfc} \ln \left\{ \frac{1 - K_{CL} \ (W_{F_T}/W_{GTO})}{1 - [1 - (K_D + K_R)]\ W_{F_T}/W_{GTO}} \right\}, \text{km}$$

If the data base does not include climb range, this component may be approximated by:

$$R_{CL} = R_{CR} \left(\frac{K_{CL}}{2 - 1.5K_{CL}} \right), \text{km}$$

Similarly, descent range may be approximated by:

$$R_D = \left(\frac{R_{CR}}{2} \right) \left(\frac{K_{CL}}{2 - 1.5K_{CL}} \right), \text{km}$$

Operational or total range, then, is:

$$R_T = R_{CL} + R_{CR} + R_D, \text{ km (miles)}$$

Preparation of output data packages: The baseline definition items and technology parameter summaries, Tables 2-III and 2-IV in the "Output Data" portion of this method shall then be completed. The descriptive summary of the baseline HST shall also be prepared in accordance with the guidelines and outline, Table 2-V. The completed output is to be distributed to the companion modules of this overall procedure by the Project Office.

Output Data

The output of the baseline HST definition method module shall be:

- o A set of tabular data prepared using the forms contained in this section.

- o A summary description of the baseline prepared in accordance with the guidelines contained in this section.

Tabular data for DOC and Technology Parameter equations.- Table 2-III presents the information items and format to be employed in preparing the portion of the definition required for the DOC equations, module no. 3, and for use in the technology modules, numbers 4 and 5. Five of the information items, identified by asterisks (*) in Table 2-III are defined as drivers of direct operating cost.

Tabular summary of Technology Parameters.- Table 2-IV identifies the Technology Parameters that relate to and impact the DOC drivers. The table also provides the format to be employed in quantifying these Technology Parameters as a part of this baseline definition. The table is an output for use in module no. 4.

Descriptive summary of baseline.- The descriptive summary of the HST baseline is complementary to the tabular summaries. The method outlined herein for preparation of this complementary output offers sufficient flexibility in preparing information content to accommodate special areas of technical interest within the overall descriptive framework. Guidelines are of two categories: (1) information subject and organization guidelines, and (2) guidelines for describing information subjects.

Information subject and organization guidelines: Major information subjects and their recommended organization in this descriptive summary are

TABLE 2-III.- BASELINE DATA FOR DOC AND TECHNOLOGY PARAMETER EQUATIONS - REQUIRED OUTPUT FROM MODULE 2

Baseline characteristics	Baseline values: SI units	Baseline values: English units
Mission		
Cruise Mach number, M		
Operational range, R_T	km	miles
Performance		
* Cruise specific fuel consumption, sfc	$\frac{kg}{N\text{-}hr}$	$\frac{lb_m}{lb_f\text{-}hr}$
* Cruise lift-drag ratio, L/D		
Climb fuel fraction, $K_{CL} = W_{f_{CL}}/W_{f_T}$		
Descent fuel fraction, $K_D = W_{f_D}/W_{f_T}$		
Reserve fuel fraction, $K_R = W_{f_R}/W_{f_T}$		
Fuel weight fraction, W_{f_T}/W_{GTO}		
Operations		
Ratio of block to cruise velocity, V_B/V_{CR}		
Time of flight, t_F	hr	
Flight cycles during depreciable life		
Vehicle characteristics		
Wing loading at take-off, $(W/S)_{GTO}$	kg/m^2	lb/ft^2
Maximum thrust-weight ratio take-off, $(T/W)_{GTO}$		
Turbojet SLS thrust per engine, T_{TJ}	N	lb
Number of turbojet engines, N_{TJ}		
* Turbojet propulsion specific weight, $(W/T)_{TJ}$		

* DOC Drivers

TABLE 2-III.- BASELINE DATA FOR DOC AND TECHNOLOGY PARAMETER EQUATIONS - REQUIRED OUTPUT FROM MODULE 2 - Concluded

Baseline characteristics	Baseline values	
	SI units	English units
Number of ramjet engines, N_{RJ}		
Total ramjet cowl area, A_C	m^2	ft^2
* Ramjet sizing parameter, $W_{RJ}/A_C C_{TRJ}$	kg/m^2	lb/ft^2
Airplane cruise drag coefficient, C_D		
Weight characteristics		
Gross take-off weight, W_{GTO}	kg	lb
* Airframe weight fraction, W_{AF}/W_{GTO}		
Avionics weight fraction, W_{AV}/W_{GTO}		
Payload weight fraction, W_{PL}/W_{GTO}		
Turbojet weight fraction, W_{TJ}/W_{GTO}		
Ramjet weight fraction, W_{RJ}/W_{GTO}		
Weight ratio, wing-to-airframe, W_W/W_{AF}		
Weight ratio, fuselage-to-airframe, W_F/W_{AF}		
Weight ratio, empennage-to-airframe, W_E/W_{AF}		
Weight ratio, propellant system-to-airframe, W_{PS}/W_{AF}		
Weight ratio, thermal protection system-to-airframe, W_{TP}/W_{AF}		
Weight ratio, other systems-to-airframe, W_{Equip}/W_{AF}		

* DOC Drivers

TABLE 2-IV.- TECHNOLOGY PARAMETERS - REQUIRED OUTPUT FROM MODULE 2

Technology Parameter		Baseline values	
		SI units	English units
Aerodynamics			
C_{D_o}	zero-lift drag coefficient		
C_{D_i}/C_L^2	induced drag factor		
Propulsion			
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)		
$(W/A_C)_{RJ}$	ramjet specific weight	kg/m^2	lb/ft^2
η_K	ramjet inlet kinetic energy efficiency		
η_C	ramjet combustion efficiency		
η_{KN}	ramjet nozzle kinetic energy efficiency		
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a Driver Parameter)		
Aggregate material properties			
FMP	fuselage material properties		
WMP	wing material properties		

TABLE 2-IV.- TECHNOLOGY PARAMETERS - REQUIRED OUTPUT FROM MODULE 2 - Concluded

Technology Parameter		Baseline values	
		SI units	English units
Airframe design			
$F_{W,B}$	design factor for wing structure designed by buckling criteria		
$F_{W,C}$	design factor for wing structure designed by crippling criteria		
$F_{W,S}$	design factor for wing structure designed by stiffness criteria		
$F_{W,Y}$	design factor for wing structure designed by yield criteria		
$F_{W,F}$	design factor for wing structure not designed by primary loads		
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria		
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria		
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria		
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria		
$F_{F,F}$	design factor for fuselage structure not designed by primary loads		
F_E	design factor for empennage weight		
$F_{T,P}$	design factor for thermal protection system weight		
F_P	design factor for propellant system weight		

presented in Table 2-V. The organization facilities relation to the baseline characteristics of Table 2-III and Technology Parameters in Table 2-IV.

Guidelines for describing information subject: Because descriptive information needs vary among the subjects listed in Table 2-V, the following are offered as general guidelines.

- The descriptive summary should identify baseline information sources used.
- The descriptions should summarize conditions and assumptions basic to values of baseline definition items in Tables 2-III and 2-IV.
- The descriptions should provide indicators of the technology level of the baseline HST.
- The descriptive summary should be concise; information should be selective, with references noted where expanded data are available.

TABLE 2-V.- DESCRIPTIVE INFORMATION SUBJECTS

Mission

- o Nature of payload
- o Flight profile

Performance

- o Conditions and assumptions in defining components of range

Operational Characteristics

- o Flight and block times during depreciable life
- o Ground time available for turnaround

Vehicle characteristics

- o Configuration and general arrangement
- o Aerodynamic characteristics
- o Turbojet performance characteristics
- o Ramjet performance characteristics
- o Summary description of major design groups

  Wing structure, materials
  Empennage structure, materials
  Fuselage structure, materials
  Tankage structure, materials
  Thermal management
  Propulsion systems installation
  Turbojet description
  Ramjet description
  Avionics
  Equipment

Weight Statement

Weight accounting relation to MIL-M-38310A

DEMONSTRATION

This section illustrates the implementation of the baseline definition methodology in defining and describing an HST technical baseline. The baseline HST output in this example is that employed as a reference in the overall procedure development of which this module is a part.

Requirements and Ground Rules

As indicated in the logic diagram, figure 2-1, in the preceding "Baseline Definition Methodology" section, the HST baseline definition activity is initiated upon receipt of a set of requirements and ground rules from Method Module 1.

Basic requirements and ground rules for this demonstration are presented in Table 2-VI.

Because this particular set of ground rules specified that mission and general characteristics, the structural characteristics, and the configuration be obtained from three different references, baseline HST generation activities were required which are outside the scope of this baseline HST definition module. The separate baseline generator activities are summaried in the Appendix.

Information Processing and Documentation

Upon completion of prior steps in the information definition process, confirmation or adjustment of baseline values is performed. As a last step, operational range is calculated. The cruise range, calculated from the formula,

$$R_{CR} = \frac{1000M}{9}\frac{L/D}{sfc}\ln\left\{\frac{1-K_{CL}\ (W_{f_T}/W_{GTO})}{1-\left[1-(K_D+K_R)\right]\ W_{f_T}/W_{GTO}}\right\}\ \text{km}$$

is:

TABLE 2-VI.- BASELINE HST REQUIREMENTS AND GROUND RULES

Mission and operational requirements are:

Payload . . . . 22 700 kg (50 000 lb)
Cruise Mach number 6.0
Operational range. . . . . . to be determined in definition

Flight cycles: during 10-year depreciable life . . . 13 350
for use in structures definition . . . 20 000

The fuel is liquid hydrogen.

Existing data are to be used wherever possible:

HST aerodynamic configuration and aerodynamic characteristics from NASA TN D-6181, reference 2.

Structural design and weights from General Dynamics reports supplemented by Bell Aerospace cooled structures data, references 3, 4 and 5.

The primary airframe structure basically is 7075 aluminum alloy, actively cooled with a closed water-glycol system.

Gross take-off weight is to be in the order of 227 000 kg (approximately 500 000 lb).

Cruise engines are an array of integrated ramjet modules; the modules are actively cooled and employ supersonic combustion during cruise.

The technology state-of-the-art for the baseline HST is defined as that which is presently postulated or immediately foreseeable.

The baseline vehicle is to be used for demonstration of the methodology only; it will not represent an optimized design.

The descriptive data should be of sufficient depth to supplement the specific baseline values with an understanding of the HST and its technology state-of-the-art.

$$R_{CR} = \frac{1000(6)}{9} \frac{4.6}{0.113} \ln \left\{ \frac{1-0.40(0.3178)}{1-\left[1-(0.02 + 0.10)\right] 0.3178} \right\}$$

$$= 5180 \text{ km (3220 miles)}$$

Climb range, approximated using the formula,

$$R_{CL} = R_{CR} \left(\frac{K_{CL}}{2-1.5\ K_{CL}} \right)$$

is:

$$R_{CL} = 5180 \left(\frac{0.40}{2-1.5(0.40)} \right) = 1480 \text{ km (920 miles)}$$

Descent range, approximated using the formula,

$$R_D = \left(\frac{R_{CR}}{2} \right) \left(\frac{K_{CL}}{2-1.5\ K_{CL}} \right)$$

is:

$$R_D = \left(\frac{5180}{2} \right) \left(\frac{0.40}{2-1.5(0.40)} \right) = 740 \text{ km (460 miles)}$$

Operational range, the sum of the cruise, climb and descent components, is:

$$R_T = 5180 + 1480 + 740 = 7400 \text{ km (4600 miles)}$$

Upon completion of this last step in the baseline identification process a full information package is available for use in preparing the required HST documentation.

Tabular Documentation of Baseline

Quantitative HST data for DOC and Technology Parameter equations.- Table 2-VII presents the quantitative characteristics of the baseline HST as required by the terms within the Technology Parameter and DOC equations (including the DOC Drivers). The format is that specified by Table 2-III in the "Methodology" section.

TABLE 2-VII.- BASELINE DATA FOR DOC AND TECHNOLOGY PARAMETER EQUATIONS - DEMONSTRATION DATA OUTPUT FROM MODULE 2 (Reference Table 2-III)

Baseline characteristics	Baseline values	
	SI units	English units
Mission		
Cruise Mach number, M	6.0	
Operational range, R_T	7400 km	4600 miles
Performance		
* Cruise specific fuel consumption, sfc	0.113 $\frac{kg}{N\text{-}hr}$	1.12 $\frac{lb_m}{lb_f\text{-}hr}$
* Cruise lift-drag ratio, L/D	4.6	
Climb fuel fraction, $K_{CL} = W_{f_{CL}}/W_{f_T}$	0.40	
Descent fuel fraction, $K_D = W_{f_D}/W_{f_T}$	0.02	
Reserve fuel fraction, $K_R = W_{f_R}/W_{f_T}$	0.10	
Fuel weight fraction, W_{f_T}/W_{GTO}	0.3178	
Operations		
Ratio of block to cruise velocity, V_B/V_{CR}	0.513	
Time of flight, t_F	2.00 hr	
Flight cycles during depreciable life	13 350	
Vehicle characteristics		
Wing loading at take-off, $(W/S)_{GTO}$	252 kg/m^2	51.6 lb/ft^2
Maximum thrust-weight ratio take-off, $(T/W)_{GTO}$	0.482	
Turbojet SLS thrust per engine, T_{TJ}	258 000 N	58 000 lb
Number of turbojet engines, N_{TJ}	4	
* Turbojet propulsion specific weight, $(W/T)_{TJ}$	0.1595	

* DOC Drivers

TABLE 2-VII.- BASELINE DATA FOR DOC AND TECHNOLOGY PARAMETER EQUATIONS - DEMONSTRATION DATA OUTPUT FROM MODULE 2 (Reference Table 2-III) - Concluded

Baseline characteristics	Baseline values	
	SI units	English units
Number of ramjet engines, N_{RJ}	9	
Total ramjet cowl area, A_C	7.73 m^2	83.2 ft^2
* Ramjet sizing parameter, $W_{RJ}/A_C C_{TRJ}$	758 kg/m^2	155 lb/ft^2
Airplane cruise drag coefficient, C_D	0.0112	
Weight characteristics		
Gross take-off weight, W_{GTO}	218 400 kg	481 400 lb
* Airframe weight fraction, W_{AF}/W_{GTO}	0.447	
Avionics weight fraction, W_{AV}/W_{GTO}	0.00665	
Payload weight fraction, W_{PL}/W_{GTO}	0.1039	
Turbojet weight fraction, W_{TJ}/W_{GTO}	0.0769	
Ramjet weight fraction, W_{RJ}/W_{GTO}	0.0337	
Weight ratio, wing-to-airframe, W_W/W_{AF}	0.151	
Weight ratio, fuselage-to-airframe, W_F/W_{AF}	0.285	
Weight ratio, empennage-to-airframe, W_E/W_{AF}	0.032	
Weight ratio, propellant system-to-airframe, W_{PS}/W_{AF}	0.177	
Weight ratio, thermal protection system-to-airframe, W_{TP}/W_{AF}	0.160	
Weight ratio, other systems-to-airframe, W_{Equip}/W_{AF}	0.195	

* DOC Drivers

Technology Parameters.- Table 2-VIII presents the baseline values for the Technology Parameters using the format from Table 2-IV of the "Methodology" section.

Descriptive Summary of Baseline

This descriptive summary of the baseline HST follows the outline in Table 2-V and responds to the associated guidelines given in the "Methodology" section. Summary characteristics of this baseline HST are presented in Table 2-IX.

Mission.- The mission of the baseline HST is to transport cargo weighing 22 700 kg (50 000 lb) over a flight profile having a Mach 6 cruise segment for an operational range of 7400 km (4600 miles).

The basic payload is cargo. (Direct operating costs are expressed in cents per ton-mile). A potential capability to carry passengers with limited cargo also may be desirable for an HST airplane. Design flexibility to accommodate this alternative has been noted earlier under "Conditions and Qualifications."

The flight profile for the baseline mission is shown in figure 2-2. Cruise altitude for the Breguet path varies from 27 600 m (90 600 ft) to 28 800 m (94 600 ft) as cruise fuel is consumed. Total flight time is 2.0 hours.

Performance.- The climb and descent components shown in the flight profile represent 30 percent of the operational range. The formulas used earlier to calculate approximate values for these components were derived to represent climb and descent data from reference 3.

Conditions and/or assumptions for all terms in the cruise range equation, page 24 , are summarized in the following tabulation:

- Cruise Mach number, M, of 6 a requirement.

- Lift-drag ratio, L/D, of 4.6 a conservative value relative to a maximum L/D of 5.0 for the wind tunnel model, reference 2.

- Specific fuel consumption, sfc, of 0.113 kg/N-hr for liquid hydrogen-burning scramjet and performance conditions summarized later under "Ramjet performance characteristics."

- Climb fuel fraction, K_{CL}, of 0.40 an approximation derived from references 3 and 5.

TABLE 2-VIII.- TECHNOLOGY PARAMETERS - DEMONSTRATION DATA OUTPUT FROM MODULE 2 (Reference Table 2-IV)

Technology Parameter		Baseline values	
		SI units	English units
Aerodynamics			
C_{D_o}	zero-lift drag coefficient	0.0075	0.0075
C_{D_i}/C_L^2	induced drag factor	1.65	1.65
Propulsion			
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)	1.255	1.255
$(W/A_C)_{RJ}$	ramjet specific weight	951 kg/m^2	195 lb/ft^2
η_K	ramjet inlet kinetic energy efficiency	0.975	0.975
η_C	ramjet combustion efficiency	0.95	0.95
η_{KN}	ramjet nozzle kinetic energy efficiency	0.98	0.98
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a Driver Parameter)	0.1595	0.1595
Aggregate material properties			
FMP	fuselage material properties	(a)	(a)
WMP	wing material properties	(a)	(a)

(a) - Values to be developed in Module 4, "Technology Parameter Equations"

TABLE 2-VIII.- TECHNOLOGY PARAMETERS - DEMONSTRATION DATA OUTPUT FROM MODULE 2 (Reference Table 2-IV) - Concluded

Technology Parameter		Baseline values	
		SI units	English units
Airframe design			
$F_{W,B}$	design factor for wing structure designed by buckling criteria	1.00	
$F_{W,C}$	design factor for wing structure designed by crippling criteria	1.00	
$F_{W,S}$	design factor for wing structure designed by stiffness criteria	1.00	
$F_{W,Y}$	design factor for wing structure designed by yield criteria	1.00	
$F_{W,F}$	design factor for wing structure not designed by primary loads	1.00	
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria	1.00	
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria	1.00	
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria	1.00	
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria	1.00	
$F_{F,F}$	design factor for fuselage structure not designed by primary loads	1.00	
F_E	design factor for empennage weight	1.00	
$F_{T,P}$	design factor for thermal protection system weight	1.00	
F_P	design factor for propellant system weight	1.00	

TABLE 2-IX.- BASELINE HST SUMMARY CHARACTERISTICS

Mission	
Cruise Mach number	6.0
Payload weight	22 700 kg (50 000 lb)
Payload volume	453 m^3 (16 000 ft^3)
Performance	
Fuel	liquid hydrogen
Operations	
Flight cycles for structural design	20 000

Vehicle

Aero configuration: blended wing-body with single vertical tail per reference 2, modified to enhance precompression and accommodate propulsion system installation.

General arrangement: non-integral fuel tanks fore and aft; centrally located payload compartment.

Accelerator/loiter engines: four P&W STF-230A-type
Cruise/accelerator engines: horizontal array of dual-combustion-mode, variable-geometry scramjets

Design and structures

Wing: actively-cooled aluminum alloy per reference 4
Vertical tail: uncooled Inconel 718 per reference 4
Fuselage: actively-cooled aluminum alloy per reference 3
Scramjets: actively-cooled, two-dimensional modules
Propulsion installation: per reference 6
Fuel tanks: multicell Inconel 718 per reference 3
Thermal management: airframe cooling system and operating temperatures per reference 4, 5 and 6; external heat shields on portions of wing and fuselage to reduce cooling load per references 3, 4 and 5; hermetically sealed polyurethane foam insulation system for fuel tanks.

Weight

Gross take-off weight of 218 400 kg (481 400 lb)

Technology level

Presently postulated or immediately foreseeable

(Sources: References 3 and 5)

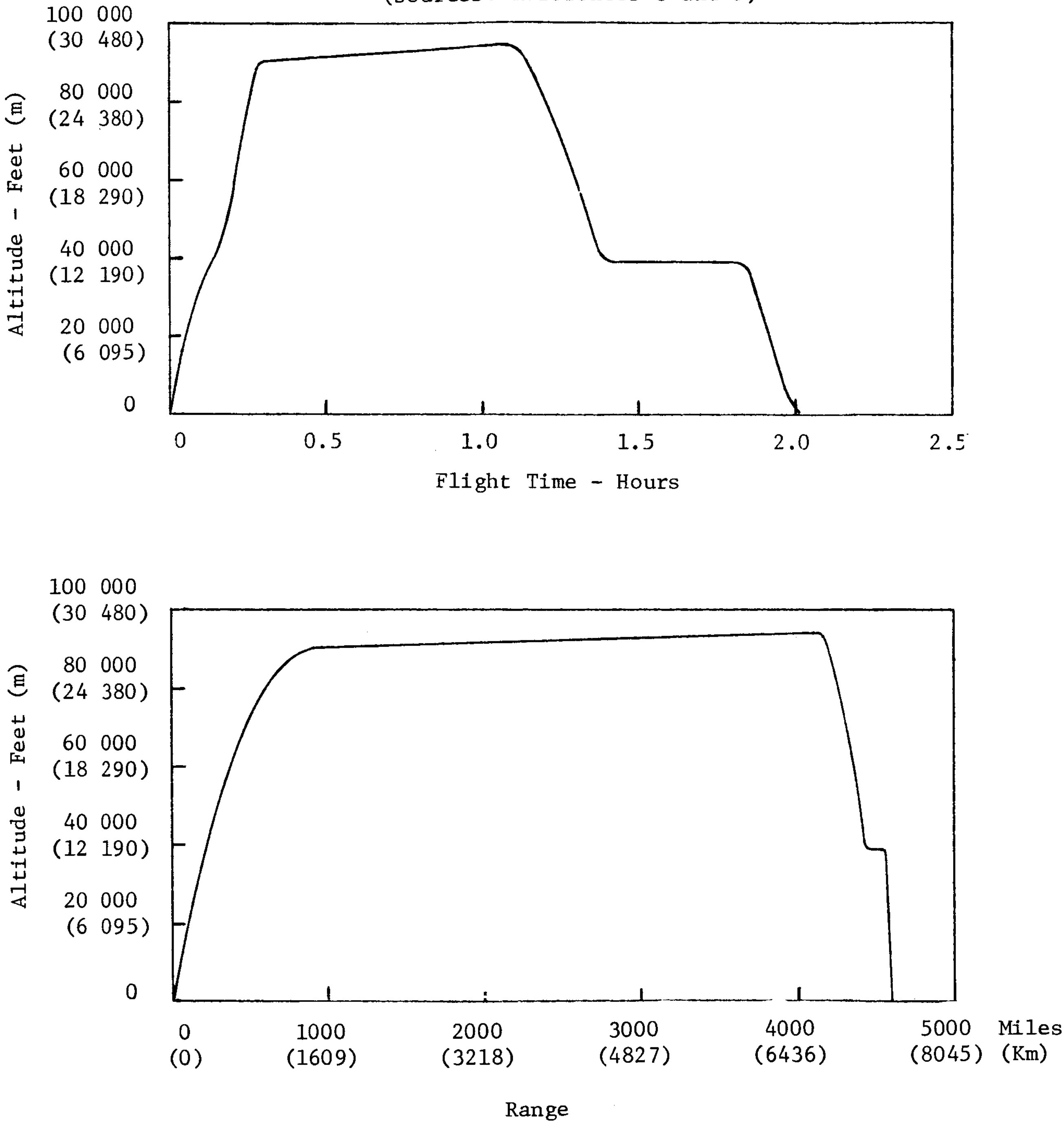

Figure 2-2.- Flight Profile

- Descent fuel fraction, K_D, of 0.02 an approximation derived from reference 3.

- Reserve fuel fraction, K_R, of 0.10 a recommended value for calculation of nominal operational range.

- Fuel weight fraction, W_{f_T}/W_{GTO}, of 0.3178 from baseline HST weight statement.

The sum of the climb, descent and reserve fuel fractions is 0.52. Thus, 48 percent of the total fuel, W_{f_T}, is available for cruise.

Operational characteristics.- The HST will be required to operate safely and reliably, with routine maintenance, over an extended time period. Key related operational characteristics are:

Time of flight, t_F = 2.0 hr

Block time, t_B = 2.25 hr

Average utilization, U = 3000 block hr/yr

Depreciable life, L_d = 10 yr

Utilization during depreciable life = 30 000 block hr

Nonutilization during depreciable life: 57 600 hr

Flight time during depreciable life: 26 700 hr

Flight cycles during depreciable life: 13 350

Vehicle characteristics.-

Configuration and general arrangement: The general arrangement of the baseline HST used in this demonstration is shown in figure 2-3. Consistent with the Guidelines, the configuration is derived from that described in reference 2. The reference configuration features (1) a body width-height ratio of 2 to improve the lifting capability of the fuselage, (2) negative camber in the forward fuselage to minimize trim drag penalties on maximum lift-drag ratio, (3) strakes to retard windward pressure bleed-off at angle of attack, and (4) wing-body blending to minimize adverse component interference effects. The wing leading edge is swept 65°. Pitch control and trim are effected with elevons. The single vertical tail is swept 60°. A split rudder provides directional control.

The illustrative configuration, figure 2-3, is similar to the reference 3 model with the following modifications. (1) The underside of the forward fuselage is shaped to provide a continuous precompression surface for the turbojet and ramjet inlets. (2) The fuselage depth at the ramjet engine installation is increased to accommodate the combined turbojet and ramjet installation concept from reference 7. (3) The fuselage afterbody is modified to integrate the ramjet exhaust nozzle and to incorporate the turbojet engines. (4) The vertical tail is reduced to 64 percent of the reference 4 area based on interpretation of the wind tunnel data.

Liquid hydrogen fuel is carried in non-integral tanks located in the forward and aft fuselage sections. Multicell or "pillow" fuel tank configurations provide for efficient use of the available volume while maintaining moderate tank frame weights. The payload compartment is located at the c.g. for balance control. The payload compartment structure is integral with the fuselage structure. An inert gas, helium in this example, occupies the space surrounding the liquid hydrogen tanks and the space between the payload compartment pressure vessel and the fuselage covers. There is no access from the payload to the forward crew compartment.

Quantitative characteristics which contribute to definition of the baseline HST configuration and summarize weights are listed in Table 2-X.

Aerodynamic characteristics: Aerodynamic characteristics of the wind tunnel model, reference 2, are assumed to be representative of the modified design shown in figure 2-3. Cruise characteristics, for the purposes of this baseline, embody a conservatism relative to the maximum of 5.0 at Mach 6:

$$\alpha = 3.2^\circ$$
$$C_L = 0.0515$$
$$C_D = 0.0112$$
$$L/D = 4.60$$

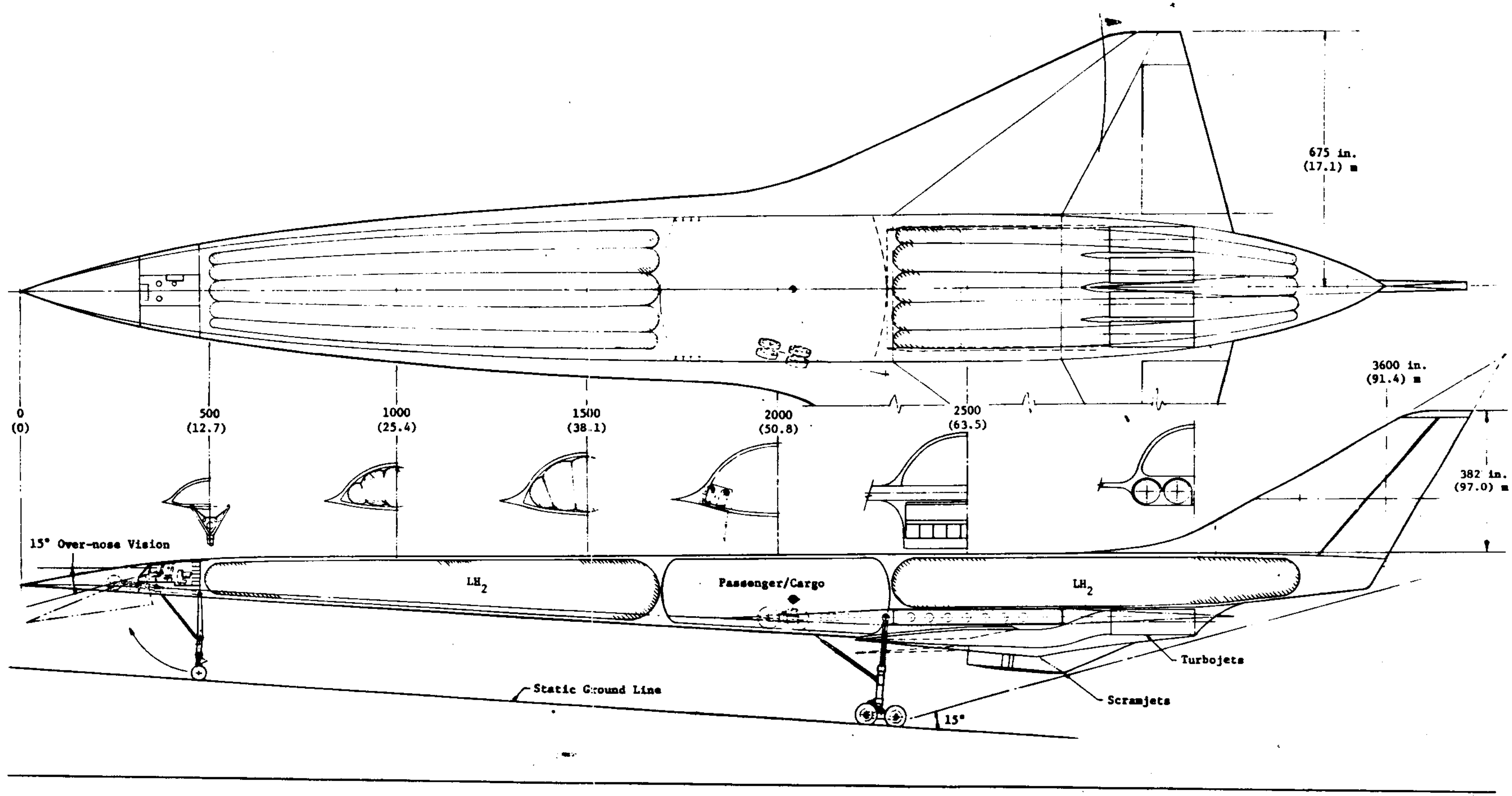

Figure 2-3.- Baseline Hypersonic Transport

TABLE 2-X.- AIRPLANE CONFIGURATION AND WEIGHT SUMMARY DATA

Fuselage length, l_F	91.4 m (300 ft)
Reference area (projected wing), S	866 m^2 (9323 ft^2)
Wing loading at take-off, $(W/S)_{GTO}$	252 kg/m^2 (51.6 lb/ft^2)
Wing thickness ratio, t/c	0.03
Vertical tail area, S_V	94.8 m^2 (1020 ft^2)
Payload compartment volume	453 m^3 (16 000 ft^3)
Total fuel tank volume	1020 m^3 (36 000 ft^3)
Total turbojet thrust (S.L. static), $T_{TJ}\,N_{TJ}$	1 032 000 N (232 000 lb)
Maximum thrust-weight ratio at take-off, $(T/W)_{GTO}$	0.482
Scramjet module size:	0.927 m x 0.927 m (3.04 ft x 3.04 ft) inlets 6.4 m (21 ft) length
Dry airplane weight, W_e	123 200 kg (271 600 lb)
Fuel weight, W_{f_T}	69 400 kg (153 000 lb)
Gross take-off weight, W_{GTO}	218 400 kg (481 400 lb)
Dry airframe/gross take-off weight, W_e/W_{GTO}	0.5641
Payload/gross take-off weight, W_{PL}/W_{GTO}	0.1038
Main fuel/gross take-off weight, W_{f_T}/W_{GTO}	0.3178

Detailed plots of aerodynamic characteristics of the model appear in reference 2.

Other cruise conditions, based on a C_L of 0.0515 are listed in the following table.

Begin-cruise	
Airplane weight	190 600 kg (420 200 lb)
Free-stream dynamic pressure	41 900 N/m^2 (875 lb/ft^2)
Altitude	27 600 m (90 600 ft)
End-cruise	
Airplane weight	157 300 kg (346 800 lb)
Free-stream dynamic pressure	34 600 N/m^2 (722 lb/ft^2)
Altitude	28 800 m (94 600 ft)

Turbojet performance characteristics: Key performance characteristics of the P&W STF-230A fuel-rich turbofan ramjet as applied to the nominal climb trajectory of reference 3 are listed in the following table:

Flight Mach No.	Thrust Ratio to S.L. Static Value	Specific Fuel Consumption, sfc
0.27	1.0	0.099 kg/N-hr $\left(0.98 \frac{lb_m}{lb_f\text{-hr}}\right)$
1.4	0.54	0.077 kg/N-hr $\left(0.76 \frac{lb_m}{lb_f\text{-hr}}\right)$
3.0	1.21	0.094 kg/N-hr $\left(0.93 \frac{lb_m}{lb_f\text{-hr}}\right)$

The Mach 1.4 condition is the "pinch point" in engine sizing. The accelerator engines are aided by the ramjet engines in passing the pinch point, thus permitting scale-reduction in the STF-230A engines. Summary characteristics of the Mach 1.4 pinch point are tabulated below.

Altitude	13 800 m (45 000 ft)
Acceleration	0.76 m/sec^2 (2.5 ft/sec^2)
Thrust to accelerate	177 000 N (39 800 lb)
Thrust to overcome drag	505 000 N (113 600 lb)
Total thrust required	682 000 N (153 400 lb)
Ramjet thrust available (approx. M=1.5)	125 000 N (28 200 lb)
Turbofan ramjet thrust required	557 000 N (125 200 lb)

The total required sea level static thrust of the four scaled versions of the STF-230A engines, then, is:

557 000 N/0.54 = 1 032 000 N (232 000 lb)

Scale, from the basic per engine rating of 333 600 N (75,000 lb), is:

1 032 000 N/4 x 333 600 N = 0.773.

Ramjet performance characteristics: Performance of the ramjet engines for the baseline HST is based on a procedure developed by the Marquardt Aircraft Corporation.

The ramjets employ a dual combustion mode with subsonic combustion during accelerating flight through the transonic and supersonic regimes, and supersonic combustion during cruise of Mach 6. As noted in the preceding turbojet performance definition, the ramjets provide all the propulsive force at Mach numbers above 3.0 where the turbojet is shut down and the turbojet inlet is closed. The Mach 3 thrust requirement is the sizing condition for the ramjet engines.

Performance of the ramjet engines as a combined set is summarized in Table 2-XI for the two primary flight conditions: Propulsive take-over at Mach 3.0 and cruise at Mach 6.0.

TABLE 2-XI.- RAMJET PERFORMANCE SUMMARY

Characteristic	Ramjet acceleration		Scramjet cruise	
	SI units	English units	SI units	English units
Flight Mach number, M	3.0		6.0	
Flow precompression turning angle,	7.0		8.0	
Inlet Mach number, M_o	2.62		4.8	
Pressure field area ratio, A_∞ / A_o	1.37		2.01	
Inlet cowl capture area ratio, A_o/A_C	0.75		1.0	
Inlet contraction area ratio, A_C/A_2	2.57		8.29	
Inlet Kinetic energy efficiency, η_K	0.94		0.975	
Combustion efficiency, η_C	0.95		0.95	
Nozzle efficiency, η_{KN}	0.98		0.98	
Nozzle expansion area ratio, A_N/A_C	2.0 (a)		3.5	
Free stream area, A_∞	7.94 m^2	85.5 ft^2	15.53 m^2	167.2 ft^2
Inlet capture area, A_o	5.80 m^2	62.4 ft^2	7.73 m^2	83.2 ft^2
Inlet cowl area, A_C	7.73 m^2	83.2 ft^2	7.73 m^2	83.2 ft^2
Inlet throat area, A_2	3.01 m^2	32.4 ft^2	0.932 m^2	10.03 ft^2
Fuel	LH_2		LH_2	
Combustion mode	Subsonic		Supersonic	
Fuel equivalence ratio, Ø	1.0		0.609	
Fuel temperature	47K	-376°F	47K	-376°F
Thrust coefficient x reference area, $C_{TRJ} A_C$	15.46 m^2	166.4 ft^2	9.70 m^2	104.4 ft^2
Thrust coefficient, C_{TRJ}	2.00		1.255	
Specific fuel consumption, sfc	0.203 Kg/N-hr	1.20 $\frac{lb_m}{lb_f\text{-hr}}$	0.113 Kg/N-hr	1.12 $\frac{lb_m}{lb_f\text{-hr}}$

a - assumed effective expansion ratio

Propulsive take-over at Mach 3.0 is based on the following conditions:

Altitude	18 300 m (60 000 ft)
Dynamic pressure, q	45 400 N/m^2 (948 lb/ft^2)
Lift coefficient, C_L	0.0498
Drag coefficient, C_D	0.014
Lift-drag ratio, L/D	3.55
Drag	547 000 N (123 000 lb)
Acceleration	0.76 m/sec^2 (2.5 ft/sec^2)
Thrust required for acceleration	152 000 N (34 200 lb)
Total thrust required	698 000 N (157 000 lb)
C_{TRJ}/A_C	15.49 m^2 (166.7 ft^2)

Most conditions which determine ramjet cruise performance at Mach 6.0 are listed in the Table 2-XI. Others are:

The drag of a boundary layer diverter, if required, forward of the turbojet and ramjet inlets, is included in the airplane drag coefficient.

Ramjet performance is reduced by boundary layer bleed equivalent to 100 percent momentum loss of 2.5 percent of the airflow into the ramjet inlet.

Inlet cowl drag is a part of the nacelle drag included in the airplane drag coefficient per the wind tunnel model, reference 2.

No spillage drag for an inlet capture area ratio of 1.0.

Ramjet performance at a flight Mach number of 1.5 is summarized in the following tabulation.

Precompression turning angle (approx.)	0^o
Throat/free stream area ratio, A_2/A_∞	0.9852
Exit/throat area ratio, A_6/A_2	3.67
Throat area	3.01 m^2 (32.4 ft^2)
Inlet Kinetic energy efficiency, η_k	0.95
Combustion efficiency, η_C	0.95
Nozzle Kinetic energy efficiency, η_{KN}	0.98
Fuel-air mixture	stoichiometric

Thrust coefficients, C_{TRJ} 0.85
Ramjet cowl area, A_C. . . . . 7.73 m^2 (83.2 ft^2)
Dynamic pressure . . . . .19 700 N/m^2 (412 lb/ft^2)
Ramjet thrust . . . . 125 000 N (28 000 lb)
Specific fuel consumption, sfc . . . . 0.21 kg/N-hr (2.1 lb_m/lb_f-hr)

Summary description of major design groups: The following paragraphs present a summary description of the illustrative HST design. The description provides a reference for assessing the technology level inherent in the HST example for this methodology demonstration. The airplane environmental data from references 3, 4 and 5 are assumed to provide generally applicable background to this discussion.

Wing structure, materials The wing is a partially shielded 7075-T6 aluminum alloy structure convectively cooled to a mean temperature of 367 K (200°F). The multi-beam, multi-rib structural design concept shown in figure 2-4 is assumed. Coolant passages are integral with the Z stringer-stiffened skin as indicated. Minimum skin thickness is 1.6 mm (0.063 inches).

The wing has a symmetrical wedge-bar-wedge cross section with a thickness ratio, t/c, of 0.03. To achieve a small leading edge radius, the unshielded, cooled leading edge concept employs a flat, machined block having closely spaced coolant passages sealed with a cover skin.

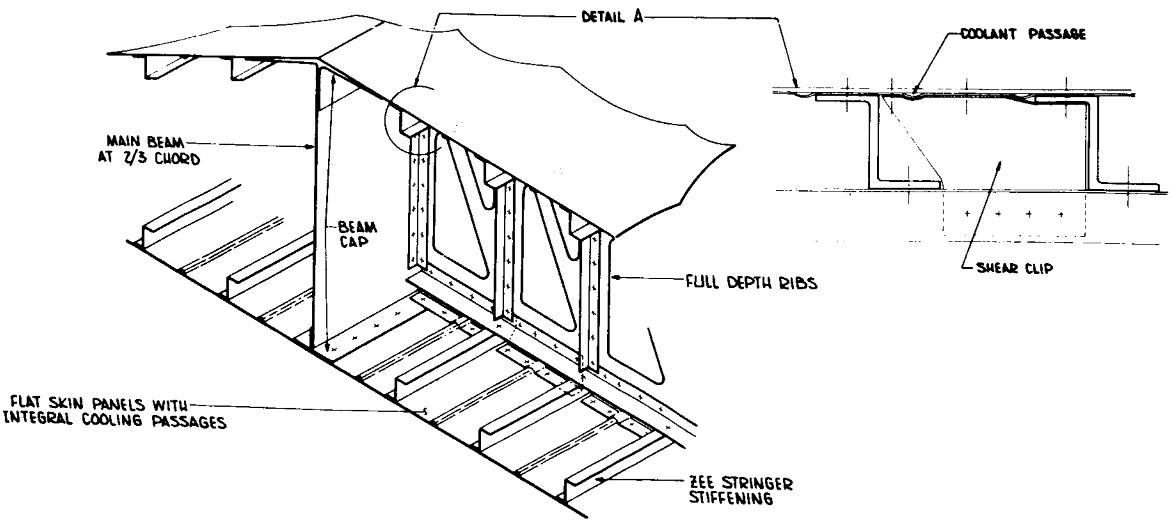

Figure 2-4.- Cooled Wing Structural Design Concept

Water-glycol coolant is circulated through all coolant passages in a closed-loop system to absorb incident aerodynamic heat and transfer it to a heat exchanger for rejection to the hydrogen fuel.

An air gap/radiation external shield on the lower surface aft of the unshielded leading edge section reduces the cooling system thermal load and heat rates. The external shield is assumed to be fabricated of TD nickle.

Wing component weights are based on the following unit values:

Main structure	26 kg/m^2 (5.41 lb/ft^2)
Cooling system	4.5 kg/m^2 (0.93 lb/ft^2)
Heat shield	4.4 kg/m^2 (0.9 lb/ft^2)

Empennage structure, materials The baseline configuration employs a fixed vertical tail with a split rudder and has no horizontal tail. The vertical tail has an area of 94.8 m^2 (1020 ft^2). With the rudder surfaces at 2° incidence to the center line, the effective thickness ratio of the single wedge is 0.07.

The vertical tail is an uncooled Inconel 718 structure. Operating temperature is assumed to be 811 K (1000°F). The baseline design has a unit weight of 29 kg/m^2 (5.9 lb/ft^2). The same unit weight is applied to each 3215 m^2 (350 ft^2) section of the split rudder.

Fuselage structure, materials The structural materials and cooling system concept for the fuselage are consistent with the wing structural/cooling system concept. The airframe is 7075-T6 aluminum alloy cooled to an average temperature of 367 K (200°F). Cooling is by means of the indirect convective cooling system employing water-glycol as a heat transport fluid at 1.03 x 10^{6}N/m^2 (150 psi). The heat load is transferred to the liquid hydrogen heat sink through a heat exchanger. Heat shields are employed over portions of the fuselage subject to highest heat loads (radiation equilibrium temperature exceeds 811 K (1000°F)). This limits the capacity and weight of the coolant system and reduces the portion of the hydrogen heat sink required for fuselage cooling.

Detailed data applicable to the cooling of the fuselage structure appear in reference 3. Detailed data descriptive of the cooling system for the complete airframe appear in reference 5.

Inverted hat section stiffeners are assumed for the skins. The hat sections, per reference 3 typically are on about 0.07-m (2.6-in.) centers. Zee-section ring frames have spacing variations between 0.51 m (20 in.) and 1.02 m (40 in.). A minimum gauge of 1.0 mm (0.040 in.) is used for the cooled aluminum alloy skins.

Frame weight estimates are based on a pressure differential of 1380 N/m^2 (0.2 psi) across the fuselage covers and a relatively flat underside 1.7 times the width of the design in reference 3. Frame weight, therefore, is estimated to be $(1.7)^{1.5} = 2.22$ times the reference 3 value.

Tankage structure, materials In establishing tank sizes, it is assumed that the airframe structure extends seven inches from the mold lines and that three inches are required for tank insulation and to accomodate relative deflections. An effective density of 68.1 kg/m^3 (4.25 lb/ft^3), including ullage, is used for liquid hydrogen tank sizing. As noted previously under "Configuration and general arrangement", the fore and aft-located main hydrogen tanks are of multicell structural configuration.

The tanks are designed to a working pressure of 172 000 N/m^2 (25 psi) and a burst pressure of 344 000 N/m^2 (50 psi). The general tank structural arrangement, per references 3 and 5, consists of an integrally stiffened pressure shell with internal rings necessitated by the bending moments induced due to the fuel weight and methods of support. Tension membranes are employed at the cell intersections. Support is provided at two major rings while lighter rings are used on 1.0m (40-in.) centers to aid in stiffening the shell. Integral stiffeners are used to stabilize the shell against buckling. The tanks have elliptical heads. The material is Inconel 718. Ultimate tensile strength for a 20 000 cycle fatigue life and temperature of 256 K (0°F) above the ullage is about 938×10^6 N/m^2 (136 000 psi). Skin thickness is 1.0 mm (0.040 in.).

The estimated weight per unit volume of the multi-cell tanks is 14 kg/m^3 (0.89 lb/ft^3).

Thermal management Thermal management, as summarized here, includes fuel tank and compartment insulation and the limiting of thermal inputs to the sink capacity of the engine fuel flow.

Hermetically sealed, polyurethane foam insulation panels are adopted in the baseline for thermal isolation of the liquid hydrogen tanks. Sealing to prevent cryopumping is by means of multiple layers of plastic film which are bonded and secured to the fuel tank walls. The polyurethane foam panels have a density of 32 kg/m^3 (2 lb/ft^3) and a maximum thickness of 1.9 cm (0.75 in.). The insulation system weight includes a helium purge system and hydrogen boil-off during a 30-minute ground hold.

The payload compartment pressure vessel is supported by fuselage frames which are a part of the 367 K (200°F) cooled airframe structure. Ends of the compartment are adjacent to the main fuel tanks. The purge gas between the compartment and tanks is estimated to be at about 250 K (-10°F). The thermal management concept for the compartment includes a combination thermal/sound insulation and a heat exchanger system.

Through the use of air-gap thermal shields on the undersurface of the wing, active cooling of the wing to 367 K (200°F) utilizes about 20 percent of the available heat capacity of the hydrogen fuel flow. Active cooling of the fuselage requires about 30 percent of the liquid hydrogen available heat capacity; thus, 50 percent is available for cooling the scramjet engines.

Propulsion systems installation The illustrative baseline HST utilizes a liquid hydrogen-fueled, air-breathing engine, referred to generically as a "turbojet" engine, for initial acceleration and climb, and for final descent, loiter and landing phases. The turbojet accelerator engine is a bypass type. Cruise propulsion is provided by an integrated array of supersonic combustion, scramjet engines. This is a specific application within the broader term "ramjet" which is employed in this method module. The dual-combustion-mode scramjet is used in conjunction with the turbojet during the mid-acceleration phase and develops all of the acceleration and cruise propulsive thrust after turbojet shut-down (Mach 3 in this example).

The turbojet installation is integral within the fuselage, and the scramjet installation is integrated both geometrically and aerodynamically with the fuselage. The resulting over and under arrangement, shown earlier in figure 2-3 is adapted from the concept presented in reference 6.

In this installation concept the turbojets require a large adjustable inlet door and variable internal geometry to match the airflow requirements of the engines over the Mach 0-3 range. The adjustable inlet door closes-off the turbojet ducting above Mach 3 and serves as a precompression ramp for the integrated scramjet engines. Boundary layer build-up over the 63 m (208 ft) of body length forward of the inlet is expected to pose a significant problem which may be alleviated with a diverter system.

The scramjet array, including its integral nacelle, is detachable from the basic airframe. However, scramjet weight estimates assume that, after installation, the deep body frames will contribute to support of the adjacent scramjet surfaces.

Turbojet description On the basis of comparison of six candidate engine types, a hydrogen-burning design designated "Pratt and Whitney STF-230A, fuel-rich turbofan ramjet" was selected as the most suitable accelerator propulsion system. The engine features the highest ratio of thrust over the Mach 0.3-to-3.0 range to the sea level static rating. Specific fuel consumption is less than 0.08 kg/N-hr (0.8 lb_m/lb_f-hr) in the low supersonic Mach number range, but is higher than other candidate engines, sfc = 0.096 kg/N-hr (0.95 lb_m/lb_f-hr) at low subsonic speeds.

The four accelerator engines in the illustrative design are scaled from the STF-230A engine. The thrust scaling factor is 0.773 for a SLS thrust rating of 258 000 N (58 000 lb) per engine. Predicted engine specific thrust, $T_{TJ}/W_{TJ\ engine}$, is 9.3.

Ramjet description The ramjet propulsion system for the HST airplane example is a horizontal array of nine parallel engines or modules. The engines are in the air stream throughout flight and operate from low transonic Mach numbers through the acceleration and cruise phases. For effective performance over the Mach number range, the engines incorporate variable geometry throats as shown in figure 2-5. At lower Mach numbers, the throats may be opened to more than 3 times the minimum area at Mach 6 cruise conditions. The variable geometry also facilitiates inlet starting, permits attainment of higher inlet capture area ratios, and reduces spillage drag. Throat geometry is varied by lateral movement of side plates and corresponding swiveling of outboard fuel struts. To accommodate angular movement of the side plates, the upper and lower surfaces are parallel. To produce the desired parallel flow conditions in the vertical plane, normal wedges are employed in the inlet. The forward portion of the inlet wedges and cowl surface are of fixed geometry.

The scramjet engines operate in a dual mode: supersonic combustion at Mach 6 cruise conditions and subsonic combustion at transonic and lower supersonic flight Mach numbers. Supersonic combustion is selected for the baseline cruise conditions as recommended in reference 6 to reduce engine air induction system length and weight, and to minimize the engine thermal load for the active cooling system.

Performance characteristics of the dual-mode ramjets have been summarized in Table 2-XI.

Avionics The avionics systems for the baseline HST are: guidance and navigation, instrumentation and communications. Estimated weights are from reference 3.

Guidance and navigation,	W =	360 kg (800 lb)
Instrumentation,	W =	180 kg (400 lb)
Communications	W =	910 kg (2000 lb)

Equipment This category includes launch and recovery gear, prime power and distribution, and payload provisions.

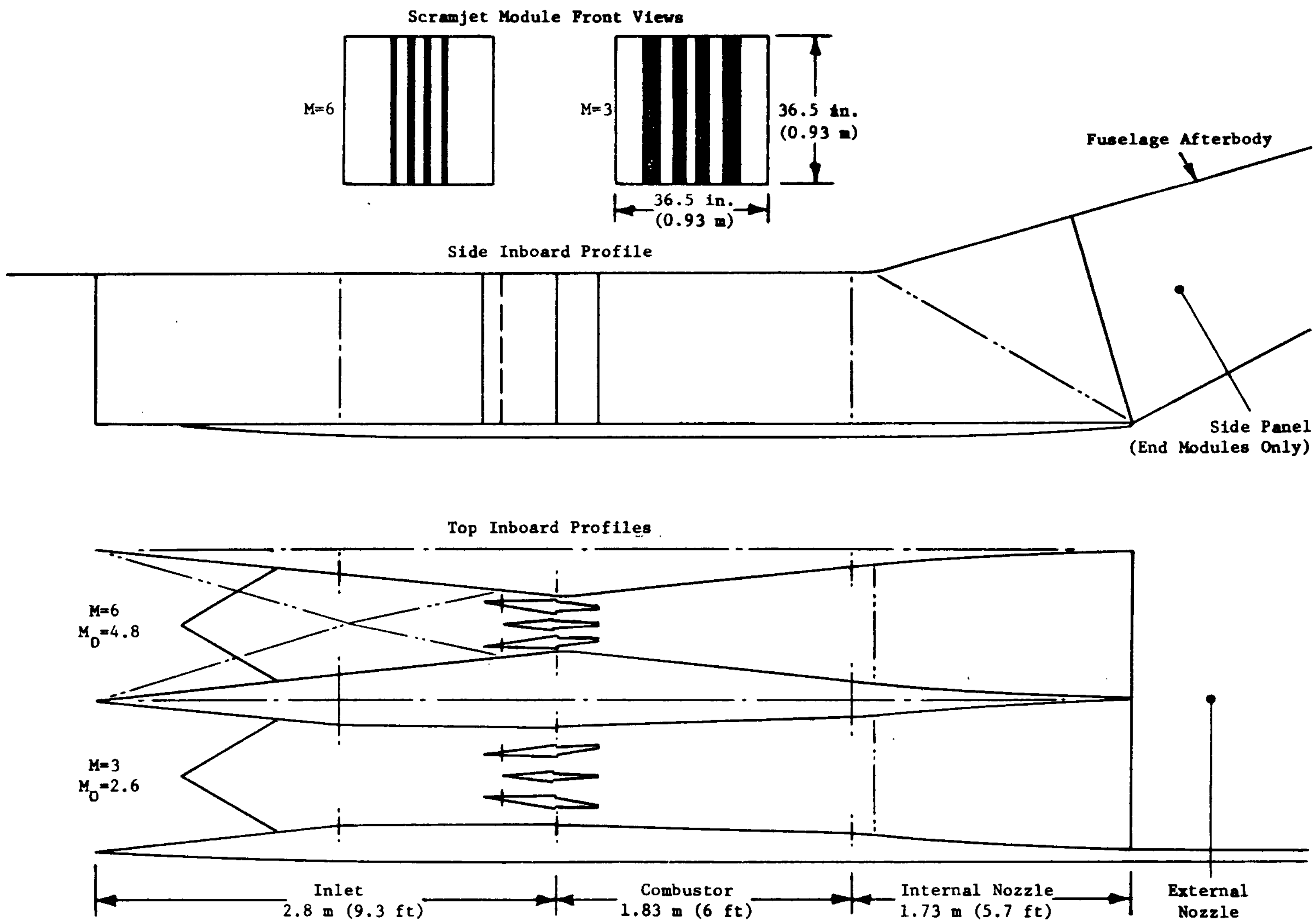

Figure 2-5.- Scramjet Module Geometry and Mach Numbers of 6 and 3

The landing gear of the baseline configuration are stowed within the cooled fuselage during flight. Consequently, their thermal environment is limited to 367 K (200°F). The weight estimate represents a scaling from the reference 3 design based on weight being proportional to the 0.8 power of the length. The main gear is estimated to weigh 6360 kg (14 000 lb) and the nose gear 1860 kg (4100 lb).

Prime power and distribution includes:

Engine or gas generation, W = 980 kg (2150 lb)

Tank and systems, W = 480 kg (1050 lb)

Electrical distribution, W = 1600 kg (3500 lb)

Hydraulic and pneumatic, W = 500 kg (1100 lb)

Payload provisions are a substantial weight item, 7270 kg (16 000 lb). However, these provisions are not related to hypersonic technology and need not be described for reference herein.

Weight statement.- Estimated weights of the illustrative baseline HST are summarized in Table 2-XII. The weight estimates are based primarily on reference 3 data adjusted to the findings of references 3, 4 and 5 and applied to the configuration shown in figure 2-3.

The weight estimates summarized in this table are the bases for the derivation of the weight fractions required for the DOC equations, method module 3, and for airframe and propulsion weight parameters, method module 4.

Table 2-XIII lists the weight items and coding from MIL-M-38310A in conjunction with the terms employed in the baseline HST weight summary.

TABLE 2-XII.- WEIGHT SUMMARY-BASELINE HST AIRCRAFT

Group	Item	Weight kg	Weight lb
Aero Structure, W_W	Wing	14 800	32 600
W_E	Vertical Tail	3 100	6 900
Body Structure, W_F	Covers	15 300	33 600
	Frames	4 700	10 400
	Compartments	7 900	17 410
Propellant Systems, W_{PS}	Tanks	15 000	32 900
	Fuel/Pres/Lub Systems	2 400	5 200
Thermal Protection, W_{TP}	External Shields	4 600	10 200
	Cooling System	6 900	15 300
	Compartment Insulation	500	1 200
	Tank Insulation	3 400	7 590
Turbojet Propulsion, W_{TJ}	Turbojet Engines	11 400	25 000
	Turbojet Air Induction	5 500	12 000
Scramjets, W_{RJ}		7 400	16 200
Avionics, W_{AV}		1 450	3 200
Equipment, W_{Equip}	Launch and Recovery	8 200	18 100
	Prime Power & Distribution	3 500	7 800
	Payload Provisions	7 270	16 000
	Dry Airplane, W_e	123 000	271 600
Personnel, Residuals and Prime Power Reserve(1)		1 140	2 500
Payload, W_{PL}		22 700	50 000
	Wet Airplane & Payload	147 000	324 100
In-Flight Losses(1)		2 000	4 300
Main Fuel, W_{f_T}		69 400	153 000
	Gross Take-Off Weight, W_{GTO}	218 400	481 400

(1) Sum is W_{Misc} — 3 080 kg, 6 800 lb

Note: $W_{AF} = W_{GTO} - W_{f_T} - W_{TJ} - W_{RJ} - W_{AV} - W_{PL} - W_{Misc}$ — 97 600 kg, 215 200 lb

TABLE 2-XIII.- HST WEIGHT ITEMS RELATION TO MIL-M-38310A

HST description	MIL-M-38310A	
	Code	Description
Aero surfaces	1.0	Aero surfaces
Body structure	2.5 2.11 2.12	Structure enclosing nonintegral tanks Pressurized compartment Non-pressurized compartment
Propellant systems	2.1 5.9 5.10 5.16 6.0	Structural fuel tank Fuel system Pressurization system-fuel Lubricating system Orient. controls, separ. & ullage
Thermal protection system	3.1 3.2 12.0	Thermal protection (active) Thermal protection (passive) Environmental control
Turbojet propulsion	5.6	Air-breathing engine and accessories (including air induction system)
Scramjet	5.6	Air-breathing engine and accessories (including air induction system)
Avionics	9.0 10.0 11.0	Guidance and navigation Instrumentation Communication
Equipment	4.0 7.0 8.0 14.0 15.0	Launch, recovery and docking Prime power source Power conversion and distribution Personnel provisions Crew station control and panels
Personnel, residuals and prime power reserve	17.0 21.0 22.0	Personnel Residual propellant and service items Reserve propellant and service items
Payload	18.0	Cargo
In-flight losses	23.0	In-flight losses
Main fuel	25.0	Full thrust propellant

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4. McConarty, W.A., and Anthony, F.M.: Design and Evaluation of Active Cooling Systems for Mach 6 Cruise Vehicle Wings, NASA CR-1916, December 1971.

5. Helenbrook, R.G., and Anthony, F.M.: Design of a Convective Cooling System for a Mach 6 Hypersonic Transport Airframe, NASA CR-1918, December 1971.

6. Henry, J.R., and Anderson, G.Y., Design Considerations for the Airframe-Integrated Scramjet, 1st International Symposium on Air Breathing Engines, Marseille, France, June 19-23, 1972.

APPENDIX 2-A

GENERATION OF HST BASELINE DATA

The generation of baseline data apart from the HST definition method was required in order to:

(1) augment the groundrules and thereby further constrain the definition process,

(2) generate new data where reference data were insufficient to meet the input data needs of the method.

Augmentation of Ground Rules

The requirements and ground rules as presented in the "Demonstration" section, Table 2-VI, leave a number of options open in the definition of HST governing characteristics. The separate activity reported here was therefore conducted to constrain the definition process by selecting characteristics from among these options for use in the definition.

Table 2-XIV lists major options considered and identifies those which were selected as most suitable for the purposes of this baseline definition. These selections are incorporated in Table 2-IX in the "Demonstration" section of this method module.

Suitability is based on the criteria of reduced HST dry weight and/or improved performance . . . with the expectation of resultant reductions in direct operating costs.

Regarding the vertical tail, reference 4 indicates a weight savings of 25 percent for the uncooled tail relative to a cooled design. Additionally, a reduced structural complexity and cooling load are associated with this option.

At liquid hydrogen tank temperatures and 20,000 pressure cycles, the weights of aluminum alloy and Inconel tanks should be similar. The use of Inconel 718 for the tank structure in this demonstration is based solely on the recommendation in reference 3.

Of the alternate fuel tank insulation approaches, the sealed foam insulating system offers a weight reduction of some 60 percent from the CO_2 frost system. This amounts to about 4950 kg (10 900 lb) first-order reduction in empty weight of the baseline vehicle. The sealed foam system requires that a reliable method of bonding the multiple thin films of aluminized plastic to the multi-cell tanks be available to prevent cryopumping.

TABLE 2-XIV.- MAJOR DESIGN OPTIONS

Fuselage, wing and empennage structure	
o All external surfaces actively-cooled aluminum alloy	
o As above except for uncooled vertical tail, Inconel 718	√
Fuel tank structure	
o Aluminum alloy	√
o Inconel 718	
Fuel tank insulation	
o CO_2 frost thermal protection system	√
o Sealed foam insulation system	
Accelerator/descent (turbojet-type engines)	
o STRJ-197A High temperature turbine, afterburner	
o SWAT-201A Turboramjet	√
o STF-230A Fuel-rich turbofan ramjet	
o GE5-JZ1 - Study B Stoichiometric turbine, no afterburner	
Degree of airframe-engine integration	
o Scramjets mounted per reference 2	
o Modification of underside of fuselage to enhance production of thrust per reference 6	√
Inlet general concept	
o Shared variable geometry inlets per reference 1	√
o Separate turbojet and ramjet inlets per reference 6	
Scramjet structural design complexity	
o Fixed geometry	√
o Variable geometry	

Key: √ Identified as most suitable for baseline

Reference 6 notes that . . . "significant reductions in structural weight and engine cooling requirements can accrue from efficient integration of the engine into the airframe at hypersonic speeds . . . . the vehicle forebody acts as an inlet spike and the afterbody acts as an exhaust nozzle. Therefore, in order to obtain an efficient propulsive system, the underside of the vehicle must be designed as much from propulsive requirements as from the usual aerodynamic considerations of attaining high L/D." Implementation of this option is described in this demonstration under "HST baseline description."

The employment of a separate inlet for the ramjets as in reference 6 permits design of relatively short, efficient scramjet inlets with substantially lower cooling loads at hypersonic speed.

Variable geometry in the throat and adjoining sections of the ramjet strongly improves the ramjets' performance as accelerator engines without compromising cruise performance.

Generation of New Data

Because the baseline HST represents a composite of characteristics from a number of sources, major deficiencies in baseline characteristics were encountered relative to the data required as input to the baseline HST definition method. Primary deficiencies were:

- HST airplane sizing (fuselage length and wing area)
- HST airplane configuration drawing showing general arrangement
- Surface areas and volumes of major components and groupings
- Sizing of accelerator/loiter engines
- Sizing of scramjet engines
- Loads on major components
- Selective analyses of airframe structure in support of weight estimates and definition of airframe design and technology parameters.
- Estimated weights of major components and groupings
- Integrated weight statement for baseline HST airplane
- Scramjet baseline performance conditions and cruise sfc
- Scramjet performance trades for use in deriving partials
- Values of definition parameters required by subsequent modules.

The data required in the above information categories were generated separately from the definition method. These new data, in effect, became a part of the reference information sources used in the definition.

METHOD MODULE 3

DOC FORMULAS AND DRIVERS

METHOD MODULE 3 - DOC FORMULAS AND DRIVERS

Logic

This method module presents the procedures and the equations for calculating direct operating cost (DOC) for the HST aircraft as a function of Driver Parameters and the change in the DOC which would result from improvements in the values of the Driver Parameters. By definition, the Driver Parameters are parameters appearing in the DOC formulas which are directly relatable to hypersonic technology. The DOC formulas have been organized to express the Driver Parameters in normalized form (e.g., W_{AF}/W_{GTO}, airframe weight fraction) or other forms which are convenient for the purposes of the overall method.

The DOC values are calculated using the DOC Formulas and are expressed in the form of cents per ton-mile. The changes in the DOC which result from improvements in the Drivers are calculated using equations called Driver Equations and are expressed in the ratio (ΔDOC/DOC)/(ΔDriver/Driver). The ratios (ΔDOC/DOC)/(ΔDriver/Driver) are called "Driver Partials" herein for convenience. The logic sequence for this method module is illustrated in figure 3-1.

A demonstration section is included in which the procedures presented here are illustrated for the baseline HST aircraft defined in Module 2, Baseline HST Definition. In addition, a sensitivity analysis is included which indicates variations in the values of the Driver Partials, (ΔDOC/DOC)/(ΔDriver/Driver), which would result from uncertainties in parameters other than Drivers which are treated as constants in the DOC formulas. The "sensitivity parameters" include operational and cost factors which are a matter of judgment or independent estimate such as aircraft utilization, load factor, or the purchase price of fuel.

The expressions given in this module present individual weight and cost terms for the turbojet and ramjet elements of the propulsion system. However, this method is not dependent on there being separate engines. In the case of composite engines, Method Module 2 develops and provides appropriate terms for the accelerator and cruise portions of the composite engines which are to be used respectively for the turbojet and ramjet terms herein.

Input Data

Input data for this method module consist of the aircraft and mission parameters listed in Table 3-I, which are provided by the output of Module 2, Baseline HST Definition, (reference Table 2-III).

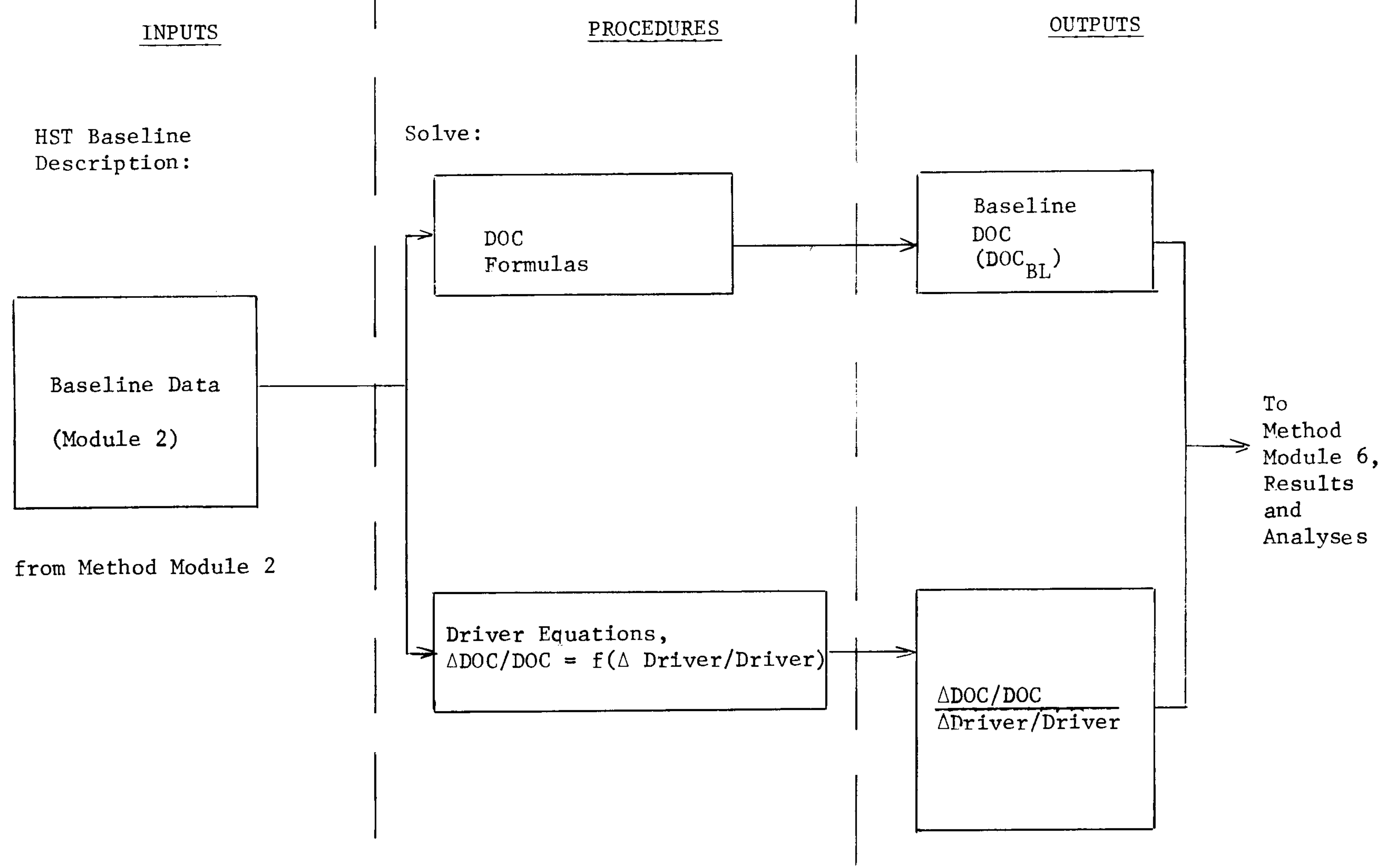

Figure 3-1.- Logic Sequence for Method Module 3

TABLE 3-I.- INPUT DATA REQUIRED FOR MODULE 3

Symbol	Units	Parameter
Driver Parameters		
L/D	-	Cruise lift-drag ratio
sfc	Kg/N-hr $\frac{lb_m}{lb_f x hr}$	Specific fuel consumption
(W_{AF}/W_{GTO})	-	Airframe weight fraction
$(W/T)_{TJ}$	-	Turbojet specific weight
$(W_{RJ})/(A_C C_{TRJ})$	kg/m^2 (lb/ft^2)	Ramjet sizing parameter
Other Aircraft Parameters		
Ac	m^2 (ft)^2	Total cowl inlet area, ramjet engines
N_{TJ}	-	Number of turbojet engines per aircraft
N_{RJ}	-	Number of ramjet engine modules per aircraft
T_{TJ}	N (lb)	Turbojet thrust (SL static) per engine
$(T/W)_{GTO}$	-	Maximum thrust to weight ratio at take-off
W_{AV}/W_{GTO}	-	Avionics equipment weight fraction
W_{f_T}/W_{GTO}	-	Fuel weight fraction
W_{GTO}	kg (lb)	Gross take-off weight
W_{PL}/W_{GTO}	-	Payload weight fraction
W_{RJ}/W_{GTO}	-	Installed ramjet engines weight fraction
W_{TJ}/W_{GTO}	-	Installed turbojet engine and duct weight fraction

TABLE 3-I.- INPUT DATA REQUIRED FOR MODULE 3 - Concluded

Symbol	Units	Parameter
<u>Mission Parameters</u>		
K_D	-	Descent fuel fraction
K_R	-	Reserve fuel fraction
K_{CL}	-	Climb fuel fraction
M	-	Cruise Mach no.
R_T	km (miles)	Operational range
t_F	hr	Time of flight
V_B/V_{CR}	-	Ratio, block velocity to cruise velocity

Procedures

The procedures for this Method Module consist of solving the DOC Formulas and the Driver equations and compiling the results in appropriate format for delivery to the Project Office. The derivation of the DOC formulas which are based on the Air Transport Association of America (ATA) convention (reference 1) is given in Appendix 3-A. The derivation of the Driver equations is given in Appendix 3-B. The steps of the procedure are:

1. Determine the baseline DOC value for each of the DOC elements and for the DOC total using the DOC formulas. Enter the values for the DOC elements at locations (a) in column (1) of the Work Sheet, Table 3-II. Enter the DOC total in column (1) at (b).

2. Determine the Driver Partial for each Driver Parameter and DOC element using the Driver Equations and compile the results in columns (2) through (6) of the Work Sheet, Table 3-II, using the following steps:

    Enter the Driver Partials (c) from the solutions of the Driver Equations in columns (2) through (6) for each Driver and for each element of DOC.

    Calculate (Driver Partial) x DOC_i, (d), for each DOC element (i) and each Driver.

    Sum the values of (Driver Partial) x DOC_i for each of the values in the second line from the bottom of the Work Sheet, (e).

    Calculate the Driver Partial (total) for each Driver by dividing the entries of (e) above by the baseline DOC total, (DOC_{BL}), and enter at the bottom of the Work Sheet, (f).

TABLE 3-II.- WORK SHEET

	Baseline DOC Values - \$ Per Ton-Mile (1)	Driver Partials for Driver Parameters:				
		$\frac{W_{AF}}{W_{GTO}}$ (2)	$\left(W/T\right)_{TJ}$ (3)	$\frac{W_{RJ}}{A_C/C_{TRJ}}$ (4)	L/D (5)	sfc (6)
DOC_f Driver Partial Driver Partial x DOC_f	(a)	(c) (d)				
DOC_C Driver Partial Driver Partial x DOC_C						
DOC_I Driver Partial Driver Partial x DOC_I						
DOC_D Driver Partial Driver Partial x DOC_D						
$DOC_{M/AF/L}$ Driver Partial Driver Partial x $DOC_{M/AF/L}$						
$DOC_{M/AF/M}$ Driver Partial Driver Partial x $DOC_{M/AF/M}$						
$DOC_{M/TJ/L}$ Driver Partial Driver Partial x $DOC_{M/TJ/L}$						
$DOC_{M/TJ/M}$ Driver Partial Driver Partial x $DOC_{M/TJ/M}$						

Note: Parenthetical entries (a), (b), . . . are correlated to procedure.

Continued

Table 3-II.- WORK SHEET - Concluded

	Baseline DOC Values - $ Per Ton-Mile (1)	Driver Partials for Driver Parameters: $\frac{W_{AF}}{W_{GTO}}$ (2)	$\left(W/_{T}\right)_{TJ}$ (3)	$\frac{W_{RJ}}{A_C/C_{TRJ}}$ (4)	L/D (5)	sfc (6)
$DOC_{M/RJ/L}$ Driver Partial Driver Partial x $DOC_{M/RJ/L}$						
$DOC_{M/RJ/M}$ Driver Partial Driver Partial x $DOC_{M/RJ/M}$						
TOTAL DOC_{BL} Σ(Driver Partial x DOC_i)	(b)	(e)				
Driver Partial$_{(total)}$ $(=(\Sigma Dr.Partial x DOC_i)/DOC_{BL})$		(f)				

DOC formulas.- The DOC formulas are organized in the manner indicated in figure 3-2. A separate formula exists for each DOC element, fuel, crew, insurance, etc. These are then summed to give DOC_{Total}. The operational constants and cost factors not given in the baseline HST definition, but required to solve the DOC equations are provided in Appendix 3-C. The input and output values of all cost values in the DOC formulas are in dollars, so that the calculated DOC values are in dollars per ton-mile. The formulas are expressed with coefficients in SI units so that inputs to the formulas must be in SI units.

The DOC formulas are:

DOC Equations

DOC_T Total = DOC_f Fuel + DOC_C Crew + DOC_I Insurance + DOC_D Depreciation + DOC_M Maintenance

DOC_M = $DOC_{M/AF/L}$, Maintenance Labor, Excluding Engines
+ $DOC_{M/AF/M}$, Maintenance Material, Excluding Engines
+ $DOC_{M/TJ/L}$, Turbojet Maintenance, Labor
+ $DOC_{M/TJ/M}$, Turbojet Maintenance, Materials
+ $DOC_{M/RJ/L}$, Ramjet Maintenance, Labor
+ $DOC_{M/RJ/M}$, Ramjet Maintenance, Materials

Figure 3-2.- DOC Formula Summary

Fuel:

$$DOC_{Fuel} = \frac{1460\ C_f\ \left(W_{f_T}/W_{GTO}\right)\ (1 - K_R)}{(LF)\ \left(W_{PL}/W_{GTO}\right)\ R_T}$$

Where,

C_f = cost of fuel per unit weight, \$/kg (reference Appendix 3-C)

W_{f_T}/W_{GTO} = fuel weight fraction

K_R = reserve fuel fraction

R_T = operational range, km

LF = average load factor; use 0.6 unless specified otherwise by Module 1 (reference Appendix C)

W_{PL}/W_{GTO} = payload weight fraction

Crew:

$$DOC_{Crew} = \frac{320/W_{GTO}}{0.725\ (LF)\left(\frac{W_{PL}}{W_{GTO}}\right) M\ \left(V_B/V_{CR}\right)}$$

Where,

W_{PL} = payload weight, kg

M = cruise Mach number

V_B/V_{CR} = ratio of block velocity to cruise velocity

Insurance:

$$DOC_{Insurance} = \frac{(IR)(C_{HST}/W_{GTO})}{0.725\ (LF)(W_{PL}/W_{GTO})\ M\ (V_B/V_{CR})\ U}$$

Where,

IR = annual insurance rate, %/100; use 0.02 unless specified otherwise by Module 1. (reference Appendix 3-C)

C_{HST}/W_{GTO} = ratio, cost of airplane (total) to gross takeoff weight, $/kg; use cost estimating relationship in Appendix 3-C unless specified otherwise by Module 1.

W_{PL}/W_{GTO} = payload weight fraction

U = aircraft utilization, block hrs/yr; use 3000 hours unless specified otherwise by Module 1 (reference Appendix 3-C)

Depreciation:

$$DOC_{Depreciation} = \frac{1.1(C_{HST}/W_{GTO}) + 0.3(C_{TJ}/W_{GTO} + C_{RJ}/W_{GTO})}{0.725(LF)(W_{PL}/W_{GTO})\ M(V_B/V_{CR})\ U(L_d)}$$

Where,

C_{TJ}/W_{GTO} = ratio, cost of turbojet engine set per aircraft to gross takeoff weight, $/kg

C_{RJ}/W_{GTO} = ratio, cost of ramjet engine set per aircraft to gross takeoff weight, $/kg; use cost estimating relationships in Appendix C for C_{TJ}/W_{GTO} and C_{RJ}/W_{GTO} unless specified otherwise by Module 1.

L_d = depreciation life of aircraft, years; use 10 years unless specified otherwise by Module 1 (reference Appendix 3-C)

Maintenance:

$$DOC_{Maintenance} = DOC_{M/AF/L} + DOC_{M/AF/M} + DOC_{M/TJ/L} + DOC_{M/TJ/M} + DOC_{M/RJ/L} + DOC_{M/RJ/M}$$

Where subscripts,

M/AF/L = airframe and subsystems maintenance labor, excluding engines

M/AF/M = airframe and subsystems maintenance material, excluding engines

M/TJ/L = turbojet maintenance labor

M/TJ/M = turbojet maintenance material

M/RJ/L = ramjet maintenance labor

M/RJ/M = ramjet maintenance material

Airframe and subsystems maintenance labor (excluding engines):

$$DOC_{M/AF/L} = \frac{(3.22 + 1.93\ t_F)\left[0.05\left(\frac{W_{AF}}{W_{GTO}} + \frac{W_{AV}}{W_{GTO}}\right) + 0.009\right] M^{\frac{1}{2}}(r_L)}{(LF)\ (W_{PL}/W_{GTO})\ R_T}$$

Where,

t_F = time of flight, hours

$\frac{W_{AF}}{W_{GTO}}$ = aircraft weight fraction (excludes engines and avionics)

$\frac{W_{AV}}{W_{GTO}}$ = avionics weight fraction

r_L = average maintenance labor rate for all personnel; use \$5.30 unless specified otherwise by Module 1 (reference Appendix 3-C)

Airframe and subsystems maintenance material (excluding engines):

$$DOC_{M/AF/M} = \frac{\left(4.52\ t_F + 9.04\right)\left(\frac{C_{HST}}{W_{GTO}} - \frac{C_{TJ}}{W_{GTO}} - \frac{C_{RJ}}{W_{GTO}}\right)}{(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T \times 10^3}$$

Turbojet engine maintenance labor:

$$DOC_{M/TJ/L} = \frac{(T/W)_{GTO}(1 + 0.3\ t_F)\left(\frac{8.60}{T_{TJ}/10^3} + 0.087\right) r_L\ K_{LTJ}}{(LF)\ (W_{PL}/W_{GTO})\ R_T}$$

Where,

$(T/W)_{GTO}$ = thrust to weight ratio at take-off

T_{TJ} = thrust of turbojet engines per engine (sea level static), N

K_{LTJ} = ratio, maintenance labor for HST turbojet engines to present subsonic engines; use 2.0 unless specified otherwise by Module 1 (reference Appendix 3-C)

Turbojet engine maintenance material:

$$DOC_{M/TJ/M} = \frac{\frac{C_{TJ}}{W_{GTO}}\left(0.011\ t_F + 0.029\right)\ K_{MTJ}}{(LF)\ (W_{PL}/W_{GTO})\ R_T}$$

Where,

K_{MTJ} = ratio, maintenance material for HST turbojet engines to present subsonic turbojet engines; use 2.0 unless specified otherwise by Module 1 (reference Appendix 3-C)

Ramjet engine maintenance labor:

$$DOC_{M/RJ/L} = \frac{(1 + t_F)\left(\frac{0.876\ N_{RJ}\ (L/D)}{W_{GTO}/10^3} + 0.087\right) r_L\ K_{LRJ}}{(L/D)\ (LF)\ (W_{PL}/W_{GTO})\ R_T}$$

Where,

K_{LRJ} = ratio, maintenance labor for ramjet engines to present subsonic turbojet engines; use 2.0 unless specified otherwise by Module 1 (reference Appendix 3-C)

N_{RJ} = number of ramjet modules per aircraft

L/D = cruise lift to drag ratio

Ramjet engine maintenance material:

$$DOC_{M/RJ/M} = \frac{\frac{C_{RJ}}{W_{GTO}}(0.036\ t_F + 0.029)\ K_{MRJ}}{(LF)\ (W_{PL}/W_{GTO})\ R_T}$$

Where,

K_{MRJ} = ratio maintenance materials for ramjet engines to present subsonic turbojet engines; use 3.0 unless specified otherwise by Module 1. (reference Appendix 3-C)

Driver definitions.- Driver parameters have been defined as parameters which enter into the calculation of DOC and significantly impact its value and which are directly relatable to hypersonic technology.

The following terms have been defined as Driver Parameters:

Airframe weight fraction	-	W_{AF}/W_{GTO}
Turbojet propulsion specific weight	-	$(W/T)_{TJ}$
Ramjet sizing parameter	-	$W_{RJ}/A_C C_{TRJ}$
Lift-to-drag ratio	-	L/D
Specific fuel consumption	-	sfc

In most of the DOC equations, the Driver Parameters are contained in the two terms

$$\frac{W_{f_T}}{W_{GTO}} \quad \text{and} \quad \frac{W_{PL}}{W_{GTO}} .$$

The equation for

$$\frac{W_{f_T}}{W_{GTO}} ,$$

(Fuel Fraction) is developed in Appendix 3-D and is repeated here as:

$$W_{f_T}/W_{GTO} = \frac{1 - \exp\left\{9.1\times10^{-3} \frac{(R_T)sfc}{L/D\ (M)} (1-0.75\ W_{f_{CL}}/W_{f_T})\right\}}{W_{f_{CL}}/W_{f_T} - [1-(K_D+K_R)]\exp\left\{9.1\times10^{-3} \frac{(R_T)sfc}{(L/D)\ M} (1-0.75\ W_{f_{CL}}/W_{f_T})\right\}}$$

The Drivers L/D and sfc both appear in this expression.

The payload weight fraction is written as:

$$\frac{W_{PL}}{W_{GTO}} = 1 - \frac{W_{AF}}{W_{GTO}} - \frac{W_{TJ}}{W_{GTO}} - \frac{W_{RJ}}{W_{GTO}} - \frac{W_{AV}}{W_{GTO}} - \frac{W_{f_T}}{W_{GTO}}$$

The first term is the airframe weight fraction which is a Driver Parameter. The second term can be written as :

$$\frac{W_{TJ}}{W_{GTO}} = \left(\frac{W}{T}\right)_{TJ} \left(\frac{W}{T}\right)_{GTO}$$

where,

$$\left(\frac{W}{T}\right)_{TJ}$$

is the Driver Parameter.

The Final Driver is contained in the ramjet weight term as :

$$\frac{W_{RJ}}{W_{GTO}} = \left(\frac{W_{RJ}/A_C}{C_{TRJ}}\right) \frac{C_L}{(L/D)\,(W/S)_{GTO}}$$

The five Driver Parameters given above are now used along with the basic DOC equations to develop the Driver "Partials" in the next section.

Driver equations.- The Driver equations are organized with separate equations for each Driver Parameter and for each of the DOC elements, fuel, crew, insurance, etc. The derivation of these equations is given in Appendix 3-B.

The solutions to the Driver equations are the "Driver Partials" to be entered in the Work Sheet, Table 3-II. The Driver Partials are in the form of (ΔDOC/DOC)/(ΔDriver/Driver) for each element of DOC and for each driver.

The Driver Partials are given as follows:

Airframe weight fraction, W_{AF}/W_{GTO}:

For Driver W_{AF}/W_{GTO}
$$\frac{\Delta DOC_f/DOC_f}{\dfrac{\Delta W_{AF}/W_{GTO}}{W_{AF}/W_{GTO}}} = \frac{\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{AF}}{W_{GTO}}}$$

For Driver W_{AF}/W_{GTO}
$$\frac{\Delta DOC_i/DOC_i}{\dfrac{\Delta W_{AF}/W_{GTO}}{W_{AF}/W_{GTO}}} = \frac{\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{AF}}{W_{GTO}}}$$

where,

i = the DOC elements, crew insurance, depreciation, M/AF/M, M/TJ/L, M/TJ/M, M/RJ/L, and M/RJ/M

For Driver W_{AF}/W_{GTO}
$$\frac{\Delta DOC_{M/AF/L}/DOC_{M/AF/L}}{\dfrac{\Delta W_{AF}/W_{GTO}}{W_{AF}/W_{GTO}}} = \frac{1.2\,\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{AF}}{W_{GTO}}}$$

Turbojet propulsion specific weight, $(W/T)_{TJ}$:

For Driver $(W/T)_{TJ}$
$$\frac{\Delta DOC_i/DOC_i}{\Delta(W/T)_{TJ}/(W/T)_{TJ}} = \frac{\frac{W_{TJ}}{W_{GTO}}}{\frac{W_{PL}}{W_{GTO}} + 0.1\,\frac{W_{TJ}}{W_{GTO}}}$$

where,

i = all DOC elements.

Ramjet sizing parameter, $W_{RJ}/A_C C_{TRJ}$:

For Driver $W_{RJ}/A_C C_{TRJ}$
$$\frac{\Delta DOC_i/DOC_i}{\frac{\Delta W_{RJ}/A_C C_{TRJ}}{W_{RJ}/A_C C_{TRJ}}} = \frac{\frac{W_{RJ}}{W_{GTO}}}{\frac{W_{PL}}{W_{GTO}} + 0.1\,\frac{W_{RJ}}{W_{GTO}}}$$

where,

i = all DOC elements.

Lift-to-drag, L/D:

For Driver L/D

$$\frac{\dfrac{\Delta DOC_f}{DOC_f}}{\dfrac{\Delta L/D}{L/D}} = \frac{\dfrac{W_{f_T}}{W_{GTO}} + \dfrac{W_{PL}}{W_{GTO}}}{(L/D)\left(\dfrac{W_{f_T}}{W_{GTO}}\right)\left(\dfrac{W_{PL}}{W_{GTO}}\right)} A\ e^{A/(L/D)} \left[\frac{(1 - D\ W_{f_T}/W_{GTO})}{K_{CL} - D\ e^{A/(L/D)}}\right]$$

where,

$$W_{f_T}/W_{GTO} = \frac{1 - \exp\left[\dfrac{R_T\ (sfc)}{110\ M\ (L/D)}\ (1\text{-}0.75\ K_{CL})\right]}{K_{CL} - D\exp\left[\dfrac{R_T\ (sfc)}{110\ M\ (L/D)}\ (1\text{-}0.75\ K_{CL})\right]}$$

$$A = \frac{R_T\ (sfc)}{110\ M}\ (1\text{-}0.75\ K_{CL})$$

$$D = [1 - (K_D + K_R)\ ]$$

For Driver L/D

$$\frac{\Delta DOC_{M/RJ/L}\ /DOC_{M/RJ/L}}{\Delta(L/D)/(L/D)} = \frac{L/D}{W_{PL}/W_{GTO}}\ \frac{Ae^{A(L/D)}}{(L/D)^2}\ \frac{1 - D\ \dfrac{W_{f_T}}{W_{GTO}}}{K_{CL} - De^{A(L/D)}}$$

For Driver L/D

$$\frac{\dfrac{\Delta DOC_i}{DOC_i}}{\dfrac{\Delta L/D}{L/D}} = \left[\frac{\dfrac{W_{f_T}}{W_{GTO}}}{\dfrac{W_{f_T}}{W_{GTO}} + \dfrac{W_{PL}}{W_{GTO}}}\right] \frac{\dfrac{\Delta DOC_f}{DOC_f}}{\dfrac{\Delta L/D}{L/D}}$$

where,

i = the DOC elements, crew, insurance, depreciation, M/AF/L, M/AF/M, M/TJ/L, M/TJ/M, and M/RJ/M.

Specific fuel consumption, (sfc):

For Driver (sfc)

$$\frac{\dfrac{\Delta DOC_f}{DOC_f}}{\dfrac{\Delta (sfc)}{(sfc)}} = \frac{\left(\dfrac{W_{f_T}}{W_{GTO}} + \dfrac{W_{PL}}{W_{GTO}}\right) A' \, e^{A'(sfc)} \left(D \dfrac{W_{f_T}}{W_{GTO}} - 1\right) (sfc)}{\left(\dfrac{W_{f_T}}{W_{GTO}}\right)\left(\dfrac{W_{PL}}{W_{GTO}}\right)\left(K_{CL} - D \, e^{A'(sfc)}\right)}$$

where,

$$A' = \frac{R_T}{110 \; M \; (L/D)} \left(1 - 0.75 \, \frac{W_{f_{CL}}}{W_{f_T}}\right)$$

$$D = [1 - (K_D + K_R)]$$

For Driver (sfc)
$$\frac{\Delta DOC_i/DOC_i}{\Delta(sfc)/(sfc)} = \left[\frac{\dfrac{W_{f_T}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + \dfrac{W_{f_T}}{W_{GTO}}}\right] \times \left[\frac{\dfrac{\Delta DOC_f}{DOC_f}}{\dfrac{\Delta(sfc)}{(sfc)}}\right]$$

where,

i = the DOC elements crew, insurance, depreciation, M/AF/L, M/AF/M, M/TJ/L, M/TJ/M, M/RJ/L, M/RJ/M.

Output Data

The output data for this method module consist of the total DOC value for the HST aircraft and the Driver Partials which are proportional improvement in DOC which would result from proportional improvements in each driver parameter, (ΔDOC/DOC)/(ΔDriver/Driver).

Forward the following seven values to the Project Office, taken from the Work Sheet, Table 3-II.

TABLE 3-III.- OUTPUT DATA REQUIRED FROM MODULE 3

Baseline DOC (¢/Ton-Mile)		Driver Partials for Driver				
DOC_{BL}	DOC_f	$\frac{W_{AF}}{W_{GTO}}$	$(W/T)_{TJ}$	$\frac{W_{RJ}}{A_C C_{TRJ}}$	L/D	sfc

DEMONSTRATION

This section provides an illustration of how the procedures of this method module are to be applied.

Input Data

The "Input Data" requirements are taken from the output of the Demonstration section of Module 2 of this report, "Baseline HST Definition," (reference Table 2-VII). The input data values for the module are given in Table 3-IV.

Procedures

The first step in the procedure is the solution of the DOC equations. As these are solved the results are entered in Column (1) of the Work Sheet which is illustrated in Table 3-V. For example, the first DOC equation is:

$$DOC_{Fuel} = \frac{1460\ C_f\ (W_{f_T}/W_{GTO})(1-K_R)}{R_T\ (LF)\ (W_{PL}/W_{GTO})}$$

The solution of the DOC_{Fuel} equation gives a value of \$0.257 (or 25.7¢) per ton-mile direct operating cost for fuel. DOC_{Fuel} and the values derived from the other DOC equations are entered in Column (1) of the Work Sheet (reference Table 3-V) and summed, giving a DOC_{Total} of \$0.468 per ton-mile for operating the baseline HST aircraft.

Values for all parameters required for solution of the equations are either inputs to the method module (reference Table 3-IV) or an appropriate value is given with the equations in the Procedures section or in Appendix C.

The next step in the Method Module procedure is the solution of the Driver Equations to obtain the Driver Partials. These are solved in a manner similar to the DOC equations with values presented in the Procedures section for all required parameters which are not included in the Input Data, Table 3-IV.

For example, for the driver, W_{AF}/W_{GTO}, (airframe weight fraction) the initial Driver Equation is:

TABLE 3-IV.- INPUT DATA REQUIRED FOR MODULE 3 - DEMONSTRATION DATA (Reference Table 3-I)

Symbol	Value	Units
Driver Parameters		
L/D	4.6	
sfc	0.113 (1.12)	kg/Nhr $\left(\frac{lb_m}{lb_f\text{-}hr}\right)$
W_{AF}/W_{GTO}	0.4470	
$(W/T)_{TJ}$	0.1595	
$W_{RJ}/A_C C_{TRJ}$	758 (155.1)	kg/m^2 (lb/ft^2)
Other Aircraft Parameters		
A_C	7.73 (83.2)	m^2 (ft^2)
N_{TJ}	4	
N_{RJ}	9	
T_{TJ}	258 000 (58 000)	N (lb)
$(T/W)_{GTO}$	0.482	
W_{AV}/W_{GTO}	0.00665	
W_{GTO}	218 400 (481 400)	N (lb)
W_{f_T}/W_{GTO}	0.3178	
W_{PL}/W_{GTO}	0.1039	
W_{RJ}/W_{GTO}	0.0336	
W_{TJ}/W_{GTO}	0.0769	
Mission Parameters		
K_D	0.02	
K_R	0.1	
K_{CL}	0.4	
M	6	
R_T	7400 (4600)	km (statute miles)
t_F	2.0	hr
(V_B/V_{CR})	0.513	

TABLE 3-V.- WORK SHEET - DEMONSTRATION DATA (Reference Table 3-II)

	Baseline DOC Values - $ Per Ton-Mile	Driver Partials for Driver Parameters				
		$\frac{W_{AF}}{W_{GTO}}$	$(W/T)_{TJ}$	$\frac{W_{RJ}}{A_C/C_{TRJ}}$	L/D	sfc
	(1)	(2)	(3)	(4)	(5)	(6)
DOC_f	0.257	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-3.224	3.224
Driver Partial × DOC_f	------	0.774	0.177	0.080	-0.829	0.829
DOC_C	0.0102	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-2.429	2.429
Driver Partial × DOC_C	------	0.031	0.007	0.003	-0.025	0.025
DOC_I	0.0209	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-2.429	2.429
Driver Partial × DOC_I	------	0.063	0.014	0.007	-0.051	0.051
DOC_D	0.120	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-2.429	2.429
Driver Partial × DOC_D	------	0.361	0.083	0.038	-0.291	0.291
$DOC_{M/AF/L}$	0.00645	------	------	------	------	------
Driver Partial	------	3.61	0.689	0.313	-2.429	2.429
Driver Partial × $DOC_{M/AF/L}$	------	0.023	0.004	0.002	-0.016	0.016
$DOC_{M/AF/M}$	0.0147	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-2.429	2.429
Driver Partial × $DOC_{M/AF/M}$	------	0.044	0.010	0.005	-0.036	0.036
$DOC_{M/TJ/L}$	0.00169	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-2.429	2.429
Driver Partial × $DOC_{M/TJ/L}$	------	0.005	0.001	0.001	-0.004	0.004
$DOC_{M/TJ/M}$	0.00932	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-2.429	2.429
Driver Partial × $DOC_{M/TJ/M}$	------	0.028	0.006	0.003	-0.023	0.023
$DOC_{M/RJ/L}$	0.00380	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-2.430	2.429
Driver Partial × $DOC_{M/RJ/L}$	------	0.011	0.003	0.001	-0.009	0.009
$DOC_{M/RJ/M}$	0.0236	------	------	------	------	------
Driver Partial	------	3.01	0.689	0.313	-2.429	2.429
Driver Partial × $DOC_{M/RJ/M}$	------	0.071	0.016	0.007	-0.057	0.057
TOTAL						
DOC_{BL}	0.468	------	------	------	------	------
Σ(Driver Partial × DOC_i)	------	1.407	0.321	0.31	-1.207	1.207
Driver Partial (Total) (=(Σ Dr. Partial×DOC_i)/DOC_{BL})	------	3.006	0.70	0.30	-2.579	2.579

$$\frac{\Delta DOC_F/DOC_F}{\dfrac{\Delta W_{AF}/W_{GTO}}{W_{AF}/W_{GTO}}} = \frac{\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\dfrac{W_{AF}}{W_{GTO}}}$$

Note: The equation is linearized about the value $(\Delta W_{AF}/W_{GTO})(W_{AF}/W_{GTO}) = 0.1$, a 10% decrease in the driver, W_{AF}/W_{GTO}. (See Appendix 3-B, page 3-B-5.)

The solution to the initial driver equation gives a value of

$$\frac{\Delta DOC_F/DOC_F}{\dfrac{\Delta W_{AF}/W_{GTO}}{W_{AF}/W_{GTO}}} = 3.01,$$

which indicates, for example, that a 10% decrease in the Driver W_{AF}/W_{GTO} would yield a 30.1% decrease in ΔDOC_{Fuel}. The value of 3.01 for the Driver Partial is entered in Column (2) of the Work Sheet (Table 3-V) for DOC_{Fuel}. The other Driver Partials are entered in the Work Sheet in a similar manner. The Driver Partials are multiplied by the appropriate DOC values. The products are summed and entered at the bottom of the Work Sheet. The sums are then divided by DOC_{BL} to give the Driver Partial (total) for each Driver.

The results of the tabulation indicates that the airframe weight fraction W_{AF}/W_{GTO} is the most significant Driver, with a Driver Partial = 3.0. The Drivers sfc and L/D rank second and third with comparable values of -2.6 and 2.6, respectively.

As a matter of interest the baseline HST DOC values have been tabulated in Table 3-VI for comparison with costs for the larger subsonic jets (B747 class). The subsonic jet costs have been calculated on the basis of the ATA formulas using them precisely as given by ATA (reference 1) with the exception that labor pay rates were increased at the rate of 6% per year to bring them to 1972 dollar levels. The same range and load factor parameters were used for the subsonic jet calculations as for the HST calculations. The results give a DOC_T = 12.6¢ per ton-mile for the subsonic jets and compares favorably with current industry experience when account is made for comparable range and load factor parameters. Current (first nine months of 1972) B747 costs are 16.7¢ per ton-mile with an average load factor of 40% (reference 3). Recent industry B747 load factors have been depressed, however, and when adjusted to a 60% load factor used in the present study the current B747 costs are 11.1¢ per ton-mile. The B747 and large subsonic jet costs are below the current industry average which is now about 20¢ per ton-mile (reference 4).

TABLE 3-VI.- COMPARATIVE DIRECT OPERATING COST

DOC Element	Cents Per Ton-Mile			
	Large Subsonic Jet (B747 Class)		Baseline HST (Near Term Technology)	
Fuel - DOC_f	5.0		25.7	
Crew - DOC_C	1.5		1.0	
Insurance - DOC_I	0.7		2.1	
Depreciation - DOC_D	2.9	10.1	12.0	40.8
Maintenance - $DOC_{M/AF/L}$	0.6		0.6	
- $DOC_{M/AF/M}$	0.5		1.5	
- $DOC_{M/TJ/L}$	0.3		0.2	
- $DOC_{M/TJ/M}$	1.1		0.9	
- $DOC_{M/RJ/L}$	—		0.4	
- $DOC_{M/RJ/M}$	—		2.4	
Total Maintenance, DOC_M		2.5		6.0
TOTAL		12.6		46.8
Average Load Factor (Assumed)	60%		60%	

Output

The following seven figures (Table 3-VII) taken from the Work Sheet, Table 3-V, are to be forwarded to the Project Office, for use in Module 6.

TABLE 3-VII.- OUTPUT DATA REQUIRED FROM MODULE 3 - DEMONSTRATION DATA (Reference Table 3-III)

Baseline DOC (¢/Ton-Mile)		Driver Partials for Driver:				
DOC_{BL}	DOC_f	$\frac{W_{AF}}{W_{GTO}}$	$(W/T)_{TJ}$	$\frac{W_{RJ}}{A_C C_{TRJ}}$	L/D	sfc
46.8	25.7	3.0	0.7	0.3	-2.6	2.6

SENSITIVITY DATA

The purpose of the sensitivity analysis is to determine the sensitivity of the Driver Partials to variations in the selection of values for the fixed operational constants and cost factors in the DOC equations. The parameters of concern are as follows:

U	Aircraft utilization, block hours per years
LF	Load factor
C_f	Cost of fuel per unit weight
C_{HST}	Acquisition cost of the HST aircraft
C_{TJ}	Acquisition cost of the turbojet engine
C_{RJ}	Acquisition cost of the ramjet engine
K_{LTJ}	Turbojet maintenance labor ratio
K_{MTJ}	Turbojet maintenance material ratio
K_{LRJ}	Ramjet maintenance labor ratio
K_{MRJ}	Ramjet maintenance material ratio
K_R	Reserve fuel ratio
K_{CL}	Climb fuel ratio

The climb fuel ratio, K_{CL}, is different from the other parameters above in that it is defined by the baseline definition of the aircraft and its mission. Its value is therefore an input to this module from the Baseline HST Definition module, No. 2. It is included among the above parameters, however, because its value is relatively large (40% for the present baseline) and it therefore has a significant effect on ΔDOC. It is also subject to uncertainties which are beyond the control of the designer. For example, a change in the maximum allowable ground overpressure could change the allowable climb trajectory and hence the climb fuel ratio. The reserve fuel ratio, K_R, is also provided by the Baseline HST Definition module because it is a part of the total fuel, W_{f_T}, defined there. However, it is also subject to factors beyond the control of the designer, such as government safety regulations.

In order to show the sensitivity of the Driver Partials to variations in the parameters, discussed above, the driver partials have been recalculated based on the revisions in the parameters shown in Table 3-VIII. The driver partials taken from the Demonstration section above are shown in the top line of the table.

The results of the analysis show no significant change in any of the driver partials with the exception of those for revisions in the reserve fuel ratio and the climb fuel ratio. In these cases, although the magnitude of the driver partial changes, the rank order of the driver partials among the driver parameters does not appreciably change; i.e., the relative importance of the drivers remains approximately the same.

The conclusion which is made from the sensitivity analysis is that although reasonable care should be used in determining input values for the sensitivity parameters, relatively large variations in the values selected will not appreciable affect the outputs of the study.

The influence of the sensitivity parameters on the driver partials can be seen from an examination of the individual driver equations. In nearly all cases except for K_{CL} and K_R, the parameters of concern do not appear in the driver equations. This is because the parameters are multipliers or dividers of the entire DOC equations and therefore affect ΔDOC in the same proportion as they affect DOC.

TABLE 3-VIII.- SENSITIVITY OF THE DRIVER PARTIALS TO REVISIONS IN COST AND OPERATIONAL PARAMETERS

	Revision in Parameter, %	Driver Partial for Driver				
		W_{AF}/W_{GTO}	$(W/T)_{TJ}$	$\frac{W_{RJ}}{A_C C_{TRJ}}$	L/D	sfc
Baseline driver partials		3.0	0.7	0.3	-2.6	2.6
Revised parameters:						
Utilization	30	3.0	0.7	0.3	-2.6	2.6
Load factor	30	3.0	0.7	0.3	-2.6	2.6
Price of fuel	50	3.0	0.7	0.3	-2.6	2.7
Cost of aircraft	50	3.0	0.7	0.3	-2.5	2.6
Cost of turbojets	50	3.0	0.7	0.3	-2.6	2.6
Cost of scramjets	50	3.0	0.7	0.3	-2.6	2.6
Maintenance ratios:						
KLTJ	50	3.0	0.7	0.3	-2.6	2.6
KMTJ	50	3.0	0.7	0.3	-2.6	2.6
KLRJ	50	3.0	0.7	0.3	-2.6	2.6
KMRJ	50	3.0	0.7	0.3	-2.6	2.6
Reserve fuel ratio	50	3.5	0.8	0.4	-3.2	3.2
Climb fuel ratio	-33	2.6	0.5	0.2	-1.8	2.0

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1. Anon: Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes, published by the Air Transport Association of America, December 1967.

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7. Wilcox, D.E., Smith, C.L., Totlen, H.C., and Hallett, N.C.: Future Cost of Liquid Hydrogen for Use as an Aircraft Fuel, NASA, Ames Research Center, and Air Products and Chemicals, Inc., published in Aviation and Space Progress and Prospects, American Society of Mechanical Engineering, June 1968.

APPENDIX 3-A

DERIVATION OF DOC FORMULAS

The DOC formulas are based on the formulas developed by the Air Transport Association of America (ATA), entitled Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Planes (reference 1). The ATA method was first developed in 1944 and has been revised and updated every few years with the last revision in December 1967.

The last revision covers turboprop and turbojet subsonic aircraft and supersonic aircraft of the SST class. A large number of studies of direct operating costs were made by the aircraft industry during the period of the SST proposal period (e.g., reference 6) and the December 1967 revision of the ATA formulas benefited from these other studies. In the present analysis the ATA formula for the subsonic and supersonic aircraft have been examined and extrapolations have been made or factors introduced when required to extend the supersonic aircraft formulas to the HST case. The quantity of fuel to be used by the HST has been developed separately with direct application to the HST aircraft configuration.

The ATA formulas are based on commercial airlines' costs and experience. Certain special terms and practice reflected in the formulas are described below. Miles are expressed in statute miles. The term "block time" or "block hours" corresponds to the time from initial aircraft movement prior to taxi and take-off (removal of the wheel "blocks") until the engines are shut down after landing (replacement of the wheel "blocks"). Block hours, therefore, correspond roughly to the time from engines on to engines off.

The ATA procedure gives a time of 0.25 hours for preflight and postflight taxi time to be added to flight time t_F to make block time t_B, and

$$\text{Block Velocity, } V_B = \frac{R_T}{t_B}$$

where,

R_T = operational range

The term, V_B/V_{CR}, which is equal to the ratio of block velocity to cruise velocity, is sometimes used in the equations to convert cruise velocity or Mach number to block velocity where required.

The ATA formulas are developed using English units of measure. The extrapolations below are therefore made in English units and are then converted to SI units.

The ATA formula gives costs in terms of cost per air mile. The costs are initially presented in terms of cost per block hour for crew, cost per year for insurance and depreciation, and cost per flight and cost per flight hour for maintenance. The above measures are then converted to cost per air mile by dividing by miles per block hour, miles per year, miles per flight and miles per flight hour, respectively.

The derivation below starts with the initial ATA terms and makes the conversion to cost per ton mile as follows:

$$\text{Cost per ton mile} = \frac{\text{cost/block hour}}{\text{tons}\left(\frac{\text{miles}}{\text{hour}}\right)} = \frac{\text{cost/block hour}}{(LF)\left(\frac{W_{PL}}{2000}\right) 680\ M(V_B/V_{CR})}$$

where,

$\frac{W_{PL}}{2000}$	=	payload in tons
(LF)	=	load factor, ratio of the average payload carried to normal full payload
M	=	cruise Mach number
(V_B/V_{CR})	=	ratio of block velocity to cruise velocity
$680\ M(V_B/V_{CR})$	=	block velocity

$$\text{Cost per ton-mile} = \frac{\text{annual cost}}{\text{tons}\left(\frac{\text{miles}}{\text{hour}}\right)\left(\frac{\text{hours}}{\text{year}}\right)} = \frac{\text{annual cost}}{(LF)\left(\frac{W_{PL}}{2000}\right) 680\ M(V_B/V_{CR})\ U}$$

where,

U = aircraft utilization in block hours per year.

$$\text{Cost per ton-mile} = \frac{\text{cost per flight}}{\text{ton-miles}} = \frac{\text{cost per flight}}{(LF)\left(\frac{W_{PL}}{2000}\right) R_T}$$

where,

R_T = operational range, statute miles.

Fuel Cost

The cost of fuel per flight is expressed simply by the ATA as the unit cost of fuel times the quantity used. With an allowance for reserve fuel dividing by the term for ton-miles from above, this becomes

$$DOC_f = \frac{C_f\ W_{f_T}\ (1-K_R)}{(LF)(W_{PL}/2000)\ R_T}$$

where,

C_f = cost of fuel per unit weight

W_{f_T} = total fuel

K_R = reserve fuel fraction

Dividing the numerator and denominator by W_{GTO} (gross take-off weight) to normalize the fuel and payload terms and converting to SI units this becomes:

$$DOC_f = \frac{1460\ C_f\ W_{f_T}/W_{GTO}\ (1-K_R)}{(LF)\,(W_{PL}/W_{GTO})\ R_T}$$

(For English Units, replace 1460 by 2000).

It should be noted that the Drivers L/D and sfc are contained in the term W_{f_T}/W_{GTO}. All other Drivers are contained in the term W_{PL}/W_{GTO}. (See subsection Driver Definitions.)

Crew Cost

Crew costs include crew salary, fringe benefits, training programs and travel expense. The large subsonic jets have a crew of three which was planned for the SST and is the assumed number for the HST. Stewardess' costs associated with passenger airlines are classified as a "Passenger Service Cost" which is an indirect operating cost under the CAB classification and are therefore not included in DOC.

The ATA formula for crew cost for a crew of three is:

$$\$/\text{block hr} = (0.05\ \frac{W_{GTO}}{1000} + K_C)$$

where,

W_{GTO} = gross take-off weight

K_C = 118 for turboprops

155 for turbojets

200 for SST

For 450 000 lb gross take-off weight aircraft, the formula yields the following \$/block hour for 1967 cost levels. The conversion to 1972 levels is made by applying a 6% annual increase for five years.

\$/Block hr:	1967	1972
Turboprop	141	190
Turbojet	178	240
SST	223	300
Extrapolated to HST		(320)

The extrapolation made here to the HST assumes a 33% increase over the turbojet level. These costs compare with current (first nine months of 1972) crew costs for the B747 which are approximately \$275 per block hour (reference 3).

For the HST then

$$DOC_{Crew} = \frac{320}{0.34\ (LF)\ W_{PL}\ M(V_B/V_{CR})}$$

The denominator converts the expression to \$/ton-mile as described above.

In SI units this becomes,

$$\boxed{DOC_{Crew} = \frac{320}{0.725\ (LF)\ W_{PL}\ M(V_B/V_{CR})}}$$

(For English Units, replace 0.725 with 0.34).

Insurance Cost

Insurance cost covers insurance of the aircraft itself and is calculated simply as an annual rate times the acquisition cost of the aircraft.

The ATA formula is:

$$\text{Annual insurance cost} = (IR)(C_{HST})$$

where,

IR = the annual insurance rate

C_{HST} = cost of the aircraft

For the HST then, in SI units,

$$DOC_{Insurance} = \frac{(IR)(C_{HST}/W_{GTO})}{0.725\,(LF)(W_{PL}/W_{GTO})\,M(V_B/V_{CR})\,U}$$

(For English Units replace the coefficient 0.725 by 0.340).

Depreciation Cost

Depreciation cost is an expense provided to recover the original cost of the aircraft, plus the initial stock of spare parts, over an assigned depreciation life of the aircraft. (Subsequent purchase of spares to replace spares used from the initial stock are a maintenance expense.) The ATA formula includes 10% of the aircraft cost less engines and 40% of the engine costs for the initial spares stock.

The ATA gives:

$$\text{Annual depreciation cost} = \frac{C_a + 0.1\,(C_a - C_e) + 0.4\,C_e}{L_d}$$

where,

C_a = cost of the aircraft

C_e = cost of the engines

L_d = the assigned depreciation life

For the HST, this converts to the following DOC in SI units,

$$DOC_{Depreciation} = \frac{1.1(C_{HST}/W_{GTO}) + 0.3\,(C_{TJ}/W_{GTO} + C_{RJ}/W_{GTO})}{0.725\ (LF)(W_{PL}/W_{GTO})\ M(V_B/V_{CR})\ U(L_d)}$$

where,

C_{TJ} = cost of the turbojet engines

C_{RJ} = cost of the ramjet engines

(For English Units replace the coefficient .725 by 0.340).

Maintenance Cost

The maintenance formulas are based on cost estimating relationships developed from industry data on airline maintenance costs. In the case of the airframe and subsystems, other than engines, the ATA expressions include velocity, weight, and cost terms which make them applicable to both subsonic and supersonic planes of the SST class. These equations have been considered applicable for the extrapolation to the HST case. The ATA formula has been simplified where it was determined that the simplification could be introduced without significantly changing the maintenance estimates.

In the case of engines, the ATA introduced larger coefficients in the estimating relationships for the supersonic (SST) engines than for the subsonic engines. This in effect amounted to the equivalent of estimating maintenance costs for supersonic turbojet (SST) engines by taking a ratio to the costs for subsonic turbojets of comparable size. The value of this ratio for SST supersonic turbojets to subsonic turbojets from the ATA cost relationships is equivalent to approximately 1.7 to 1.

Using this approach, four coefficients have been introduced into the equations for estimating HST maintenance costs of both the HST turbojet engines and the ramjet engines.

K_{LTJ} turbojet maintenance labor - ratio, HST turbojets to present subsonic turbojets, per flight hour

K_{MTJ} turbojet maintenance material - ratio, HST turbojets to present subsonic turbojets, per flight hour

K_{LRJ} ramjet maintenance labor - ratio, HST ramjets to present subsonic turbojets, per flight hour

K_{MRJ} ramjet maintenance material - ratio, HST ramjets to present subsonic turbojets, per flight hour

In all cases the above factors represent ratios of maintenance costs for the HST engines to present state-of-the-art subsonic turbojet engines of equivalent size and thrust. The JT9 in the B747 or the RB211 in the L1011 are representative of this class.

The above factors do not reflect increased price of engine parts (spares) because the maintenance materials estimating relationships include an engine acquisition cost term to reflect higher purchase price of spares. The Sensitivity analysis section indicated that the maintenance ratios are not critical items in the overall analysis.

The ATA formulas divide maintenance costs into four categories, separating the engines and the remainder of the aircraft and separating each of these into labor and materials. In each category, the ATA introduces terms reflecting maintenance actions related to flight cycles and maintenance actions related to flight hours. The former covers items such as the landing gear which is used once each flight or inspections which occur on a per-flight basis. The latter covers wear and tear and periodic maintenance actions which occur on a per-flight-hour basis.

<u>Airplane maintenance labor excluding engines, M/AF/L</u>.- The ATA gives the following:

$$\frac{MMH}{\text{Flight Cycle}} = \left[0.05\ \frac{W_{AF} + W_{AV}}{1000} + 6 - \frac{630}{\frac{W_{AF} + W_{AV}}{1000} + 120}\right] M^{1/2}$$

$$\frac{MMH}{\text{Flight Hour}} = \left[0.59 \left(\frac{MMH}{\text{Flight Cycle}}\right)\right]$$

where,

MMH = maintenance manhours

W_{AF} = weight of airframe

W_{AV} = weight of avionics

Then,

$$\frac{\$\ \text{Cost}}{\text{Flight}} = \left[(1+0.59\ t_F)\left(0.05\ \frac{W_{AF} + W_{AV}}{1000} + 6 - \frac{630}{\frac{W_{AF} + W_{AV}}{1000} + 120}\right)\right] M^{1/2}\ r_L$$

where,

t_F = time of flight, hours

r_L = average labor rate per hour for all personnel involved in maintenance

M = cruise Mach number

M is set equal to 1 for subsonic planes. The ATA (reference 1) considers that this expression is applicable to both subsonic planes and to the SST. It appears to be a reasonable extension to apply it to the HST where the term $M = 6$ yields maintenance costs of about 2.4 to 1 over subsonic planes.

Introducing appropriate terms for ton-miles, and dividing the numerator and denominator by W_{GTO}, this becomes,denominator by W_{GTO}, this becomes,

$$\$/\text{ton-mile} = \frac{(1+0.59t_F)\left(0.05\,\dfrac{W_{AF}+W_{AV}}{10^3 W_{GTO}} + \dfrac{6}{W_{GTO}} - \dfrac{630}{\left(\dfrac{W_{AF}+W_{AV}}{10^3} + 120\right) W_{GTO}}\right) M^{\frac{1}{2}} r_L}{\dfrac{R\ (LF)}{2000}\left(\dfrac{W_{PL}}{W_{GTO}}\right)}$$

where,

W_{AF} = airframe and subsystems weight excluding engines

W_{AV} = avionics weight

The baseline value of the term,

$$\left(\frac{6}{W_{GTO}} - \frac{630}{\left(\dfrac{W_{AF}+W_{AV}}{10^3} + 120\right) W_{GTO}}\right) = 0.009/10^3$$

is substituted for simplicity.

Then multiplying by 1.609 to convert R_T to SI units.

$$DOC_{M/AF/L} = \frac{(3.22+1.93\ t_F)\left[0.05\left(\dfrac{W_{AF}}{W_{GTO}} + \dfrac{W_{AV}}{W_{GTO}}\right) + 0.009\right] M^{\frac{1}{2}}\ r_L}{(LF)\,(W_{PL}/W_{GTO})\ R_T}$$

(For English Units replace the coefficients 3.22 and 1.93 by 2 and 1.2, respectively).

Airplane maintenance materials excluding engines. - The ATA formula gives the following applicable to both subsonic and supersonic aircraft,

$$\text{Cost per flight hour} = C_{FH} = 3.08\ (C_A - C_{ENG})/10^6$$

$$\text{Cost per flight cycle} = C_{FC} = 6.24\ (C_A - C_{ENG})/10^6$$

where,

C_A = cost of the aircraft

C_{ENG} = cost of the engines

Then,

$$\frac{\text{Material cost}}{\text{Flight}} = (3.08\ t_F + 6.24)\ (C_A - C_{ENG})/10^6$$

Substituting HST symbols, dividing by terms for ton-miles per flight, dividing numerator and denominator by W_{GTO}, and converting to SI units, this becomes

$$DOC_{M/AF/M} = \frac{(4.52\ t_F + 9.04)\left(\frac{C_{HST}}{W_{GTO}} - \frac{C_{TJ}}{W_{GTO}} - \frac{C_{RJ}}{W_{GTO}}\right)}{(LF)(W_{PL}/W_{GTO})\ R_T \times 10^3}$$

(For English Units replace the coefficients 4.52 and 9.04 by 6.2 and 12.4, respectively).

Turbojet engines maintenance labor.- The ATA formula gives:

$$\frac{\text{MMH}}{\text{Flight Cycle}} = (0.3 + 0.03\ T_{TJ}/10^3)\ N_{TJ}$$

$$\frac{\text{MMH}}{\text{Flight Hour}} = (0.6 + 0.027\ T_{TJ}/10^3)\ N_{TJ}$$

where,

T_{TJ} = thrust of each engine

N_{TJ} = number of engines

For large turbojet engines as in the baseline HST, there is less than 10% difference in the above two terms. Therefore, for simplification, they are combined in the following expression with time of flight, t_F,

$$\frac{\text{MMH}}{\text{Per Flight}} = \frac{\text{MMH}}{\text{Flt Cycle}} + \left(\frac{\text{MMH}}{\text{Flt Hr}} \times t_F\right)$$

$$\approx (1 + t_F)(0.6 + 0.027\ T_{TJ}/10^3)\ N_{TJ}$$

Introducing r_L, cost per manhours of labor, terms for ton-miles, and converting to SI units, this becomes,

$$\text{Cost/ton-mile} = \frac{(1+t_F)(0.6+0.027\ T_{TJ}/10^3)\ N_{TJ}\ r_L\ 2000}{(LF)\ W_{PL}\ R_T}$$

$$= \frac{\dfrac{T_{TJ}\ N_{TJ}}{10^3 W_{GTO}}\ (1 + t_F)\left(\dfrac{0.6}{T_{TJ}/10^3} + 0.027\right) r_L\ 2000}{(LF)\left(\dfrac{W_{PL}}{W_{GTO}}\right) R_T},$$

For application to the turbojet engines in the HST, the maintenance ratio K_{LTJ} is introduced, and 0.3 t_F is substituded for t_F to reflect the approximate time of operation of the turbo jets during the HST flight. Then, in SI units.

$$DOC_{M/TJ/L} = \frac{(T/W)_{GTO}\ (1+0.3\ t_F)\left(\frac{8.6}{T_{TJ}/10^3} + 0.087\right)\ r_L\ K_{LTJ}}{(LF)(W_{PL}/W_{GTO})\ R_T}$$

where,

$(T/W)_{GTO}$ = gross thrust to weight at take-off

K_{LTJ} = turbojet maintenance labor - ratio, HST turbojets to present subsonic turbojets per flight hour.

(For English Units replace the coefficients 8.6 and 0.087 by 1.2 and 0.054, respectively).

Turbojet engines maintenance materials.- The ATA formula gives:

$$\frac{\text{Cost}}{\text{Flight Cycle}} = 2.5\ C_{TJ}/10^5$$

$$\frac{\text{Cost}}{\text{Flight Hour}} = 2.0\ C_{TJ}/10^5$$

Combining these terms and introducing the terms for flight hours, t_F, and the terms for ton-miles, this becomes

$$\text{Cost/ton-mile} = \frac{2.5\ C_{TJ}/10^5\ t_F + 2.0\ C_{TJ}/10^5}{(LF)\left(\frac{W_{PL}}{2000}\right)\ R_T}$$

For application to the turbojet engines in the HST, the maintenance ratio K_{MTJ} is introduced and 0.3 t_F is substituted for t_F to reflect the approximate operating time of the turbojets during the HST flight. Then in SI units,

$$DOC_{M/TJ/M} = \frac{\frac{C_{TJ}}{W_{GTO}} (0.011\ t_F + 0.029)\ K_{MTJ}}{(LF)(W_{PL}/W_{GTO})\ R_T}$$

where,

K_{MTJ} = turbojet maintenance materials, ratio of HST turbojets to present subsonic turbojets per flight hour

(For English Units replace the coefficients .011 and .029 by 0.015 and 0.04, respectively).

Ramjet engines maintenance labor.- Scramjet maintenance labor is estimated in a manner similar to that for the HST turbojets by introducing ratios for ramjet maintenance to subsonic turbojet maintenance into the ATA expressions for subsonic turbojet maintenance. Given the HST turbojet maintenance labor formula as derived above (English units),

$$DOC_{M/TJ/L} = \frac{(T/W)_{GTO}\ (1+0.3\ t_F) \left(\frac{1.2}{T_{TJ}/10^3} + 0.054\right)\ r_L\ K_{LTJ}}{(LF)(W_{PL}/W_{GTO})\ R_T}$$

For application to the ramjet engine, the term $(T/W)_{GTO}$, gross thrust to weight ratio at take-off, is replaced by the reciprocal of L/D. The turbojet thrust term, T_{TJ}, is replaced by term $W_{GTO}/(L/D)$. This term is then divided by N_{RJ}, the number of ramjet modules, to make it equivalent to the turbojet thrust term which is applicable to each engine or module. The factor 0.3, which was introduced in the HST turbojet equation to reflect the use of the turbojets only during climb and descent, is eliminated, and finally the maintenance ratio K_{LTJ} is replaced by an equivalent term for the ramjets, K_{LRJ}. Then, in SI units,

$$DOC_{M/RJ/L} = \frac{(1 + t_F)\left(\frac{0.876\ N_{RJ}(L/D)}{W_{GTO}/10^3} + 0.087\right) r_L\ K_{LRJ}}{(L/D)\ (LF)\ (W_{PL}/W_{GTO})\ R_T}$$

where,

L/D = lift-to-drag ratio

N_{RJ} = number of ramjet modules per aircraft

K_{LRJ} = ramjet maintenance labor, ratio of HST ramjets to present subsonic turbojets per flight hour

(For English Units replace the coefficients 8.6 and 0.949 by 1.2 and 0.054, respectively).

Ramjet engines maintenance materials.- In a manner similar to that for ramjet maintenance labor above, starting with the HST turbojet maintenance materials formula as derived above (English units),

$$DOC_{M/TJ/M} = \frac{\frac{C_{TJ}}{W_{GTO}}\left(0.05\ (0.3\ t_F) + 0.04\right)\ K_{MTJ}}{(LF)\ (W_{PL}/W_{GTO})\ R_T}$$

Substituting t_F for $0.3\ t_F$ and K_{MRJ} for K_{MTJ} and other ramjet terms for turbojet terms, this becomes, in SI units,

$$DOC_{M/RJ/M} = \frac{\frac{C_{RJ}}{W_{GTO}}\ (0.036\ t_F + 0.029)\ K_{MRJ}}{(LF)\ (W_{PL}/W_{GTO})\ R_T}$$

$$\frac{\Delta\, DOC_f}{DOC_f} = \frac{1 - \left(\frac{W_e}{W_{GTO}}\right)}{(L/D)\,\frac{W_{f_T}}{W_{GTO}}\,\frac{W_{PL}}{W_{GTO}}}\; Ae^{A/(L/D)} \frac{\left(1 - D\,\frac{W_{f_T}}{W_{GTO}}\right)}{\left(B - De^{A/(L/D)}\right)}\,\frac{\Delta\, L/D}{L/D}$$

Finally,

$$\frac{\frac{\Delta DOC_f}{DOC_f}}{\frac{\Delta\, L/D}{L/D}} = \frac{\left(\frac{W_{f_T}}{W_{GTO}} + \frac{W_{PL}}{W_{GTO}}\right)}{(L/D)\left(\frac{W_{f_T}}{W_{GTO}}\right)\left(\frac{W_{PL}}{W_{GTO}}\right)}\; Ae^{A/(L/D)}\;\frac{\left(1 - D\,\frac{W_{f_T}}{W_{GTO}}\right)}{\left(B - De^{A/(L/D)}\right)}$$

for the driver, L/D.

Ramjet engines maintenance labor.- The equation given earlier for $DOC_{M/RJ/L}$ is:

$$DOC_{M/RJ/L} = \frac{(1 + t_F)\left[\frac{0.876\, N_{RJ}\,(L/D)}{W_{GTO}/10^3} + 0.087\right] r_L\, K_{LRJ}}{(L/D)\;(LF)\left(\frac{W_{PL}}{W_{GTO}}\right) R_T}$$

This can be rewritten as:

$$DOC_{M/RJ/L} = \frac{E\;(L/D) + F}{G\;(L/D\;(L/F)\;\left(1 - \frac{W^*}{W_{GTO}} - \frac{W_{f_T}}{W_{GTO}}\right)}$$

APPENDIX 3-B

DERIVATION OF DRIVER PARTIALS

This appendix details the derivation of the driver partials, ΔDOC/DOC/ΔDRIVER/DRIVER which are presented in the Procedures section.

In the development of the driver equations, it is assumed that the acquisition cost of the HST is not decreased by improvements in the technology. In other words, an improvement in engine performance (e.g., ΔC_{TRJ}) would result in a smaller, but not necessarily a cheaper engine. It would, however, indirectly decrease DOC due to weight reductions which translate into increased payload fractions.

Each of the five driver parameters and their effects on all elements of DOC will be treated in turn.

Airframe Weight Fraction, W_{AF}/W_{GTO}

Fuel cost.- The basic equation for DOC_f is:

$$DOC_f = \frac{1460\, C_f \, (W_{f_T}/W_{GTO})}{(LF)\,(W_{PL}/W_{GTO})\, R_T} \quad \$/\text{Ton-Mile}$$

where,

$$W_{f_T}/W_{GTO} = \frac{1 - \exp\left\{\frac{9}{1000}\,\frac{(R)(sfc)}{(L/D)\ M}\,(1-0.75\ W_{f_{CL}}/W_{f_T})\right\}}{W_{f_{CL}}/W_{f_T} - [1-(K_D+K_R)]\exp\left\{\frac{9}{1000}\,\frac{(R)(sfc)}{(L/D)\ M}\left[1-0.75\left(\frac{W_{f_{CL}}}{W_{f_T}}\right)\right]\right\}}$$

(See Appendix 3-D for derivation of W_{f_T}/W_{GTO}.)

and,

$$W_{PL}/W_{GTO} = 1 - \frac{W_{f_T}}{W_{GTO}} - (W/T)_{TJ}(T/W)_{GTO} - \left(\frac{W_{RJ}/A_C}{C_{TRJ}}\right)\frac{C_L}{(L/D)(W/S)_{GTO}} - \left(\frac{W_{AF}}{W_{GTO}}\right) - \left(\frac{W_{AV}}{W_{GTO}}\right)$$

$$(W/T)_{TJ}(T/W)_{GTO} = \frac{W_{TJ}}{W_{GTO}}$$

$$(W_{RJ}/A_C C_{TRJ}) \times C_D/(W/S)_{GTO} = \frac{W_{RJ}}{W_{GTO}}$$

Note that,

$(W/T)_{TJ}$ is the driver, turbojet specific weight

$(W_{RJ}/A_C C_{TRJ})$ is the driver, ramjet sizing parameter

$$\text{Let } W_{PL}/W_{GTO} = 1 - \frac{W_{f_T}}{W_{GTO}} - W_e/W_{GTO}$$

The empty weight fraction, W_e/W_{GTO}, may be written as:

$$W_e/W_{GTO} = W_{AF}/W_{GTO} + W_{TJ}/W_{GTO} + W_{RJ}/W_{GTO} + W_{AV}/W_{GTO}$$

or more simply,

$$W_e/W_{GTO} = W_{AF}/W_{GTO} + W^*/W_{GTO}$$

where,

$$\frac{W^*}{W_{GTO}} = \frac{W_{TJ}}{W_{GTO}} + \frac{W_{RJ}}{W_{GTO}} + \frac{W_{AV}}{W_{GTO}}$$

In the above equations, it is assumed that improved technology which would result in lower airframe weights would lower the DOC_f by allowing the HST to carry a higher payload over a constant range. It is further assumed that payload and airframe weight are interchangeable so that a decrease of 1 kg (1b) of airframe weight results in an increase of 1 kg (lb) in payload. Under these assumptions, a simple expression for the change in DOC_f caused by a modest change in airframe weight may be written. First, the basic equation is simplified to

$$DOC_f = \frac{B}{C - W_{AF}/W_{GTO}}$$

where,

$$B = \frac{1460\ C_f}{R_T(LF)} \quad W_{f_T}/W_{GTO} \qquad (1-K_R)$$

$$C = 1 - \frac{W_{f_T}}{W_{GTO}} - \frac{W^*}{W_{GTO}}$$

All the terms in B and C are unaffected by changes in airframe weight by our basic assumptions. Now, to find the requisite expression for ΔDOC_f, we note that:

$$\Delta DOC_f = \frac{B}{C - \left(\frac{W_{AF}}{W_{GTO}} + \Delta \frac{W_{AF}}{W_{GTO}}\right)} - \frac{B}{C - \left(\frac{W_{AF}}{W_{GTO}}\right)}$$

$$\Delta DOC_f = B \left[\frac{C - \left(\frac{W_{AF}}{W_{GTO}}\right) - C + \left(\frac{W_{AF}}{W_{GTO}}\right) + \Delta \frac{W_{AF}}{W_{GTO}}}{\left\{C - \left(\frac{W_{AF}}{W_{GTO}}\right)\right\} \left\{C - \left(\frac{W_{AF}}{W_{GTO}} + \Delta \frac{W_{AF}}{W_{GTO}}\right)\right\}} \right]$$

$$\Delta DOC_f = \frac{B \, \Delta \frac{W_{AF}}{W_{GTO}}}{\left[C - \left(\frac{W_{AF}}{W_{GTO}}\right)\right]\left[C - \left(\frac{W_{AF}}{W_{GTO}}\right)\left\{1 + \frac{\Delta \frac{W_{AF}}{W_{GTO}}}{\left(\frac{W_{AF}}{W_{GTO}}\right)}\right\}\right]}$$

Now since

$$\frac{B}{C - \frac{W_{AF}}{W_{GTO}}} = DOC_f$$

we have

$$\frac{\Delta \, DOC_f}{DOC_f} = \frac{\frac{\Delta\left(\frac{W_{AF}}{W_{GTO}}\right)}{\left(\frac{W_{AF}}{W_{GTO}}\right)}\left(\frac{W_{AF}}{W_{GTO}}\right)}{C - \left(\frac{W_{AF}}{W_{GTO}}\right)\left[1 + \frac{\Delta \frac{W_{AF}}{W_{GTO}}}{\left(\frac{W_{AF}}{W_{GTO}}\right)}\right]}$$

Since

$$C - \frac{W_{AF}}{W_{GTO}} = \frac{W_{PL}}{W_{GTO}}$$

and letting,

$$\frac{\Delta \frac{W_{AF}}{W_{GTO}}}{\left(\frac{W_{AF}}{W_{GTO}}\right)} = P,$$

we have,

$$\frac{\Delta DOC_f}{DOC_f} = \frac{P \frac{W_{AF}}{W_{GTO}}}{\frac{W_{PL}}{W_{GTO}} - P \frac{W_{AF}}{W_{GTO}}}$$

The factor P in this equation is the proportional change in the Driver Parameter, W_{AF}/W_{GTO}, from the baseline value. If this change is of the order of -5 to -20%, a good approximation can be obtained by using P = -0.1 in the equation. The final form then is:

$$\frac{\left(\frac{\Delta DOC_f}{DOC_f}\right)}{\frac{\Delta\left(\frac{W_{AF}}{W_{GTO}}\right)}{\left(\frac{W_{AF}}{W_{GTO}}\right)}} = \frac{\frac{W_{AF}}{W_{GTO}}}{\frac{W_{PL}}{W_{GTO}} + 0.1 \frac{W_{AF}}{W_{GTO}}}$$

for the driver W_{AF}/W_{GTO}

Depreciation cost.- The equation for DOC_D given earlier in this method module is:

$$DOC_D = \frac{1.1\ C_{HST}/W_{GTO} + 0.3 \left(\frac{C_{TJ} + C_{RJ}}{W_{GTO}}\right)}{0.725\ (LF)\ M(V_B/V_{CR})\ U(W_{PL}/W_{GTO})\ L_d}$$

The only term affected by changes in W_{AF}/W_{GTO} is the payload term. The equation can thus be rewritten as:

$$DOC_D = \frac{\text{Constant}}{1 - \frac{W_{f_T}}{W_{GTO}} - \frac{W^*}{W_{GTO}} - \frac{W_{AF}}{W_{GTO}}}$$

This is the same form as was found for the expression for DOC_f. Therefore, by similarity with the previous derivation, for the driver W_{AF}/W_{GTO}

$$\frac{\dfrac{\Delta DOC_D}{DOC_D}}{\dfrac{\Delta\left(\dfrac{W_{AF}}{W_{GTO}}\right)}{\left(\dfrac{W_{AF}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{AF}}{W_{GTO}}}$$

Insurance cost.- The equation used for insurance costs is:

$$DOC_{Ins} = \frac{(IR)\ (C_{HST}/W_{GTO})}{0.725\ (LF)\ (V_B/V_{CR})\ (M)\ (U)\ (W_{PL}/W_{GTO})}$$

Again, the only term affected by changes in the airframe weight is the payload term, so we have:

$$\frac{\dfrac{\Delta DOC_{Ins}}{DOC_{Ins}}}{\dfrac{\Delta\left(\dfrac{W_{AF}}{W_{GTO}}\right)}{\left(\dfrac{W_{AF}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{AF}}{W_{GTO}}}$$

for the driver, W_{AF}/W_{GTO}.

Crew cost.- The equation used for crew costs:

$$DOC_{Crew} = \frac{320/W_{GTO}}{0.725\ M(V_B/V_{CR})\ (LF)\ \left(W_{PL}/W_{GTO}\right)}$$

Again, by similarity with the above cases,

$$\frac{\dfrac{\Delta DOC_{Crew}}{DOC_{Crew}}}{\dfrac{\Delta\left(\dfrac{W_{AF}}{W_{GTO}}\right)}{\left(\dfrac{W_{AF}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\ \dfrac{W_{AF}}{W_{GTO}}}$$

for the driver, W_{AF}/W_{GTO}.

Airplane maintenance labor excluding engines, M/AF/L.-

$$DOC_{M/AF/L} = \frac{(3.22+1.93\ t_F)(0.05\ W_{AF}/W_{GTO}+0.05\ \dfrac{W_{AV}}{W_{GTO}} + 0.009)\ M^{\frac{1}{2}}\ r_L}{(LF)\ (R_T)\ W_{PL}/W_{GTO}}$$

This can be rewritten as:

$$DOC_{M/AF/L} = \frac{A\left[W_{AF}/W_{GTO}\right] + B}{\left(1 - W_{f_T}/W_{GTO} - \dfrac{W^*}{W_{GTO}} - W_{AF}/W_{GTO}\right)} = \frac{A\ W_{AF}/W_{GTO} + B}{C - W_{AF}/W_{GTO}}$$

where,

$$(1 - W_{f_T}/W_{GTO} - W^*/W_{GTO} - W_{AF}/W_{GTO}) = W_{PL}/W_{GTO}$$

A, B, and C are terms not containing the driver W_{AF}/W_{GTO}

By a simple manipulation, this can be put into the following form:

$$\frac{A\, W_{AF}/W_{GTO} + B - CA + CA}{(C - W_{AF}/W_{GTO})} = -A + \frac{CA + B}{(C - W_{AF}/W_{GTO})}$$

Now we can operate only on the second term which contains W_{AF}/W_{GTO}, so as before,

$$\frac{\Delta DOC_{M/AF/L}}{DOC_{M/AF/L}} = \frac{(DOC_{M/AF/L})_2 - (DOC_{M/AF/L})_1}{(DOC_{M/AF/L})_1}$$

and finally

$$\frac{\dfrac{\Delta DOC_{M/AF/L}}{DOC_{M/AF/L}}}{\dfrac{\Delta\left(\dfrac{W_{AF}}{W_{GTO}}\right)}{\left(\dfrac{W_{AF}}{W_{GTO}}\right)}} \cong \frac{1.2\,\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{AF}}{W_{GTO}}}$$

for the driver W_{AF}/W_{GTO}.

Airplane maintenance materials, excluding engines, M/AF/M.- The $DOC_{M/AF/M}$ equation is:

$$DOC_{M/AF/M} = \frac{(9.04 + 4.52\, t_F)\left[\frac{C_{HST}}{W_{GTO}} - \frac{C_{TJ}}{W_{GTO}} - \frac{C_{RJ}}{W_{GTO}}\right]}{(LF)\ (R_T)\ (W_{PL}/W_{GTO}) \times 10^3}$$

By similarity to earlier forms, we get

$$\frac{\dfrac{\Delta DOC_{M/AF/M}}{DOC_{M/AF/M}}}{\dfrac{\Delta\left(\dfrac{W_{AF}}{W_{GTO}}\right)}{\left(\dfrac{W_{AF}}{W_{GTO}}\right)}} = \frac{\left(\dfrac{W_{AF}}{W_{GTO}}\right)}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{AF}}{W_{GTO}}}$$

for the driver W_{AF}/W_{GTO}.

Engine maintenance, M/TJ/L, M/TJ/M, M/RJ/L M/RJ/L.- The maintenance equations for the engines are also affected by changes in airframe weight through the payload term in the denominator. All of these equations, however, have the same basic form, i.e., A/(B-x); therefore, as derived above, the final result is

$$\frac{\dfrac{\Delta DOC_i}{DOC_i}}{\dfrac{\Delta\left(\dfrac{W_{AF}}{W_{GTO}}\right)}{\left(\dfrac{W_{AF}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{AF}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{AF}}{W_{GTO}}}$$

where i = M/TJ/L, M/TJ/M, M/RJ/L, M/RJ/M

for the driver W_{AF}/W_{GTO}.

Turbojet Specific Weight, $(W/T)_{TJ}$

The turbojet specific weight can be written as:

$$(W/T)_{TJ} = (W_{TJ}/W_{GTO})\ \frac{1}{(T/W)_{GTO}}$$

where $(T/W)_{GTO}$ is a constant for a given baseline.

This identity will now be applied to each of the DOC elements.

Fuel costs.- In a manner similar to that used before, the DOC_{Fuel} equation can be written as:

$$DOC_f = \frac{A}{\left(1 - W_{f_T}/W_{GTO} - W^*/W_{GTO} - W_{TJ}/W_{GTO}\right)} = \frac{A}{\left(W_{PL}/W_{GTO}\right)}$$

where $WX/W_{GTO} = \dfrac{W_{AF}}{W_{GTO}} + \dfrac{W_{RJ}}{W_{GTO}} + \dfrac{W_{AV}}{W_{GTO}}$

Changes in $(W/T)_{TJ}$ are equivalent to changes in (W_{TJ}/W_{GTO}) which translate into changes in DOC_f. The final equation (by similarity to the previous derivations) is:

$$\frac{\Delta DOC_f}{DOC_f} = (P)\ (T/W)_{GTO}\ \frac{(W/T)_{TJ}}{W_{PL}/W_{GTO}} \left[\frac{1}{1 - \left\{ (P)\ (T/W)_{GTO}\ \frac{(W/T)_{TJ}}{W_{PL}/W_{GTO}} \right\}} \right]$$

Simplifying, we have:

$$\frac{\dfrac{\Delta DOC_f}{DOC_f}}{\dfrac{\Delta\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}{\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{TJ}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\ \dfrac{W_{TJ}}{W_{GTO}}}$$

for the driver, $(W/T)_{TJ}$.

Depreciation cost.- As before, the only element affected by weight changes is the payload weight so that by similarity we get:

$$\frac{\dfrac{\Delta DOC_D}{DOC_D}}{\dfrac{\Delta\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}{\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{TJ}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\ \dfrac{W_{TJ}}{W_{GTO}}}$$

for the driver, $(W/T)_{TJ}$.

Insurance cost.- The insurance cost is determined the same way as depreciation. The equation is:

$$\frac{\dfrac{\Delta DOC_{Ins}}{DOC_{Ins}}}{\dfrac{\Delta\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}{\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{TJ}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{TJ}}{W_{GTO}}}$$

for the driver, $(W/T)_{TJ}$.

Crew cost.- Again, as derived above,

$$\frac{\dfrac{\Delta DOC_{Crew}}{DOC_{Crew}}}{\dfrac{\Delta\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}{\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{TJ}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{TJ}}{W_{GTO}}}$$

for the driver, $(W/T)_{TJ}$.

Maintenance costs.- For all maintenance elements, the equation for the ΔDOC is given, as before, as:

$$\frac{\dfrac{\Delta DOC_i}{DOC_i}}{\dfrac{\Delta\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}{\left(\dfrac{W_{TJ}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{TJ}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{TJ}}{W_{GTO}}}$$

for the driver, $(W/T)_{TJ}$.

where,

i = M/AF/L, M/AF/M, M/TJ/L, M/TJ/M, M/RJ/L, M/RJ/M,

(This change implies a change in weight, not thrust.)

Ramjet Sizing Parameter $\left(\dfrac{W_{RJ}}{A_C\ C_{TRJ}}\right)$

As was the case with the previous drivers, changes in the ramjet sizing parameter manifest themselves through the payload weight term. For this case, the basic equation was derived earlier and is repeated symbolically here:

$$\frac{\dfrac{\Delta DOC_i}{DOC_i}}{\dfrac{\Delta\left(\dfrac{W_{RJ}}{W_{GTO}}\right)}{\left(\dfrac{W_{RJ}}{W_{GTO}}\right)}} = \frac{\dfrac{W_{RJ}}{W_{GTO}}}{\dfrac{W_{PL}}{W_{GTO}} + 0.1\,\dfrac{W_{RJ}}{W_{GTO}}}$$

for the driver, $\left(\dfrac{W_{RJ}}{A_C\ C_{TRJ}}\right)$

where,

i = fuel, depreciation, crew, insurance, M/AF/L, M/AF/M, M/TJ/L, M/TJ/M, M/RJ/L, M/RJ/M,

Lift-to-Drag Ratio, L/D

Fuel cost.- The DOC_{Fuel} equation is:

$$DOC_f = \frac{1460}{R_T(LF)} \frac{(W_{fT}/W_{GTO})\ C_f\ (1-K_R)}{(W_{PL}/W_{GTO})}$$

where,

$$W_{f_T}/W_{GTO} = \frac{1 - \exp\left[\frac{R_T\ (sfc)}{110\ M(L/D)}\ (1 - 0.75\ K_{CL})\right]}{K_{CL} - (1 - K_D - K_R)\ \exp\left[\frac{R_T\ (sfc)}{110\ M(L/D)}\ (1 - 0.75\ K_{CL})\right]}$$

(See Appendix D for derivation of W_{f_T}/W_{GTO}.)

(For English units replace the coefficient 110 by 680).

Now, to find the change in DOC_f for a given change in L/D, we use

$$\frac{\partial DOC_f}{\partial L/D} = \left(\frac{\partial DOC_f}{\partial \frac{W_{f_T}}{W_{GTO}}}\right)\left(\frac{\partial \frac{W_{f_T}}{W_{GTO}}}{\partial L/D}\right)$$

where

$$\frac{\partial \, DOC_f}{\partial \, \dfrac{W_{f_T}}{W_{GTO}}} = \frac{DOC_f \left(1 - \dfrac{W_e}{W_{GTO}}\right)}{\left(\dfrac{W_{f_T}}{W_{GTO}}\right)\left(\dfrac{W_{PL}}{W_{GTO}}\right)}$$

and

$$\frac{\partial \, DOC_f}{\partial \, L/D} = \left(\frac{DOC_f \left(1 - \dfrac{W_e}{W_{GTO}}\right)}{\left(\dfrac{W_{f_T}}{W_{GTO}}\right)\left(\dfrac{W_{PL}}{W_{GTO}}\right)}\right) \frac{A \, e^{A/L/D}}{(L/D)^2} \, \frac{\left(1 - D \dfrac{W_{f_T}}{W_{GTO}}\right)}{(B - De^{A/L/D})}$$

where

$$A = \left(\frac{1}{110}\right) \frac{R_T \quad (sfc)}{M} \left(1 - 0.75 \, \frac{W_{f_{CL}}}{W_{f_T}}\right) ; \quad B = \frac{W_{f_{CL}}}{W_{f_T}} = K_{CL}$$

and

$$D = \left[1 - (K_D + K_R)\right]$$

To find the change in DOC, we have

$$\frac{\Delta \, DOC_f}{DOC_f} = \frac{\partial \, DOC_f}{\partial \, L/D} \, \frac{\Delta \, L/D}{L/D} \, \frac{L/D}{DOC_f}$$

where,

K_{MRJ} = ramjet maintenance labor, ratio of HST ramjets to present subsonic turbojets per flight hour.

(For English Units replace the coefficients .036 and .029 by 0.05 and 0.04, respectively).

where

$$\frac{W^*}{W_{GTO}} = \frac{W_{AF}}{W_{GTO}} + \frac{W_{TJ}}{W_{GTO}} + \frac{W_{RJ}}{W_{GTO}} + \frac{W_{AV}}{W_{GTO}}$$

E, F, and G are terms not containing L/D

As before, to find the change in $DOC_{M/RJ/L}$ for a given change in L/D, we use

$$\frac{\partial DOC_{M/RJ/L}}{\partial L/D} = \left(\frac{\partial DOC_{M/RJ/L}}{\partial \frac{W_{f_T}}{W_{GTO}}}\right)\left(\frac{\partial \frac{W_{f_T}}{W_{GTO}}}{\partial (L/D)}\right)$$

Taking the partial of $DOC_{M/RJ/L}$ with respect to the fuel fraction, we have:

$$\frac{\partial DOC_{M/RJ/L}}{\partial \frac{W_{f_T}}{W_{GTO}}} = \frac{(E\ (L/D) + F)\ (G\ (L/D))}{\left[G(L/D)\left(1 - \frac{W^*}{W_{GTO}} - \frac{W_{f_T}}{W_{GTO}}\right)\right]} = \frac{DOC_{M/RJ/L}}{W_{PL}/W_{GTO}}$$

Then with the partial of the fuel fraction with respect to L/D, from above:

$$\frac{\partial DOC_{M/RJ/L}}{\partial L/D} = \left(\frac{DOC_{M/RJ/L}}{W_{PL}/W_{GTO}}\right)\left[\frac{Ae^{A(L/D)}}{(L/D)^2}\ \frac{\left(1-D\ \frac{W_{f_T}}{W_{GTO}}\right)}{\left(B-De^{A(L/D)}\right)}\right]$$

To find the change in DOC we have,

$$\frac{\Delta DOC_{M/RJ/L}}{DOC_{M/RJ/L}} = \frac{\partial DOC_{M/RJ/L}}{\partial L/D}\quad \frac{\Delta\ L/D}{L/D}\quad \frac{L/D}{DOC_{M/RJ/L}}$$

Finally,

$$\frac{\dfrac{\Delta DOC_{M/RJ/L}}{DOC_{M/RJ/L}}}{\dfrac{\Delta L/D}{L/D}} = \frac{L/D}{W_{PL}/N_{GTO}} \quad \frac{Ae^{A\,(L/D)}}{(L/D)^2} \quad \frac{1-D\,\dfrac{W_{F_T}}{W_{GTO}}}{B-De^{A\,(L/D)}}$$

where

$$A = \frac{R_T\,(sfc)}{110\,M}\,(1 - 0.75\,K_{CL})$$

$$B = \frac{W_{f_{CL}}}{W_{f_T}} = K_{CL}$$

$$D = 1 - K_D - K_R$$

Other Cost Elements.- In all other cost elements, the effects of changes in L/D will show up in a changed fuel fraction which in turn affects payload weight. Therefore, as was found before, we have:

$$\frac{\Delta DOC_i}{DOC_i} = \left(\frac{\partial DOC_i}{\partial \dfrac{W_{f_T}}{W_{GTO}}}\right)\left(\frac{\partial \dfrac{W_{f_T}}{W_{GTO}}}{\partial L/D}\right)\left(\frac{\Delta L/D}{L/D}\right)\left(\frac{L/D}{DOC_i}\right)$$

where

$$\frac{\partial DOC_i}{\partial \dfrac{W_{f_T}}{W_{GTO}}} \cdot = \frac{DOC_i}{\dfrac{W_{PL}}{W_{GTO}}}$$

and

$$\frac{\partial \dfrac{W_{f_T}}{W_{GTO}}}{\partial L/D} = \frac{Ae^{A/(L/D)}}{(L/D)^2}\left[\frac{1 - D\dfrac{W_{f_T}}{W_{f_N}}}{B - De^{A/(L/D)}}\right]$$

$$A = \frac{1}{110}\,\frac{(R)\ SFC}{M}\left(1 - 0.75\,\frac{W_{f_{CL}}}{W_{f_T}}\right)$$

$$B = \frac{W_{f_{CL}}}{W_{f_T}}$$

$$D = \left[1 - (K_D + K_R)\right]$$

So finally we have;

$$\frac{\dfrac{\Delta DOC_i}{DOC_i}}{\dfrac{\Delta L/D}{L/D}} = \frac{A}{(L/D)\left(\dfrac{W_{PL}}{W_{GTO}}\right)}\ e^{A/(L/D)}\left[\frac{1 - D\dfrac{W_{f_T}}{W_{GTO}}}{B - De^{A(L/D)}}\right]$$

which will be recognized as:

$$\frac{\dfrac{\Delta DOC_i}{DOC_i}}{\dfrac{\Delta L/D}{L/D}} = \left[\frac{\dfrac{W_{f_T}}{W_{GTO}}}{\dfrac{W_{f_T}}{W_{GTO}} + \dfrac{W_{PL}}{W_{GTO}}}\right]\frac{\dfrac{\Delta DOC_f}{DOC_f}}{\dfrac{\Delta L/D}{L/D}}$$ for the Driver, L/D

Specific Fuel Consumption, sfc

Fuel Cost.- The equation for the change in DOC with SFC is derived in the same way as the equation for L/D. The final result is similar to the result obtained for L/D and is

$$\frac{\frac{\Delta DOC_f}{DOC_f}}{\frac{\Delta sfc}{sfc}} = \frac{\left(\frac{W_{f_T}}{W_{GTO}} + \frac{W_{PL}}{W_{GTO}}\right) A' \; e^{A'(sfc)} \left(D \frac{W_{f_T}}{W_{GTO}} - 1\right) sfc}{\left(\frac{W_{f_T}}{W_{GTO}}\right)\left(\frac{W_{PL}}{W_{GTO}}\right) \left(B - De^{A' sfc}\right)}$$

for the Driver, sfc

where

$$A' = \frac{1}{110} \frac{R_T}{(L/D)} \frac{1}{M} \left(1 - 0.75 \; W_{f_{CL}}/W_{f_T}\right)$$

$$B = W_{f_{CL}}/W_{f_T}$$

$$D = \left[1 - (K_D + K_r)\right]$$

and K is the percentage change in sfc.

Other Cost Elements.- All other cost elements are only affected through the fuel fraction and, in turn, through the payload. The same equation given previously is, therefore, used

$$\frac{\frac{\Delta DOC_i}{DOC_i}}{\frac{\Delta sfc}{sfc}} = \left[\frac{\frac{W_{f_T}}{W_{GTO}}}{\frac{W_{PL}}{W_{GTO}} + \frac{W_{f_T}}{W_{GTO}}} \right] \left[\frac{\frac{\Delta DOC_f}{DOC_f}}{\frac{\Delta sfc}{sfc}} \right]$$

for the Driver, sfc.

APPENDIX 3-C

OPERATIONAL CONSTANTS AND COST FACTORS

This appendix provides information about the operational constants and cost factors required for solution of the DOC equations which are not defined in the baseline HST Definition. Rationale is provided for the values which are suggested in the Procedures section. The Sensitivity analysis has indicated that the outputs of the study are not sensitive to these factors; nevertheless, reasonable care should be used in their selection.

Operational Constants

Load factor (LF).- Is the ratio of the average payload carried to the maximum payload which the aircraft is capable of carrying in normal operation. The current industry average was 44% in 1971 (reference 4); however, the industry has been somewhat depressed economically in recent years. Cargo planes in regular operation run higher than passenger planes. Therefore, a value of 60% has been used for the HST calculation.

Utilization (U).- Aircraft utilization is the average block hours of use of the aircraft in a year. Typical utilization for industry varies from about 3000 hours to 4500 hours during normal times depending on the aircraft and air lines involved. 3000 hours, at the low end of the scale, was selected for the HST because of its high speed and short flight time.

Cost Factors

Cost of fuel C_f .- Typical current (1972) value for liquid hydrogen delivered to a user site is 20 cents per pound (44 cents per kg) (reference 7). This has been projected to a value of 13 cents per pound (28.6 cents per kg) in 1985 (which is the value used here), and to 8 cents per pound (17.64 cents per kg) in the year 2000 (the latter per NASA CR 73226, Air Products and Chemical Co.) (see figure 6-4). The method is applicable to other fuels when applicable cost per unit weight of fuel is used.

Insurance rate, IR.- The ATA convention states that aircraft insurance rates for new aircraft are typically 5 percent of the original acquisition cost but drop to 2 percent in 4 to 5 years which is given as a typical industry average (reference 2); 0.02 is the value suggested for the current study.

Depreciation lift, L_d.- 15 years is a typical value for subsonic commercial aircraft depreciation periods in accordance with industry accounting practice. This has been shortened to 10 years for the HST calculations.

Average maintenance labor rate, r_L.- The average labor rate of $5.30 per hour has been suggested for use in the present study and relates to all maintenance personnel. The ATA (reference 1) gives $4.00 as the input value for this parameter in its formula, at 1967 dollars. This has been increased to $5.30 at 1972 dollars by allowing a 6-percent annual increase for 5 years.

Cost of C_{HST} aircraft and its components.- Acquisition costs for the total aircraft C_{HST} and certain of its elements are required for use in the DOC formulas. These costs may be developed independently, by any method, or they may be estimated using the following estimating relationships which have been developed for the baseline HST. The costs are expressed in normalized form (i.e., divided by the gross take-off weight of the aircraft, W_{GTO}) for use in the DOC equations.

$$\frac{C_{HST}}{W_{GTO}} = \frac{C_{AF}}{W_{GTO}} + \frac{C_{RJ}}{W_{GTO}} + \frac{C_{TJ}}{W_{GTO}} + \frac{C_{AV}}{W_{GTO}} \quad \$/kg$$

where,

		Value for Baseline HST (Demonstration)
C_{HST}	= cost of HST airplane (total), $	$ 98.3 M
C_{AF}	= cost of airplane less engines and avionics, $	77.8
C_{RJ}	= cost of ramjet engine set per aircraft , $	7.7
C_{TJ}	= cost of turbojet engine set per aircraft, ¢	8.8
C_{AV}	= cost of avionics, $	4.0
W_{GTO}	= gross take-off weight, kg	

$$\frac{C_{AF}}{W_{GTO}} = \frac{855\,(W_{AF})^{0.68}\,M^2}{W_{GTO}}, \quad \$/kg$$

(For English Units replace the coefficient 855 by 500).

$$\frac{C_{TJ}}{W_{GTO}} = 6300\,(N_{TJ})^{-0.15}\,(T_{TJ})^{-0.33}\,(T/W)_{GTO}, \quad \$/kg$$

(For English Units replace the coefficient 6300 by 1750)

$$\frac{C_{RJ}}{W_{GTO}} = \frac{33\,900\ (A_C)^{0.9}\ (M^2)}{W_{GTO}}$$ (For English Units replace the coefficient 33 900 by 4000)

$$\frac{C_{AV}}{W_{GTO}} = 2760\ \frac{W_{AV}}{W_{GTO}}$$ (For English Units replace the coefficient 2760 by 1250)

where,

W_{AF} = weight of airplane less engines and avionics

W_{AV} = weight of avionics

Maintenance ratios, K_{LTJ}, K_{MTJ}, K_{LRJ}, K_{MRJ}.- The maintenance ratios are factors relating maintenance requirements of both the HST supersonic turbojet engines and scramjet/ramjet engines to the maintenance requirements of current large subsonic turbojet engines. The labor factors (L subscripts) relate to maintenance manhours per engine operating hour. The materials factors (M subscripts) relate to maintenance replacements per flight hour. The DOC maintenance equations contain separate engine purchase cost terms so that the materials factors are not intended to reflect a higher cost for parts, only an increased frequency of replacement. Engine overhauls and even complete replacements are a part of maintenance costs so that if the mean-time-between overhaul were to be reduced from 3000 hours (subsonic turbojets) to 1000 hours for the scramjets, this should be reflected in a factor $K_{MRJ} = 3.0$.

Whereas selection of accurate values for these factors appears difficult, the sensitivity analysis has indicated that the Driver Partials are almost completely insensitive to large (50%) changes in these factors.

The ATA formulas on which the DOC formulas are based covered supersonic (SST) as well as subsonic turbojets and utilized coefficients in their supersonic and subsonic formulas which gave an equivalent value of K_{LTJ} and K_{MTJ} of approximately 1.7 to 1 (reference 1). A value of 2.0 to 1 has been used in the demonstration calculations for the HST because the HST turbojets are estimated to have higher maintenance requirements per hour of operation than the SST turbojets. They operate primarily in a climb node, and reach a higher Mach number (3-4) than the SST (2.7).

For scramjet engines, factors of $K_{MRJ} = 3$ and $K_{LRJ} = 2$ have been used in the demonstration calculations for materials and labor, respectively. The scramjet will operate at much higher temperature, (3000 K) (5000°F) compared with 1400 K (2000°F) for turbojets. Although they have no rotating machinery, they will have regenerative cooling. A value of 2 instead of 3 was selected for the labor factor to reflect a labor requirement reduced by one-third per maintenance action because of the essentially simple construction of the scramjet versus the turbojet engine.

APPENDIX 3-D

FUEL WEIGHT FRACTION

This appendix presents the development of the formula for the fuel weight fraction (W_{f_T}/W_{GTO}). The required value for W_{f_T}/W_{GTO} is determined in the Procedures of Module 2, Baseline HST Definition, and is an input to the present Module. Nevertheless, the equation is used in the derivation of certain of the driver equations of Appendix 3-B, and it is therefore included here.

Symbols used in this derivation are as shown in the section of this Module, entitled "SYMBOLS".

The quantity of fuel used is derived from the Breguet formula,

$$\text{Breguet cruise range} = R_{CR} = \frac{L/D}{sfc} V_{CR} \ln \frac{W_{CR_o}}{W_{CR_i}}$$

Now,

$$\frac{W_{CR_o}}{W_{CR_i}} = \frac{W_{GTO} - W_{f_{CL}}}{W_e + (K_D+K_R) W_{f_T} + W_{PL}}$$

or,

$$\frac{W_{CR_o}}{W_{CR_i}} = \frac{W_{GTO} - W_{f_{CL}}}{W_{GTO} - W_{f_{CL}} - W_{f_{CR}}}$$

$$W_{f_T} = W_{f_{CL}} + W_{f_{CR}} + K_D W_{f_T} + K_R W_{f_T}$$

so,

$$W_{f_{CL}} + W_{f_{CR}} = \left[1 - (K_D+K_R)\right] W_{f_T}$$

$$\frac{W_{CR_o}}{W_{CR_i}} = \frac{W_{GTO} - W_{f_{CL}}}{W_{GTO} - \left[1 - (K_D+K_R)\right] W_{f_T}} = \frac{1 - \dfrac{W_{f_{CL}}}{W_{GTO}}}{1 - \left[1 - (K_D+K_R)\right] \dfrac{W_{f_T}}{W_{GTO}}}$$

Now,

$$\frac{W_{f_{CL}}}{W_{GTO}} = \left(\frac{W_{f_{CL}}}{W_{f_T}}\right)\left(\frac{W_{f_T}}{W_{GTO}}\right)$$

Finally,

$$\frac{W_{CR_o}}{W_{CR_i}} = \frac{1 - \left(\frac{W_{f_{CL}}}{W_{f_T}}\right)\left(\frac{W_{f_T}}{W_{GTO}}\right)}{1 - \left[\,1 - (K_D+K_R)\right] \frac{W_{f_T}}{W_{GTO}}}$$

and so,

$$R_{CR} = (0.161)\ \frac{L/D}{sfc}\ \ 680\ M_{CR}\ \ \ln \left\{ \frac{1 - \frac{W_{f_{CL}}}{W_{f_T}}\ \frac{W_{f_T}}{W_{GTO}}}{1 - \left[1 - (K_D+K_R)\right]\ \frac{W_{f_T}}{W_{GTO}}} \right\}$$

(in SI units)

assuming,

$$V_{CR} = 680\ M_{CR},$$ (in miles per hour)

Now,

R_T = total range = $R_B + R_{CL} + R_D$

R_{CL} = range covered during climb

R_D = range covered during descent

Now,

$$R_{CL} = f\left(\frac{W_{f_{CL}}}{W_{f_T}}\right)$$

From the HST baseline, Module 2, we find

$$\frac{W_{f_{CL}}}{W_{f_T}} = 0.4$$

and

$$R_{CL}/R_T = 0.2$$

so we assume

$$R_{CL}/R_T \cong 1/2 \frac{W_{f_{CL}}}{W_{f_T}} .$$

Also, assume

$$R_D \cong 1/2 \; R_{CL}$$

so,

$$R_T = R_{CR} + 1/2 \frac{W_{f_{CL}}}{W_{f_T}} R_T + 1/4 \frac{W_{f_{CL}}}{W_{f_T}} R_T$$

$$1 = \frac{R_{CL}}{R_T} + (1/2 + 1/4) \frac{W_{f_{CL}}}{W_{f_T}}$$

$$\frac{R_{CR}}{R_T} = 1 - 3/4 \frac{W_{f_{CL}}}{W_{f_T}}$$

or

$$R_T = \frac{R_{CR}}{1 - 3/4 \frac{W_{f_{CL}}}{W_{f_T}}} .$$

Solving now for R_{CL},

$$R_{CL} = 1/2 \frac{W_{f_{CL}}}{W_{f_T}} R_T$$

or

$$R_{CL} = R_{CR} \frac{W_{f_{CL}}/W_{f_T}}{2 - 1.5 W_{f_{CL}}/W_{f_T}}$$

So, finally

$$R_T = R_B + R_{CL} + R_D = R_B + 1.5 R_{CL}$$

$$R_T = \left(1 + \frac{1.5 W_{f_{CL}}/W_{f_T}}{2 - 1.5 W_{f_{CL}}/W_{f_T}}\right) R_B$$

So,

$$R_T = \left[1 + \frac{1.5 W_{f_{CL}}/W_{f_T}}{2 - 1.5 W_{f_{CL}}/W_{f_T}}\right] 109.4 \frac{L/D}{sfc} M_{CR} \ln \left\{\frac{1-(W_{f_{CL}}/W_{f_T} \quad W_{f_T}/W_{GTO})}{1-[1-(K_D+K_R)]W_{f_T}/W_{GTO}}\right\}$$

Solving this for W_{f_T}/W_{GTO}, we have

$$W_{f_T}/W_{GTO} = \frac{1 - \exp\left\{9.1\times10^{-3} \frac{(R_T)sfc}{L/D\ (M)} (1-0.75\ W_{f_{CL}}/W_{f_T})\right\}}{W_{f_{CL}}/W_{f_T} - [1-(K_D+K_R)]\exp\left\{9.1\times10^{-3} \frac{(R_T)sfc}{(L/D)\ M} (1-0.75\ W_{f_{CL}}/W_{f_T})\right\}}$$

METHOD MODULE 4

TECHNOLOGY PARAMETER EQUATIONS

METHOD MODULE 4 - TECHNOLOGY PARAMETER EQUATIONS

General

This module presents the procedures and equations required to determine the effects of changes in the selected Technology Parameters on the designated Driver Parameters. The procedures are set up in a systematic step-by-step fashion so that the results can be obtained simply and quickly. Explanatory information and the derivation of equations is presented in Appendix 4-A.

Logic

In order to establish the effects of changes in Technology Parameters on the designated Driver Parameters, it is necessary to first define the relationship between them. This can be done either analytically through explicit equations, or empirically through graphs, curve fits, etc. With the relationships established, the changes can be found by using approximate differentials (herein called "partials"). The equations finally derived apply to all cruise vehicles of interest to the hypersonic technology planner. The constants are adjusted for each defined baseline vehicle.

The Driver Parameters used in this module are listed in Table 4-I while the associated Technology Parameters are listed in Table 4-II. The expressions relating Driver Parameters to Technology Parameters are presented in the Appendix 4-A. The first Driver, airframe weight fraction, W_{AF}/W_{GTO}, has been expanded into six elements as shown in the table. Of these six, the first two, fuselage weight and wing weight, contribute the major part of the airframe weight. These elements have been described in terms of both the material properties and design factors listed in Table 4-II to allow the user maximum flexibility in determining technology effects. The remaining elements are treated in a more simplified manner since they contribute relatively little to the airframe weight and are not as sensitive to technology changes.

The second Driver Parameter listed in Table 4-I is the turbojet specific weight which is the total weight of the installed turbojets and ducting divided by the total maximum sea-level thrust. No Technology Parameters have been defined for this Driver since the development of turbojet technology is expected to progress independently of hypersonic technology. This parameter will be treated to progress independently of hypersonic technology. This parameter will be treated in Module 5 as a Technology Parameter.

The remaining propulsion system parameters are ramjet engine parameters which are intimately connected with hypersonic technology. Expressions for these parameters in terms of selected Technology Parameters have been developed with the help of unpublished data supplied by the Marquardt Corporation. These expressions are included in the Appendix 4-A.

TABLE 4-1.– DRIVER PARAMETERS

a)	W_{AF}/W_{GTO}	-	airframe weight fraction which includes the following elements:
	$\frac{W_F}{W_{GTO}}$	-	fuselage weight fraction
	$\frac{W_W}{W_{GTO}}$	-	wing weight fraction
	$\frac{W_E}{W_{GTO}}$	-	horizontal and vertical surfaces weight fraction
	$\frac{W_{TP}}{W_{GTO}}$	-	thermal protection weight fraction
	$\frac{W_{PS}}{W_{GTO}}$	-	propellant system weight fraction
	$\frac{W_{sys}}{W_{GTO}}$	-	other airframe systems as landing gear, power, hydraulics, etc.
b)	$(W/T)_{TJ}$	-	installed turbojet propulsion specific weight including the inlet ducting
c)	$\left(\frac{W_{RJ}}{A_C C_{TRJ}}\right)$	-	ramjet sizing parameter
d)	sfc	-	cruise specific fuel consumption
e)	(L/D)	-	cruise lift-to-drag ratio

TABLE 4-II.- TECHNOLOGY PARAMETERS

Aerodynamics	
C_{D_o}	zero-lift drag coefficient
C_{D_i}/C_L^2	induced drag factor
Propulsion	
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)
$(W/A_C)_{RJ}$	ramjet specific weight, kg/m^2 (lb/ft^2)
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a Driver Parameter)
η_K	ramjet inlet kinetic energy efficiency
η_C	ramjet combustion efficiency
η_{KN}	ramjet nozzle kinetic energy efficiency
Aggregate materials properties	
FMP	fuselage material properties
WMP	wing material properties

TABLE 4-II.- TECHNOLOGY PARAMETERS - Concluded

Airframe design	
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)
$F_{W,F}$	design factor for wing structure not designed by primary loads
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)
$F_{F,F}$	design factor for fuselage structure not designed by primary loads
F_E	design factor for empennage weight (= 1.00 for baseline)
F_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)
F_P	design factor for propellant system weight (= 1.00 for baseline)

The last Driver Parameter shown is the cruise lift-to-drag ratio which has been related to the zero lift drag coefficient and an induced drag factor in Appendix 4-A. All the relationships have been reduced to approximate partials with respect to the appropriate Technology Parameters to obtain the final forms used in the module. With the final equations available, the baseline vehicle characteristics are now inserted and for given percentage changes in the Technology Parameters, the corresponding changes in the Driver Parameters are computed. This process is illustrated in the last section of this module wherein the baseline vehicle characteristics developed in the Baseline Vehicle Method Module are used to compute numerical values of the final equations.

Input Data

The input data required to utilize this module is shown in Table 4-III and includes values of the baseline vehicle parameters. The final equations to be used are given in the next section. The input data is taken from Tables 2-III and 2-IV.

Procedures

This section contains the step-by-step procedures to be followed in order to establish the relationships between changes in Technology Parameters and the corresponding changes in the Driver Parameters. The use of these procedures will be illustrated later in the section entitled "Demonstration."

Vehicle Parameters.- The first step in the procedure requires the evaluation of the parameters listed in Table 4-III, Input Data Requirements. The airframe weight, wing weight, fuselage weight, horizontal and vertical surface weight, propellant system weight and thermal protection system weight are found from the output of the Baseline HST Definition Module.

Technology Parameter Partials.- In order to simplify the computation procedure, Table 4-IV has been prepared which lists the expressions to be used to determine the values of the Technology Parameter Partials. The expressions given in Table 4-IV are developed in Appendix 4-A. The computation procedure then simply entails entering Table 4-IV with the appropriate weight fraction obtained in the previous step (vehicle parameters) and entering the numerical value in the worksheet, Table 4-IV.

TABLE 4-III.- BASELINE VEHICLE PARAMETERS - REQUIRED INPUT FOR MODULE 4

Airframe Weight Parameters		
$\frac{W_{sys}}{W_{AF}}$	-	ratio of miscellaneous systems weight to total airframe weight (i.e., landing gear, power, etc.)
$\frac{W_F}{W_{AF}}$	-	ratio of fuselage weight to total airframe weight
$\frac{W_W}{W_{AF}}$	-	ratio of wing weight to total airframe weight
$\frac{W_E}{W_{AF}}$	-	ratio of horizontal and vertical surface weights to total airframe weight
$\frac{W_{TP}}{W_{AF}}$	-	ratio of thermal protection system weight to total airframe weight
$\frac{W_{PS}}{W_{AF}}$	-	ratio of propellant system weight to total airframe weight
Lift-to-Drag Ratio Parameters		
C_D	-	total airplane cruise drag coefficient
C_{D_o}	-	zero lift cruise drag coefficient
C_{D_i}/C_L^2	-	cruise induced drag factor

TABLE 4-IV.- TECHNOLOGY PARAMETER PARTIALS – REQUIRED OUTPUT FROM MODULE 4

Technology Parameter	Driver Parameter	$\dfrac{\Delta \text{Driver} / \text{Driver}}{\Delta \text{Tech. Parameter} / \text{Tech. Parameter}}$ = Technology Parameter Partial	Value
C_{D_o}	L/D	$-C_{D_o}/C_D$	
$C_{D_i}/C_L{}^2$	"	$-\dfrac{C_D - C_{D_o}}{C_D}$	
$(W/A_C)_{RJ}$	$\dfrac{W_{RJ}}{A_C C_{TRJ}}$	1	
C_{TRJ}	"	-1	
η_K	sfc	-0.195	
η_C	"	-0.730	
η_{KN}	"	-2.93	
$F_{W,B}$	$\dfrac{W_{AF}}{W_{GTO}}$	$-\left(\dfrac{W_W'}{W_{AF}}\right)\left\{\dfrac{W_{W,B}}{W_W'}\right\}$	
$F_{W,C}$	"	$-\left(\dfrac{W_W'}{W_{AF}}\right)\left\{\dfrac{W_{W,C}}{W_W'}\right\}$	
$F_{W,S}$	"	$-\left(\dfrac{W_W'}{W_{AF}}\right)\left\{\dfrac{W_{W,S}}{W_W'}\right\}$	
$F_{W,Y}$	"	$-\left(\dfrac{W_W'}{W_{AF}}\right)\left\{\dfrac{W_{W,Y}}{W_W'}\right\}$	

TABLE IV.- TECHNOLOGY PARAMETER PARTIALS - REQUIRED OUTPUT FROM MODULE 4 - Continued

Technology Parameter	Driver Parameter	$\dfrac{\Delta\text{Driver}/\text{Driver}}{\Delta\text{Tech. Parameter}/\text{Tech. Parameter}}$ = Technology Parameter Partial	Value
$F_{W,F}$	$\dfrac{W_{AF}}{W_{GTO}}$	$-\dfrac{W_{F,F}}{W_{A,F}}$	
$F_{F,B}$	"	$-\left(\dfrac{W_F'}{W_{AF}}\right)\left\{\dfrac{W_{F,B}}{W_F'}\right\}$	
$F_{F,C}$	"	$-\left(\dfrac{W_F'}{W_{AF}}\right)\left\{\dfrac{W_{F,C}}{W_F'}\right\}$	
$F_{F,S}$	"	$-\left(\dfrac{W_F'}{W_{AF}}\right)\left\{\dfrac{W_{F,S}}{W_F'}\right\}$	
$F_{F,Y}$	"	$-\left(\dfrac{W_F'}{W_{AF}}\right)\left\{\dfrac{W_{F,Y}}{W_F'}\right\}$	
$F_{F,F}$	"	$-\dfrac{W_{F,F}}{W_{AF}}$	
F_E	"	$-\left(\dfrac{W_E}{W_{AF}}\right)\Big/ 1 + \left(\dfrac{\Delta F_E}{F_E}\right)$	
T_{TP}	"	$-\left(\dfrac{W_{TP}}{W_{AF}}\right)\Big/ 1 + \left(\dfrac{\Delta F_{TP}}{F_{TP}}\right)$	
F_{PS}	"	$-\left(\dfrac{W_{PS}}{W_{AF}}\right)\Big/ 1 + \left(\dfrac{\Delta F_{PS}}{F_{PS}}\right)$	
WMP	"	$\left(W_W/W_{AF}\right)$	
FMP	"	$\left(W_F/W_{AF}\right)$	

TABLE 4-IV.- TECHNOLOGY PARAMETER PARTIALS -
REQUIRED OUTPUT FROM MODULE 4- Concluded

Note that in the above equations,

$$W_F' = W_{Fuselage} - W_{F,Fixed}$$

$$W_W' = W_{Wing} - W_{W,Fixed}$$

The data required to complete Table 4-IV consists of two parts, the first is input data from Table 4-III and includes the baseline vehicle weight fractions. The second part requires the evaluation of the fractions of the fuselage and wing weight designed by buckling, crippling, yield and stiffness criteria. These fractions are then applied only to that portion of the fuselage and wing weight not included in the fixed weight. The fixed weight is the weight of all elements not designed by primary loads. The fractions to be used are given in Table 4-V which were adapted from the data in reference 1. In order to use this data, the ratio of fuselage fixed weight to total fuselage weight and wing fixed weight to total wing weight must be known. The analyst has the option of using any value he may desire but if these values are not available, then the following are recommended:

$$\frac{W_{F,F}}{W_F} = 0.67 \qquad \frac{W_{W,F}}{W_W} = 0.4$$

Using these values then, we get

$$\frac{W_F'}{W_{AF}} = 0.33 \frac{W_F}{W_{AF}} \quad ; \quad \frac{W_W'}{W_{AF}} = 0.6 \frac{W_W}{W_{AF}}$$

These are the values needed in the expressions given in Table 4-IV.

Output Data

The output data of this module is all contained in the worksheet, Table 4-IV, and consists of the numerical values of the ratios. These values are required input data for the Results and Analyses Method Module 6.

TABLE 4-V.- APPROXIMATE WEIGHT RATIOS FOR PRIME STRUCTURAL ELEMENTS OF HYPERSONIC TRANSPORT AS DESIGNED BY VARIOUS CRITERIA

Design Criterion	Element, Symbol	Weight Ratio	
		Sandwich Panel Construction	Skin-Stiffened Construction
Buckling	Fuselage, $\frac{W_{F,B}}{W_F'}$	0.40	0.50
	Wing, $\frac{W_{W,B}}{W_W'}$	0.33	0.20
Crippling	Fuselage, $\frac{W_{F,C}}{W_F'}$	0.25	0.10
	Wing, $\frac{W_{F,C}}{W_F'}$	0.21	0.10
Stiffness	Fuselage, $\frac{W_{F,S}}{W_F'}$	0.05	0.05
	Wing, $\frac{W_{W,S}}{W_W'}$	0.10	0.10
Yield	Fuselage, $\frac{W_{F,Y}}{W_F'}$	0.30	0.30
	Wing, $\frac{W_{W,Y}}{W_W'}$	0.41	0.60

Note that these percentages apply to the total wing or fuselage weight minus the wing or fuselage fixed weight. In the above,

$W_F' = W_F - W_{F,F}$ (total fuselage weight - fixed fuselage weight)

$W_W' = W_W = W_{W,F}$ (total wing weight - fixed wing wing)

DEMONSTRATION

Introduction

This section of the module presents a numerical example of the procedures and equations presented earlier, utilizing the baseline vehicle described in Module 2 of this report, Baseline HST Definition. The example matches identically the instructions given in the earlier section entitled "Procedures" and is developed in a step-by-step fashion.

Procedures

Vehicle Parameters.- The first step requires the input of the baseline vehicle parameters listed earlier in Table 4-III. These values are obtained from the output of the Baseline HST Definition module (reference Tables 2-VII and 2-VIII) and are summarized in Table 4-VI.

Technology Parameter Partials.- With the baseline vehicle parameters established, we now go directly to Table 4-III (which is simply a reproduced copy of Table 4-IV) and enter in Table 4-VII the values obtained by solving equations using the values from Tables 4-V and 4-VI. For this demonstration, we will take:

$$\frac{W_{F,F}}{W_F} = 0.67 \quad \text{and} \quad \frac{W_{W,F}}{W_W} = 0.4$$

This gives the following:

$$\frac{W'_F}{W_{AF}} = 0.33 \ \frac{W_F}{W_{AF}} = (0.33)\ (0.285) = 0.095$$

$$\frac{W'_W}{W_{AF}} = (0.6) \ \frac{W_W}{W_{AF}} = (0.6)(0.191) = 0.115$$

The output data is shown in Table 4-VII.

TABLE 4-VII. - TECHNOLOGY PARAMETER PARTIALS DEMONSTRATION DATA OUTPUT FROM MODULE 4 (Reference Table 4-IV) - Continued

Technology Parameter	Driver Parameter	$\dfrac{\Delta \text{Driver}/\text{Driver}}{\Delta \text{Tech. Parameter}/\text{Tech. Parameter}}$ = Technology Parameter Partial	Value
$F_{W,F}$	$\dfrac{W_{AF}}{W_{GTO}}$	$-\dfrac{W_{F,F}}{W_{A,F}}$	-0.076
$F_{F,B}$	"	$-\left(\dfrac{W_F'}{W_{AF}}\right)\left\{\dfrac{W_{F,B}}{W_F'}\right\}$	-0.038
$F_{F,C}$	"	$-\left(\dfrac{W_F'}{W_{AF}}\right)\left\{\dfrac{W_{F,C}}{W_F'}\right\}$	-0.024
$F_{F,S}$	"	$-\left(\dfrac{W_F'}{W_{AF}}\right)\left\{\dfrac{W_{F,S}}{W_F'}\right\}$	-0.005
$F_{F,Y}$	"	$-\left(\dfrac{W_F'}{W_{AF}}\right)\left\{\dfrac{W_{F,Y}}{W_F'}\right\}$	-0.029
$F_{F,F}$	"	$-\dfrac{W_{F,F}}{W_{AF}}$	-0.190
F_E	"	$-\left(\dfrac{W_E}{W_{AF}}\right)\Big/ 1+\left(\dfrac{\Delta F_E}{F_E}\right)$	-0.029
T_{TP}	"	$-\left(\dfrac{W_{TP}}{W_{AF}}\right)\Big/ 1+\left(\dfrac{\Delta F_{TP}}{F_{TP}}\right)$	-0.107
F_{PS}	"	$-\left(\dfrac{W_{PS}}{W_{AF}}\right)\Big/ 1+\left(\dfrac{\Delta F_{PS}}{F_{PS}}\right)$	-0.161
WMP	"	$\left(W_W/W_{AF}\right)$	0.115
FMP	"	$\left(W_F/W_{AF}\right)$	0.095

TABLE 4-VII. - TECHNOLOGY PARAMETER PARTIALS - DEMONSTRATION DATA OUTPUT FROM MODULE 4 (Reference Table 4-IV) - Concluded

Note that in the above equations,

$$W_F' = W_{Fuselage} - W_{F,Fixed}$$

$$W_W' = W_{Wing} - W_{W,Fixed}$$

REFERENCE

1. Taylor, Robert J., "High Temperature Airframe Weight Estimation," Society of Aeronautical Weight Engineers Technical Report No. 479, May 1965.

APPENDIX 4-A

TECHNOLOGY PARAMETER EQUATIONS

Introduction

Expressions for each of the five Driver Parameters previously listed in Table 4-I are presented in the Appendix in terms of the Technology Parameters previously listed in Table 4-II. Each expression is then analytically or numerically differentiated to obtain a relationship between changes in Technology Parameters and corresponding changes in the Driver Parameters. Finally, expressions for the ratios of the percentage changes in the Driver Parameters to the percentage changes in the Technology Parameters are formulated and are used to determine the required numerical values previously given in Table 4-IV. Each Driver Parameters is treated in turn in the following sections.

Airframe Weight Fraction.- The airframe weight fraction, W_{AF}/W_{GTO}, is broken into six components as shown below.

1) W_F/W_{AF} - Fuselage weight to total airframe weight
2) W_W/W_{AF} - Wing weight to total airframe weight
3) W_E/W_{AF} - Empennage weight to total airframe weight
4) W_{TP}/W_{AF} - Thermal protection weight to total airframe weight
5) W_{PS}/W_{AF} - Propellant system weight to total airframe weight
6) W_{Equip}/W_{AF} - Miscellaneous systems weight to total airframe weight

The fractional change in airframe weight fraction for a given change in any of the above six parameters is given by:

$$\frac{\Delta W_{AF}}{W_{AF}} = \left(\frac{\Delta W_i}{W_i}\right)\left(\frac{W_i}{W_{AF}}\right)$$

where i = F, W, E, TP, PS or Sys

Each of these components can now be expressed in terms of the Technology Parameters listed earlier in Table 4-II.

Fuselage weight: The fuselage is designed by a combination of buckling, crippling, yield and stifness criteria and so the fuselage weight may be expressed as:

$$W_F = W_{F,B} + W_{F,C} + W_{F,Y} + W_{F,S} + W_{F,F}$$

where,

$W_{F,B}$ is the weight of the fuselage required to meet buckling criteria,

$W_{F,C}$ is the fuselage weight required to meet crippling criteria, etc.

This expression can be rewritten as:

$$\frac{W_F}{W_{AF}} = \frac{W'_F}{W_{AF}} \left[\frac{W_{F,B}}{W_F'} + \frac{W_{F,C}}{W_F'} + \frac{W_{F,Y}}{W_F'} + \frac{W_{F,S}}{W_F'}\right] + \frac{W_{F,F}}{W_{AF}}$$

where,

$\frac{W_F'}{W_{AF}}$ is the total fuselage weight minus the fixed fuselage weight divided by the airframe weight and the ratios in brackets represent the fractions of this weight designed by the various criteria.

The final term,

$\frac{W_{F,F}}{W_{AF}}$ is the fuselage fixed weight divided by the airframe weight.

For our purposes, the fuselage fixed weight is taken to be 2/3 of the total fuselage weight, i.e.,

$$\frac{W_{F,F}}{W_F} = 2/3; \quad \frac{W'_F}{W_F} = 1/3$$

Expressions for each of the weight elements in the above equation can now be derived as shown in Reference 1. For example, for the buckling criteria, the critical stress level, F_{CR}, for a panel of length (a), width (b), and thickness (t) subject to flat-plate buckling is:

$$F_{CR} = KE\left(\frac{t}{b}\right)^2$$

The maximum load (P) carried by this plate is:

$$P = F_{CR}\ bt$$

and the theoretical weight of the plate is:

$$W = abt\rho$$

Combining these equations and substituting for F_{CR} we obtain:

$$W = \rho_1 \frac{K_B}{E^{0.333}}$$

where,

$$K_B = ab\left(\frac{Pb}{K}\right)^{1/3}$$

The factor K_B does not vary with material properties.

A "Design Factor," F, is now introduced into the equation to account for possible improvements in manufacturing techniques, analysis methods, etc. This factor would have the value 1.0 for the baseline and would increase for improved design techniques. The final equation then is:

<u>Buckling</u> $$W_{F,B} = \left[\frac{\rho_F\ K_{F,B}}{F_{F,B}\ E_F^{0.333}}\right]$$

Similar reasoning leads to the following equations:

Crippling $$W_{F,C} = \left[\frac{\rho_F \, K_{F,C}}{F_{F,C} \, E_F^{0.225} \, f_{cy_f}^{0.325}} \right]$$

Yield $$W_{F,Y} = \left[\frac{\rho_F \, K_{F,Y}}{F_{F,Y} \, f_{cy_F}} \right]$$

Stiffness $$W_{F,S} = \left[\frac{\rho_F \, K_{F,S}}{E_{F,S} \, E_F} \right]$$

Fixed Weight $$W_{F,F} = \left[\frac{\rho_F \, K_{F,F}}{F_{F,F}} \right]$$

A separate design factor is used for each portion of the fuselage so that improvements affecting only the portion of the fuselage designed by one of the four criteria can be taken into account without affecting the remaining weight.

It should be recognized that the three material Technology Parameters (E, fy, ρ) are strongly interrelated and should be treated together as aggregate material Technology Parameters for the fuselage (FMP) and for the wing (WMP).

The "driver partial" with variations in all three material parameters is defined by

$$\frac{\Delta W_F}{W_F} = \frac{(\rho_F + \Delta\rho_F)}{W_F} \left[\frac{K_{F,B}}{F_{F,B}(E_F+\Delta E_F)^{0.333}} + \frac{K_{F,C}}{F_{F,C}(E_F+\Delta E_F)^{0.225}(f_{cy}+\Delta f_{cy})^{0.325}} + \frac{K_{FF}}{F_F} + \frac{K_{F,Y}}{F_{F,Y}(f_{cy}+\Delta f_{cy})} + \frac{K_{F,S}}{F_{F,S}(E_F+\Delta E_F)} \right] - 1$$

Since the parameter changes are small, then

$$\frac{1}{(TP+\Delta TP)^b} \approx \frac{1 - b\left(\frac{\Delta TP}{TP}\right)}{TP^b}$$

Substituting this approximation and the previously defined weight components into the "driver partial" equation, we obtain the following:

$$\left(\frac{\Delta W_F}{W_F}\right)_{FMP} = \frac{\Delta FMP}{FMP}$$

where,

$$\frac{\Delta FMP}{FMP} = \left(\frac{\Delta\rho_F}{\rho_F}\right)\left(1 - \frac{W_{FF}}{W_F}\right) - \left(1 + \frac{\Delta\rho_F}{\rho_F}\right)\left[\left(\frac{\Delta E_F}{E_F}\right)\left\{.333\left(\frac{W_{F,B}}{W_F}\right) + .225\left(\frac{W_{F,C}}{W_F}\right) + \left(\frac{W_{F,S}}{W_F}\right)\right\} + \left(\frac{\Delta f_{cy_F}}{f_{cy_F}}\right)\left\{.325\left(\frac{W_{F,C}}{W_F}\right) + \left(\frac{W_{F,Y}}{W_F}\right)\right\}\right]$$

The design factors can be varied independently and their "driver partials" can be obtained in a similar fashion; therefore,

$$\left(\frac{\Delta W_F}{W_F}\right)_{F_i} = -\frac{\Delta F_{F,i}}{F_{F,i}}\left[\frac{W_{F,i}}{W_F}\right]$$

where i = buckling, crippling, yield stiffness, and fixed weight

Finally, the change in airframe weight produced by a given change in a Technology Parameter is given by

$$\left(\frac{\Delta W_{AF}}{W_{AF}}\right)_{TP} = \left(\frac{\Delta W_F}{W_F}\right)_{TP}\left(\frac{W_F}{W_{AF}}\right)$$

We finally obtain the equations given earlier in Table 4-IV

$$\left(\frac{\Delta W_{AF}}{W_{AF}}\right)_{FMP} = \left(\frac{\Delta FMP}{FMP}\right)\left(\frac{W_F}{W_{AF}}\right)$$

and

$$\left(\frac{\Delta W_{AF}}{W_{AF}}\right)_{F_i} = -\frac{\Delta F_{F,i}}{F_{F,i}}\left(\frac{W_{F,i}}{W_F}\right)\left(\frac{W_F}{W_{AF}}\right)$$

The wing weight is determined in exactly the same way as the fuselage weight to provide

$$\left(\frac{\Delta W_{AF}}{W_{AF}}\right)_{WMP} = \left(\frac{\Delta WMP}{WMP}\right)\left(\frac{W_W}{W_{AF}}\right)$$

$$\left(\frac{\Delta W_{AF}}{W_{AF}}\right)_{F_i} = -\left(\frac{\Delta W_{F,i}}{W_{F,i}}\right)\left(\frac{W_{W,i}}{W_W}\right)$$

where

$$\frac{\Delta WMP}{WMP} = \left(\frac{\Delta\rho_W}{\rho_W}\right)\left(1 - \frac{W_{WF}}{W_W}\right) - \left(1 + \frac{\Delta\rho_W}{\rho_W}\right)\left[\left(\frac{\Delta E_W}{E_W}\right)\left\{.333\left(\frac{W_{W,B}}{W_W}\right) + .255\left(\frac{W_{W,C}}{W_W}\right) + \left(\frac{W_{W,S}}{W_W}\right)\right\} + \left(\frac{\Delta f_{cy_W}}{f_{cy_W}}\right)\left\{.325\left(\frac{W_{W,C}}{W_W}\right) + \left(\frac{W_{W,Y}}{W_W}\right)\right\}\right]$$

Horizontal and vertical surfaces: The horizontal (if any) and vertical surfaces are not a large percentage of the total airframe weight and, in general, are not as likely to be significantly affected by technology changes as the wing and fuselage. Consequently, they will be handled in a simplified manner using only one Technology Parameter, i.e., the design factor, F_E. The equation is:

$$W_E = \left(\frac{W}{A}\right)_E \left(\frac{A_E}{F_E}\right)$$

where,

$\left(\frac{W}{A}\right)_E$ is the average weight per unit area of the surfaces, and

A_E is the total planform area of the surfaces.

The change in surface weight caused by a change in design factor is

$$\frac{\Delta W_E}{W_E} = \left(\frac{\Delta W_E}{\Delta F}\right)\left(\frac{\Delta F}{F}\right)\left(\frac{F}{W_E}\right)$$

or

$$\frac{\Delta W_E}{W_E} = \frac{\left(\frac{\Delta F}{F}\right)}{1 + \left(\frac{\Delta F}{F}\right)}$$

The final equation then is:

$$\frac{\Delta W_{AF}}{W_{AF}} = - \frac{\left(\frac{\Delta F_E}{F_E}\right)}{1 + \left(\frac{\Delta F_E}{F_E}\right)} \left(\frac{W_E}{W_{AF}}\right)$$

Thermal protection weight: The thermal protection weight includes insulation and heat shields where appropriate. This weight is handled in exactly the same way as the horizontal and vertical surface weight. The final equation is:

$$\frac{\Delta W_{AF}}{W_{AF}} = \frac{\left(\frac{\Delta F_{TP}}{F_{TP}}\right)}{1 + \left(\frac{\Delta F_{TP}}{F_{TP}}\right)} \left(\frac{W_{TP}}{W_{AF}}\right)$$

Propellant system weight: The propellant system weight includes the tanks and pressurization system. It is assumed that this weight can be given as a percentage of the total fuel weight, as:

$$W_{PS} = \left(\frac{W}{W_{f_T}}\right)_{PS} \left(\frac{W_{f_T}}{F_{PS}}\right)$$

where,

$\frac{W}{W_{f_T}}_{PS}$ is the weight per unit fuel weight, and

F_{PS} is a design factor.

The final equation is:

$$\frac{\Delta W_{AF}}{W_{AF}} = \frac{\left(\frac{\Delta F_{PS}}{F_{PS}}\right)}{1 + \left(\frac{\Delta F_{PS}}{F_{PS}}\right)} \left(\frac{W_{PS}}{W_{AF}}\right)$$

Miscellaneous systems weight: This category includes landing gear, power, power distribution, hydraulics and all other airframe subsystems not included elsewhere. For this study, it is assumed that the miscellaneous systems weight is a constant.

Turbojet propulsion specific weight.- The turbojet weight fraction can be expressed as:

$$\frac{W_{TJ}}{W_{GTO}} = \left(\frac{W_{TJ}}{T_{TJ}}\right)\left(\frac{T}{W}\right)_{GTO}$$

where,

$\left(\frac{W}{T}\right)_{TJ}$ is the total installed turbojet propulsion system specific weight including ducting.

This parameter can be related to the engine alone specific weight as:

$$\left(\frac{W}{T}\right)_{TJ} \cong 1.67 \left(\frac{W}{T}\right)_{ENG}$$

The parameter $\left(\frac{W}{T}\right)_{ENG}$ is the parameter for which technology projections will be made in Module 5.

Ramjet Sizing Parameter.- The ramjet sizing parameter is defined as $\left(\frac{W_{RJ}}{A_C\ C_{TRJ}}\right)$ and is composed of two Technology Parameters, the ramjet specific weight and the ramjet thrust coefficient. Changes in these parameters produce changes in the ramjet sizing parameter as follows:

$$\frac{\Delta\left(\frac{W_{RJ}}{A_C C_{TRJ}}\right)}{\left(\frac{W_{RJ}}{A_{CTRJ}}\right)} = \frac{\Delta \frac{W_{RJ}}{A_C}}{\left(\frac{W_{RJ}}{A_C}\right)}$$

$$\frac{\Delta\left(\frac{W_{RJ}}{A_C C_{TRJ}}\right)}{\left(\frac{W_{RJ}}{A_C C_{TRJ}}\right)} = -\frac{\left(\frac{\Delta C_{TRJ}}{C_{TRJ}}\right)}{1+\left(\frac{\Delta C_{TRJ}}{C_{TRJ}}\right)}$$

Lift-to-Drag Ratio.- The vehicle cruise L/D can be written as

$$L/D = \frac{C_L}{C_D}$$

where $C_D = C_{DO} + C_{Di}$

C_{Do} = zero lift drag coefficient and

C_{Di} is the induced drag coefficient

The induced drag coefficient can be written as

$C_{Di} = \left(\frac{C_{Di}}{C_L 2}\right) C_L 2$ where $\frac{C_{Di}}{C_L 2}$ is the induced drag factor. Both C_{Do} and $\frac{C_{Di}}{C_L 2}$ are taken as Technology Parameters. To find the change in L/D for a given change in these parameters we use:

$$\frac{\Delta L/D}{L/D} = \left(\frac{\delta L/D}{\delta TP}\right)\left(\frac{\Delta TP}{TP}\right)\left(\frac{TP}{L/D}\right)$$

Zero-lift drag coefficient: The partial derivative of L/D with C_{D_o} is given by:

$$\frac{\delta L/D}{\delta C_{D_o}} = \frac{-C_L}{\left(C_{D_o} + \frac{C_{D_i}}{C_L^2} C_L^2\right)^2}$$

The change in L/D then is given by:

$$\frac{\Delta L/D}{L/D} = \frac{-C_L}{\left(C_{D_o} + \frac{C_{D_i}}{C_L^2} C_L^2\right)^2} \quad \frac{\left(\frac{C_{D_o}}{C_L}\right)}{\left(C_{D_o} + \frac{C_{D_i}}{C_L^2} C_L^2\right)} \quad \left(\frac{\Delta C_{D_o}}{C_{D_o}}\right)$$

or

$$\frac{\Delta L/D}{L/D} = -\frac{C_{D_o}}{C_D}\left(\frac{\Delta C_{D_o}}{C_{D_o}}\right)$$

Induced drag factor: The change in L/D for a change in the induced drag factor is found in exactly the same way as done above:

$$\frac{\Delta L/D}{L/D} = \frac{\left(\frac{C_{D_i}}{C_L^2}\right)}{C_L^2\ C_D}\left(\frac{\Delta C_{D_i}/C_L^2}{C_{D_i}/C_L^2}\right) = -\frac{\left(C_D - C_{D_o}\right)}{C_D}$$

Specific fuel consumption.- The ramjet cruise specific fuel consumption is a function of the engine design and operating characteristics as well as the type fuel used and the combustion mode. A review of the available propulsion literature has shown that a consistent set of data coupling all the above parameters is not readily available. One set of consistent data for a particular engine design was obtained from unpublished Marquardt Corporation data. Analysis of this set of data has resulted in the following set of equations relating changes in the Technology Parameters η_K, η_C, and η_{KN} (inlet efficiency, combustion efficiency and nozzle efficiency) to changes in sfc.

Inlet efficiency $$\frac{\Delta sfc}{sfc} = -0.195 \frac{\Delta \eta_K}{K}$$

Combustion efficiency $$\frac{\Delta sfc}{sfc} = -0.730 \frac{\Delta \eta_C}{C}$$

Nozzle efficiency $$\frac{\Delta sfc}{sfc} = -2.93 \frac{\Delta \eta_{KN}}{KN}$$

The user is cautioned that these equations were developed using a single set of hydrogen fueled, Mach 6 ramjet data and its applicability to a wide range of fuels and conditions is questionalbe. Their use should be limited to vehicles similar to the baseline described in Module 2.

METHOD MODULE 5

TECHNOLOGY PROJECTIONS

METHOD MODULE 5 - TECHNOLOGY PROJECTION METHODOLOGY

Logic

The function of the subject methodology is to provide estimates of the potential technology improvements which could impact the operating cost of a cruise hypersonic transport aircraft (HST).

The estimates of the technology improvements are to be made by specialists in the affected technology areas (e.g., aerodynamics). The estimates may be derived by a judgmental process, but the rationale for the judgment is to be documented. The rationale will include such considerations as the technology incorporated into the baseline aircraft, historical trends, fundamental physical limits, and the specialists' conception of future developments to the end of the century.

To promote consistency across the range of technology projections, the specialists will be provided a "Technological Scenario." The scenario will present a framework of perspectives and conditions within which the HST technological developments may be assumed to unfold. An example of a Technological Scenario is given in the Demonstration section of this module.

The specialists are also to be provided the results of Method Module 2.- Baseline HST Definition. That module generates a comprehensive understanding of the baseline HST, its technology state of the art, and the specific baseline values for the Technology Parameters.

The Technology Parameters listed in Table 5-I are terms expressive of the state of the art within specific technology areas and which have quantitative relationships (reference Module 4.- Technology Parameter Equations) with the Drivers.

The parameters are listed within four technology areas: aerodynamics; propulsion; airframe design; and materials. The aerodynamics parameters are identified for the complete airframe configuration; at the option of the user, these parameters may be subdivided into wave, friction, and interference drag for the isolated and integrated aero surfaces. The propulsion parameters denote state-of-the-art values (C_{TRJ}, $(W/A_C)_{RJ}$, $(W/T)_{TJ}$) for engine thrust and weight and ramjet cycle efficiencies affecting specific fuel consumption. The airframe design parameters, $F_{(\ )}$, and aggregate material parameters (FMP, WMP) are values affecting airframe structural weight. For the present method, the parameters apply only to the prime structure of the fuselage and wing elements of the airframe. The aggregate material parameters are synthesized terms

TABLE 5-I.- TECHNOLOGY PARAMETERS

Aerodynamics	
C_{D_o}	zero-lift drag coefficient
C_{D_i}/C_L^2	induced drag factor
Propulsion	
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)
$(W/A_C)_{RJ}$	ramjet specific weight, kg/m^2 (lb/ft^2)
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a Driver Parameter)
η_K	ramjet inlet kinetic energy efficiency
η_C	ramjet combustion efficiency
η_{KN}	ramjet nozzle kinetic energy efficiency
Aggregate materials properties	
FMP	fuselage material properties
WMP	wing material properties

TABLE 5-I.- TECHNOLOGY PARAMETERS - Concluded

<u>Airframe design</u>	
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)
$F_{W,F}$	design factor for wing structure not designed by primary loads
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)
$F_{F,F}$	design factor for fuselage structure not designed by primary loads
F_E	design factor for empennage weight (= 1.00 for baseline)
F_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)
F_P	design factor for propellant system weight (= 1.00 for baseline)

(developed in Module 4) which reflect the resultant impact which material properties (ρ, fcy, and E) have upon fuselage and wing structural weight. The purpose of these terms is to correlate the interdependent effects which advanced materials properties would have upon weight. The design parameters are factors reflecting the state of the art of analysis and manufacturing. By definition, these factors apply inversely to the weights of the airframe components and are unity for the baseline. As knowledge, techniques, and tools improve in the areas of thermal and structural analysis, material properties, and fabrication, the design factors would be expected to exceed unity.

With the inputs listed below, the technology specialists shall prepare their estimates of the potential improvements in the Technology Parameters and submit their products as directed.

Input Data

The following information shall be input to this module:

HST baseline data (re: Module 2, Tables 2-III and 2-IV).-

Mission definition:

(W_{PL}, M, R_T)

(Mission profile)

Performance characteristics:

(L/D, sfc, W_{f_T}/W_{GTO})

Operational characteristics:

(t_F, U, L_d)

Vehicle characteristics:

(Configuration; general arrangement)

($(W/S)_{GTO}$, C_D, C_L)

(N_{TJ}, T_{TJ}, $(T/W)_{GTO}$)

(A_C, N_{RJ}, C_{TRJ}, C_D/C_{TRJ})

Weight characteristics:

(Summary weight statement)

$((W/T)_{TJ}, \quad (W/A_C)_{RJ}$

Design description:

(Wing structure, materials)

(Empennage structure, materials)

(Fuselage structure, materials)

(Tankage structure, material)

(Thermal management)

(Propulsion systems installation)

(Turbojet description)

(Ramjet description)

(Avionics)

(Equipment)

Technology parameters: The baseline Technology Parameters shall have been specified in the format shown in the Demonstration section (Table 5-VI) of this module.

Technological scenario (re: Module 1).-

Procedures

1. The specialist shall review the input data for information relevant in his technology area(s).

2. For each Technology Parameter as listed in Table 5-I, the specialist shall forecast the potential technology improvement(s) and prepare a Technology Projection Sheet, as shown on figure 5-1. These improvements shall be projected within the framework of the Technological Scenario. They are to be summarized in Table 5-II.

Technology Parameter: (1) ______

Baseline Value: (2) ______

Baseline Reference Report: (3) ______

Technology Parameter Improvement:

Basis for Estimate	% Improvement
≈90% (Conservative)	______
≈50% (Probable)	(4) ______
≈10% (Optimistic)	______

Rationale (use additional page, as required):

(5)

Submitted by:

Name: ______
Mail Code: ______
Telephone: ______
Date: ______

Figure 5-1.- Sample format: Technology Projection Sheet
(See Attachment for notes of explanation)

Attachment to Figure 5-1.- Notes of explanation

(1) Enter the name and symbol of the Technology Parameter, e.g., zero-lift drag coefficient, C_{D_o}.

(2) Enter the value from the input data.

(3) Enter the document references which provide the basis for the Baseline Value.

(4) At a minimum, enter the 50% confidence-level (CL) estimate as a percentage of the baseline value. The higher and lower CL estimates are desired, but not mandatory. The 50% CL estimate is considered to be as likely to be attained as it is not to be attained.

(5) Enter a narrative rationale supportive of the probable estimate. The rationale may use historical trends and/or future expectations.

TABLE 5-II.- TECHNOLOGY PROJECTION SUMMARY - REQUIRED OUTPUT FROM MODULE 5

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
Aerodynamics				
C_{D_o}	zero-lift drag coefficient			
$C_{D_i}/C_L{}^2$	induced drag factor			
Propulsion				
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_c)			
$\left(W/A_c\right)_{RJ}$	ramjet specific weight, kg/m^2 (lbf/ft^2)			
η_K	ramjet inlet kinetic energy efficiency			
η_C	ramjet combustion efficiency			
η_{KN}	ramjet nozzle kinetic energy efficiency			
$\left(W/T\right)_{TJ}$	turbojet propulsion specific weight (also identified as a Driver Parameter)			

TABLE 5-II.- TECHNOLOGY PROJECTION SUMMARY - REQUIRED OUTPUT FROM MODULE 5 - Continued

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
Airframe design				
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)			
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)			
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)			
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)			
$F_{W,F}$	design factor for wing structure not designed by primary loads (= 1.00 for baseline)			
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)			
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)			
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)			
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)			

TABLE 5-II.- TECHNOLOGY PROJECTION SUMMARY - REQUIRED OUTPUT FROM MODULE 5 - Concluded

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
$F_{F,F}$	design factor for fuselage structure not designed by primary loads (= 1.00 for baseline)			
F_E	design factor for empennage weight (= 1.00 for baseline)			
T_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)			
F_P	design factor for propellant system weight (= 1.00 for baseline)			
Aggregate materials properties				
FMP	fuselage material properties			
WMP	wing material properties			

a. In forecasting improvements in the aggregate material parameters, the individual properties (ρ, fcy, E) of advanced materials shall be entered into the following expressions:

(2) $$\frac{\Delta FMP}{FMP} = \left(1 + \frac{\Delta\rho_F}{\rho_F}\right)\left[1 - \left(\frac{\Delta E_F}{E_F}\right)\left(0.33\,\frac{W_{F,B}}{W_F'} + 0.23\,\frac{W_{F,C}}{W_F'} + \frac{W_{F,S}}{W_F'}\right) - \left(\frac{\Delta f_{cy}}{f_{cy}}\right)\left(0.33\,\frac{W_{F,C}}{W_F'} + \frac{W_{F,Y}}{W_F'}\right)\right] - 1$$

(3) $$\frac{\Delta WMP}{WMP} = \left(1 + \frac{\Delta\rho_W}{\rho_W}\right)\left[1 - \left(\frac{\Delta E_W}{E_W}\right)\left(0.33\,\frac{W_{W,B}}{W_W'} + 0.23\,\frac{W_{W,C}}{W_W'} + \frac{W_{W,S}}{W_W'}\right) - \left(\frac{\Delta f_{cy}}{f_{cy}}\right)\left(0.33\,\frac{W_{W,C}}{W_W'} + \frac{W_{W,Y}}{W_W'}\right)\right] - 1$$

where the weight ratios are obtained from Table 5-III. (Note: The weight ratios shown are appropriate to the accuracy requirements of this method. If, however, estimates are available for the specific baseline HST design, it is suggested they be used in lieu of Table 5-III.)

b. In forecasting the improvement in turbojet propulsion specific weight, $(W/T)_{TJ}$, the projection should be made as a percentage improvement for the specific weight of the dry delivered engine, and then factored by 0.6 to reflect the overall turbojet propulsion improvement.

3. All Technology Projection Sheets shall be collected and compiled within a summary table as shown in Table 5-II.

TABLE 5-III.- APPROXIMATE WEIGHT RATIOS FOR PRIME STRUCTURAL ELEMENTS OF HYPERSONIC TRANSPORT AS DESIGNED BY VARIOUS CRITERIA

Design criterion	Element, symbol	Weight Ratio: Sandwich panel construction	Weight Ratio: Skin-stiffened construction
Buckling	Fuselage, $\frac{W_{F,B}}{W_F'}$	0.40	0.50
	Wing, $\frac{W_{W,B}}{W_W'}$	0.33	0.20
Crippling	Fuselage, $\frac{W_{F,C}}{W_F'}$	0.25	0.10
	Wing, $\frac{W_{W,C}}{W_W'}$	0.21	0.10
Stiffness	Fuselage, $\frac{W_{F,S}}{W_F'}$	0.05	0.05
	Wing, $\frac{W_{W,S}}{W_W'}$	0.10	0.10
Yield	Fuselage, $\frac{W_{F,Y}}{W_F'}$	0.30	0.30
	Wing, $\frac{W_{W,Y}}{W_W'}$	0.41	0.60

Output Data

The output of this module shall be Technology Projection Sheets (reference figure 5-1), corresponding to the Technology Parameters given in Table 5-I, and the Technology Projection Summary shown in Table 5-II.

DEMONSTRATION

This section provides a typical example of how the procedures of this method module are to be applied. The example given below includes data from the HST baseline defined in Module 2 of this report. The selection of data and format responds to the preceding "Input Data" requirements.

Input Data

HST baseline data.-

Mission definition: The design mission for the baseline HST is summarized in terms of payload, cruise Mach number, and range (reference Tables 2-VII and 2-VIII). The payload may be either cargo or passengers.

Payload weight, W_{PL} = 22 700 kg (50 000 lb)

Cruise Mach number, M = 6

Operational range, R = 7400 km (4600 miles)

The baseline mission is further described by the flight profile, figure 5-2. Cruise altitude for the Breguet path varies from 27 600 m (90 600 ft) to 28 800 m (94 600 ft). The operational range is the sum of climb, cruise and descent (including loiter) components. Climb and descent components are estimated from reference 1 data.

Performance characteristics: Major technology-oriented performance descriptors in addition to cruise Mach number are the lift-drag ratio, specific fuel consumption and fuel/gross weight fraction terms of the Breguet cruise range equation. (Climb, descent, and reserve fuel factors are considered operational parameters here.) Illustrative baseline values for the primary terms and the associated cruise range are tabulated below:

Lift-drag ratio, L/D = 4.6

Specific fuel consumption, sfc = 0.113 kg/N-hr (lb_m/lb_f-hr)

Fuel weight fraction, W_{f_T}/W_{GTO} = 0.3178

Cruise range, R_{CR} = 5180 km (3220 miles)

(Sources: Reference 1)

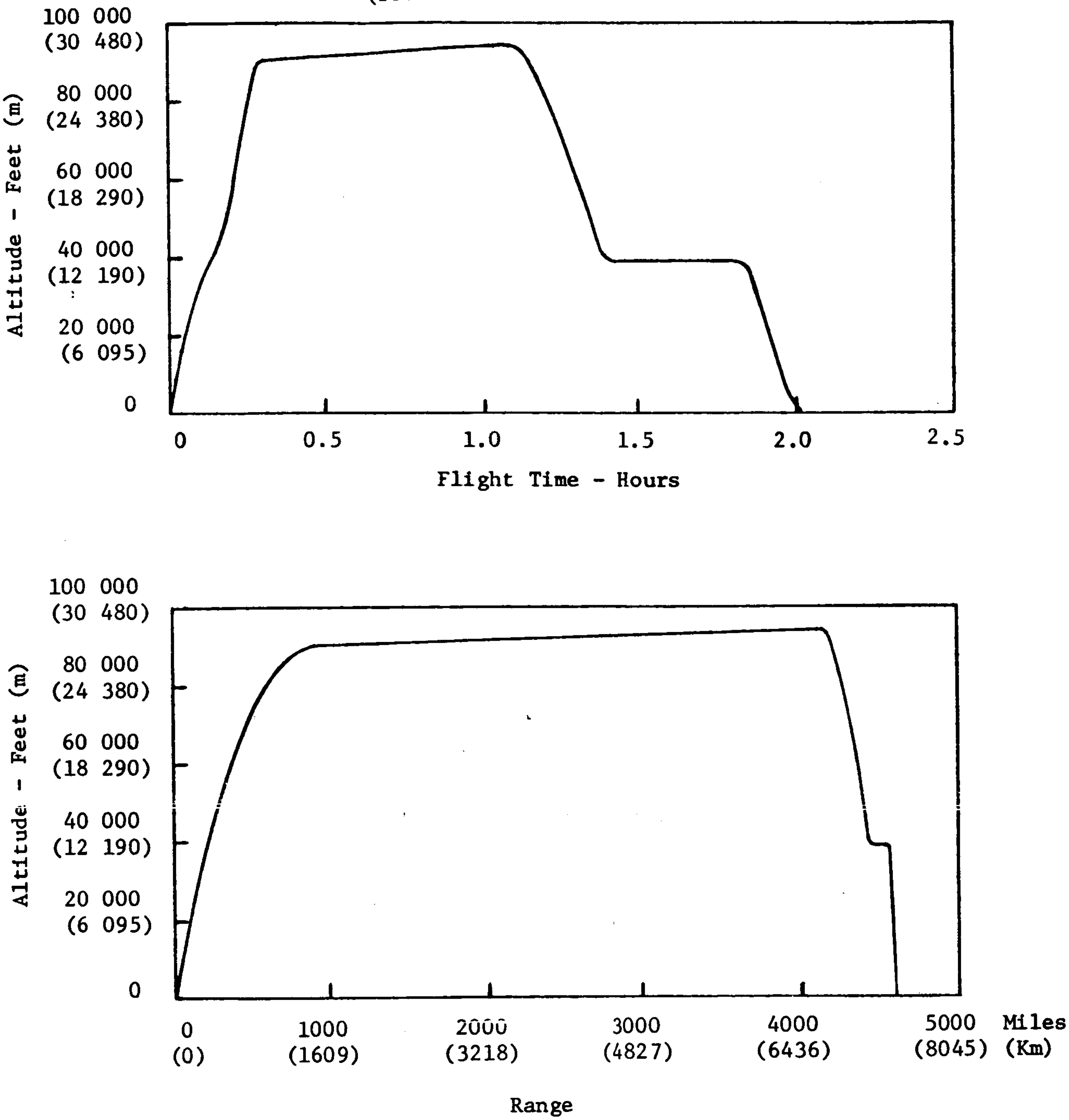

Figure 5-2.- Flight Profile

Operational characteristics: The HST will be required to operate safely and reliably, with routine maintenance, over an extended time period. Key related operational characteristics are:

Time of flight, $t_F = 2.0$ hr

Block time, $t_B = 2.25$ hr

Average utilization, $U = 3000$ block hr/yr

Depreciable life, $L_d = 10$ yr

Utilization during depreciable life = 30 000 block hr

Nonutilization during depreciable life = 57 600 hr

Flight time during depreciable life = 26 700 hr

Flight cycles during depreciable life = 13 350

Vehicle characteristics: The configuration of the baseline HST has been derived from that described in reference 2. The reference configuration features (1) a body width-height ratio of 2 to improve the lifting capability of the fuselage, (2) negative camber in the forward fuselage to minimize trim drag penalties on maximum lift-drag ratio, (3) strakes to retard windward pressure bleed-off at angle of attack, and (4) wing-body blending to minimize adverse component interference effects. The wing leading edge is swept 65°. Pitch control and trim are effected with ailerons. The single vertical tail is swept 60°. A split rudder provides directional control.

The general arrangement of the baseline HST used in this demonstration is shown in figure 5-3. The illustrative configuration is similar to the reference 2 model with the following modifications: (1) the underside of the forward fuselage is shaped to provide a continuous precompression surface for the turbojet and ramjet inlets; (2) the fuselage depth at the ramjet engine installation is increased to accommodate the combined turbojet and ramjet installation concept from reference 3; (3) the fuselage afterbody is modified to integrate the ramjet exhaust nozzle and to incorporate the turbojet engines; (4) the vertical tail is reduced to 64 percent of the reference 1 area based on interpretation of the wind tunnel data.

Liquid hydrogen fuel is carried in non-integral tanks located in the forward and aft fuselage sections. Multicell or "pillow" fuel tank configurations provide for efficient use of the available volume while maintaining moderate tank frame weights. The payload compartment is located at the c.g. for balance

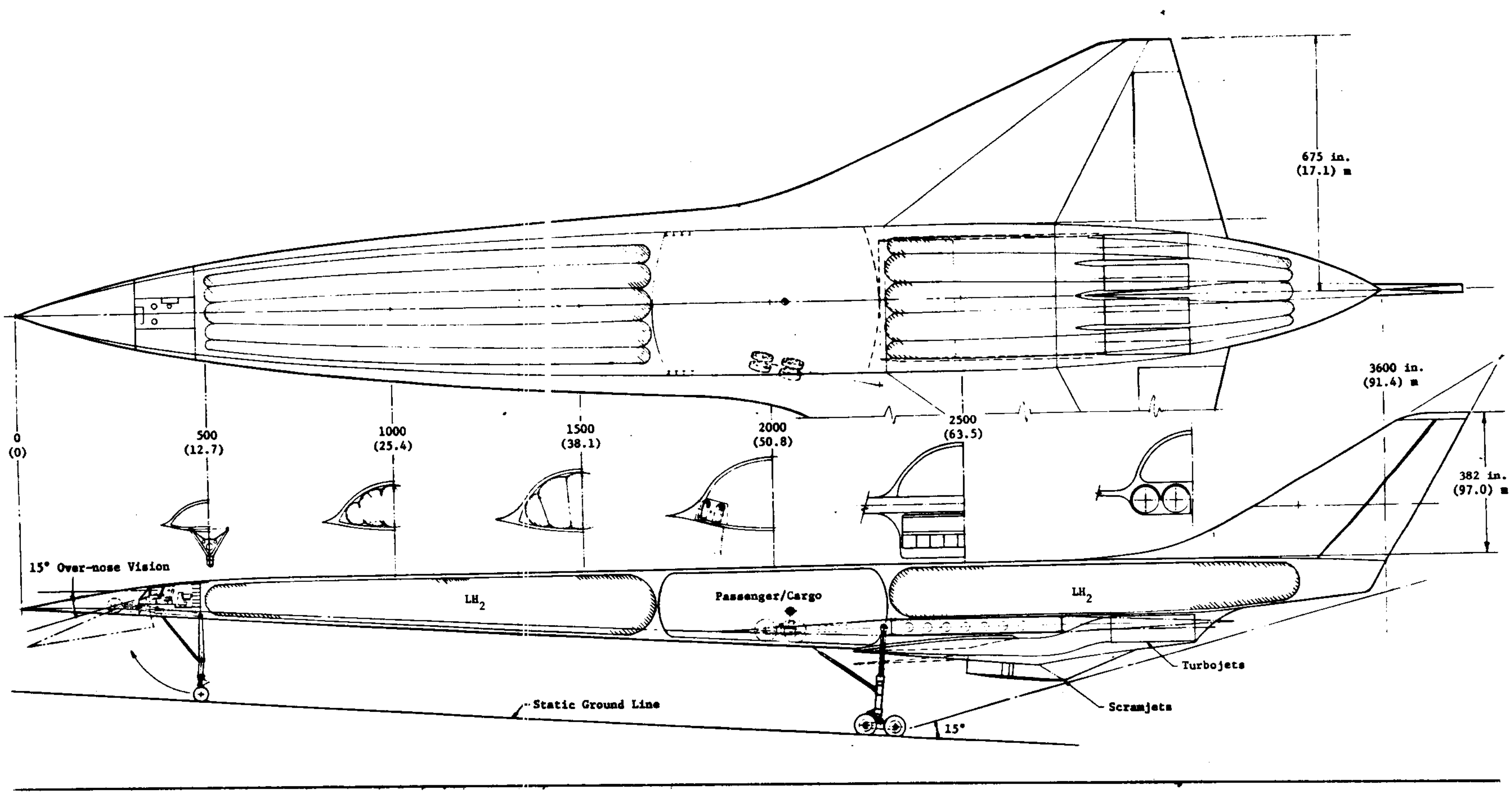

Figure 5-3.- Baseline Hypersonic Transport

control. The payload compartment structure is integral with the fuselage structure. An inert gas, helium in this example, occupies the space surrounding the liquid hydrogen tanks and the space between the payload compartment pressure vessel and the fuselage covers. There is no access from the payload to the forward crew compartment.

Quantitative summary characteristics of the illustrative baseline HST airplane are tabulated below:

Fuselage length, l = 91.4 m (300 ft)

Reference area (projected wing), S = 866 m^2 (9323 ft^2)

Wing loading at take-off, $(W/S)_{GTO}$ = 252 kg/m^2 (51.6 lb/ft^2)

Airplane drag coefficient at cruise, C_D = 0.0112

Airplane lift coefficient at cruise, C_L = 0.0515

Number of turbojets, N_{TJ} = 4

SLS thrust per turbojet, T_{TJ} = 258 000 N (58 000 lb)

Max. thrust-weight ratio at take-off, $(T/W)_{GTO}$ = 0.482

Ramjet total cowl area, A_C = 7.73 m^2 (83.2 ft^2)

Ramjet thrust coefficient at cruise C_{TRJ} = 1.255

Ramjet transition (take-over) Mach number = 3.0

Weight characteristics: The estimated weights of the illustrative baseline HST are summarized in Table 5-IV. The weight estimates are based primarily on reference 1 data as adjusted and applied to the configuration shown in figure 5-3.

Summary weight and related fractions are:

Dry airframe/gross take-off weight, W_e/W_{GTO} = 0.5641

Payload/gross take-off weight, W_{PL}/W_{GTO} = 0.1038

Main fuel/gross take-off weight, W_{f_T}/W_{GTO} = 0.3178

Turbojet engine specific thrust, $T_{TJ}/W_{TJ\ engine}$ = 9.3

Ramjet specific weight, W_{RJ}/A_C = 951 kg/m^2 (195 lb/ft^2)

TABLE 5-IV.- WEIGHT SUMMARY— BASELINE HST AIRCRAFT

Group	Item	Weight kg	Weight lb
Aero Structure, W_W	Wing	14 800	32 600
W_E	Vertical Tail	3 100	6 900
Body Structure, W_F	Covers	15 300	33 600
	Frames	4 700	10 400
	Compartments	7 900	17 410
Propellant Systems, W_{PS}	Tanks	15 000	32 900
	Fuel/Pres/Lub Systems	2 400	5 200
Thermal Protection, W_{TP}	External Shields	4 600	10 200
	Cooling System	6 900	15 300
	Compartment Insulation	500	1 200
	Tank Insulation	3 400	7 590
Turbojet Propulsion, W_{TJ}	Turbojet Engines	11 400	25 000
	Turbojet Air Induction	5 500	12 000
Scramjets, W_{RJ}		7 400	16 200
Avionics, W_{AV}		1 450	3 200
Equipment, W_{Equip}	Launch and Recovery	8 200	18 100
	Prime Power & Distribution	3 500	7 800
	Payload Provisions	7 270	16 000
	Dry Airplane, W_e	123 000	271 600
Personnel, Residuals and Prime Power Reserve[(1)]		1 140	2 500
Payload, W_{PL}		22 700	50 000
	Wet Airplane & Payload	147 000	324 100
In-Flight Losses[(1)]		2 000	4 300
Main Fuel, W_{f_T}		69 400	153 000
	Gross Take-Off Weight, W_{GTO}	218 400	481 400

	kg	lb
[(1)] Sum is W_{Misc}	3 080	6 800
Note: $W_{AF} = W_{GTO} - W_{f_T} - W_{TJ} - W_{RJ} - W_{AV} - W_{PL} - W_{Misc}$	97 600	215 200

Design description: The following paragraphs present a summary description of the illustrative HST design. The descriptions provide a reference for assessing the technology level inherent in the HST example for this methodology demonstration.

Wing structure, materials The wing is a partially shielded 7075-T6 aluminum alloy structure convectively cooled to a mean temperature of 367 K (200°F). The multi-beam, multi-rib structural design concept shown in figure 5-4 is assumed. Coolant passages are integral with the Z stringer-stiffened skin as indicated. Minimum skin thickness is 1.6 mm (0.063 inches).

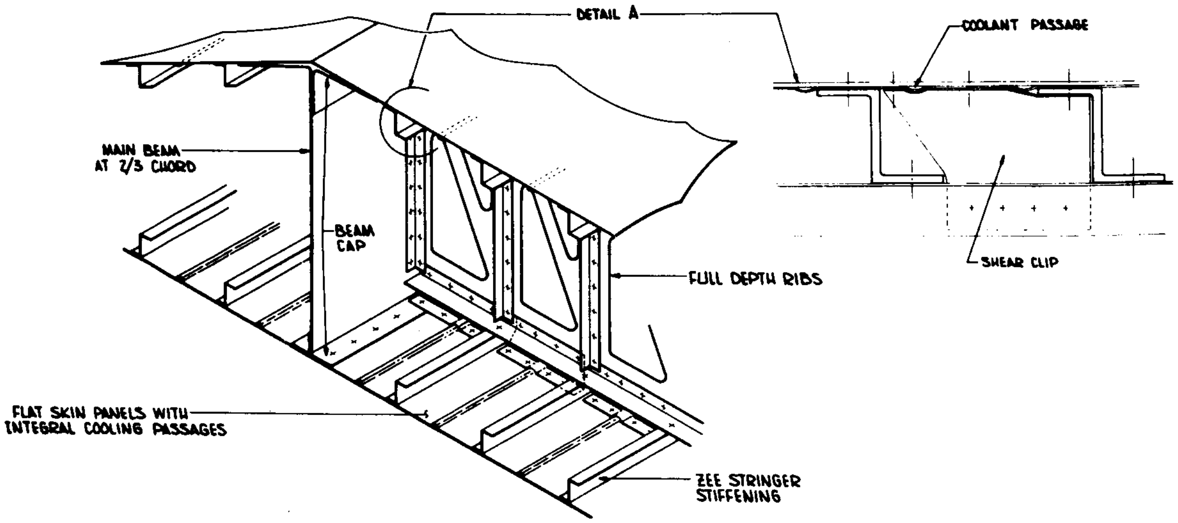

Figure 5-4.- Cooled Wing - Structural Concept

The wing has a symmetrical wedge-bar-wedge cross section with a thickness ratio, t/c, of 0.03. To achieve a small leading edge radius, the unshielded, cooled leading edge concept employs a flat, machined block having closely spaced coolant passages sealed with a cover skin.

Water-glycol coolant is circulated through all coolant passages in a closed-loop system to absorb incident aerodynamic heat and transfer it to a heat exchanger for rejection to the hydrogen fuel.

An air gap/radiation external shield on the lower surface aft of the unshielded leading edge section reduces the cooling system thermal load and heat rates. The external shield is assumed to be fabricated of TD nickel.

Wing component weights are based on the following unit values:

Main structure	26 kg/m^2 (5.41 lb/ft^2)
Cooling system	4.5 kg/m^2 (0.93 lb/ft^2)
Heat shield	4.4 kg/m^2 (0.9 lb/ft^2)

Empennage structure, materials The baseline configuration employs a fixed vertical tail with a split rudder and has no horizontal tail. The vertical tail has an area of 94.8 m^2 (1020 ft^2). With the rudder surfaces at 2° incidence to the center line, the effective thickness ratio of the single wedge is 0.07.

The vertical tail is an uncooled Inconel 718 structure. Operating temperature is assumed to be 811 K (1000°F). The baseline design has a unit weight of 29 kg/m^2 (5.9 lb/ft^2). The same unit weight is applied to each 32.5 m^2 (350 ft^2) section of the split rudder.

Fuselage structure, materials The structural materials and cooling system concept for the fuselage are consistent with the wing structural/cooling system concept. The airframe is 7075-T6 aluminum alloy cooled to an average temperature of 367 K (200°F). Cooling is by means of the indirect convective cooling system employing water-glycol as a heat transport fluid at 1.03 x $10^6 N/m^2$ (150 psi). The heat load is transferred to the liquid hydrogen heat sink through a heat exchanger. Heat shields are employed over portions of the fuselage subject to highest heat loads (radiation equilibrium temperature exceeds 811 K (1000°F). This limits the capacity and weight of the coolant system and reduces the portion of the hydrogen heat sink required for fuselage cooling.

Inverted hat section stiffeners are assumed for the skins. The hat sections, per reference 1, typically are on about 0.07-m (2.6-in.) centers. Zee-section ring frames have spacing variations between 0.51 m (20 in.) and 1.02 m (40 in.). A minimum gauge of 1.0 mm (0.040 in.) is used for the cooled aluminum alloy skins.

Frame weight estimates are based on a pressure differential of 1380 N/m^2 (0.2 psi) across the fuselage covers and a relatively flat underside 1.7 times the width of the design in reference 1. Frame weight, therefore, is estimated to be $(1.7)^{1.5} = 2.22$ times the reference 1 value.

Tankage structure, materials In establishing tank sizes, it is assumed that the airframe structure extends seven inches from the mold lines and that three inches are required for tank insulation and to accommodate relative deflections. An effective density of 68.1 kg/m^3 (4.25 lb/ft^3), including ullage, is used for liquid hydrogen tank sizing. As noted previously under "HST Baseline Data," the fore and aft-located main hydrogen tanks are of multicell structural configuration.

The tanks are designed to a working pressure of 172 000 N/m^2 (25 psi) and a burst pressure of 344 000 N/m^2 (50 psi). The general tank structural arrangement, per reference 1, consists of an integrally stiffened pressure shell with internal rings necessitated by the bending moments induced due to the fuel weight and methods of support. Tension membranes are employed at the cell intersections. Support is provided at two major rings while lighter rings are used on 1.0 m (40-in.) centers to aid in stiffening the shell. Integral stiffeners are used to stabilize the shell against buckling. The tanks have elliptical heads. The material in Inconel 718. Ultimate tensile strength for a 20 000 cycle fatigue life and temperature of 256 K (0°F) above the ullage is about 938×10^6 N/m^2 (136 000 psi). Skin thickness is 1.0 mm (0.040 in.).

The estimated weight per unit volume of the multi-cell tanks is 14 kg/m^3 (0.89 lb/ft^3).

Thermal management Thermal management, as summarized here, includes fuel tank and compartment insulation and the limiting of thermal inputs to the sink capacity of the engine fuel flow.

Hermetically sealed, polyurethane foam insulation panels are adopted in the baseline for thermal isolation of the liquid hydrogen tanks. Sealing to prevent cryopumping is by means of multiple layers of plastic film which are bonded and secured to the fuel tank walls. The polyurethane foam panels have a density of 32 kg/m^3 (2 lb/ft^3) and a maximum thickness of 1.9 cm (0.75 in.). The insulation system weight includes a helium purge system and hydrogen boil-off during a 30-minute ground hold.

The payload compartment pressure vessel is supported by fuselage frames which are a part of the 367 K (200°F) cooled airframe structure. Ends of the compartment are adjacent to the main fuel tanks. The purge gas between the compartment and tanks is estimated to be at about 250K (-10°F). The thermal management concept for the compartment includes a combination thermal/sound insulation and a heat exchanger system.

Through the use of air-gap thermal shields on the undersurface of the wing, active cooling of the wing to 367 K (200°F) utilizes about 20 percent of the available heat capacity of the hydrogen fuel flow. Similarly, by use of thermal shields over portions of the fuselage covers to minimize cooling loads, active cooling of the fuselage requires about 30 percent of the liquid hydrogen available heat capacity. Thus, 50 percent is available for cooling the scramjet engines.

Propulsion systems installation The illustrative baseline HST utilizes a liquid hydrogen-fueled, air-breathing engine, referred to generically as a "turbojet" engine, for initial acceleration and climb, and for final descent, loiter and landing phases. The turbojet accelerator engine is a bypass type. Cruise propulsion is provided by an integrated array of supersonic combustion, scramjet engines. This is a specific application within the broader term "ramjet" which is employed in this method module. The dual-combustion-mode scramjet is used in conjunction with the turbojet during the mid-acceleration phase and develops all of the acceleration and cruise propulsive thrust after turbojet shut-down (Mach 3 in this example).

The turbojet installation is integral within the fuselage, and the scramjet installation is integrated both geometrically and aerodynamically with the fuselage. The resulting over and under arrangement, shown earlier in figure 5-3, is adapted from the concept presented in reference 3.

In this installation concept the turbojets require a large adjustable inlet door and variable internal geometry to match the airflow requirements of the engines over the Mach 0-3 range. The adjustable inlet door closes-off the turbojet ducting above Mach 3 and serves as a precompression ramp for the integrated scramjet engines. Boundary layer build-up over the 63 m (208 ft) of body length forward of the inlet is expected to pose a significant problem which may be alleviated with a diverter system.

The scramjet array, including its integral nacelle, is detachable from the basic airframe. However, scramjet weight estimates assume that, after installation the deep body frames will contribute to support of the adjacent scramjet surfaces.

Turbojet description On the basis of comparison of six candidate engine types, a hydrogen-burning design designated "Pratt and Whitney STF-230A, fuel-rich turbofan ramjet" was selected as the most suitable accelerator propulsion system. The engine features the highest ratio of thrust over the Mach 0.3-to-3.0 range to the sea-level static rating. Specific fuel consumption is less than 0.08 kg/N-hr (0.8 lb_m/lb_f-hr) in the low supersonic Mach number range, but is higher than other candidate engines, sfc = 0.096 kg/N-hr (0.95 lb_m/lb_f-hr) at low subsonic speeds.

The four accelerator engines in the illustrative design are scaled from the STF-230A engine. The thrust scaling factor is 0.773 for a SLS thrust rating of 258 000 N (58 000 lb) per engine. Predicted engine specific thrust, $T_{TJ}/W_{TJ\ engine}$, is 9.3.

Ramjet description The ramjet propulsion system for the HST airplane example is a horizontal array of nine parallel engines or modules. The engines are in the air stream throughout flight and operate from low transonic Mach numbers through the acceleration and cruise phases. For effective performance over the Mach number range, the engines incorporate variable geometry throats as shown in figure 5-5. At lower Mach numbers, the throats may be opened to more than 3 times the minimum area at Mach 6 cruise conditions. The variable geometry also facilitates inlet starting, permits attainment of higher inlet capture area ratios, and reduces spillage drag. Throat geometry is varied by lateral movement of side plates and corresponding swiveling of outboard fuel struts. To accommodate angular movement of the side plates, the upper and lower surfaces are parallel. To produce the desired parallel flow conditions in the vertical plane, normal wedges are employed in the inlet. The forward portion of the inlet wedges and cowl surface are of fixed geometry.

The scramjet engines operate in a dual mode: supersonic combustion at Mach 6 cruise conditions and subsonic combustion at transonic and lower supersonic flight Mach numbers. Supersonic combustion is selected for the baseline cruise conditions as recommended in reference 3 to reduce engine air induction system length and weight, and to minimize the engine thermal load for the active cooling system.

Performance characteristics of the dual-mode scramjets are presented in Table 5-V.

Avionics The avionics systems for the baseline HST are: guidance and navigation, instrumentation and communications. Estimated weights are from reference 1.

Guidance and navigation,	W = 360 kg (800 lb)
Instrumentation,	W = 180 kg (400 lb)
Communications,	W = 910 kg (2000 lb)

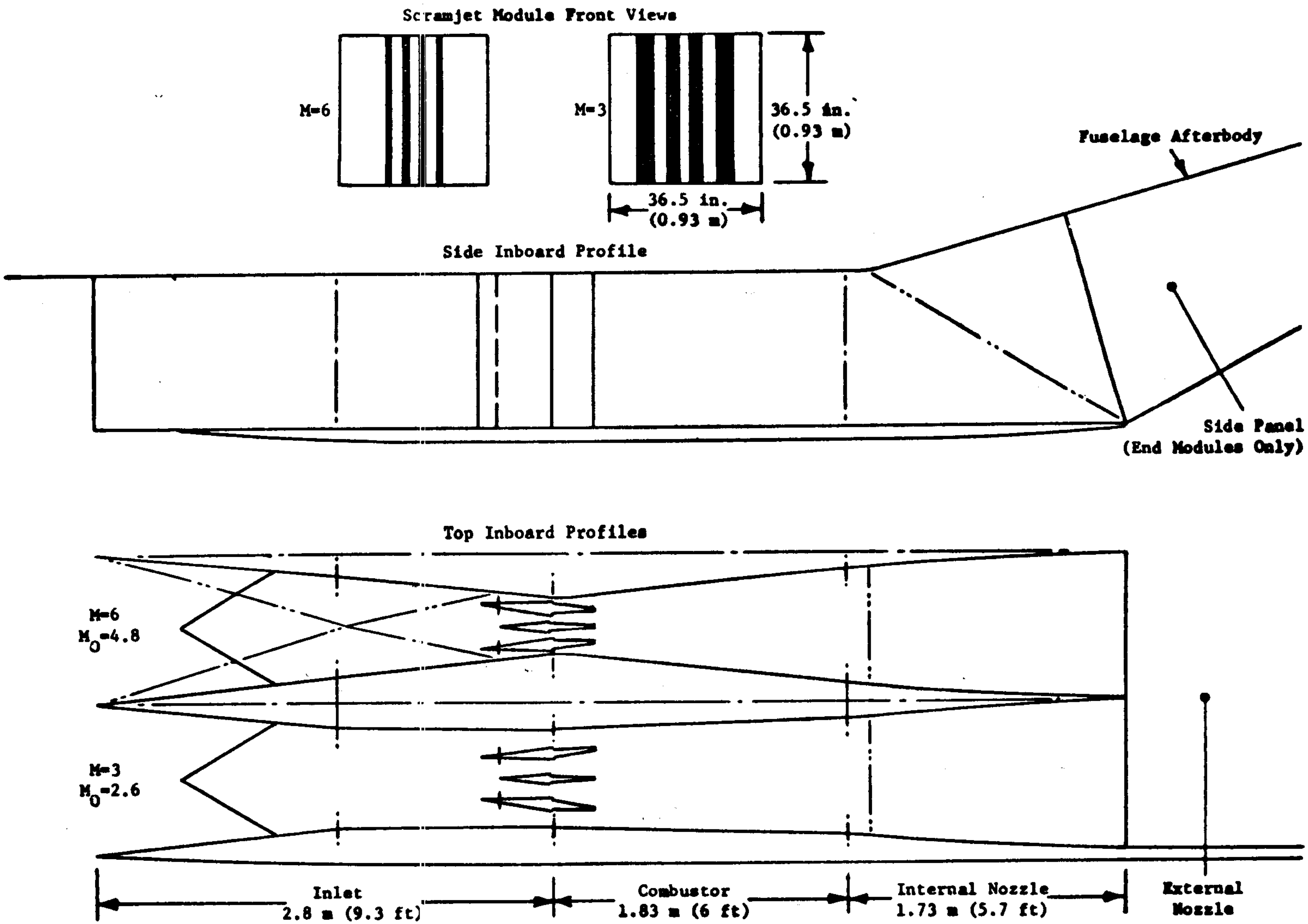

Figure 5-5.- Scramjet Module Geometry and Mach Numbers of 6 and 3

TABLE 5-V.- RAMJET PERFORMANCE SUMMARY

Characteristic	Ramjet acceleration		Scramjet cruise	
	SI units	English units	SI units	English units
Flight Mach number, M	3.0		6.0	
Flow precompression turning angle,	7.0		8.0	
Inlet Mach number, M_o	2.62		4.8	
Pressure field area ratio, A_∞ / A_o	1.37		2.01	
Inlet cowl capture area ratio, A_o/A_C	0.75		1.0	
Inlet contraction area ratio, A_C/A_2	2.57		8.29	
Inlet Kinetic energy efficiency, η_K	0.94		0.975	
Combustion efficiency, η_C	0.95		0.95	
Nozzle efficiency, η_{KN}	0.98		0.98	
Nozzle expansion area ratio, A_N/A_C	2.0 (a)		3.5	
Free stream area, A_∞	7.94 m^2	85.5 ft^2	15.53 m^2	167.2 ft^2
Inlet capture area, A_o	5.80 m^2	62.4 ft^2	7.73 m^2	83.2 ft^2
Inlet cowl area, A_C	7.73 m^2	83.2 ft^2	7.73 m^2	83.2 ft^2
Inlet throat area, A_2	3.01 m^2	32.4 ft^2	0.932 m^2	10.03 ft^2
Fuel	LH_2		LH_2	
Combustion mode	Subsonic		Supersonic	
Fuel equivalence ratio, Ø	1.0		0.609	
Fuel temperature	47K	84°R	47K	84°R
Thrust coefficient x reference area, $C_{TRJ}\ A_C$	15.46 m^2	166.4 ft^2	9.70 m^2	104.4 ft^2
Thrust coefficient, C_{TRJ}	2.00		1.255	
Specific fuel consumption, sfc	0.203 Kg/N-hr	1.20 $\frac{lb_m}{lb_f\text{-hr}}$	0.113 Kg/N-hr	1.12 $\frac{lb_m}{lb_f\text{-hr}}$

a - assumed effective expansion ratio

Equipment This category includes launch and recovery gear, prime power and distribution, and payload provisions.

The landing gear of the baseline configuration is stowed within the cooled fuselage during flight. Consequently, its thermal environment is limited to 367 K (200°F). The weight estimate represents a scaling from the reference 1 design based on weight being proportional to the 0.8 power of the length. The main gear is estimated to weigh 6360 kg (14 000 lb) and the nose gear 1860 kg (4100 lb).

Prime power and distribution includes:

Engine or gas generation,	W = 980 kg (2150 lb)
Tanks and systems,	W = 480 kg (1050 lb)
Electrical distribution,	W = 1600 kg (3500 lb)
Hydraulic and pneumatic,	W = 500 kg (1100 lb)

Payload provisions are a substantial weight item, 7270 kg (16 000 lb). However, these provisions are not related to hypersonic technology and need not be described for reference in the technology projection.

Technology Parameters: Table 5-VI gives the baseline values for the demonstration HST design.

Technological Scenario.- During the period of the late 70's, exploratory flights of the Hypersonic Research Aircraft (HRA) will commence. Over the next several years the flights will prove the technological feasibility of sustained cruise at Mach 6.0 using LH_2 propellants in an advanced scramjet engine. Various types of thermal protection and conditioning systems will be shown to be practical - including active cooling of the airframe. The long-life reuseability and maintainability of advanced components and materials will be demonstrated. Cruise efficiencies of the aircraft will be shown to support the economic potential of a hypersonic cruise transport aircraft.

During the same period, the competition of foreign aircraft manufacturers and airlines will begin to erode the traditional lead of the U.S. Support will grow for a new aircraft which will recapture the U.S. advantage. The successes of the HRA will augment this support.

In the early 80's, the government will initiate a long-range program to achieve an economic hypersonic transport capability by the year 2000. Research and early study activity will be accelerated to support the objective. By 1985, the government will initiate the development of the baseline aircraft with the objective of first flight by 1995.

TABLE 5-VI.- TECHNOLOGY PARAMETERS

Technology Parameter		Baseline values SI units	Baseline values English units
Aerodynamics			
C_{D_o}	zero-lift drag coefficient	0.075	
C_{D_i}/C_L^2	induced drag factor	1.65	
Propulsion			
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)	1.255	
$(W/A_C)_{RJ}$	ramjet specific weight	951 kg/m^2	195 lb/ft^2
η_K	ramjet inlet kinetic energy efficiency	0.975	
η_C	ramjet combustion efficiency	0.95	
η_{KN}	ramjet nozzle kinetic energy efficiency	0.98	
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a Driver Parameter)	0.1595	
Aggregate material properties			
FMP	fuselage material properties	1.00*	
WMP	wing material properties	1.00*	

*The parameters FMP and WMP always have the value 1.0 for the baseline vehicle. (See Module 4 for definition).

TABLE 5-VI.- TECHNOLOGY PARAMETERS - Concluded

Technology Parameter		Baseline values	
		SI units	English units
Airframe design			
$F_{W,B}$	design factor for wing structure designed by buckling criteria	1.00	
$F_{W,C}$	design factor for wing structure designed by crippling criteria	1.00	
$F_{W,S}$	design factor for wing structure designed by stiffness criteria	1.00	
$F_{W,Y}$	design factor for wing structure designed by yield criteria	1.00	
$F_{W,F}$	design factor for wing structure not designed by primary loads	1.00	
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria	1.00	
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria	1.00	
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria	1.00	
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria	1.00	
$F_{F,F}$	design factor for fuselage structure not designed by primary loads	1.00	
F_E	design factor for empennage weight	1.00	
$F_{T,P}$	design factor for thermal protection system weight	1.00	
F_P	design factor for propellant system weight	1.00	

Output Data

For the baseline HST described in the preceding section, Technology Projection Sheets have been prepared for selected parameters by specialists at the Langley Research Center. Two of these sheets are shown in figure 5-6. Table 5-VII is the summary compilation of the projections given in figure 5-6 and of preliminary projections made by the method-development team at the Space Division of North American Rockwell (NR). In the case of the NR projections, upper and lower confidence values are not specified; however, Method Module 6 includes means for the entire table to be filled in.

Technology Parameter: C_{D_o}

Baseline Value: .0076

Baseline Reference Report: NASA TN D-6191, Fig. 5(f)

Technology Parameter Improvement:

Basis for Estimate	% Improvement
Conservative	0
Probable	10
Optimistic	20

Rationale:

The exact percentage reduction in C_{D_o} depends on the level of inviscid drag. Active structural cooling could either avoid or minimize the pressure drag due to leading edge and nose bluntness and surface irregularities caused by thermal distortions. Advances in control configured vehicle technology could afford additional reductions in C_{D_o}. See also AIAA Paper No. 71-132 for Reynolds number effect on drag.

Submitted by:

Name: P. J. Johnston
Mail Code: 160A
Telephone: 827-3877
Date: 12-22-72

Figure 5-6a.- Technology Projection Sheet for Zero-Lift Drag Coefficient - Demonstration Data (reference figure 5-1)

Technology Parameter: $\Delta C_D / \Delta C_L{}^2$

Baseline Value: 1.272

Baseline Reference Report: NASA TN D-6191, Fig. 5(f)

Technology Parameter Improvement:

Basis for Estimate	% Improvement
Conservative	0
Probable	2½
Optimistic	5

Rationale:

The theoretical results given in Paper No. 6, NASA SP-148, showed that warping the wing offered some slight improvement in drag due to lift even at M = 6.

The HT-4 vehicle was essentially configured for a hot structure but changes in configuration geometry afforded by actively cooled structures, for example, may offer some means of reducing drag due to lift.

Also, further benefits may accrue as engine-airframe integration technology advances.

Submitted by:

Name: P. J. Johnston
Mail Code: 160A
Telephone: 827-3877
Date: 12-22-72

Figure 5-6b.- Technology Projection Sheet for Induced Drag Factor - Demonstration Data (reference figure 5-1)

TABLE 5-VII.- TECHNOLOGY PROJECTION SUMMARY - DEMONSTRATION DATA OUTPUT FROM MODULE 5 (Reference Table 5-II)

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
<u>Aerodynamics</u>				
C_{D_o}	zero-lift drag coefficient	-20	-10	0
C_{D_i}/C_L^2	induced drag factor	-5	-2.5	0
<u>Propulsion</u>				
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)		10	
$\left(W/A_C\right)_{RJ}$	ramjet specific weight, kg/m^2 (lbf/ft^2)		-10	
η_K	ramjet specific weight, N/m^2 (lbf/ft^2)		1	
η_C	ramjet combustion efficiency		1	
η_{KN}	ramjet nozzle kinetic energy efficiency		1	
$\left(W/T\right)_{TJ}$	turbojet propulsion specific weight (also identified as a Driver Parameter)		-6	

TABLE 5-VII.- TECHNOLOGY PROJECTION SUMMARY - DEMONSTRATION DATA OUTPUT FROM MODULE 5 (Reference Table 5-II) - Continued

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
<u>Airframe design</u>			↑	
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)			
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)			
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)			
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)		10	
$F_{W,F}$	design factor for wing structure not designed by primary loads (= 1.00 for baseline)			
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)			
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)			
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)			
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)		↓	

TABLE 5-VII.- TECHNOLOGY PROJECTION SUMMARY - DEMONSTRATION DATA OUTPUT FROM MODULE 5 (Reference Table 5-II) - Concluded

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
$F_{F,F}$	design factor for fuselage structure not designed by primary loads (= 1.00 for baseline)		↑	
F_E	design factor for empennage weight (= 1.00 for baseline)		10	
T_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)			
F_P	design factor for propellant system weight (= 1.00 for baseline)		↓	
Aggregate materials properties				
FMP	fuselage material properties		-10	
WMP	wing material properties		-10	

REFERENCES

1. Helenbrook, R.G., McConarty, W.A., and Anthony, F.M.: "Evaluation of Active Cooling Systems for a Mach 6 Hypersonic Transport Airframe," NASA CR-1917, December 1971.

2. Ellison, J.E. : Investigation of the Aerodynamic Characteristics of a Hypersonic Transport Model at Mach Numbers to 6, NASA TN D-6191, 1971.

3. Henry, J.R. and Anderson, G.Y., "Design Considerations for the Airframe-Integrated Scramjet," NASA Langley Research Center, Presented at the 1st International Symposium on Air Breathing Engines, Marseille, France, June 19-23, 1972.

METHOD MODULE 6

RESULTS AND ANALYSES

Logic

The function of this module is to collect and collate the results of the overall method, and to perform analyses which shall verify the results to be valid for the purpose of technology planning.

Figure 6-1 illustrates the logic flow of this module. Modules 3, 4, and 5 provide the essential inputs in data format. The results are derived by solution of the following general expression:

$$(1)\quad \Delta DOC_{ij} = (DOC)_{BL} \times \underbrace{\left(\frac{\Delta DOC/DOC}{\Delta Dr/Dr}\right)_j}_{\text{Driver "Partial"}} \times \underbrace{\left(\frac{\Delta Dr/Dr}{\Delta TP/TP}\right)_{ij}}_{\text{Technology Parameter "Partial"}} \times \underbrace{(\Delta TP/TP)_i}_{\text{Technology Projection}}$$

The technology projection term represents the probable improvement in the baseline technology parameters, as judged by the technology specialist(s). This method identifies 23 (i = 1,2,3...23) such parameters.

The technology parameter "partial" (obtained from Module 4) relates the change in each of 5 drivers (j = 1,2...5) to the technology parameters. Since each technology parameter affects one and only one driver, there are only as many partials (23) as there are technology parameters.

The driver "partial" (obtained from Module 3) relates the change in total DOC to the drivers. This method identifies 5 such partials corresponding to the 5 (j = 1, 2..5) drivers.

The baseline value of DOC is taken from Module 3 and, when multiplied by the product of the above three terms, gives the reduction in the baseline operating cost attributable to the technology projection, $(\Delta TP/TP)_i$. Considering that a single technology parameter partial is allied to one and only one driver partial, there are then 23 values of ΔDOC_{ij} to be determined in this module. By the way the methodology is established, the method allows revision of the technology projections without change to the remaining terms of equation (1).

The results are to be integrated and presented in the results summary chart illustrated in Figure 6.1. The absicssa for each of the drivers is calculated herein and represents a set of achievable "goals" for the constituent technologies. The ordinate represents the potential economic gain realized by achieving the goals. This data format, together with a tabulation of the individual technology parameter goals and gains, is the principal product of the subject methodology.

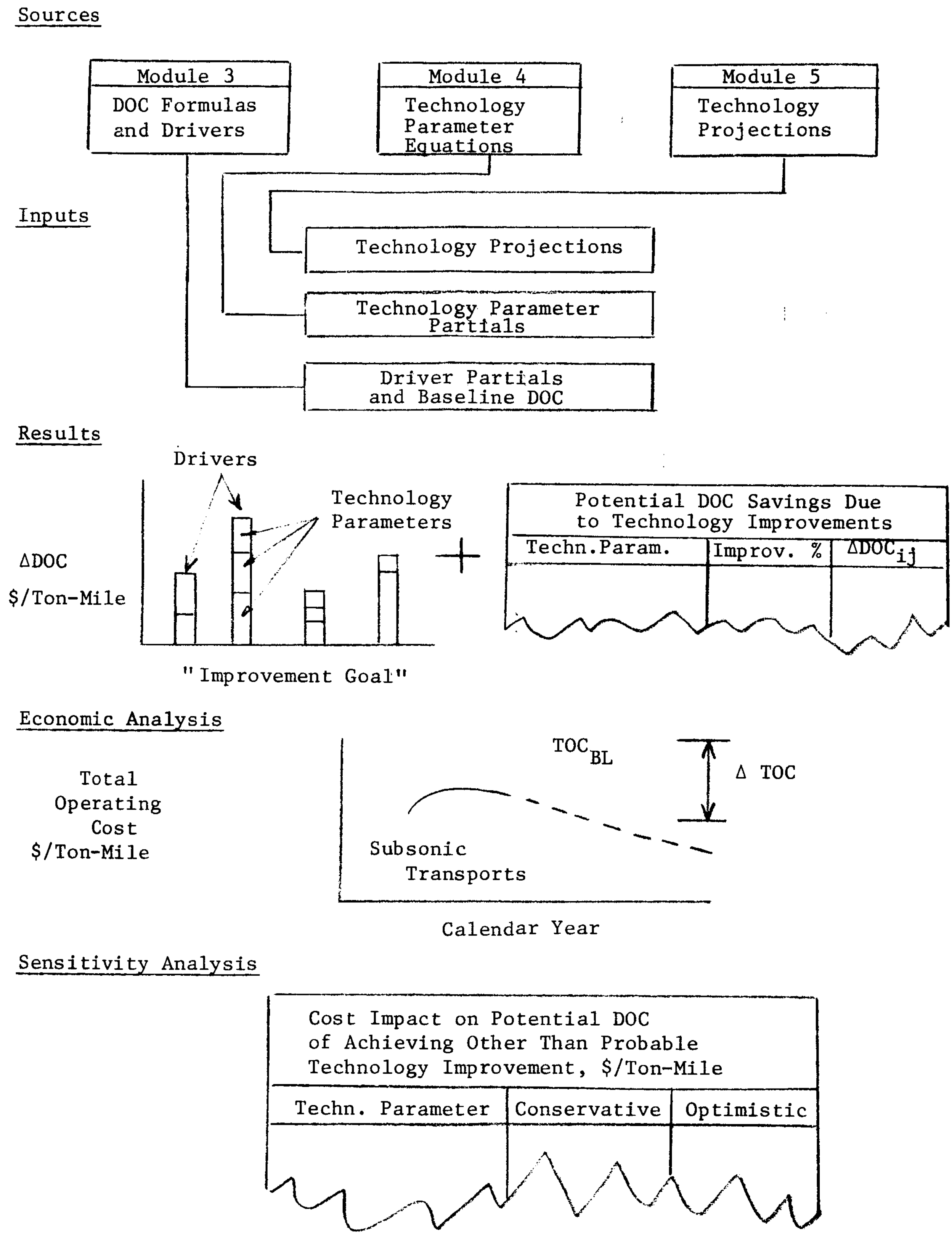

Figure 6-1.- Method Logic

This module also includes an economic (total operating cost) comparison of the HST, as improved by the technology projections, with conventional (subsonic) transport costs as forecast to the end of the century. The purpose of the comparison is to indicate, to the technology planner, the potential value of pursuing the technology goals. Appendix 6-A provides the background data and rationale on which this step in the procedure is based.

Sensitivity analyses have been made (refer to Module 3) which demonstrate that the driver partials and technology parameter partials are relatively insensitive to uncertainties in the baseline constants, costs, and operational parameters (e.g., engine maintenance ratios, depreciation life, reserve fuel fraction, etc.). These uncertainties will, however, impact the value of $(DOC)_{BL}$, but as inspection of equation (1) shows, the uncertainties will have an equivalent (percentage) effect on ΔDOC_i. Therefore, since the relative magnitudes of ΔDOC_{ij} are unaffected by the above-mentioned uncertainties, they should have little significance to the previously drawn conclusions. On the other hand, the range of confidence levels applied to the technology projections are of considerable significance. From Module No. 5 the technology projections range from conservative to optimistic values. To give the technology planner and the technology specialist an appreciation of the impact upon the potential DOC of a failure to achieve the nominal improvement (as represented by the 50% confidence level value), or of a break-through to the optimistic value, the output of this module with respect to the sensitivity analysis will be a Sensitivity Table as illustrated in Figure 6-1.

Input Data

The following data will be provided as inputs to this Method Module:

1. Technology Projections (Table 6-I).- The proportional improvement in each technology parameter (i) and the associated basis for the estimate, (percent confidence in achievement) from Method Module 5, Table 5-II.

2. Direct Operating Cost (Table 6-II).- DOC_{BL} and DOC_f for the baseline HST from Method Module 3, Table 3-III. (DOC_f is that component of DOC_{BL} chargeable to fuel cost).

3. Driver Partials (Table 6-II).- The ratio of the proportional improvement in DOC_{BL} to the proportional improvement in each driver parameter, $(\Delta DOC/DOC)/(\Delta Driver/Driver)$; for each of the five driver parameters (j), from Method Module 3, Table 3-III.

4. Technology Parameter Partials (Table 6-III).- The ratio of the proportional improvement in the applicable driver parameters to proportional improvements in each technology parameter, $\left(\frac{\Delta Driver/Driver}{\Delta TP/TP}\right)_{ij}$ from Method Module 4, Table 4-IV.

TABLE 6-I.- TECHNOLOGY PROJECTIONS - REQUIRED INPUT FOR MODULE 6

Technology Parameter, TP_i		$\Delta TP/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
Aerodynamics				
C_{D_o}	zero-lift drag coefficient			
$C_{D_i}/C_L{}^2$	induced drag factor			
Propulsion				
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)			
$\left(W/A_C\right)_{RJ}$	ramjet specific weight, kg/m^2 (lbf/ft^2)			
η_K	ramjet inlet kinetic energy efficiency			
η_C	ramjet combustion efficiency			
η_{KN}	ramjet nozzle kinetic energy efficiency			
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a driver parameter)			

TABLE 6-I.- TECHNOLOGY PROJECTIONS - REQUIRED INPUT FOR MODULE 6 - Continued

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
Airframe design				
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)			
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)			
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)			
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)			
$F_{W,F}$	design factor for wing structure not designed by primary loads (= 1.00 for baseline)			
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)			
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)			
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)			
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)			

TABLE 6-I.- TECHNOLOGY PROJECTIONS - REQUIRED INPUT FOR MODULE 6 - Concluded

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
$F_{F,F}$	design factor for fuselage structure not designed by primary loads (= 1.00 for baseline)			
F_E	design factor for empennage weight (= 1.00 for baseline)			
T_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)			
F_{PS}	design factor for propellant system weight (= 1.00 for baseline)			
<u>Aggregate materials properties</u>				
FMP	fuselage material properties			
WMP	wing material properties			

TABLE 6-II.- BASELINE DOC AND DRIVER PARTIALS - REQUIRED FOR MODULE 6

Baseline DOC, ¢/ton-mile		Driver Partials For the Driver Parameters:				
DOC_{BL}	DOC_f	W_{AF}/W_{GTO}	$(W/T)_{TJ}$	$\frac{W_{RJ}}{A_C C_{TRJ}}$	L/D	sfc

TABLE 6-III.- TECHNOLOGY PARAMETER "PARTIALS" - REQUIRED INPUT FOR MODULE 6

Technology Parameter, TP_i		Applicable Driver	Value
Aerodynamics			
C_{D_o}	zero-lift drag coefficient	L/D	
$C_{D_i}/C_L{}^2$	induced drag factor	L/D	
Propulsion			
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)	$W_{RJ}/A_C C_{TRJ}$	
$\left(W/A_C\right)_{RJ}$	ramjet specific weight, kg/m^2 (lbf/ft^2)	$W_{RJ}/A_C C_{TRJ}$	
η_K	ramjet inlet kinetic energy efficiency	sfc	
η_C	ramjet combustion efficiency	sfc	
η_{KN}	ramjet nozzle kinetic energy efficiency	sfc	
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a driver parameter)	$(W/T)_{TJ}$	

TABLE 6-III.- TECHNOLOGY PARAMETER "PARTIALS" - REQUIRED INPUT FOR MODULE 6 - Continued

Technology Parameter, TP_i		Applicable Driver	Value
Airframe design			
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)	W_{AF}/W_{GTO}	
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)	W_{AF}/W_{GTO}	
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)	W_{AF}/W_{GTO}	
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)	W_{AF}/W_{GTO}	
$F_{W,F}$	design factor for wing structure not designed by primary loads (= 1.00 for baseline)	W_{AF}/W_{GTO}	
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)	W_{AF}/W_{GTO}	
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)	W_{AF}/W_{GTO}	
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)	W_{AF}/W_{GTO}	
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)	W_{AF}/W_{GTO}	

TABLE 6-III.- TECHNOLOGY PARAMETER "PARTIALS" - REQUIRED INPUT FOR MODULE 6 - Concluded

Technology Parameter, TP_i		Applicable Driver	Value
$F_{F,F}$	design factor for fuselage structure not designed by primary loads (= 1.00 for baseline)	W_{AF}/W_{GTO}	
F_E	design factor for empennage weight (= 1.00 for baseline)	W_{AF}/W_{GTO}	
T_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)	W_{AF}/W_{GTO}	
F_{PS}	design factor for propellant system weight (= 1.00 for baseline)	W_{AF}/W_{GTO}	
<u>Aggregate materials properties</u>			
FMP	fuselage material properties	W_{AF}/W_{GTO}	
WMP	wing material properties	W_{AF}/W_{GTO}	

Procedures

1. The first step in the procedure is to calculate the proportional improvement in the baseline DOC which would result from each of the technology projections. This is accomplished by solving the following equation, using the 50% (probable) technology projections.

$$\left(\frac{\Delta DOC}{DOC}\right)_{ij} = \underbrace{\left(\frac{\Delta DOC/DOC}{\Delta Driver/Driver}\right)_{j}}_{\text{Driver Partial}} \times \underbrace{\left(\frac{\Delta Driver/Driver}{\Delta TP/TP}\right)_{ij}}_{\text{Technology Parameter Partial}} \times \underbrace{\left(\frac{\Delta TP}{TP}\right)_{i}}_{\text{Technology Projection}}$$

(There will be only one solution to the equation for each technology parameter because each technology parameter influences only one driver.)

(It may be noted that the product of the driver partials and the technology parameter partials gives the sensitivity of proportional changes in DOC to proportional changes in each technology parameter, $(\Delta DOC/DOC)/(\Delta TP/TP)$. This term may be of interest in some planning exercises.)

2. Calculate the total incremental improvement (savings) in DOC_{BL}, baseline which would result from each of the technology projections if implemented individually, by the following equation:

$$\Delta DOC_{ij} = \left(\frac{\Delta DOC}{DOC}\right)_{ij} \times DOC_{BL}$$

3. Tabulate the ΔDOC_{ij} in a table as follows:

Potential DOC Savings Due to Technology Improvements, Individually		
Technology Parameters	**% Improvement, (Probable)**	ΔDOC_{ij}

4. Calculate the potential reduction in DOC_{BL} which would result from the probable improvement in all the technology parameters taken together. This is accomplished by use of the following expression

$$\Delta DOC_{Pot} = \left\{ 1 - \prod_i \left[1 - \left| \frac{\Delta DOC}{DOC} \right|_{ij} \right] \right\} \text{ X } DOC_{BL}$$

The following three steps are to determine the values to be presented in the results summary chart shown in figure 6-1.

5. Calculate the contribution to DOC_{Pot} made by each technology parameter from the following:

$$\Delta DOC'_{ij} = \frac{\Delta DOC_{Pot}}{\Sigma \Delta DOC_{ij}} \text{ X } \Delta DOC_{ij}$$

where $\Sigma \Delta DOC_{ij}$ is the arithmetic addition of all (23) ΔDOC_{ij}.

6. Sum the $\Delta DOC'_{ij}$ for the technology parameters which affect each driver parameter (j) giving ΔDOC_j.

$$\Delta DOC_j = \Sigma \Delta DOC'_{ij} \text{ for each driver } (j = 1,2,3,4,5)$$

This is the improvement in DOC_{BL} which would result from the improvement in the jth driver.

7. Calculate the proportional improvement in each driver by the following relationship

$$\left(\frac{\Delta Driver}{Driver}\right)_j = \frac{\Delta DOC_j}{DOC_{BL}} \Big/ \left(\frac{\Delta DOC/DOC}{\Delta Dr/Dr}\right)_j$$

(The term $\left(\frac{\Delta DOC/DOC}{\Delta Driver/Driver}\right)_j$ is the driver partial which is input to this Method Module from Module 3.)

8. Plot the $\Delta DOC'_{ij}$, the ΔDOC_j and the $(\Delta Driver/Driver)_j$ from steps 5, 6 and 7 above as illustrated in Figure 6-2.

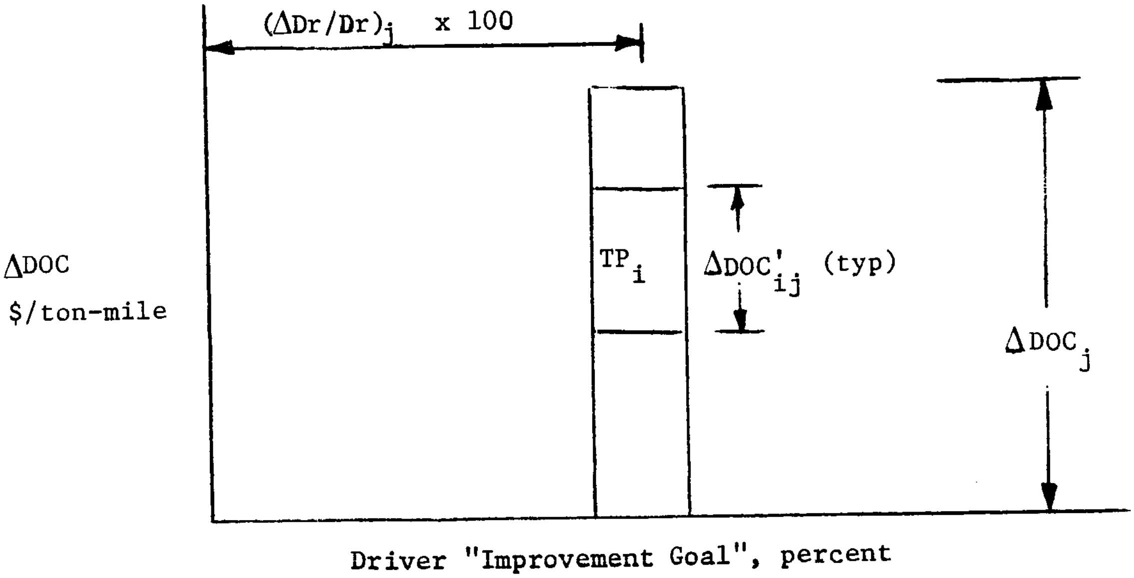

Figure 6-2.- Convention for Plotting Summary Results

9. Steps 9 through 12 provide for calculating the potential operating costs if all the technology improvements were achieved at the 50% (probable) level. A comparison is then made of this cost with projected airline industry operating costs (reference Figure 6-3. Calculate the potential DOC as follows:

$$DOC_{Pot} = DOC_{BL} - \Delta DOC_{Pot}$$

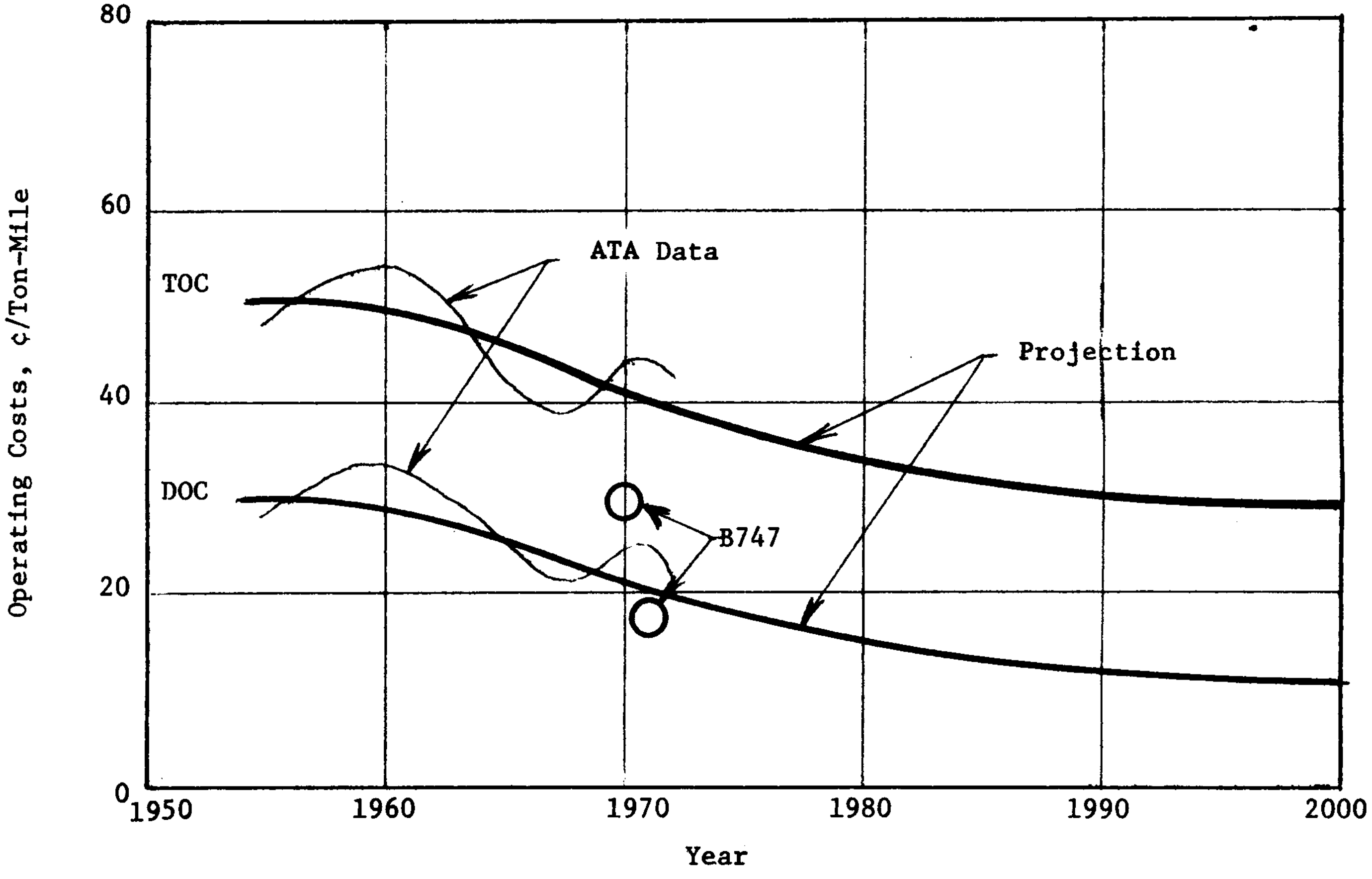

Figure 6-3.- Projected Average Airline Industry Operating Costs

10. The cost of fuel, C_f, is a significant factor in the econmics of an HST. For a hydrogen-fueled HST, the baseline DOC is based upon an estimate of 13¢ per pound of delivered LH_2 in the mid-80's. However, as shown in figure 6-4, the cost of LH_2 could potentially be as low as 8¢/lbf (reference Module 3, Appendix C) by the end of the century. In performing the economic comparison, the forecast fuel cost increment/decrement should be accounted in the following way:

$$\Delta DOC_{f'} = \left(\frac{DOC_f}{DOC_{BL}}\right) \left(1 - \frac{C_{f'}}{C_f}\right) DOC_{Pot}$$

where $C_{f'}$ = revised fuel cost projection

C_f = fuel cost used in the baseline DOC

$\frac{DOC_f}{DOC_{BL}}$ = fraction of DOC_{BL} represented by fuel, from Module 3.

11. Estimate total operating cost (TOC) by adding indirect operating cost (IOC) to DOC. IOC consists of general, administrative, and service expenses which are generally independent of the flight system technology improvements. IOC can therefore be added as a fixed value to both DOC_{BL} and DOC_{Pot}. IOC has been estimated at $.21 per ton mile (invariant with time) for the HST (reference Appendix 6-A), and TOC is computed as follows:

$$TOC_{BL} = DOC_{BL} + 0.21, \text{ (\$/ton mile)}$$

$$TOC_{Pot} = DOC_{Pot} - \Delta DOC_f' + 0.21, \text{ (\$/ton mile)}$$

12. Plot the TOC_{BL} and TOC_{Pot} on the projection of airline operating costs, Figure 6-3.

13. Sensitivity Analysis. - The subsequent steps indicate the impact on the potential TOC and DOC of achieving other than the nominal (50% probable) value for the improvement in each technology area.

When the 10% (optimistic) and 90% (conservative) confidence values for the technology projections have not been provided as data inputs to this module, estimate these values as follows:

90% (conservative) Value = 0.6 X 50% (probable) Value

10% (optimistic) Value = 1.4 X 50% (probable) Value

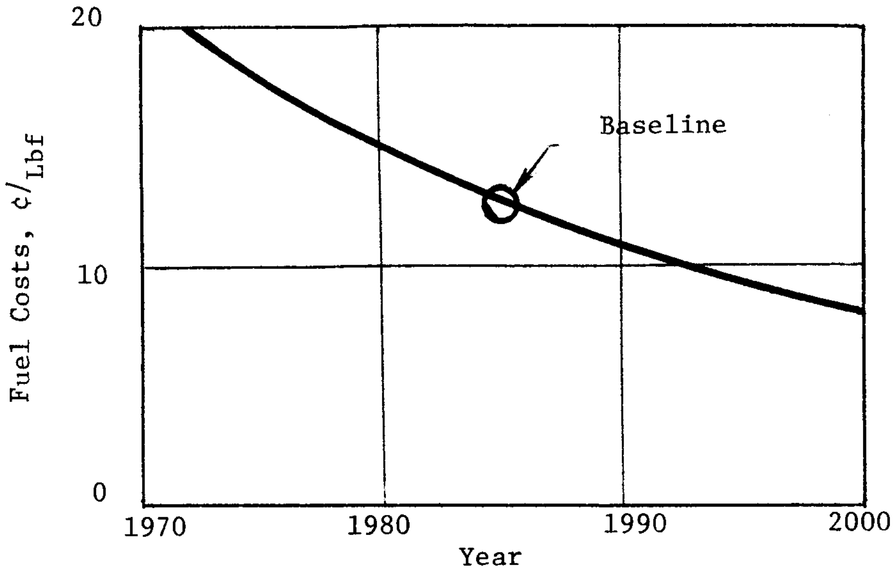

Figure 6-4.- Projected Cost of Liquid Hydrogen Fuel

14. Calculate the incremental improvement in DOC_{BL} which would result from achieving the 10% (optimistic) and 90% (conservative) levels of improvement in the technology parameters, ΔDOC_{ij}, by repeating Steps 1, 2, 4 and 5 above using the 10% (optimistic) and 90% (conservative) values.

15. Calculate the impact on the potential DOC of achieving other than the 50% (probable) level of technology by subtracting ΔDOC_{ij} calculated in Step 5 from the two sets of values obtained in Step 14 above. Tabulate these in the following format:

COST IMPACT ON POTENTIAL DOC OF ACHIEVING OTHER THAN THE PROBABLE TECHNOLOGY PROJECTIONS, $/TON MILE

Technology Parameter	Conservative Projection	Optimistic Projection

DEMONSTRATION

This section provides an illustration of how the procedures of this Method Module are to be applied.

Input Data

The input data for the demonstration are based on the data from the demonstration sections of the other Modules of this report.

1. The technology projections are given in Table 6-IV and are outputs from Module 5, Technology Projections, Table 5-VII.

2. The baseline DOC's for the baseline HST are shown in Table 6-V, taken from the output of Module 3, Table 3-VII.

3. The "Driver Partials" (ΔDOC/DOC)/(Δ Driver/Driver) are also presented in Table 6-V and are outputs from Module 3, Table VII.

. The "Technology Parameter Partials" are presented in Table 6-VI and are outputs from Module 4, Technology Parameter Equations, Table 4-VII.

Procedures

Steps 1 and 2.- The procedures of steps 1 and 2, which give the estimated reduction in the baseline DOC which would result from the technology projections, are illustrated in Table 6-VII, Tabulation Work Sheet.

The projected improvements in the Technology Parameters to the 50% probable level have been entered in column 4. The reduction in DOC for the projected improvement in each Technology Parameter is shown in column 6.

(The term (ΔDOC/DOC)/(ΔTP/TP) which is the sensitivity of proportional improvements in DOC to proportional improvements in each technology parameter is the product of Column (2) and Column (3) and can be computed separately if desired.)

TABLE 6-IV.- TECHNOLOGY PROJECTIONS - DEMONSTRATION DATA INPUT FOR MODULE 6 (Reference Table 6-I)

Technology Parameter, TP_i		$\Delta TP/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
Aerodynamics				
C_{D_o}	zero-lift drag coefficient	-20	-10	0
C_{D_i}/C_L^2	induced drag factor	- 5	- 2.5	0
Propulsion				
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)		10	
$(W/A_C)_{RJ}$	ramjet specific weight, kg/m^2 (lb/ft^2)		-10	
η_K	ramjet inlet kinetic energy efficiency		1	
η_C	ramjet combustion efficiency		1	
η_{KN}	ramjet nozzle kinetic energy efficiency		1	
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a driver parameter)		- 6	

TABLE 6-IV.- TECHNOLOGY PROJECTIONS - DEMONSTRATION DATA INPUT FOR MODULE 6 (Reference Table 6-I) - Continued

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Optimistic)	50% (Probable)	90% (Conservative)
<u>Airframe design</u>				
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)		10	
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)		10	
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)		10	
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)		10	
$F_{W,F}$	design factor for wing structure not designed by primary loads (= 1.00 for baseline)		10	
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)		10	
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)		10	
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)		10	
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)		10	

TABLE 6-IV.- TECHNOLOGY PROJECTIONS - DEMONSTRATION DATA INPUT FOR MODULE 6 (Reference Table 6-I) - Concluded

Technology Parameter, TP_i		$\Delta TP_i/TP_i$ Percent		
		10% (Opti-mistic)	50% (Prob-able)	90% (Conser-vative)
$F_{F,F}$	design factor for fuselage structure not designed by primary loads (= 1.00 for baseline)		10	
F_E	design factor for empennage weight (= 1.00 for baseline)		10	
T_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)		10	
F_{PS}	design factor for propellant system weight (= 1.00 for baseline)		10	
Aggregate materials properties				
FMP	fuselage material properties		-10	
WMP	wing material properties		-10	

TABLE 6-V.- BASELINE DOC AND DRIVER PARTIALS - DEMONSTRATION DATA INPUT FOR MODULE 6 (Reference Table 6-II)

Baseline DOC, ¢/ton-mile		Driver Partials For the Driver Parameters:				
DOC_{BL}	DOC_f	W_{AF}/W_{GTO}	$(W/T)_{TJ}$	$\frac{W_{RJ}}{A_C C_{TRJ}}$	L/D	sfc
46.8¢	25.7¢	3.0	0.7	0.3	-2.6	2.6

TABLE 6-VI.- TECHNOLOGY PARAMETER "PARTIALS" - DEMONSTRATION DATA INPUT FOR MODULE 6 (Reference Table 6-III)

Technology Parameter, TP_i		Applicable Driver	Value
Aerodynamics			
C_{D_o}	zero-lift drag coefficient	L/D	-0.670
$C_{D_i}/C_L{}^2$	induced drag factor	L/D	-0.390
Propulsion			
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)	$(W_{RJ}/A_C C_{TRJ})$	-1.0
$\left(W/A_C\right)_{RJ}$	ramjet specific weight, kg/m^2 (lb/ft^2)	$(W_{RJ}/A_C C_{TRJ})$	1.0
η_K	ramjet inlet kinetic energy efficiency	sfc	-0.195
η_C	ramjet combustion efficiency	sfc	-0.730
η_{KN}	ramjet nozzle kinetic energy efficiency	sfc	-2.930
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a driver parameter)	$(W/T)_{TJ}$	1.0

TABLE 6-VI.- TECHNOLOGY PARAMETER "PARTIALS" - DEMONSTRATION DATA INPUT FOR MODULE 6 (Reference Table 6-III) - Continued

Technology Parameter, TP_i		Applicable Driver	Value
Airframe design			
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.038
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.024
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.060
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.047
$F_{W,F}$	design factor for wing structure not designed by primary loads (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.076
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.038
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.024
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.005
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.029

TABLE 6-VI.- TECHNOLOGY PARAMETER "PARTIALS" - DEMONSTRATION DATA INPUT FOR MODULE 6 (Reference Table 6-III) - Concluded

Technology Parameter, TP_i		Applicable Driver	Value
$F_{F,F}$	design factor for fuselage structure not designed by primary loads (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.190
F_E	design factor for empennage weight (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.029
T_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.107
F_{PS}	design factor for propellant system weight (= 1.00 for baseline)	(W_{AF}/W_{GTO})	-0.161
Aggregate materials properties			
FMP	fuselage material properties	(W_{AF}/W_{GTO})	0.095
WMP	wing material properties	(W_{AF}/W_{GTO})	0.115

TABLE 6-VII.– TABULATION WORK SHEET FOR PROCEDURES STEPS 1-7

Technology Parameter	Applicable Driver	"Driver Partial"	"TP Partial"	Technology Projection, 50% (Probable)	$\left(\frac{\Delta DOC}{DOC}\right)_{ij}$
Column No.	(1)	(2)	(3)	(4)	(5) = (2) x (3) x (4)
Procedures Step No. →	← 1 →				
C_{D_o}	L/D	-2.6	-0.670	-.10	-.174
C_{D_i}/C_L^2	L/D	-2.6	-0.390	-.025	-.025
$(W/A_C)_{RJ}$	$W_{RJ}/A_C C_{TRJ}$	0.3	1.0	-.10	-.030
C_{TRJ}	"	0.3	-1.0	.10	-.030
η_K	sfc	2.6	-0.195	.01	-.005
η_C	"	2.6	-0.730	.01	-.019
η_{KN}	"	2.6	-2.93	.01	-.076
$F_{W,B}$	W_{AF}/W_{GTO}	3.0	-0.038	.10	-.011
$F_{W,C}$	"	3.0	-0.024	.10	-.007
$F_{W,S}$	"	3.0	-0.060	.10	-.018
$F_{W,Y}$	"	3.0	-0.047	.10	-.015
$F_{W,F}$	"	3.0	-0.076	.10	-.025
$F_{F,B}$	"	3.0	-0.038	.10	-.012
$F_{F,C}$	"	3.0	-0.024	.10	-.008
$F_{F,S}$	"	3.0	-0.005	.10	-.002
$F_{F,Y}$	"	3.0	-0.029	.10	-.009
$F_{F,F}$	"	3.0	-0.190	.10	-.063
F_E	"	3.0	-0.029	.10	-.009
F_{TP}	"	3.0	-0.107	.10	-.036
F_{PS}	"	3.0	-0.161	.10	-.054
WMP	"	3.0	0.115	-.10	-.038
FMP	"	3.0	0.095	-.10	-.032
$(W/T)_{TJ}$	$(W/T)_{TJ}$	0.7	1.0	-.06	-.042

TABLE 6-VII. TABULATION WORK SHEET FOR PROCEDURES STEPS 1-7 - Concluded

Technology Parameter	ΔDOC_{ij} 50% (Probable) \$/ton mile	$\left(1-\left\|\frac{\Delta DOC}{DOC}\right\|\right)_{ij}$	$\Delta DOC'_{ij}$	ΔDOC_j \$/ton mile	$\left(\frac{\Delta\ Driver}{Driver}\right)_j$
Column No.	(6) = (5) x DOC_{BL}	(7)	(8)	(9)	(10) = ((9) / DOC_{BL})/(2)
Procedures Step No. →	2	4	5	6	7
C_{D_o}	-.081	.826	-.057		
C_{D_i}/C_L^2	-.012	.975	-.008	-.065	.053
$(W/A_C)_{RJ}$	-.014	.970	-.010		
C_{TRJ}	-.014	.970	-.010	-.020	-.142
η_K	-.002	.995	-.001		
η_C	-.008	.981	-.006		
η_{KN}	-.036	.924	-.026	-.033	-.027
$F_{W,B}$	-.005	.989	-.004		
$F_{W,C}$	-.003	.993	-.002		
$F_{W,S}$	-.008	.982	-.006		
$F_{W,Y}$	-.007	.985	-.005		
$F_{W,F}$	-.018	.975	-.013		
$F_{F,B}$	-.006	.988	-.004		
$F_{F,C}$	-.004	.992	-.003		
$F_{F,S}$	0	.998	0		
$F_{F,Y}$	-.004	.991	-.003		
$F_{F,F}$	-.029	.937	-.021		
F_E	-.004	.991	-.003		
F_{TP}	-.017	.964	-.012		
F_{PS}	-.025	.946	-.018		
WMP	-.018	.962	-.012		
FMP	-.015	.968	-.011	-.117	-.083
$(W/T)_{TJ}$	-.022	.960	-.016	-.016	-.048
	$\prod_i \left(1-\left\|\frac{\Delta DOC}{DOC}\right\|_{ij}\right) =$	.464	-.251	-.251	

Step 3.- The tabulation of ΔDOC_{ij} for the improvement in each Technology Parameter has been tabulated in Table 6-VIII. The results indicate, for example, that the 10% improvement projected in C_{D_o} taken individually would yield a 8.1¢ per ton mile reduction in DOC.

Step 4.- The potential reduction in DOC_{BL} which would result from the projected 50% (probable) improvements in all the Technology Parameters combined is calculated as 25.1¢ per ton mile by the relationship:

$$\Delta DOC_{Pot} = \left\{ 1 - \prod_i \left[1 - \left| \frac{\Delta DOC}{DOC} \right|_{ij} \right] \right\} \times DOC_{BL}$$

$$= \left\{ 1 - .464 \right\} \times .468$$

$$= \$.251/\text{ton mile}$$

The values of $1 - \left| \frac{\Delta DOC}{DOC} \right|_{ij}$ and their products are taken from column 7 of Table 6-VII.

Step 5.- The approximate proportional contribution of the improvement in each Technology Parameter to ΔDOC_{Pot} is calculated in Column 8 of Table 6-VII.

$$\Delta DOC_{ij} = \frac{\Delta DOC_{pot}}{\Sigma D_{ij}} \times D_{ij}$$

$$= \frac{\$.251}{.352} \times DOC_{ij}$$

The contribution of the improvement in the Technology Parameter C_{D_o} to the overall reduction, if all improvements were achieved, is approximately 5.7¢ per ton mile. The technology parameters are not independent so that this contribution is less than if the reduction in C_{D_o} were achieved individually.

Steps 6 and 7.- The proportional improvement in each Driver and the contribution of each Driver to the combined reduction in DOC is calculated in columns 9 and 10 of Table 6-VII.

Step 8.- The results of steps 6 and 7 are plotted in figure 6-5.

Step 9.- The potential DOC value which would result from achievement of the 50% (probable) level of improvement in all the Technology Parameters combined is calculated as 21.7¢ per ton mile as follows:

TABLE 6-VIII.- REDUCTION IN DOC_{BL} FROM ACHIEVEMENT OF THE PROBABLE IMPROVEMENT IN EACH TECHNOLOGY PARAMETER, INDIVIDUALLY

	Technology Parameter, TP_i	% improvement in Technology Parameter	ΔDOC_{ij} ¢/ton-mile
Aerodynamics			
C_{D_o}	zero-lift drag coefficient	-10	-8.1
$C_{D_i}/C_L{}^2$	induced drag factor	-2.5	-1.2
Propulsion			
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)	10	-1.4
$\left(W/A_C\right)_{RJ}$	ramjet specific weight, kg/m^2 (lbf/ft^2)	-10	-1.4
η_K	ramjet inlet kinetic energy efficiency	1	-0.2
η_C	ramjet combustion efficiency	1	-0.8
η_{KN}	ramjet nozzle kinetic energy efficiency	1	-3.6
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a driver parameter)	-6	-2.2

TABLE 6-VIII.- REDUCTION IN DOC_{BL} FROM ACHIEVEMENT OF THE PROBABLE IMPROVEMENT IN EACH TECHNOLOGY PARAMETER, INDIVIDUALLY - Continued

Technology Parameter, TP_i		% improvement in Technology Parameter	ΔDOC_{ij} ¢/ton-mile
<u>Airframe design</u>			
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)	10	-0.5
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)	10	-0.3
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)	10	-0.8
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)	10	-0.7
$F_{W,F}$	design factor for wing structure not designed by primary loads (= 1.00 for baseline)	10	-1.8
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)	10	-0.6
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)	10	-0.4
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)	10	0
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)	10	-0.4

TABLE 6-VIII.– REDUCTION IN DOC_{BL} FROM ACHIEVEMENT OF THE PROBABLE IMPROVEMENT IN EACH TECHNOLOGY PARAMETER, INDIVIDUALLY – Concluded

Technology Parameter, TP_i		% improvement in Technology Parameter	ΔDOC_{ij} ¢/ton-mile
$F_{F,F}$	design factor for fuselage structure not designed by primary loads (= 1.00 for baseline)	10	-2.9
F_E	design factor for empennage weight (= 1.00 for baseline)	10	-0.4
T_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)	10	-1.7
F_{PS}	design factor for propellant system weight (= 1.00 for baseline)	10	-2.5
Aggregate materials properties			
FMP	fuselage material properties	-10	-1.5
WMP	wing material properties	-10	-1.8

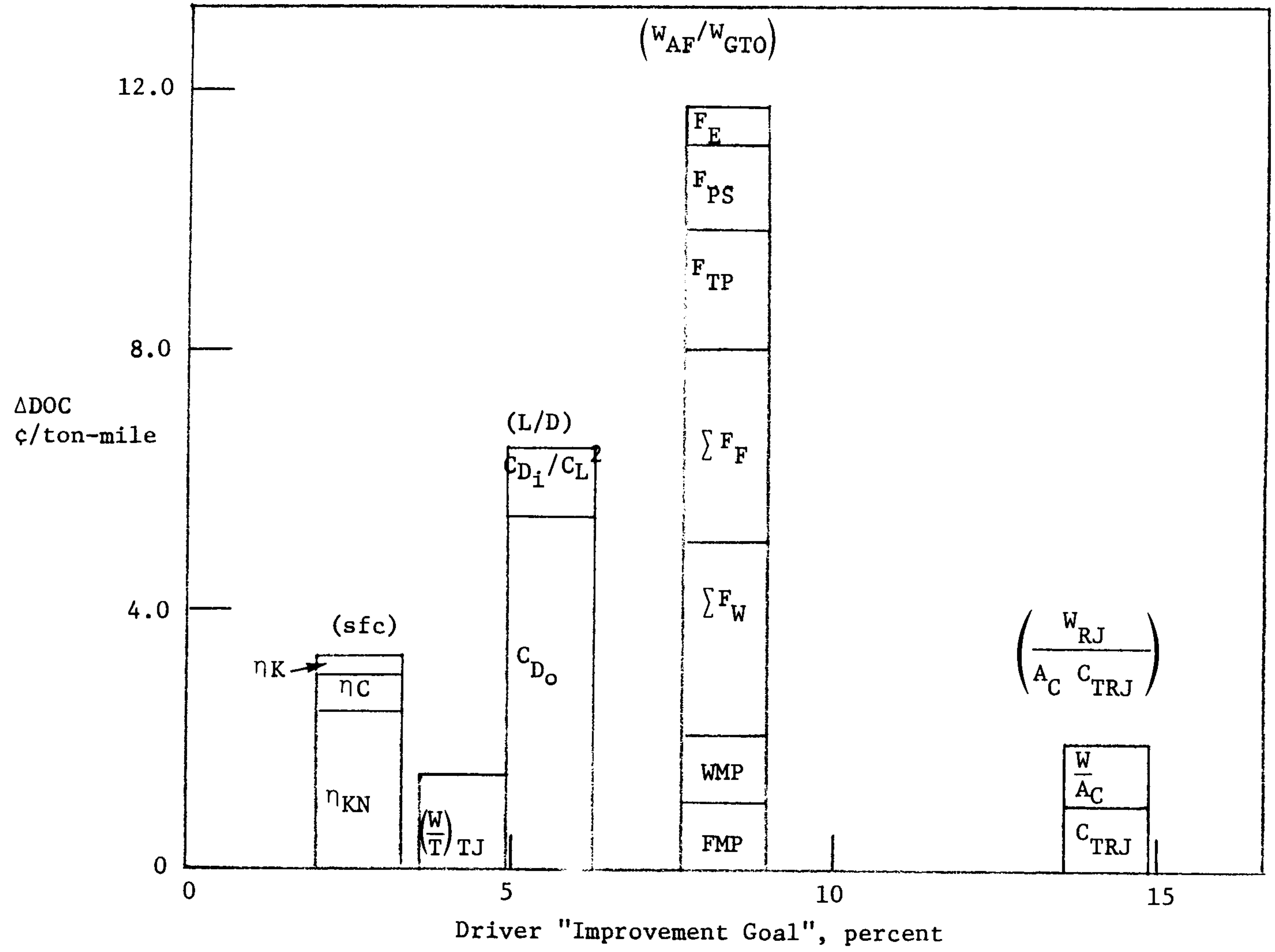

Figure 6-5.- Results Summary Chart

$$DOC_{Pot} = DOC_{BL} - DOC_{Pot}$$

$$DOC_{Pot} = 46.8 - 25.1 = 21.7¢/\text{ton mile}$$

Step 10.- The value of DOC_{Pot} above is based on a cost of fuel (C_f) of 13¢/lb. Figure 6-4 shows that the projected cost may be as low as 8¢/lb by the end of the century. Using the latter value and the relationships of procedures step 10, it is estimated that the DOC_{Pot} could be reduced an additional 4.6¢ per ton mile.

$$\Delta DOC'_f = \left(\frac{DOC_f}{DOC_{BL}}\right)\left(1 - \frac{C'_f}{C_f}\right) DOC_{Pot}$$

$$= \left(\frac{25.7}{46.8}\right) \left(1 - \frac{8¢}{13¢}\right) 21.7¢$$

$$= 4.6¢/\text{ton mile}$$

where C'_f = the revised cost of fuel.

Step 11.- The values for TOC_{BL} and $TOC_{potential}$ are calculated by adding IOC = 21¢ per ton mile to the DOC values.

$$TOC_{BL} = DOC_{BL} + 21¢ = 67.8¢ \text{ per ton mile}$$

$$TOC_{potential} = DOC_{Pot} - \Delta DOC'_f + 21¢ =$$

$$21.7 - 4.6 + 21.0 = 38.1¢ \text{ per ton mile}$$

In other words, the baseline TOC for the HST is estimated at 67.8¢ per ton mile. This could potentially be reduced to 38.1¢ per ton mile by the combined effect of the improvements 50% (probable) in all the Technology Parameters and by the projected reduction in fuel cost to the end of the century.

Step 12.- The TOC values from step 11 are compared with the projected industry operating costs in figure 6-6. The results indicate a potential HST total operating cost of 38¢ based on the achievement of all the technology improvements as projected at the 50% (probable) level would be within 10¢ of the projected industry average of 29¢ at a target date of about 2000.

The difference of less than 10¢ could probably be easily assimilated by many potential HST users in return for the cost savings and other benefits which would result from the high speed and reduced transit time of the HST (reference Appendix 6-A).

Steps 13-15, Sensitivity analysis.- The results of the sensitivity analysis, steps 13-15, are presented in Table 6-IX. The results indicate for example that achievement of only the conservative projection of the improvement in C_{D_0} would result in an increase in DOC_{Pot} of 5.7¢ per ton mile. An achievement of the optimistic projection would results in a decrease in the potential DOC of 4.5¢ per ton mile. The 90% (conservative) and 10% (optimistic) projections in the technology projections, where missing, were estimated by the procedures of step 13 for this demonstration.

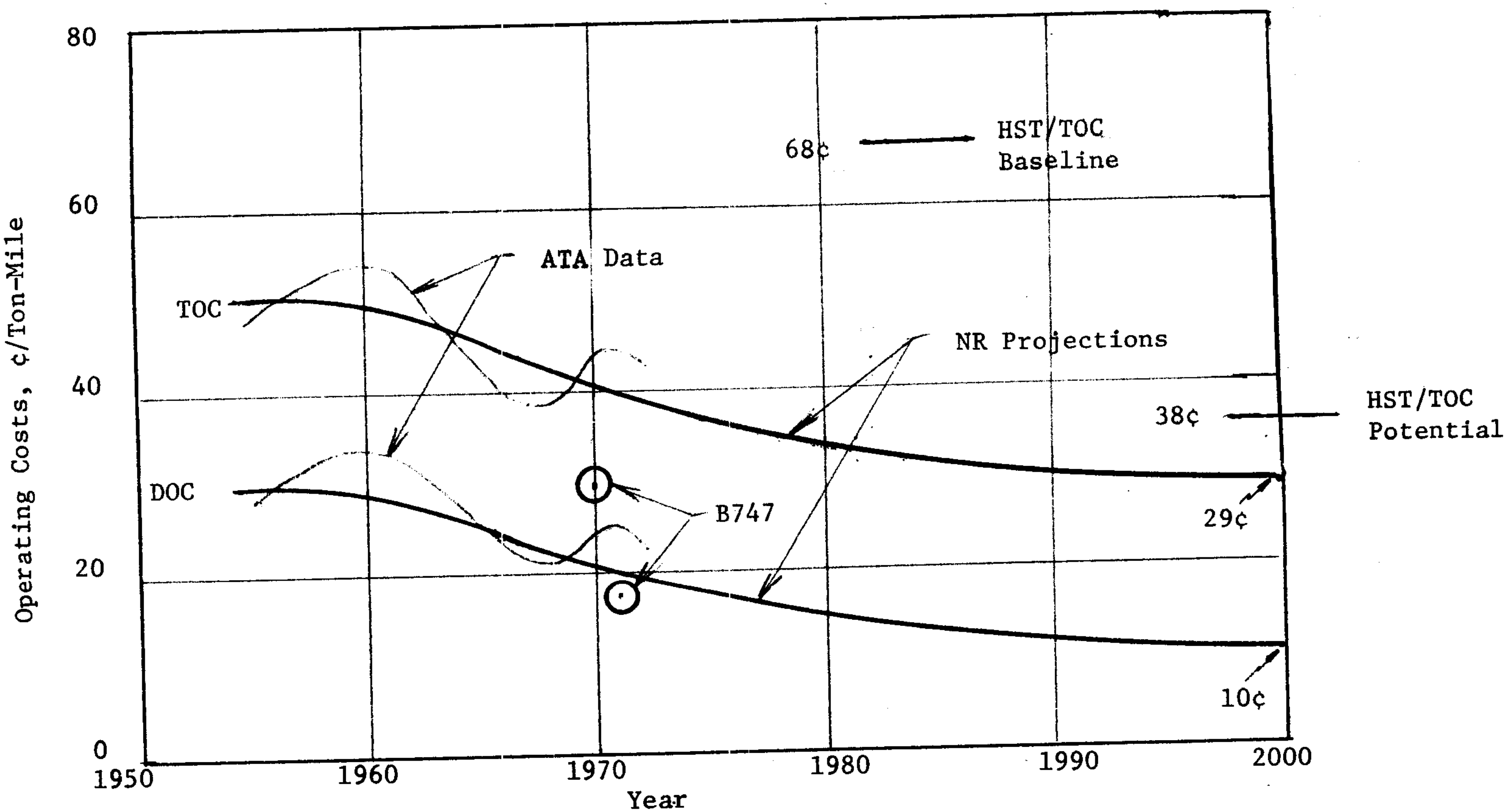

Figure 6-6.- Comparison of HST Operating Costs with Projected Airline Industry Operations Costs (50% Probable Technology Improvements)

TABLE 6-IX.- COST IMPACT ON POTENTIAL DOC OF ACHIEVING OTHER THAN THE NOMINAL TECHNOLOGY IMPROVEMENTS, ¢/TON MILE

Technology Parameter, TP_i		ΔDOC in ¢/ton-mile from 50% confidence projection	
		Conservative Projection	Optimistic Projection
Aerodynamics			
C_{D_o}	zero-lift drag coefficient	5.7	-4.5
$C_{D_i}/C_L{}^2$	induced drag factor	0.8	-0.7
Propulsion			
C_{TRJ}	installed ramjet thrust coefficient, cruise (thrust/qA_C)	0.3	-0.2
$\left(W/A_C\right)_{RJ}$	ramjet specific weight, kg/m^2 (lb/ft^2)	0.3	-0.2
η_K	ramjet inlet kinetic energy efficiency	0.1	-0.0[illegible]
η_C	ramjet combustion efficiency	0.2	-0.2
η_{KN}	ramjet nozzle kinetic energy efficiency	0.7	-0.6
$(W/T)_{TJ}$	turbojet propulsion specific weight (also identified as a driver parameter)	0.4	-0.3

TABLE 6-IX.- COST IMPACT ON POTENTIAL DOC OF ACHIEVING OTHER THAN THE NOMINAL TECHNOLOGY IMPROVEMENTS, ¢/TON MILE - Continued

Technology Parameter, TP_i		ΔDOC in ¢/ton-mile from 50% confidence projection	
		Conservative Projection	Optimistic Projection
Airframe design			
$F_{W,B}$	design factor for wing structure designed by buckling criteria (= 1.00 for baseline)	0.1	-0.1
$F_{W,C}$	design factor for wing structure designed by crippling criteria (= 1.00 for baseline)	0.1	-0.1
$F_{W,S}$	design factor for wing structure designed by stiffness criteria (= 1.00 for baseline)	0.2	-0.1
$F_{W,Y}$	design factor for wing structure designed by yield criteria (= 1.00 for baseline)	0.1	-0.2
$F_{W,F}$	design factor for wing structure not designed by primary loads (= 1.00 for baseline)	0.2	-0.2
$F_{F,B}$	design factor for fuselage structure designed by buckling criteria (= 1.00 for baseline)	0.1	-0.1
$F_{F,C}$	design factor for fuselage structure designed by crippling criteria (= 1.00 for baseline)	0.1	-0.1
$F_{F,S}$	design factor for fuselage structure designed by stiffness criteria (= 1.00 for baseline)	0	0
$F_{F,Y}$	design factor for fuselage structure designed by yield criteria (= 1.00 for baseline)	0.1	-0.1

TABLE 6-IX.– COST IMPACT ON POTENTIAL DOC OF ACHIEVING OTHER THAN THE NOMINAL TECHNOLOGY IMPROVEMENTS, ¢/TON MILE - Concluded

Technology Parameter, TP_i		ΔDOC in ¢/ton-mile from 50% confidence projection: Conservative Projection	ΔDOC in ¢/ton-mile from 50% confidence projection: Optimistic Projection
$F_{F,F}$	design factor for fuselage structure not designed by primary loads (= 1.00 for baseline)	0.5	-0.4
F_E	design factor for empennage weight (= 1.00 for baseline)	0.1	-0.1
T_{TP}	design factor for thermal protection system weight (= 1.00 for baseline)	0.3	-0.2
F_P	design factor for propellant system weight (= 1.00 for baseline)	0.5	-0.3
Aggregate materials properties			
FMP	fuselage material properties	0.3	-0.2
WMP	wing material properties	0.3	-0.3

REFERENCES

1. Anon: Air Transport Facts and Figures, Official Publication of the Air Transport Association of America, 1966.

2. Anon: Air Transport 1972, The Annual Report of the U.S. Scheduled Airline Industry, Published by the Air Transport Association of America, 1972.

3. Anon: Aviation Week and Space Technology, 747 Operating Cost Data, Prepared by Ray and Ray, July 31, 1972, October 2, 1972, and December 18, 1972.

4. H. Lewis, The Role of Air Freight in Physical Distribution, Pergamon Press, 1956.

APPENDIX 6-A

AIRLINE INDUSTRY OPERATING COSTS

Industry Cost Experience and Projections

Figures 6-3 and 6-6 in this volume present direct operating costs (DOC) and total operating costs (TOC) for the U. S. airline industry for the period from 1955 to 1972. The data from 1955 to 1971 are from actual industry records (references 1 and 2). The figures for 1972 are estimated based on data points for the 747 and on evidence of improvements in the airline industry economic situation during the year 1972. The improvement in the 747 DOC shown on figures 6-3 and 6-6 for the years 1970 and 1972 (reference 3) undoubtedly reflect improvements in both the industry economic situation and the more extensive use of the 747 in the latter year. The 747 is a more economical airplane to operate than the smaller turbojet airplanes which comprise the bulk of the industry average.

Operating Cost Projection

The industry-wide DOC and TOC values have been projected to 10¢ and 29¢ per ton mile respectively in the year 2000 based on the trend in the industry data to 1972.

The HST airplane could be competitive with the projected industry values with a TOC higher than 29¢ per ton mile because of its high speed and the economic utility of transit time to shippers of cargo, and/or to passengers. Table 6-X presents an example which indicates that actual freight costs are a small portion of total distribution costs and the reductions in distribution costs related to time for air transportation can offset the higher freight costs of surface transportation. In the case of the example in Table 6-X, packaging and crating costs yield an additional advantage for air transportation.

Indirect Operating Expenses (IOC) for HST

The U.S. airline industry data, figures 6-3 and 6-4 , indicate that IOC for the total industry have remained between 22.3 and 17.4¢ per ton mile for the past 10 years, 1961 to 1971, being 22.3¢ in 1961 and 21.3¢ in 1971. DOC costs have varied between 34.1¢ and 21.9¢ per ton mile in the same period, being 34.1¢ in 1961 and 25.2¢ in 1971. The IOC costs include passenger service costs, aircraft and passenger servicing, promotion and sales, and administrative expense. Because the IOC are relatively independent of DOC and would not be appreciably altered by technology advances, a fixed value of IOC = 21¢ per ton mile has been estimated for the HST which is reflective of the U.S. industry experience between 1961 and 1971.

TABLE 6-X. EXAMPLE OF BUSINESSMAN'S OUTLOOK ON TOTAL COST OF DISTRIBUTION

Elements of Distribution	Transportation Method	Cost in dollars/month (1970 dollars) Surface Transportation	Air Transport - 747 Type
Preparation	Packing & crating	$25 300	$4530
Trans-portation	Pickup and delivery	3600	2530
	Transfer	1071	-
	Freight	34 200	54 800
	Insurance	28 200	2760
	Documentation	695	-
	Transit Warehousing	4450	-
	Int. on capital	6030	376
		(78 246)	(60 466)
Ware-housing	Int. on capital	11 766	4425
	Inventory taxes	8711	3522
	Insurance	494	186
	Rent	12 850	9250
	Other (sal, main, supls)	82 823	82 823
		(116 644)	(100 206)
Total projected distribution cost per month		$220 190	$165 202
% freight cost		15.5%	35.4%

Export sales = 1.7 M $/mo; goods value - 11 $/# (television sets); shipping rate = 153 000 $/mo; FOB= Los Angeles to Tyoko; ref. source: "The Role of Air Freight in Physical Distribution" - H. Lewis, 1956 (reference 4)

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