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REGRESSION SIMULATION OF TURBINE ENGINE PERFORMANCE/AIRCRAFT REGRESSION MODEL

GENERAL ELECTRIC COMPANY
CINCINNATI, OHIO 45215

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NOVEMBER 1978

TECHNICAL REPORT AFAPL-TR-78-76
Final Report for Period September 1977 – July 1978

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James R Ruble

JAMES R. RUBLE
Project Engineer
Performance Branch

Jack Richens

JACK RICHENS, Chief
Performance Branch
Turbine Engine Division

FOR THE COMMANDER

Ernest C. Simpson

ERNEST C. SIMPSON
Director
Turbine Engine Division

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The Aircraft Regression Model (ARM) Task has explored modification of the Boeing Turbine Engine Variable Cycle Selection/Airplane Response Engine Selection (TEVCS/ARES) procedures by decoupling the representation of specific propulsion systems and the detailed mission definitions from the overall surface fit representations of the aircraft. over

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Detailed comparisons between the RSTEP/ARM techniques developed herein and another available technique for aircraft/engine design refinement are provided as the principal result of this program. All objectives of the RSTEP/ARM effort were attained. A simplified mission performance computer program was developed and tested in the evaluation of two engine cycle concepts, one a turbojet and one a turbofan. The program was simplified by using regression models for airframe geometry, weights, and drags. The program is currently operational in both the Air Force and at two industry sites. A user may screen engines with airframe algorithms provided by an airframe manufacturer, without dependence on the engine manufacturer. Representative parametric trends are obtained and absolute levels of results are reasonably accurate, as well. Development of the regression simulation of aircraft characteristics should continue. Mission performance programs like RSTEP/ARM can act as a strong and credible link between an engine company and an airframe manufacturer.

FOREWORD

This report describes a design study effort conducted by the General Electric Company and sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Contract F33615-77-C-2108, AF Project No. 3066 with James R. Ruble, AFAPL/TBA, as Project Engineer. The General Electric company was assisted by its associate contractor, The Boeing Company.

The work reported herein was performed during the report period of September 1977 through July 1978. Donald E. Uehling was the General Electric Program Manager and the technical work was performed initially under the direction of Dan J. Rundell and later under Warren Joy as Engineering Manager. The Engineering Manager was assisted by Paul J. Trenkamp and Dale A. Grudier. Computer modeling and checkout, as well as evaluation studies, were carried out by The Boeing Company, under the direction of Glenn J. Eckard. Mr. Eckard was assisted by Tom Kemple, also of The Boeing Company.

This report covers all work done under all tasks of the Regression Simulation of Turbine Engine Performance/Aircraft Regression Model Program. When referring to this program in the test which follows the abbreviation RSTEP/ARM is used.

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LIST OF ABBREVIATIONS AND ACRONYMS

A/B	Afterburner (-)
A_{capt}	Inlet Capture Area (one engine) (ft^2)
AEG	(General Electric) Aircraft Engine Group
AFAPL	Air Force Aero Propulsion Laboratory
AMPR	Aircraft Manufacturer's Planning Report
AR	Wing Aspect Ratio (-)
ARES	Airplane Responsive Engine Selection
ARM	Aircraft Regression Model
A_9	Nozzle Area - ft^2
A_{10}	Fuselage Area - ft^2
BEAM	Boeing Engine Airplane Matching
BCAS	Best Cruise Altitude and Speed
C_D	Drag Coefficient (-) [often with subscripts]
C_L	Wing Lift Coefficient (-)
D_{cc}	Diameter of Engine at Customer Connect Location (ft)
DDTL	Drag-due-to-light
D_{ff}	Diameter of Engine at Front Flange (ft)
ESIP	Exhaust System Interaction Program
f( )	Function of
h	Altitude - ft
k	1000 (used with altitude - 1000 ft)
L_{eng}	Length of Engine (ft)
M, Mach	Mach number

LIST OF ABBREVIATIONS AND ACRONYMS - Concluded

MAX.	Maximum
MAXMAN	Maximum Maneuver Capability - Agility
MIL	Military
MINFUEL	Minimum Mission Fuel - Economy
MINGWT	Minimum Gross Weight - Size
MINVIS	Minimum Visibility Index - Stealth
n.mi.	Nautical Miles
OPR	Overall Pressure Ratio (used for turbojet only) (-)
pps	Pounds Per Second
psf	Pounds Per Square Foot
PWR	Power
RAD.	Radius - n.mi.
RSTEP	Regression Simulation of Turbine Engine Performance
SCALE	Computer Parameter Relating to Scaling Engine Size
SUB.	Subsonic
TEVCS	Turbine Engine Variable Cycle Selection
TOGW	Design Aircraft Takeoff Gross Weight (lb)
t/c	Wing Thickness-to-chord Ratio (-)
T/W	Aircraft Thrust-to-weight Ratio (-)
T_{41}	Turbine Rotor Inlet Temperature (° F or ° R)
W_{eng}	Weight of Engine (lb)
W/S	Aircraft Wing Loading (lb/sq ft)
λ_{LE}	Wing Leading Edge Sweep Angle (degrees)

SUMMARY

The Aircraft Engine Group (AEG) of the General Electric Company, under contract to the Turbine Engine Division of the Air Force Aero Propulsion Laboratory, has performed the Aircraft Regression Model (ARM) Task of the Regression Simulation of Turbine Engine Performance (RSTEP) program.

The RSTEP/ARM Task has explored modification of the Boeing TEVCS/ARES procedures* with the objective of increasing the flexibility of these techniques while not suffering an excessive loss in precision. This has been accomplished by decoupling the representation of specific propulsion system and the detailed mission definition from the overall surface fit representations of the aircraft. The objective was to provide for changes in propulsion system and mission requirements without the need to reconfigure the aircraft family for each change.

The Boeing Company has performed the aircraft-related work, using the results from their Airplane Responsive Engine Selective (ARES) program as a starting point. The AEG has provided engine-related information, much of it based on work accomplished in providing the parametric turbojet customer decks to the industry.

Detailed comparisons between the RSTEP/ARM computer techniques developed herein and other available techniques for aircraft/engine design refinement are provided as the principal result of this program.

The capability sought is a low cost, easy-to-use, and flexible analysis tool which will provide engine designers with a much more detailed understanding of the ultimate effects of changes in specific mission requirements, engine technology advances, and aircraft design constraints on an overall weapon system design when both engine and aircraft designs are allowed limited perturbation.

All objectives of the RSTEP/ARM effort were attained. A simplified mission performance computer program was developed and tested in the evaluation of two engine cycle concepts, one a turbojet, and one a turbofan. The program was simplified by using regression models for airframe geometry, weights, and drags. This approach appears to be feasible and results adequate for application to conceptual and preliminary design phase screening of engine cycles. The Air Force and industry is, thus, provided with a new and responsive capability.

The computer program is currently operational in both the Air Force and at two industry sites. A user may screen his engines with airframe algorithms provided by an airframe manufacturer without dependence on the engine manufacturer. Representative parametric trends are obtained and absolute levels of results are reasonably accurate, as well.

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*See Section II for further description.

While the current capability is of substantial utility, some problem areas are acknowledged. It is felt that these problem areas can be eliminated or alleviated and appropriate action is recommended.

Additionally, due to the potential benefit of the RSTEP/ARM approach, extension of the capability is recommended. Specific recommendations in two separate categories follow:

RECOMMENDATIONS FOR IMPROVEMENT OF CURRENT CAPABILITY

- Improve drag-due-to-lift modeling through application of alternate algorithms.
- Continue efforts to improve program efficiency by modifying basic computational logic.

RECOMMENDATIONS FOR EXTENSION OF IMPROVED CAPABILITY

- Develop regression models of geometry, weights, and drag characteristics of other airframe concepts: fighters, bombers, transports, etc.
- Increase mission profile modeling capability.
- Provide capability to easily change RSTEP/ARM regression model coefficient.
- Develop a general propulsion installation procedure which is compatible with the RSTEP Aircraft Regression Model.
- Combine present program with optimizing routines.

Development of the regression simulation of aircraft characteristics should continue. Much has been learned in the accomplishment of this effort and in related analysis. This accumulation of experience would be most beneficial to additional application of the subject approach.

Mission performance computer programs like RSTEP/ARM can act as a strong and credible link between an engine company and an airframe manufacturer. This capability can shorten the iterative process of engine cycle screening in preliminary design. Thus, conceptual and preliminary design coordination conducted by an engine company and an airframe company can become more efficient and productive.

SECTION I

INTRODUCTION

Each generation of military aircraft weapon systems has been required to achieve substantial improvements in design mission performance and effectiveness, multimission versatility, life-cycle costs, and survivability. These requirements have placed increased demands on the engine designer for advanced cycle concepts, advanced material and design technology, variable geometry capabilities, and a more effective engine-aircraft installation with particular emphasis on inlet-engine airflow matching and engine-airframe thrust matching across the complete operating regime. The resulting propulsion system concept evaluation and cycle selection process has required more attention to complex engine-airframe interactions, has required study of a substantially greater number of engine and airframe design parameters, more emphasis on extensive control and flow scheduling requirements, and a consideration of broader spectrum of mission and operational requirements.

In the past few years several programs have been carried out in an effort to develop the computer programs and routines needed to assist airframe manufacturers' preliminary design groups in the optimization and selection process*. The resulting tools are accurate and provide reasonable solutions in rapid turn-around time. The same tools, however, have a number of important drawbacks and shortcomings with regard to use by the engine designer:

1. They are generally complex and expensive to use.

2. They have been devised generally by airframe companies and require intimate knowledge of aircraft detail layout and design.

3. The complex interactions between characteristics and airframe layout are not generally well understood by the engine designer; thus, it is not always possible or desirable for an engine designer to include them properly in engine selection analysis.

As a result, it has become apparent that there exists a need for further effort in creating analysis tools more suitable for use by engine designers; tools in which the airframe/engine interaction has been incorporated; tools which are easier and less expensive to use.

The effort conducted under this contract has been directed at the development of an aircraft regression model which would provide a representation of the basic airframe physical characteristics as a function of the airframe preliminary design parameters and basic engine physical characteristics such as weight, length, and diameter. A mission simulator program has been designed to use the aircraft regression model in conjunction with individual

*Boeing TEVCS/ARES is an example.

engine performance data arrays to permit estimating of mission performance capabilities. This reorganizing of the system evaluation process by separation into an independent aircraft regression model and a separate engine data array should permit more rapid selection of optimal engine cycles and with greater emphasis on the engine characteristics portion of the evaluation process.

The Boeing Company has had a substantial amount of experience in developing computer simulations for the use in engine selection studies. Boeing has evolved the Airplane Responsive Engine Selection (ARES) procedure in response to the need for modeling and evaluating the complex interactions between the engine, airframe, and the mission in the design selection phase of a new or advanced weapon system. For this reason, Boeing was selected as an associate contractor to carry out the major tasks of this contract.

It was the goal of this study to produce a computer analysis tool which would be readily usable by the engine designer and which would achieve an acceptable compromise between cost and accuracy.

The impetus for the conduct of this work has come from the recognition by the Air Force sponsor that an improved tool for engine screening in the preliminary design stage is needed by the engine designer. Appreciation is also expressed for the guidance and critiquing provided in the course of the program by the Air Force Project Engineer.

SECTION II

GENERAL APPROACH AND DEFINITION OF TASKS

To improve upon the problem areas mentioned in the preceding section, the RSTEP/ARM mission performance approach was implemented. The general approach used and the tasks which were pursued toward this implementation are described in this section.

GENERAL APPROACH

The RSTEP/ARM approach to formulaton of a engine/airframe/mission performance capability is based upon regression analysis. Parametric airframe characteristics data are generated with detail design state-of-the-art computer subroutines, using the Boeing Engine Airplane Matching (BEAM) program (Reference 1)*. These data are fitted and coefficients of functions representing these fits are derived through regression analyses. The resultant functions called Aircraft Regression Models (ARM) reflect the logic built into the "parent" subroutines. Presumably, the functions are much simpler than the parent logic and, thus, could be used to build a more efficient mission performance program.

The airframe characteristics for which functions were derived in the RSTEP/ARM effort fall into three major areas: geometry, weights, and drag. These three areas are affected by scaling airframe size, by design changes, and by engine cycle variations. An objective was to make the ARM functions independent of engine performance (thrust, airflow, etc.). Of course, engine size and cycle variations affect performance, but airframe weight, geometry and drag "feel" these variations through associated engine shape and weight changes. Thus, ARM functions are developed in terms of major engine shape and weight descriptors, as well as airframe design variables. That is, the airframe characteristics data are generated for parametric variations in parameters such as engine diameter, engine length, engine weight and airplane design gross weight, wing loading, aspect ratio, etc. These are the independent variables to which geometry, weight, and drag functions are correlated.

The "parent" subroutines used in RSTEP/ARM analysis were those incorporated in the Boeing BEAM program, which has evolved to its present state over many years of usage. Much of its logic has been enhanced under contract to Air Force agencies through projects such as Exhaust System Interaction Program (ESIP) and Turbine Engine Variable Cycle Selection program (TEVCS) - both sponsored by AFAPL.

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*See also description in Section III. A.

BEAM is a complex and detailed computer program which designs an aircraft, does a layout, calculates areas and volumes, estimates weight and balance, and estimates drag and other aerodynamic characteristics. All calculations and estimations are based on detailed correlations of a large amount of Boeing aircraft design data and give very accurate results for preliminary design studies. BEAM's logic is considered to be quite comprehensive and entirely adequate for airframe company preliminary design analytical studies.

Parametric design combinations which were processed through the BEAM logic were selected using an Orthogonal Latin Square technique. This technique was developed and first applied during performance of the Airplane Responsive Engine Selection (ARES) program (Reference 2),* Boeing's part of TEVCS. Regression analyses were performed using techniques that were also developed in the ARES effort.

After their derivation, the ARM functions were incorporated into a mission performance logic that is capable of either point design or parametric analysis for a tactical aircraft. The resultant package is referred to as the RSTEP/ARM performance program or simulator.

To prove the validity of the RSTEP/ARM approach the RSTEP/ARM performance program was used to generate performance for a number of point design aircraft and two sets of parametric engine data, one based on a parametric turbojet family, the other based on a fixed turbofan design. These results were compared to equivalent data generated with BEAM, the "parent" simulator.

The RSTEP/ARM approach, analysis elements, program results, and validation comparisons are presented in detail in succeeding sections.

TASK DEFINITION

Ten specific tasks have been defined. The first seven were directed toward the formulation of a simplified mission performance computer program and its application to the analysis of a parametric family of turbojet engines. The last three were directed to the application and evaluation of the RSTEP/ARM program in analysis of a point design turbofan engine.

Task I required the definition of initial concepts, analysis elements and groundrules.

Task II involved the development of aircraft model representations. These were regression simulations of airframe characteristics derived using ARES method elements.

Task III required the integration of the representations developed in Task II into a mission performance computer program. Presumably, the resultant

*See also description Section III. A.

simplified program would accurately reflect the complex logic of the "parent" program used to generate the data which yielded the Task II representations.

In Task IV, results from the simplified RSTEP/ARM program are compared to those of the complex "parent" BEAM program.

Whether or not the RSTEP/ARM performance program is viable for parametric analyses is tested in Tasks V and VI by using it in an ARES method application. A parallel application is accomplished using the parent program. The two necessary parametric data bases are developed in Task V. Results of the two ARES applications are compared in Task VI.

It should be noted that ARES is not an integrated part of the RSTEP/ARM computer program as it is presently arranged. However, Boeing has coupled ARES together with the RSTEP/ARM program in order to illustrate how the two procecdures can be used together to solve specific problems.

Task VII required the delivery of the RSTEP/ARM performance computer program to the sponsor of the effort, the Performance Branch of the Aero Propulsion Laboratory.

Task VIII through X dealt with an alternate engine cycle. In Task VIII, parametric data bases were generated for ARES analysis of a turbofan. In Task IX, interrogation criteria were evolved. Finally, in Task X, BEAM and RSTEP/ARM program data processed through the ARES method were interrogated and results were compared. Portions of Task X were to be carried out by The Boeing Company and portions were to be carried out by the General Electric Company.

SECTION III

STUDY RESULTS

This section contains summaries of work done under each task which comprised this study effort. A complete description of task results is included in R&D Status Report issued monthly during the contract period. Work under each task was conducted by The Boeing Company under the direction of the General Electric Company. Work under Task X was split between these two companies.

A. Identification of Study Elements (Task I)

The RSTEP/ARM effort was initiated with the identification of elements about which the analyses would revolve. These elements included a weapon system (airframe concept and study engine cycles) that was mutually acceptable to the participants in the effort, requirements for which the system would be evaluated, and computer programs and analytical techniques that would be used. Each of these elements is described briefly in the following pages.

1. Airframe Concept

The RSTEP/ARM approach was explored using a tactical fighter weapon system as a vehicle. In a system of this type, a relatively large fraction of the airframe design is involved with the propulsion subsystem. Therefore, the analytical approach was intended to respond to large variations in weight and shape of the propulsion subsystem, which has a great deal of leverage on the size and performance of the complete weapon system.

A twin-engine configuration, featuring fuselage-housed engines, was selected and is presented in Figure 1. The selected airframe concept is in the advanced tactical air-to-ground attack class. The configuration arrangement is conventional and has two-dimensional, horizontal-ramp, external compression inlets; conformally carried payload (4000 lb); twin engines with axisymmetric nozzles, and advanced technology structure and subsystems. It is designed for sustained cruise operation at Mach 2.4. Fuel is contained in both the wing and fuselage. The configuration is volume limited at the design weight.

2. Engine Cycles

The RSTEP/ARM approach to airplane performance program modeling - i.e., development of a performance program using regression analysis techniques - is essentially independent of specific engine cycles. This approach makes provision for propulsion system size and shape variations via parametrically varied engine "hole size" and weight. When the RSTEP/ARM program is used for study engine analyses, the geometry logic accepts the shape and weight characteristics of the cycle of interest, adjusts "hole size" accordingly, and accounts for changes in the airframe caused by "hole size" changes.

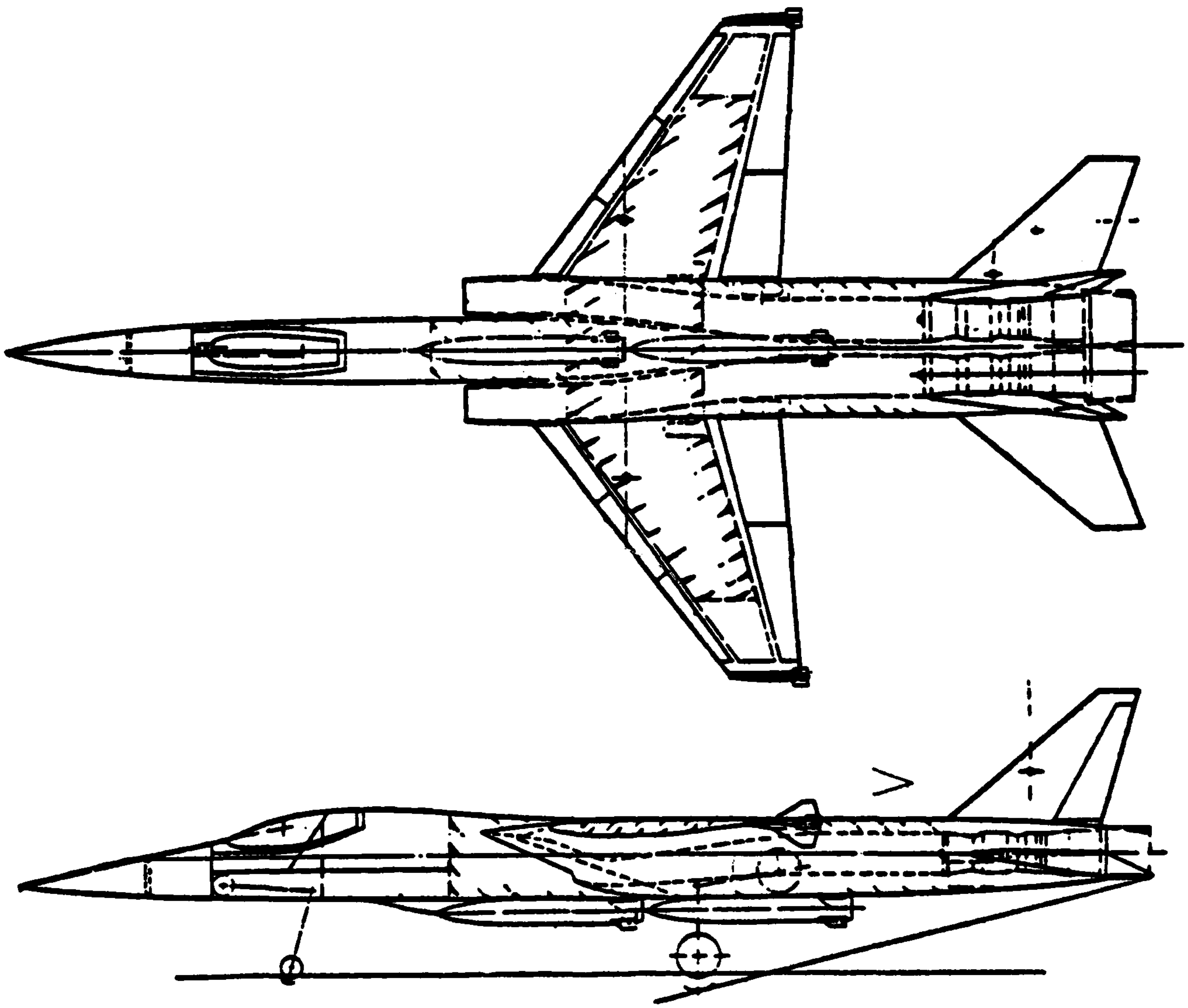


Figure 1. Aircraft Design Concept, Advanced Tactical Attack Aircraft, RSTEP/ARM Studies.

Two specific engine types were evaluated during the RSTEP/ARM effort.

The first engine type was the General Electric GE16/J4 Variable Geometry Turbine Turbojet engine. A parametric family of these engines was analyzed in which the value of overall pressure ratio ranged from 11 to 20. The characteristics of this family of engines are presented in Table 1. It is noted that engine characteristics change very little as overall pressure ratio varies.

The second engine type analyzed was a turbofan with variable geometry features designated GE16/F17 Study A. This was a single, "point design", engine cycle, having the following cycle characteristics:

Overall Pressure Ratio	24
Fan Pressure Ratio	4.0
Bypass Ratio	0.5
Design T_{41}	3660° R

Both engine types were evaluated in RSTEP/ARM parametric analyses using the ARES system. In the case of the turbojet, overall pressure ratio and engine size were two of the independent variables exercised. Engine size was the only engine-related independent variable exercised in the case of the turbofan.

Uninstalled engine data were supplied by the General Electric Company to The Boeing Company. Boeing, in turn, calculated installation losses using a procedure previously developed by them and described in Reference 3. (A fuller documentation of the installation loss method is presented in References 4, 5, 6, and 7.) At present the RSTEP/ARM computer procedure requires installed performance data to be stored in the engine performance data file.

Engine scaling calculations were carried out using the following scaling laws:

Diameter	~	$(\text{SCALE})^{0.5}$
Length	~	$(\text{SCALE})^{0.48}$
Weight	~	$(\text{SCALE})^{1.18}$
Inlet Capture Area	~	$(\text{SCALE})^{1.0}$
Thrust	~	$(\text{SCALE})^{1.0}$

The computer parameter SCALE is the ratio of scaled thrust to the reference thrust value. These scaling exponents are appropriate for the GE16/J4 Turbojet Engine Parametric Family. They were also used in scaling the turbofan engine characteristics. It should be noted that other classes or types of engines may require different scaling exponents.

Table 1. GE16/J4 Turbojet Characteristics, Airflow Size - 155 pps.

Overall Pressure Ratio	Maximum SLS Thrust Uninstalled, lb	Engine Weight, lb	Engine Length, in	Customer Connect Diameter, in	Inlet Capture Area, Ft^2
20.0	20000	2150	140.0	34.0	5.15
18.5	20010	2120	142.0	34.0	5.16
17.0	19960	2100	143.0	33.0	5.16
15.5	19880	2080	145.0	33.0	5.17
14.0	19760	2070	147.0	33.0	5.18
12.5	19610	2060	148.0	33.0	5.20
11.0	19810	2020	146.0	32.0	5.22

MIL 5008C RAM Recovery	Fuel Heating Value = 18400 Btu/lb
Design T_{41} - 3060° R	Horsepower Extraction = 50 hp
110% Overspeed	Bleed = 0.5 lb/sec

3. Weapon System

The RSTEP/ARM fighter designs were sized to and flown over the interdiction mission profile illustrated in Figure 2. Best cruise altitude and speed (BCAS) legs were performed at subsonic speeds while the dash legs were flown at parmetrically variable supersonic Mach numbers. For the purpose of this study, the subsonic (climb plus cruise) legs were fixed at 300 nmi and payload was held fixed at 4000 lbs while dash radius varied from case to case as a "fall-out" result. (A nominal 125 nmi dash radius was used as a goal in much of the optimization analyses conducted in this study.) The RSTEP/ARM mission module permits variation of dash altitude. However, in this study, dash altitude was held fixed at 20,000 ft for the cases "flown".

In this study maneuver capability is measured by combat load factor, the ratio of wing lift to aircraft flight weight. Increased values of load factor imply the ability to pull tighter turns and to perform more rapid or more difficult combat maneuvers. In a one-on-one combat engagement the aircraft with the higher value of combat load factor generally should have a tactical advantage over the other aircraft.

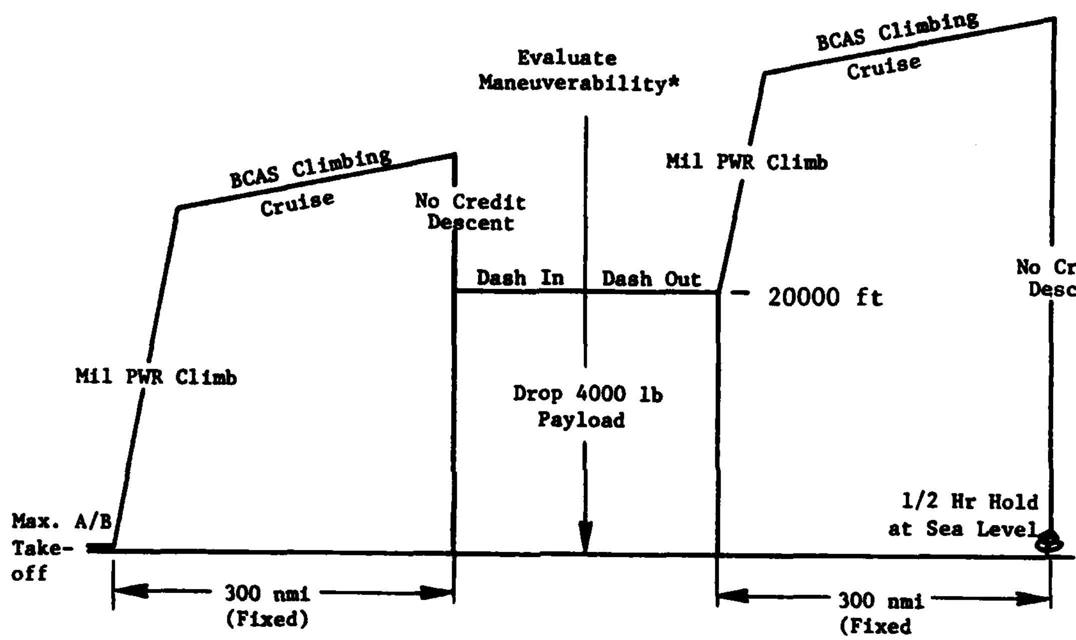
Maneuver capability was evaluated at two flight conditions: (1) "combat" at Mach 0.9 and 30,000 ft and (2) "missile avoidance" at dash Mach number and 20,000 ft. Both calculations were performed at maximum augmented power. Flight weight was that weight at the end of the first dash leg, before weapon release.

The mission is concluded with a one-half hour hold at sea level and at speed for best loiter. Reserves also include five percent of the fuel on board at takeoff. MIL-C-5011A (Reference 8) conservatism (5%) was applied to fuel burned in all mission legs.

Desirable levels of maneuver capability and maximum desirable dash power settings were identified. Combat load factor of no less than 3.0 was considered to be desirable for the system's ground attack role. Dash condition load factor capability greater than 7.0 was felt to be excessive from the standpoint of pilot comfort. An unaugmented penetration is desirable for reduced infrared signature and resultant improved stealth characteristics.

4. BEAM - The Parent Simulator

The RSTEP/ARM performance computer program is based on simple, quadratic functions which represent airplane geometry, weight and drag. These functions were formed using a regression model for geometry, weight, and drag level variations which resulted from parametric perturbation of some important airframe design and engine characteristic parameters. The level variations were generated in relatively sophisticated geometry, weight, and drag subroutines within the Boeing Engine Airplane Matching (BEAM) performance computer program, or "simulator" in the ARES vernacular. Thus, the BEAM program can be considered the parent simulator for the RSTEP/ARM performance program.



* Maneuverability Conditions:

M = 0.9 at 30,000 ft

M = Dash Mach Number at 20,000 ft

Figure 2. Mission Profile, Advanced Tactical Attack Aircraft, RSTEP/ARM Studies.

The BEAM program was used to generate input data for regression analysis leading to development of the RSTEP/ARM program and to generate data to which RSTEP/ARM program results were compared to measure the utility of the latter in point design and ARES system analysis.

5. The ARES Method

The ARES (Airplane Responsive Engine Selection) method is a state-of-the-art, parametric data management system which has been developed by The Boeing Company. It allows efficient and economical management of parametric analysis using up to ten independent variables. Features of the method include:

- Orthogonal Latin Square Design Selection - A technique by which a minimal number of proper combinations of independent variable values is selected.

- Regression Analysis - Wherein the nonnegligible coefficients in a quadratic polynomial are derived. The resultant mathematical function is a correlation of dependent parameter variation with the independent variables in the problem.

- Optimization/Interrogation - In this element, the functions derived in regression analysis are interrogated to identify characteristics of specified combinations of independent variables, optimal combinations subject to the varying requirements, sensitivities to variations of requirements or independent variables, etc.

- Validation - Processing identified combinations of independent parameters through the procedure (BEAM in this instance) which generated the dependent variable data represented by the quadratic polynomials. This confirms the validity of the optimization result.

All ARES elements were used at some point in the performance of the RSTEP/ARM effort. The generation or simulation of dependent variable data, using BEAM for instance, occurs between design selection and regression analysis. This is a necessary step in application of the method, but is not described as an element since the ARES method is not dependent on any particular source of dependent data. This is made obvious in RSTEP/ARM where both BEAM and the RSTEP/ARM performance program were used in separate ARES method applications. When ARES is used together with BEAM results are identified by the designation BEAM/ARES in this report. Likewise, when ARES is used together with the RSTEP/ARM routines the results are identified by the designation RSTEP/ARES.

Although ARES is itself not part of RSTEP/ARM, it was used by Boeing together with RSTEP/ARM elements as a means of extending the scope of application of RSTEP/ARM modules.

6. Independent Variables

The RSTEP/ARM computer is designed to be responsive to variations in engine cycle, airframe design and mission characteristics. This is made possible by the judicious selection of independent variables for which the regression models for geometry, weights, and drag in the program were developed.

Engine cycle variation was addressed by selecting propulsion system characteristic descriptors which would adequately represent a parametrically varying propulsion "hole size". Descriptors were selected to represent inlet size, engine dimensions and weight, and nozzle characteristics. All other "hole size" variation is reflected by the scaling logic in BEAM. This logic uses the same propulsion system descriptors to generate associated geometries, weight, and performance.

7 Airframe design variation was addressed by selecting as independent parameters major airfame descriptors which are normally used to characterize airplane size and shape. These descriptors are also used by airframe scaling logic to generate associated geometries, weights, and performance. Of course, the RSTEP/ARM logic cannot be responsive to changes in airframe design concept since secondary descriptors that were held constant during development of the capability are peculiar to the one airframe concept described earlier.

Mission requirements are independent upon operating conditions in the present context. Independent variables that were selected to characterize these conditions were Mach number, altitude, and lift coefficient.

Three sets of independent variables and their range of values were used during the RSTEP/ARM effort. The first of these is listed in Table 2.* This set of parameters was used in the development of the RSTEP/ARM performance program. Note that engine performance (thrust size) is not represented. It is also noteable that a total of thirteen variables are listed. This is more than the ARES capacity. Therefore, applicable independent variables in subsets of ten or less were used to develop the RSTEP/ARM models. This is possible since the subsets are logically identified. For example, Mach number, altitude, and engine weight have nothing to do with geometry and are eliminated from that consideration.

The propulsion system characteristic parameters, engine weight (W_{eng}), inlet capture area (A_{capt}), engine diameter at the front flange (D_{ff}), engine diameter at the customer connect point (D_{cc}), and engine length (L_{eng}) were "skewed" in terms of TOGW (see Table 2) to avoid severe mismatches in engine and airplane sizes. This approach causes some automatic correlation of the propulsion system parameters and TOGW. However, the consequences of this are not felt to be detrimental.

Applicable range of engine characteristics in terms of TOGW is illustrated in Figures 3 and 4.

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*The other two sets are tabulated in Tables 5 and 8.

Table 2. ARM Modeling Parameters

Parameter	Range of Variation
Design Takeoff Gross Weight, TOGW	35,000 to 75,000 lb
Takeoff Wing Loading, W/S	60 to 120 lb/ft^2
Wing Leading Edge Sweep, Λ_{LE}	30° to 60°
Wing Aerodynamic Aspect Ratio, AR	1.5 to 5.5
Wing Thickness to Chord Ratio, t/c	0.03 to 0.07
Engine Weight, W_{eng}	1050 to 5250 lb (0.03(TOGW) to 0.07(TOGW)
Inlet Capture Area, A_{capt}	2 to 15 ft^2 (0.000057(TOGW) to 0.0002(TOGW)
Engine Front Flange Diameter, D_{ff}	1.68 to 4.93 ft $(0.009\sqrt{TOGW}$ to $0.018\sqrt{TOGW})$
Engine Customer Connect Diameter, D_{cc}	1.77 to 5.67 ft $(0.00945\sqrt{TOGW}$ to $0.0207\sqrt{TOGW})$
Engine Length, L_{eng} (with nozzle)	8.38 to 19.3 ft $(0.0448\sqrt{TOGW}$ to $0.0704\sqrt{TOGW})$
Pressure Altitude, h	0 to 60,000 ft
Mach Number, M	0.35 to 21.3
Lift Coefficient, C_L	0 to 0.6

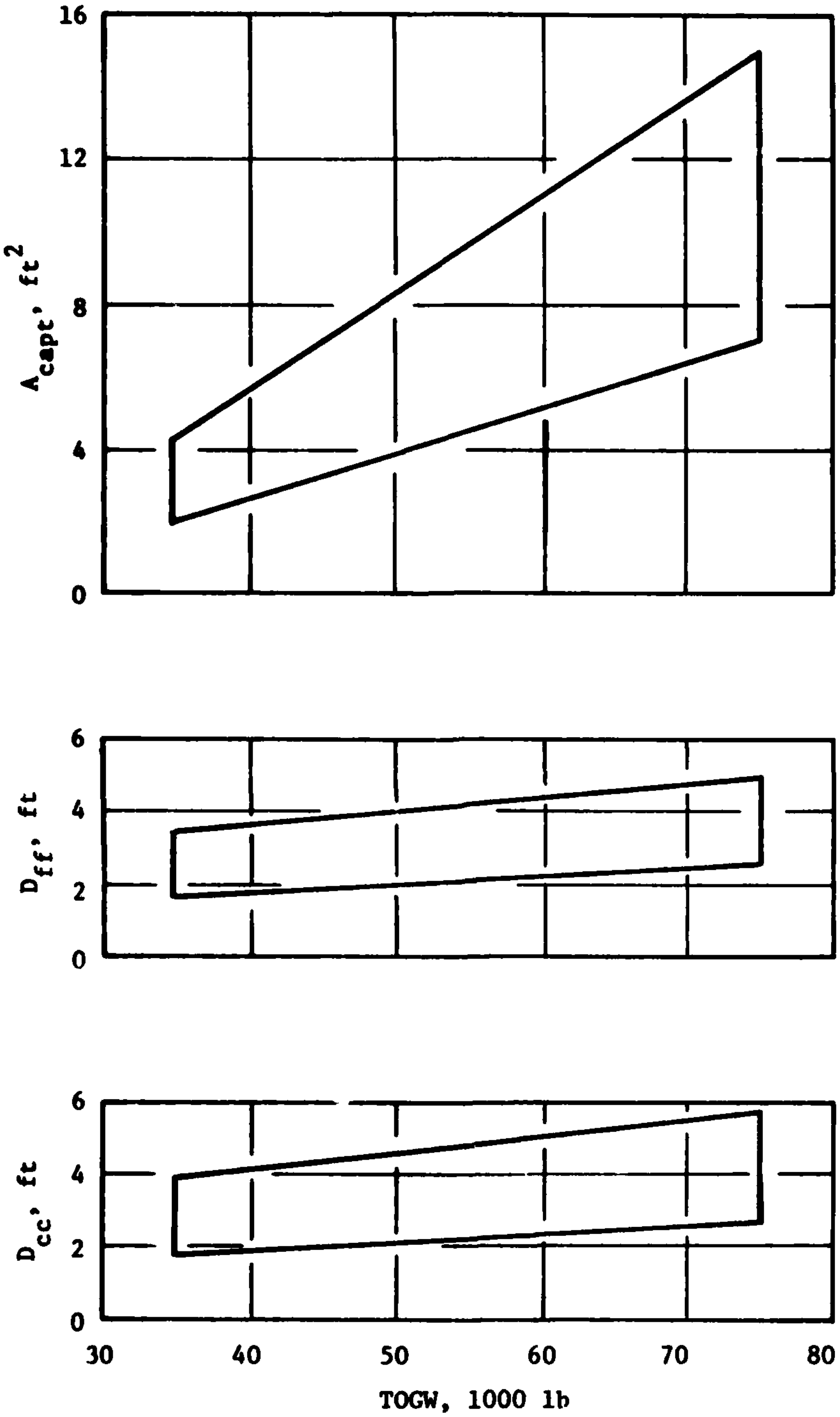


Figure 3. Engine Geometric Characteristics Limits, RSTEP/ARM Studies.

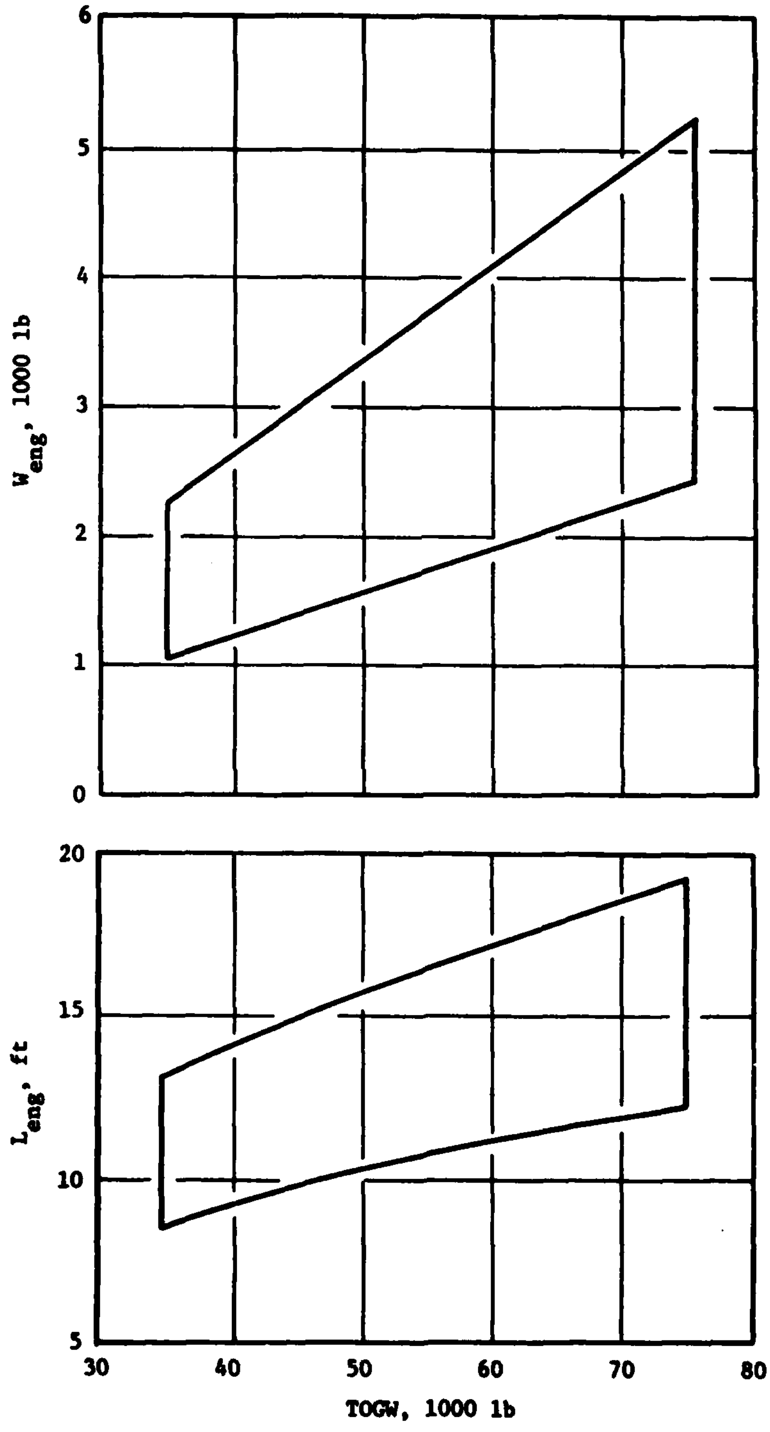


Figure 4. Engine Characteristics Limits, RSTEP/ARM Studies.

B. Regression Simulation of Airframe Characteristics (Task II)

The development of the aircraft regression models was pursued via the ARES regression analysis procedure. Application of this procedure is quite straightforward and involves only the identification of a dependent parameter and the independent variables to which the dependent parameter will be fitted and correlated. The ARES program derives coefficients for each significant term in a quadratic polynomial in all appropriate independent variables by an iterative process. The process continues until the dependent parameter's variation is adequately "modeled". Of course, if the true variation is sufficiently nonquadratic, the degree to which it may be "modeled" by quadratic regression analysis may be inadequate.

The regression program also provides statistics which are indicative of the relative adequacy of fit or explanation. In the development of the RSTEP models, the statistics indicated that most functions were representative of the dependent variables of interest.

Airframe characteristics were modeled by regression analysis in three areas: (1) geometry, (2) weights, and (3) drag.

Dependent geometrical characteristics for which models were developed are:

Exposed wing area

Body wetted area

Body volume

Tail wetted areas

Optical visibility index

Maximum body cross-sectional area

Body cross-sectional area at customer connect station

Visibility index is defined as the root-mean-square of the three areas of the aircraft (plan view, side view and front view).

Dependent weight-related surfaces included:

Operating weight

Total fuel weight

Fuel system weight

Air induction system weight

Hydraulic system weight

Engine section weight

AMPR weight

Total weight of structure

Total weight of propulsion system

Dependent drag variations were developed for the following conditions:

- Drag coefficients at zero lift at altitudes of 0, 18,000, 36,000, 45,000 and 60,000 feet with Mach number varied parametrically from 0.3 to 2.3.

- Subsonic drag-due-to-lift for parametrically varying lift coefficient (0 to 0.6) and Mach number (0.35 to 0.85).

- Transonic drag-due-to-lift at Mach numbers of 0.95, 1.05, and 1.15 with lift coefficients varying parametrically from 0 to 0.6, 0 to 0.55, and 0 to 0.5, respectively.

- Supersonic drag-due-to-lift for parametrically varying lift coefficient (0 to 0.45) and Mach number (1.25 to 2.25).

Much effort has been directed toward identification of ways to represent the drag-due-to lift component. The most promising approach was selected and is of the form:

$$C_{D_L} = \frac{C_L 2}{\pi\ AR} + \Delta\ C_{D_L}$$

where $\Delta C_{D_L} = \Delta C_{D_1} + \Delta C_{D_2}$

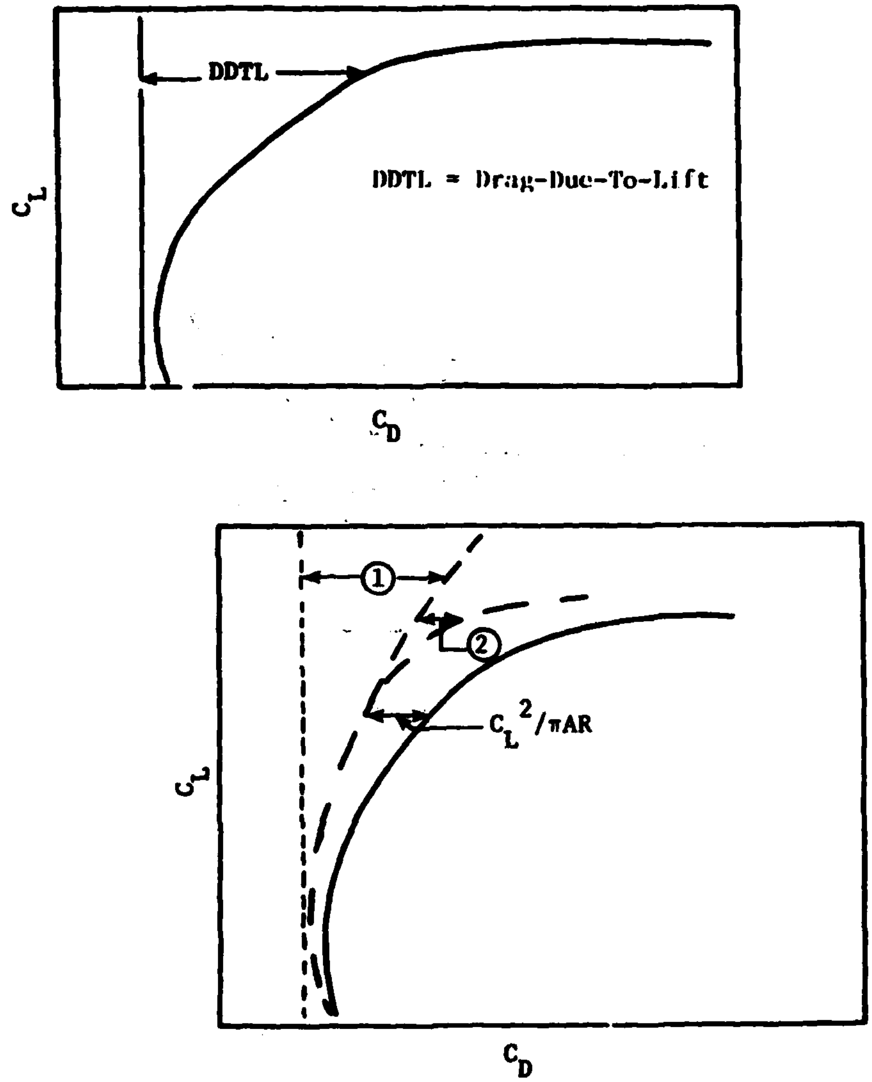
$\Delta C_{D_1} = f$ (RSTEP Variables), $C_L \leq 0.4$ and

$\Delta C_{D_2} = 0$ at $C_L < 0.4$ or

$= f$ (RSTEP Variables) at $C_L > 0.4$.

The ΔC_{D_1} function is derived by regression analysis on $(C_{D_L} - C_L{}^2/\pi\ AR)$ at $C_L \leq 0.4$ and the ΔC_{D_2} function is derived by regression analysis on $(C_{D_L} - C_L{}^2/\pi\ AR - \Delta C_{D_1} @ C_L = 0.4)$ at $C_L > 0.4$. The approach is illustrated in Figure 5. Initially, it was felt that this approach would yield acceptable drag values for demonstration purposes.

Considerations in evolving a drag-due-to-lift model have been to maintain simplicity where possible and yet achieve reasonably good accuracy. If the RSTEP/ARM approach to performance program development is to succeed, these considerations must be kept in balance.



DDTL = $f(C_L^2/\pi AR + 1 + 2)$

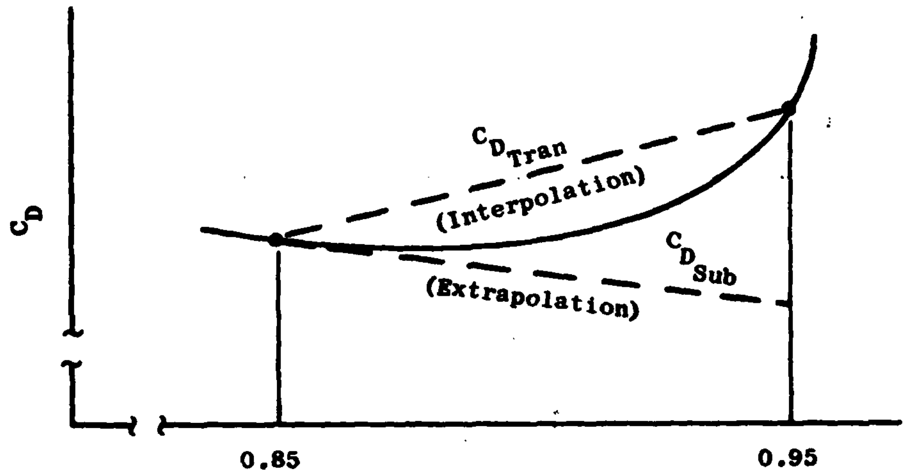
① = f(ARES/RSTEP Variables)

② = f(ARES/RSTEP Variables)

Figure 5. RSTEP/ARM Drag-due-to-Lift Modeling.

The drag-rise characteristics in the interval $0.85 \le$ Mach ≤ 0.95 use some fairing in lieu of linear interpolation with the form:

$$C_D = C_{D_{Sub}} + [(M - 0.85)/0.1]^2 \; (C_{D_{Tran}} - C_{D_{Sub}})$$



Most of the geometric and weight models serve as information sources in the RSTEP/ARM performance program. That is, their operation and output are generally nonessential in the calculation of airplane mission performance. The drag models are essential in the development of all types of airplane performance.

When the ARM representations for airplane geometry, weights, and drag had been "massaged" as much as possible within the constraints of the effort, they were coded into modules for eventual incorporation into the RSTEP/ARM performance program. With few exceptions, RSTEP/ARM models were developed with little or no problems.

After the completion of Task X, additional work was carried out in an attempt to assure that the models did represent the original aircraft characteristics over the complete range of values of the independent parameters.

C. The RSTEP/ARM Performance Program (Task III)

A flow chart of the RSTEP/ARM performance program is contained in Figure 6.

The RSTEP/ARM computer logic allows the determination of airplane performance characteristics based upon geometry, weights, and drag modules which are regression simulations. The program features three operation options. These are:

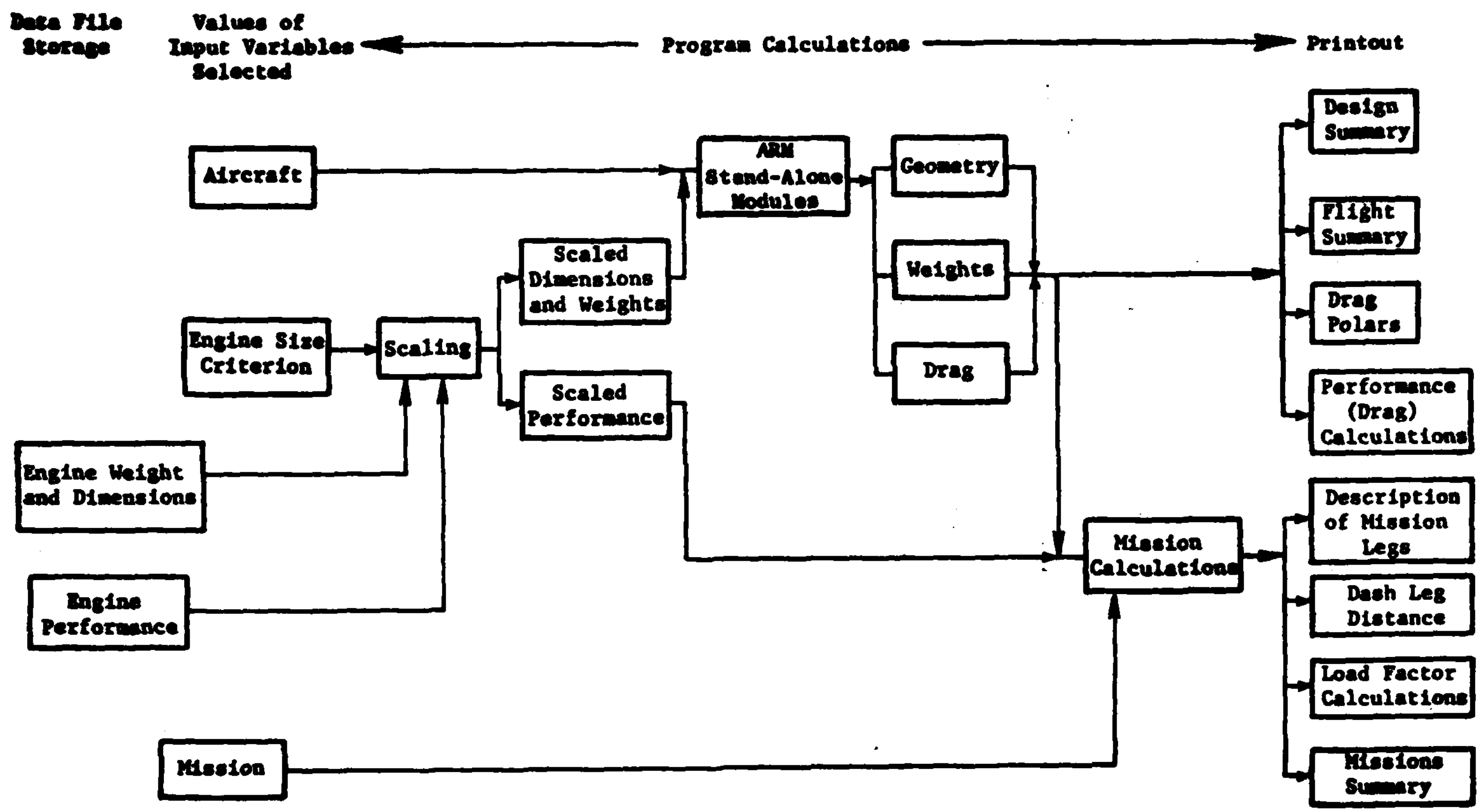


Figure 6. RSTEP Procedures, ARM Approach Flowchart.

- Interrogation - Geometry, weights, and drag are calculated for a design and for single values of Mach number, altitude, and lift coefficient.

- Drag Polar - Multiple values of drag coefficient are calculated at input altitude, for up to three Mach numbers, and for multiple values of lift coefficient (drag polars).

- Performance Analysis - Thrust required and aircraft drag are calculated at airplane operating conditions. This is the mode that is operational in mission performance calculations.

The program may be executed in either "batch" or "online" modes.

The RSTEP/ARM performance computer program is currently operational at General Electric, Evendale; Boeing, Seattle; and AFAPL, Wright-Patterson Air Force Base.

D. RSTEP/ARM and BEAM Performance Program Comparisons (Task IV)

Three point-design aircraft were selected for evaluation. The selected design parameters are tabulated below:

Configuration No.	1	2	3
Take-off Gross Weight - lb	55270	49940	51660
Wing Loading - psf	104	110	110
Wing Leading Edge Sweep Angle-degrees	45	45	45
Wing Aspect Ratio	4.609	3.945	4.60
Wing Thickness-to-Chord Ratio	0.04	0.04	0.04
Aircraft Thrust-to-Weight Ratio	0.818	0.606	0.772
Engine OPR	17.0	18.5	18.5

These particular designs do not necessarily represent optima, nor do they meet any specific performance criteria. They were chosen for illustrative purposes.

Geometry, weights, and performance levels of the three point designs which were processed through both BEAM and the RSTEP/ARM performance program are presented on Tables 3 and 4 for comparison.

All values of RSTEP/ARM geometry and weight parameters on Table 3 compare well except for a small increment in air induction weight. Slight differences in the performance parameters may be noted for takeoff fuel, subsonic cruise optimum Mach numbers, and altitudes, and maneuver load factors

Table 3. Program Comparisons - Geometry and Weights.

	Configuration 1		Configuration 2		Configuration 3	
	BEAM	RSTEP	BEAM	RSTEP	BEAM	RSTEP
GEOMETRY						
Wing Reference Area, ft^2	531	531	454	454	470	470
Wing Exposed Area ft^2	455	450	384	381	400	398
Fuselage Wetted Area, ft^2	1410	1429	1330	1325	1372	1386
Fuselage Volume, ft^3	2380	2416	2227	2226	2305	2334
Visibility Index, ft^2	552	544	470	466	486	482
Nozzle Area, A9, ft^2	13.5	13.6	9.6	9.4	12.3	12.3
Fuselage Area, A10, ft^2	45.6	46.7	38.6	38.1	42.2	43.1
WEIGHTS						
Takeoff Gross Weight, lb	55270	55270	49940	49940	51660	51660
Operating Weight Empty, lb	29300	29859	25030	25298	27260	27665
Internal Fuel Capacity, lb	21600	21082	20570	20325	20060	19670
Air Induction System Weight, lb	1520	1851	1176	1404	1400	1703
Structure Weight, lb	16000	16463	13380	13824	14560	14998
Powerplant Weight, lb	5680	5783	4147	3975	5143	5139

Table 4. Program Comparisons - Performance.

Item	Configuration 1		Configuration 2		Configuration 3	
	BEAM	RSTEP	BEAM	RSTEP	BEAM	RSTEP
Takeoff Fuel, lb	1000	1590	871	1260	940	1464
(Outbound Legs)						
Sub. Rad. Fuel, lb	4080	4099	3750	3900	3850	3904
Sub. Rad. Mach	0.950	0.912	0.941	0.919	0.947	0.916
Sub. Rad. Altitude, ft	40700	36900	38900	36300	39700	36400
Dash Rad., n. mi.	124	131	117	129	116	127
(Inbound Legs)						
Sub. Rad. Fuel, lb	2270	2521	1970	2227	2147	2376
Sub. Rad. Mach	0.950	0.928	0.945	0.925	0.947	0.928
Sub. Rad. Altitude, ft	49500	48600	48900	47500	48700	47500
Loiter Fuel, lb	2370	2363	2010	2047	2343	2352
Loiter Mach	0.320	0.334	0.320	0.334	0.340	0.341
Supersonic Maneuver Load Factor	6.10	6.64	3.99	4.86	5.58	6.08
Subsonic Maneuver Load Factor	3.40	3.65	2.88	2.93	3.16	3.42

(see Table 4). The discrepancy in take-off fuel is due to an inadvertent difference in time allowance value used in the two different programs. Dash radii, the major performance parameter, compare to within ten percent.

Drag polars were developed for all three point designs using both the BEAM and RSTEP/ARM drag polar options. Polars are concentrated at Mach numbers near the drag rise region and, therefore, allowed the construction of drag-rise cross-plots for direct comparison of drag output from the two programs. The polars and drag-rise cross-plots are presented for Configuration No. 1 only (Figures 7 and 8). Drag coefficient characteristics are shown for values of lift coefficients up to 0.8, although the RSTEP/ARM model should not be expected to produce accurate results at values of lift coefficient much above 0.6 (Mach $\leq$ 1.0) and 0.45 (Mach $\geq$ 1.0).

The BEAM polars on Figure 7 illustrate the change in curvature (predominantly subsonic and between C_L = 0.4 and 0.5) that caused difficulty in the modeling of drag-due-to-lift. The RSTEP/ARM polars on Figure 8 do not reflect this characteristic.

Drag-rise cross-plots from the polars of Figures 7 and 8 are presented on Figure 9 for comparison of BEAM and RSTEP/ARM. Agreement in level and trend is reasonably good until lift coefficient exceeds the range of validity of the RSTEP/ARM model. There are some discrepancies at the lower values of lift cofficients, no doubt due to the drag-due-to-lift modeling problems.

Supersonic drag polars (Mach 1.7) are compared on Figure 10. The small differences here are attributed to problems in pressure (wave) drag modeling.

E. Turbojet Fighter Data Bases (Task V)

As an example of the extended use of RSTEP/ARM elements, the parametric turbojet engine family discussed earlier was examined using the ARES optimization system with both the BEAM and RSTEP/ARM performance programs acting as the dependent data source. This allowed the evaluation of the utility of the RSTEP/ARM program in an ARES application.

The independent variables used in RSTEP/ARM are listed on Table 5. In this case, engine performance variations result from changes in engine size (determined by T/W) and cycle (OPR). Specified levels of T/W and OPR imply appropriate variations of propulsion system shape, weight, and performance. Forty-nine parametric combinations of the six independent variables were selected using the Orthogonal Latin Square technique. For this task, values of leading-edge sweep angle λ_{LE} and wing thickness-to-chord ratio were held fixed (see Table 5).

Seven levels of each independent variable were exercised. Therefore, seven different engine data decks (varying OPR) were required and each was used with seven different combinations of airplane design variables and

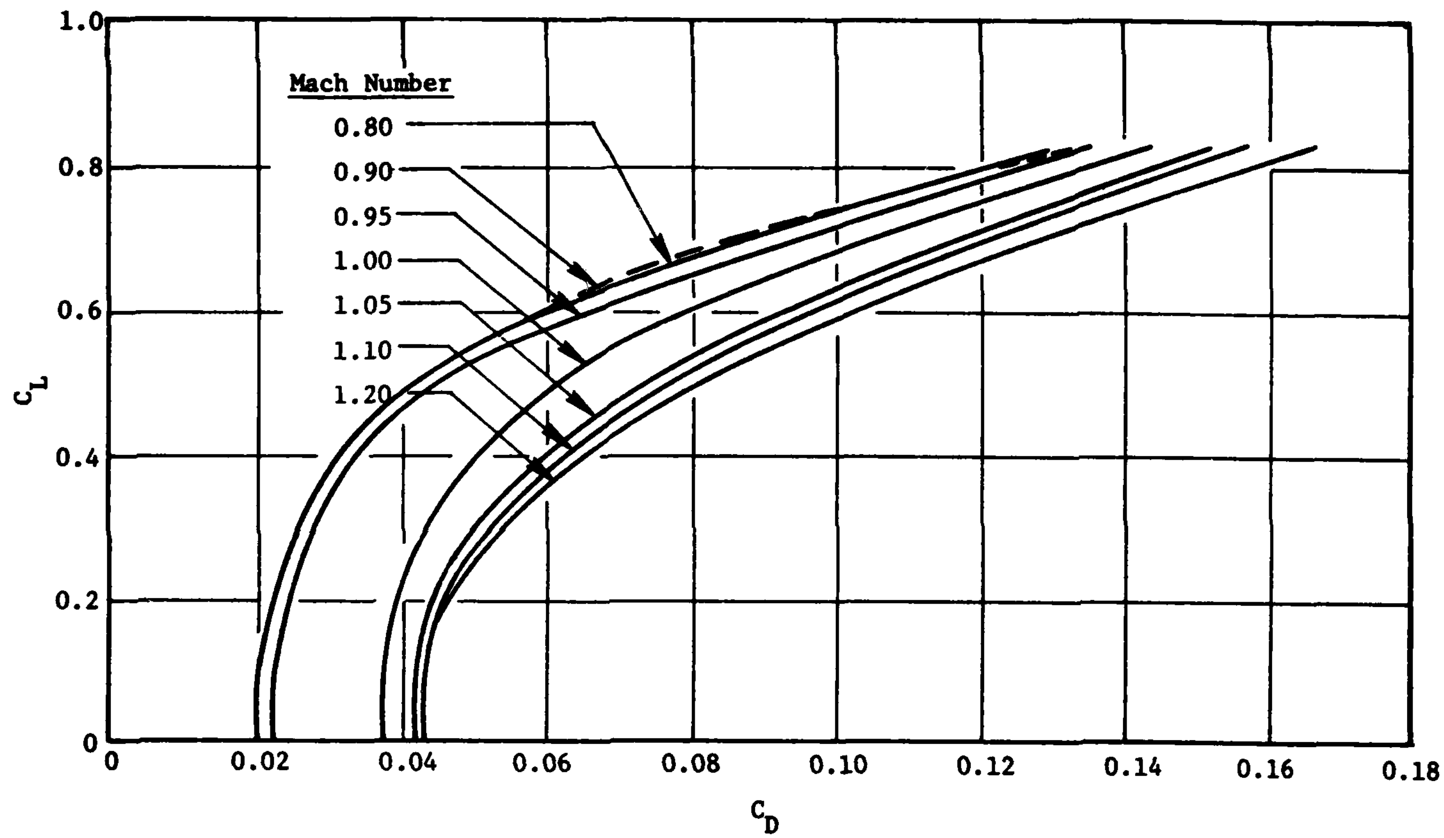


Figure 7. Drag Polars - BEAM Output, Configuration No. 1, RSTEP/ARM Study.

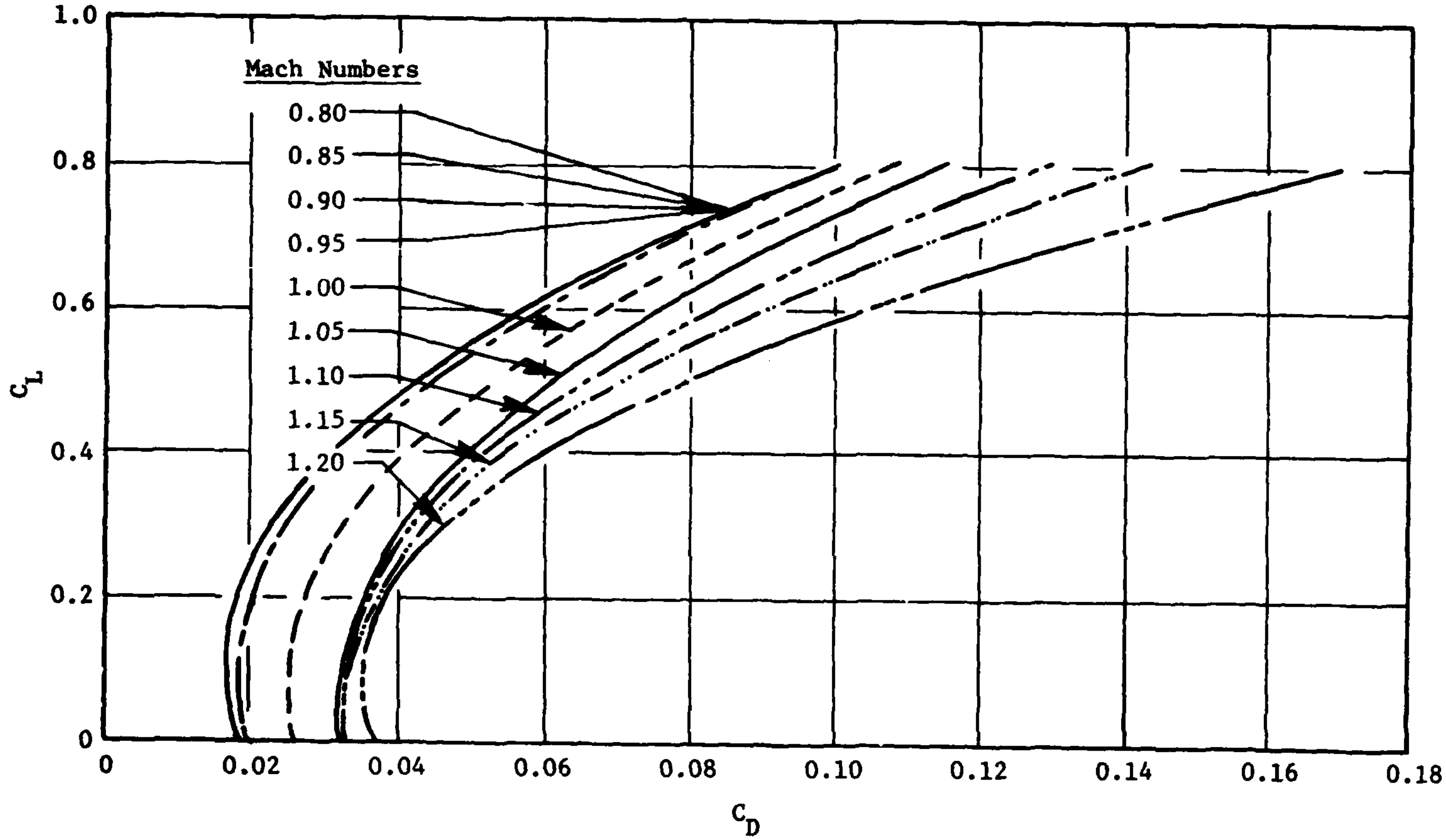


Figure 8. Drag Polars - RSTEP/ARM Output, Configuration No. 1, RSTEP/ARM Study.

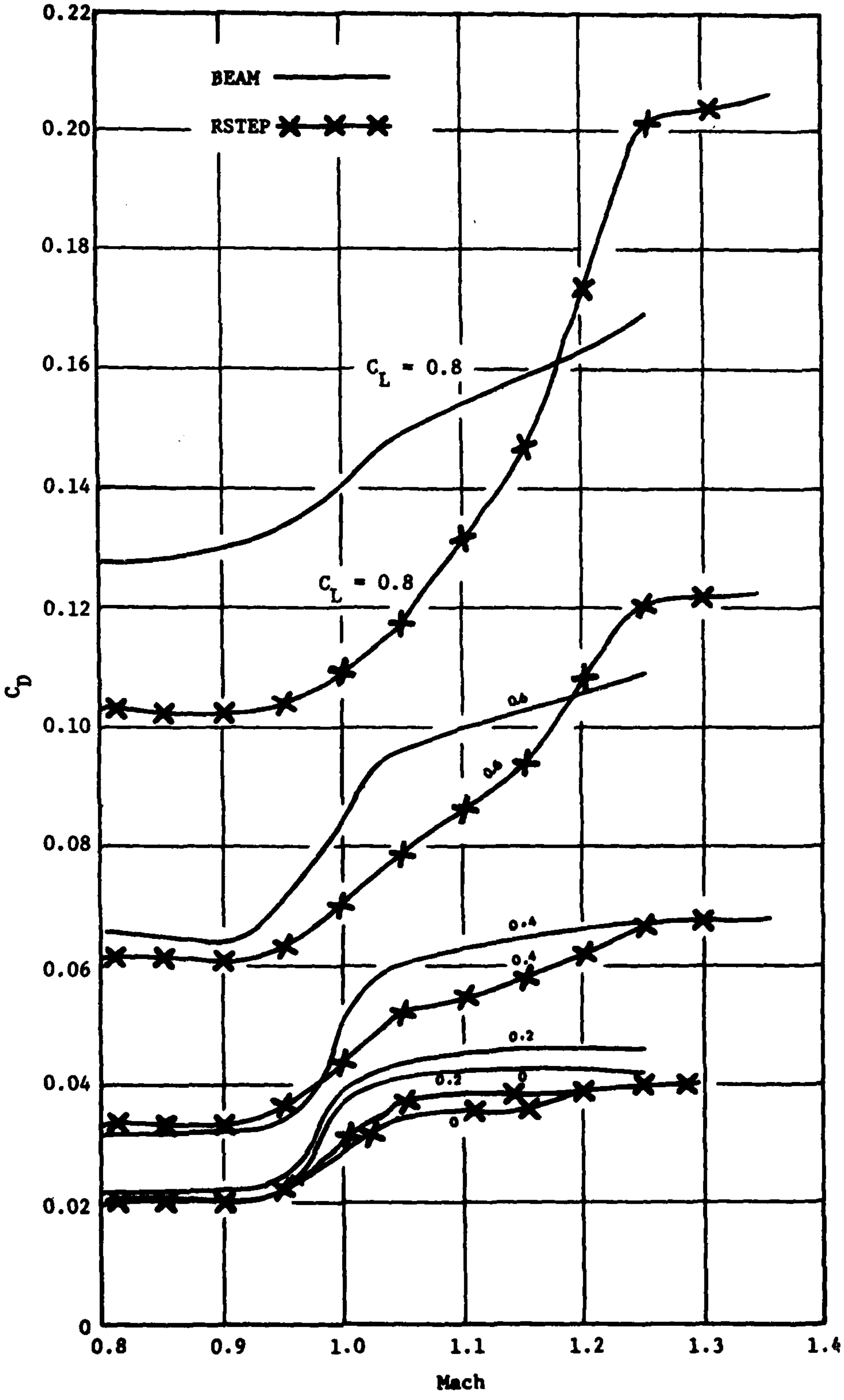


Figure 9. Drag-Rise Comparison, Configuration No. 1, BEAM Output Versus RSTEP/ARM Output.

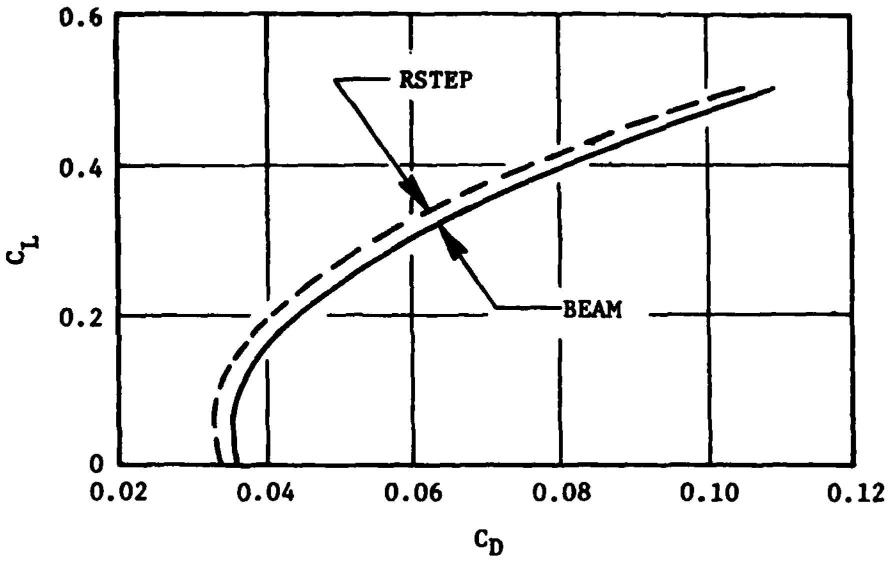


Figure 10. Supersonic Drag Polar Comparison Configuration No. 1, M = 1.70, BEAM Output Vs. RSTEP/ARM Output.

Table 5. Range of Variation of Independent Variables for RSTEP/BEAM/ARES Analysis, Turbojet.

Parameter	
Design Takeoff Gross Weight, TOGW	40,000 to 70,000 lb
Takeoff Wing Loading, W/S	70 to 110 lb/ft^2
Takeoff Thrust-to-Weight Ratio, T/W	0.6 to 1.0
Wing Aerodynamic Aspect Ratio, AR	2.0 to 5.0
Overall Pressure Ratio, OPR	11 to 20
Dash Mach Number, M	1.2 to 1.6
Wing Leading Edge Sweep, λ_{LE}	Constant (45°)
Wing Thickness to Chord Ratio, t/c	Constant (.04)

Note: For analysis carried out in Tasks IV and V the first six parameters were used as independent variables. The last two were held fixed (at values shown).

dash Mach number. The forty-nine parametric combinations were processed through the two performance programs to produce a dependent variable data base for each one. Selected parameters within these data bases were fitted in regression analyses and the resultant surfaces were interrogated for several sets of criteria. Results of these interrogations are presented and compared in Task VI (see next section).

The shape and weight characteristics of the turbojet data base propulsion systems are spotted on the RSTEP/ARM engine characteristics limits grids on Figures 11 and 12. The data base system characteristics are presented as they were scaled for parametrically varying takeoff gross weight and airplane thrust-to-weight ratio. These data also represent the slight variation of propulsion system dimensions and weights due to the variation of overall pressure ratio from 11 to 20.

Figure 11 illustrates the variation of engine weight (one engine) and length. The weight grid was covered to a fair degree except for the high engine weight region and the extremes of TOGW, which were avoided intentionally. The length grid was covered to a fair degree also.

Figure 12 illustrates the variation of engine diameter and inlet capture area. About half the area of these grids has been exercised.

F. RSTEP/ARES and BEAM/ARES Analysis Comparisons (Task VI)

Results of the interrogations of the ARES performance surfaces derived from the RSTEP- and BEAM-generated data bases (Task V) included both optima and sensitivities to changing requirements and design variables. Interrogation results are presented and compared in the following pages.

Figure 13 illustrates the response of takeoff gross weight (TOGW) to variations in dash Mach number where the optimization is constrained by varying specification of dash radius. The solid lines represent BEAM/ARES results. The dashed lines represent RSTEP/ARES results. Agreement in numerical results ranges from good at low dash radii and high dash Mach numbers to marginal (10% errors) at high dash radii and Mach numbers. However, the trends in variation of minimum TOGW with either Mach number or radius are quite similar, and optimal levels of independent parameters not shown on the graph are similar, e.g.,:

	Optimal Values	
Parameter	BEAM/ARES	RSTEP/ARES
OPR	18.4	18.3 - 19.3
W/S	110*	110*
T/W	0.62 (approx)	0.60*
AR	3.6 - 4.0	3.2 - 5.0*

*Study Limit

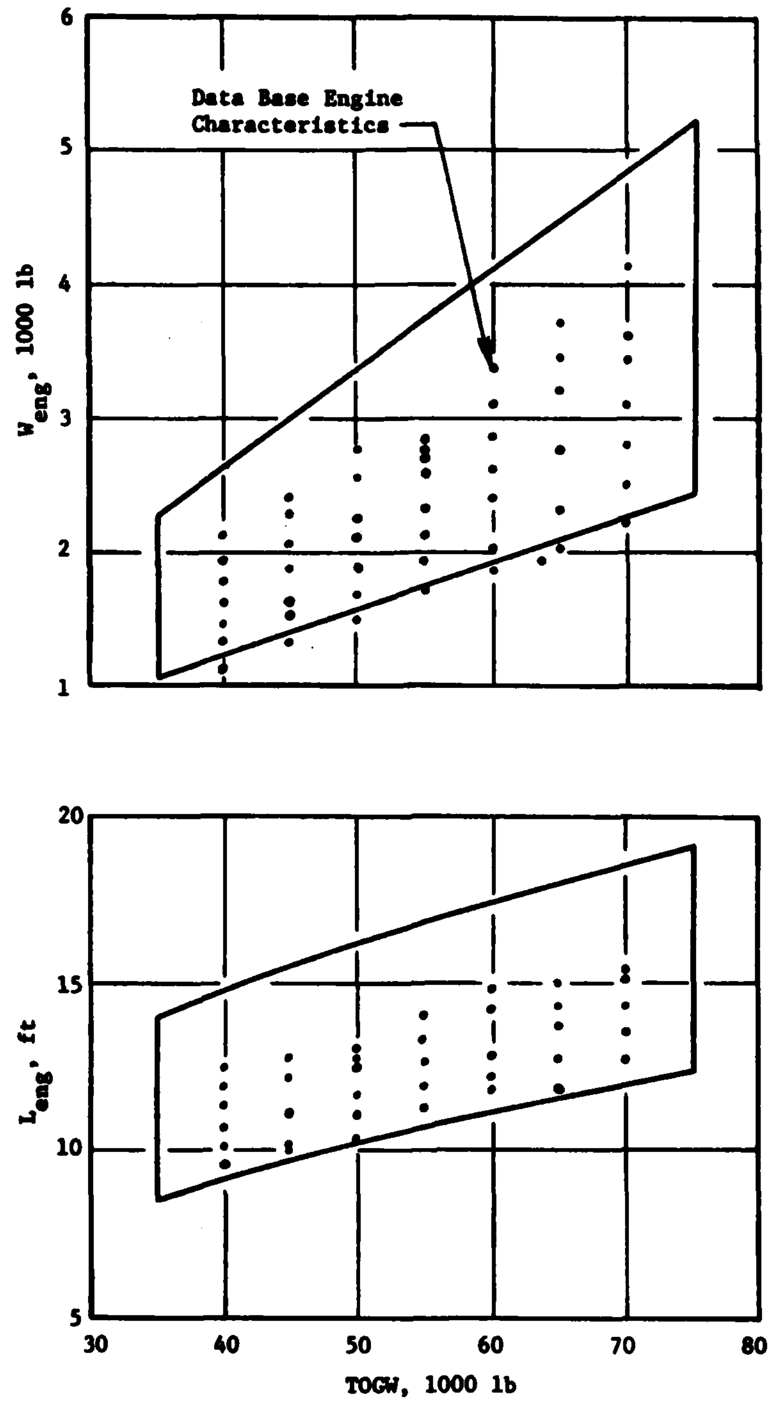


Figure 11. Variation of Engine Characteristics, RSTEP/ARM Studies.

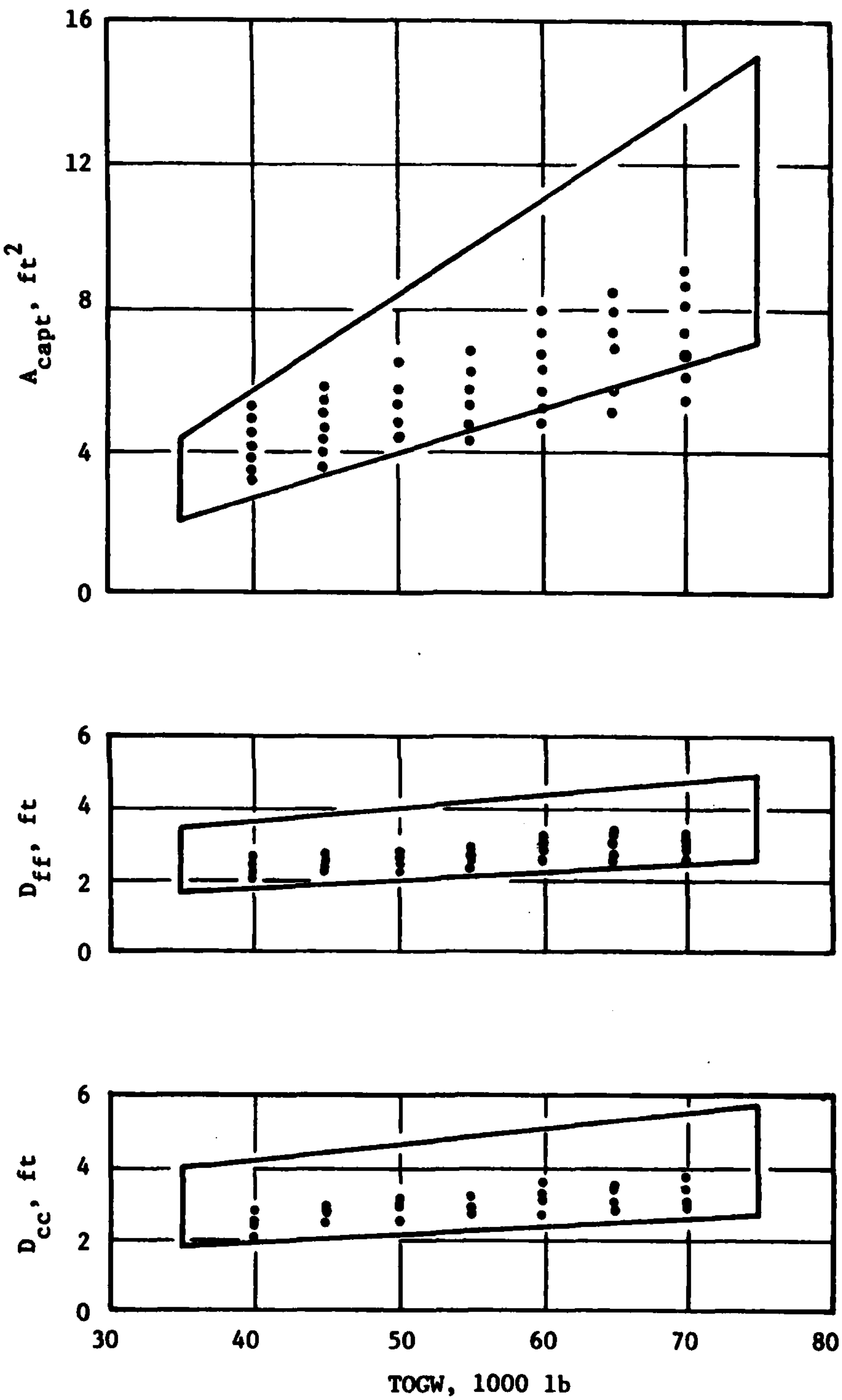


Figure 12. Variation of Engine Geometry Characteristics, RSTEP/ARM Studies.

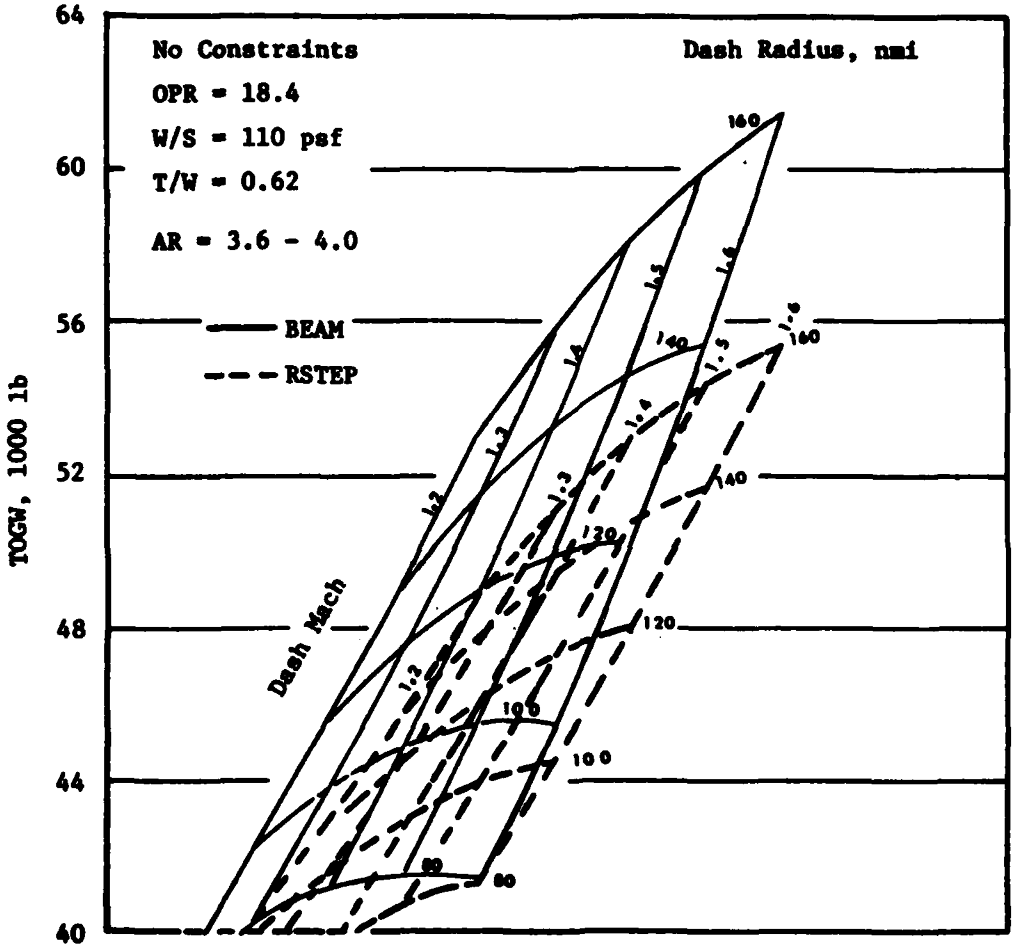


Figure 13. TOGW Sensitivity to Radius and Dash Mach Number, ARES Interrogation Results - Turbojet BEAM/ARES Vs. RSTEP/ARES.

The response of TOGW to variation of wing loading and airplane thrust-to-weight ratio for a fixed-dash Mach number and dash radius is illustrated in Figure 14. In this comparison, combat load factor is constrained to be ≥3.0. Once again, solid lines represent the BEAM/ARES optima while dashed lines represent the RSTEP/ARES result.

The trends illustrated in the two results are similar. The trend of TOGW with wing loading variation (constant thrust-to-weight ratio) is identical in both cases. The trend of TOGW with thrust-to-weight ratio variation (constant wing loading) is similar, particularly at the higher wing loadings. Errors in absolute level of TOGW are not as severe here as in the previous comparison. Both results indicate the same optimal value of T/W = 0.65.

Differences in TOGW are apparent in Figure 15 in which BEAM/ARES (solid lines) and RSTEP/ARES (dashed lines) are compared for variations in dash Mach number and engine overall pressure ratio (OPR). Larger differences in TOGW are evident at the higher OPR. Again, trends are similar and, more important, both results indicate an optimal value of OPR in the region of 17 to 19.

It is apparent that, although the use of RSTEP/ARM calculation procedures does not always result in an extremely accurate value of take-off gross weight (compared to the parent BEAM value), the RSTEP/ARM procedures do yield good results in terms of identifying trends and optima. This is further illustrated in Figure 16, which shows similar trends in values of design parameters as mission requirements (i.e., combat load factor in this case) are varied. Figure 16 shows how the airplane design reoptimizes as required combat load factor is varied from 2.8 to higher levels. Overall pressure ratio (OPR), using loading (W/S), and thrust-to-weight ratio (T/W) values all shift to new optimal values as combat load factor is varied. Values shown on Figure 16 are optimal values (or limits, in some cases) for the goal of minimized take-off-gross weight. The BEAM/ARES and RSTEP/ARES trends are similar, although substantial errors in TOGW occur at the higher load factors. Optimal OPR levels are also diverging in this area. Load factor capability for the minimum weight design is about the same for either result (2.8 to 3.0).

A validation comparison should always be performed for any ARES application early in its development. In this ARES method step, interrogation results (from the fitted surfaces) are compared to performance program results obtained directly for the same point design. This ensures that the ARES optimization result is reasonably valid.

Standard ARES validation comparisons are presented in Table 6 for the BEAM/ARES and Table 7 for the RSTEP/ARES. The BEAM/ARES validation is quite good. The RSTEP/ARES validation is reasonably good also. Some discrepancies in radius (12%) and cruise altitude (4%) are apparent. Indications are that both ARES exercises are validated. The cases in Table 6 have few constraints:

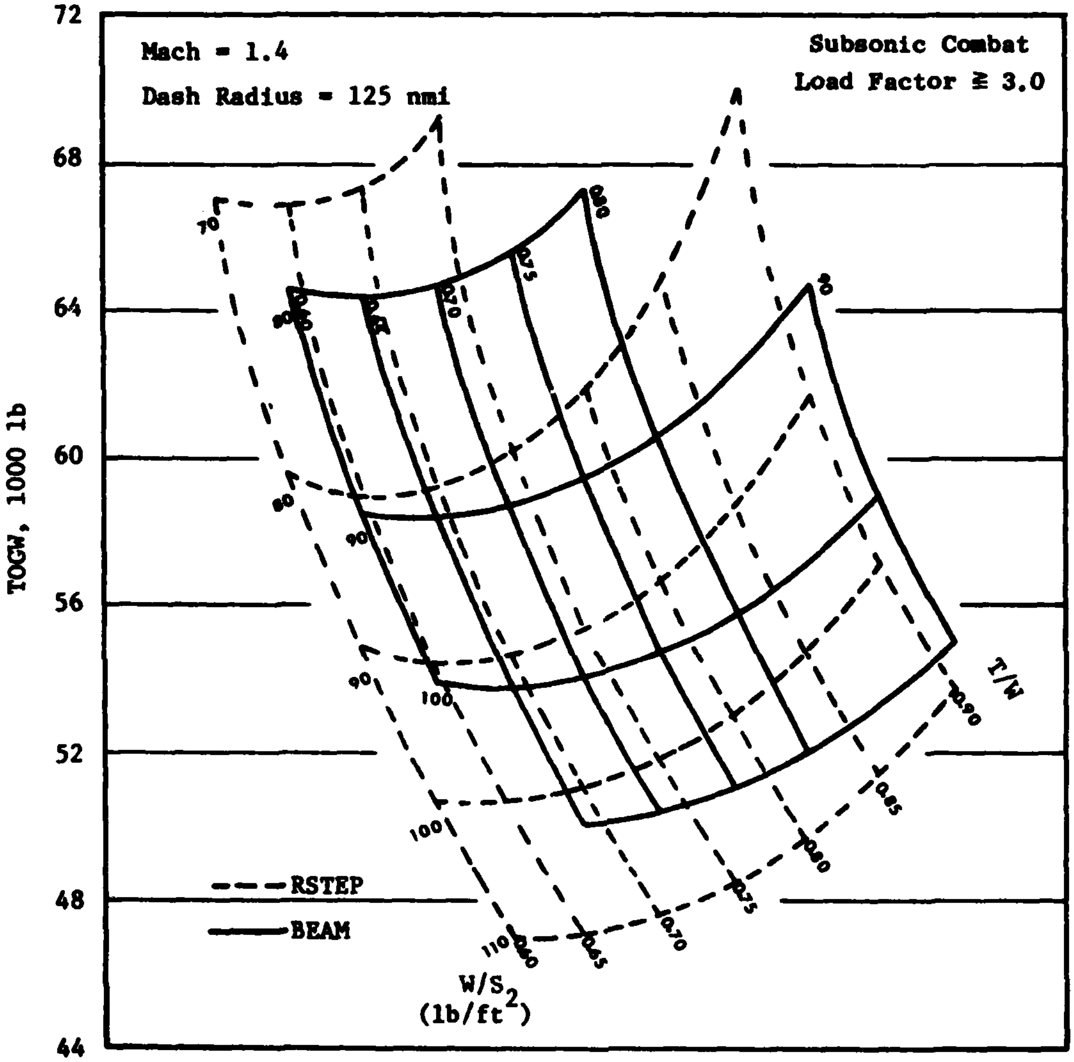


Figure 14. TOGW Sensitivity to Aircraft T/W and W/S ARES Interrogation Results - Turbojet BEAM/ARES Vs. RSTEP/ARES.

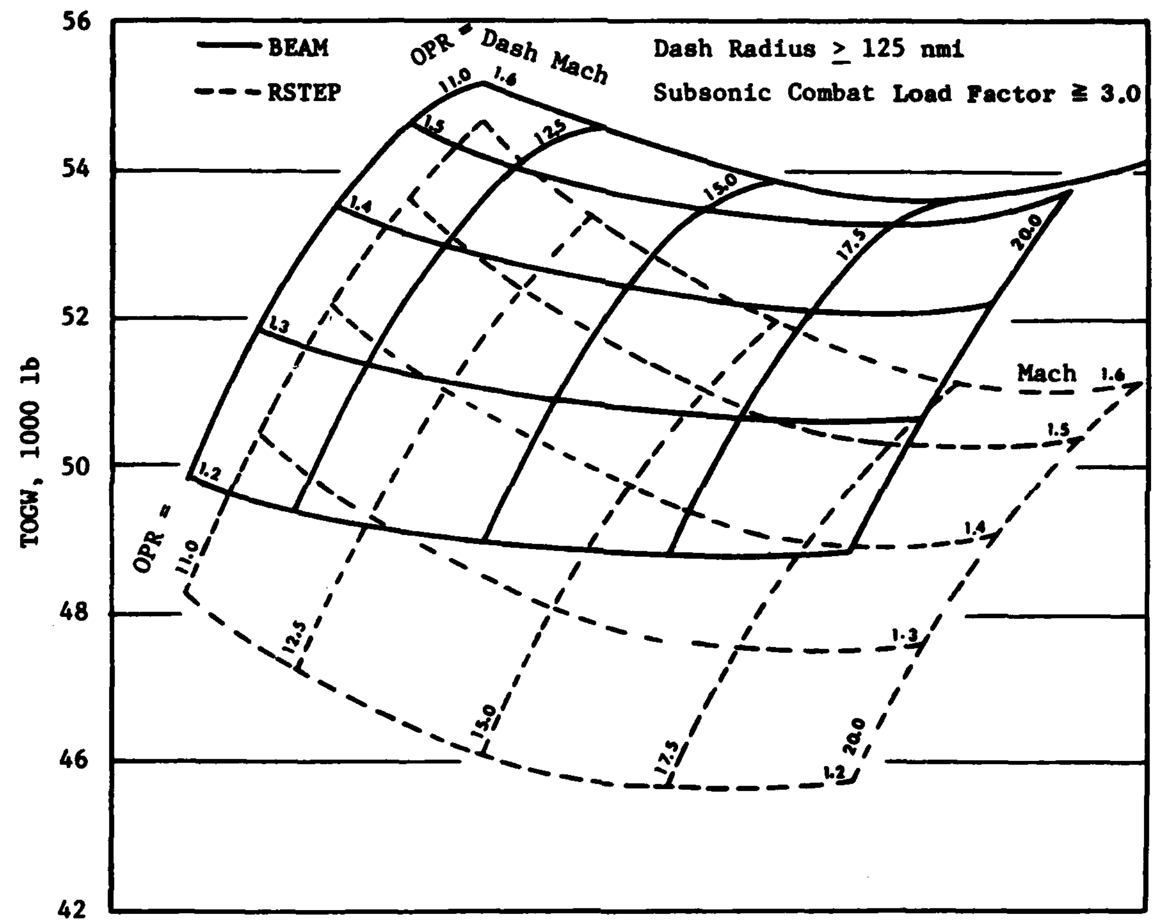


Figure 15. TOGW Sensitivity to Overall Pressure Ratio and Dash Mach Number, ARES Interrogation Results - Turbojet BEAM/ARES Vs. RSTEP/ARES.

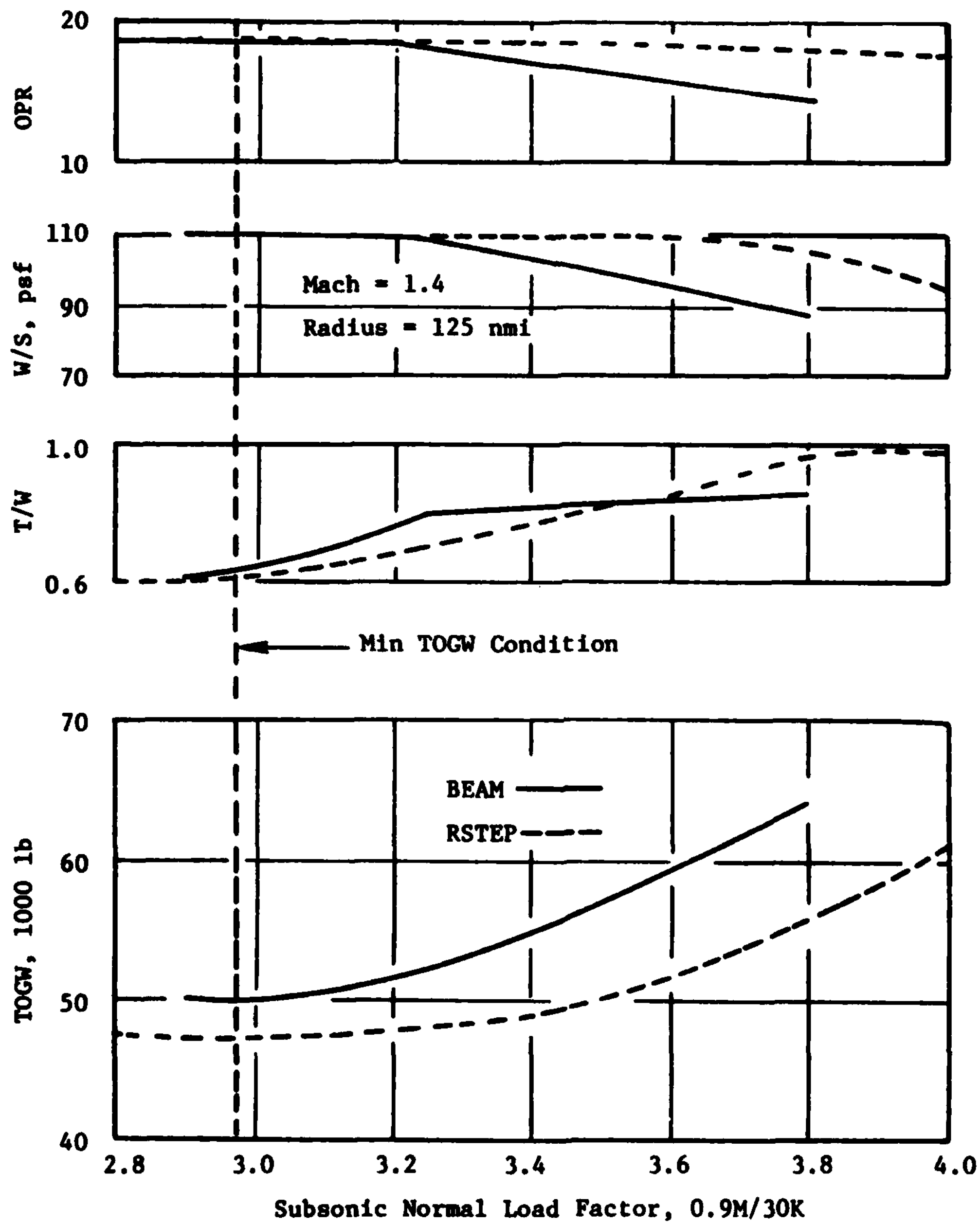


Figure 16. Variation of Aircraft Parameters with Subsonic Load Factor.

Table 6. BEAM/ARES Comparison, Turbojet Engines.

	Configuration 1		Configuration 2		Configuration 3	
	ARES	BEAM	ARES	BEAM	ARES	BEAM
Overall Pressure Ratio	17.0	17.0	18.5	18.5	18.5	18.5
Mach Number-Dash	1.4	1.4	1.4	1.4	1.4	1.4
TOGW, lb,	55270	55270	49940	49940	51670	51670
Thrust-to-Weight Ratio	0.8183	0.8183	0.606	0.606	0.772	0.772
Wing Loading-Takeoff, lb/ft^2	104	104	110	110	110	110
Wing Aspect Ratio	4.609	4.609	3.945	3.945	4.60	4.60
Dash Radius* n.mi	125	124	125	117	125	116
Operating Weight Empty, lb,	29313	29280	25104	25030	27336	27260
Mission Fuel, lbs	20536	20560	19474	19540	18993	19060
Combat Load Factor 0.9/30K*	3.400	3.371	2.905	2.881	3.200	3.160
Combat Load Factor 1.4/20K	6.163	6.139	4.004	3.994	5.576	5.585
Cruise Altitude, ft	41267	40730	39280	38910	40074	39680
Cruise Mach Number	0.945	0.947	0.942	0.941	0.943	0.947
Dash Power Setting - As Function of Military Power	1.036	1.027	1.371	1.395	1.119	1.098
Engine Scale Factor	1.136	1.133	0.756	0.756	0.998	0.997
Takeoff Distance, ft	2691	2675	3811	3848	3019	2984
Approach Speed, knots	137.8	137.6	138.2	137.9	142.0	141.5
Visibility Index, ft^2	551.4	551.9	473.8	469.5	490.7	486.3

*Constraints

Table 7. RSTEP/ARES Comparison, Turbojet Engines.

	Configuration 1		Configuration 2		Configuration 3		OPT Configuration	
	RSTEP	ARES	RSTEP	ARES	RSTEP	ARES	RSTEP	ARES
Overall Pressure Ratio	17	17	18.5	18.5	18.5	18.5	18.5	18.5
Dash Mach Number	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Takeoff Gross Weight, lb	55270	55270	49940	49940	51660	51660	46957	46957
Aircraft Thrust-to-Weight Ratio	0.818	0.818	0.606	49940	0.772	51660	0.600	0.600
Takeoff Wing Loading, lb/ft^2	104	104	110	110	110	110	110	110
Wing Aspect Ratio	4.609	4.609	3.945	3.945	4.6	4.6	4.615	4.615
Dash Radius, n.mi.	131	134	129	143	127	138	112	125
Operating Weight Empty, lb	29860	29762	25300	25343	27660	27550	24600	24535
Mission Fuel, lb	21080	21179	20320	20378	19670	19782	18040	18103
Combat Load Factor 0.9/30K	3.65	3.65	2.93	2.95	3.42	3.42	2.99	2.98
Combat Load Factor 1.4/20K	6.64	6.65	4.86	4.93	6.08	6.19	4.70	4.77
Cruise Altitude, ft	36910	37861	36290	36789	36450	37963	37070	37985
Cruise Mach Number	0.913	0.918	0.919	0.922	0.916	0.923	0.919	0.923
Dash Power Setting - as Fraction of Military Power	0.429	0.427	0.628	0.619	0.464	0.453	0.651	0.643
Engine Scale Factor	1.130	1.130	0.756	0.756	0.997	0.997	0.704	0.704
Visibility Index, ft^2	544	544	466	466	482	483	443	443

Dash radius = 125 n. mi. (ARES only)

Dash Mach number = 1.4

Subsonic maneuver load factor varies:

no constraint for Configuration 2

load factor = 3.2 for Configuration 3

load factor = 3.4 for Configuration 1

Table 7 cases have similar constraints, except that an additional case is listed (Optimum Configuration) having a load factor of 3.0.

Following approval of the preceding results and delivery of the program descriptions to the Air Force (Task VII), the RSTEP/ARM and BEAM programs were used, once again, in parallel ARES applications to evaluate a point design turbofan concept. This work constitutes Tasks VIII, IX and X and is described below.

G. Generation of Turbofan Fighter Data Bases (Task VIII)

Turbofan-powered fighter data bases were generated using the BEAM and RSTEP/ARM performance programs for seven independent variables. These variables and their ranges of variation are presented in Table 8. The engine used for the data bases was the GE16/F17 Study A engine which was described in a previous section. Performance was calculated for the same mission requirements used in the turbojet analyses.

Performance surfaces were formed for six dependent parameters in the data base using regression analysis. These variables were:

- Load factor at combat conditions (Mach 0.9 and 30,000 ft)
- Load factor at dash Mach number (20,000 ft)
- Dash radius
- Dash power setting (fraction of maximum dry power)
- Mission fuel
- Visibility Index*

They were selected for investigation based on the conclusion of the work carried out in Task IX (done concurrently).

*Defined in Section III. B.

Table 8. Range of Variation of Independent Variables for RSTEP/BEAM/ARES Analysis, Turbofan.

Parameter	
Design Takeoff Gross Weight, TOGW	35,000 to 75,000 lb
Takeoff Wing Loading, W/S	60 to 120 lb/ft^2
Takeoff Thrust-to-Weight Ratio, T/W	0.6 to 1.2
Wing Aerodynamic Aspect Ratio, AR	1.5 to 5.5
Dash Mach Number, M	1.2 to 1.8
Wing Leading Edge Sweep, λ_{LE}	30° to 60°
Wing Thickness to Chord Ratio, t/c	0.03 to 0.07

H. Turbofan Fighter Interrogation Criteria (Task IX)

In Task IX four criteria for optimzation of the turbofan-powered fighter were identified. They were:

1. Minimum Weight

2. Economy

3. Agility

4. Stealth

Criterion (1) requires the minimizing of takeoff gross weight, an independent variable. By inference, a minimum weight design is expectd to have minimum cost. Mission fuel is minimized for optimization criterion (2). In addition to the economic benefits of low operation cost (low fuel usage), reduction in fuel usage generally reduces the aircraft size as well. Agility (3) implies good maneuver or high load factor capability. Subsonic combat load factor is maximized for the optimization criterion. Supersonic combat load factor ≥ 7.0. Since cost is not a consideration in this instance, a high powered, heavy system is a most likely result. The stealth criterion (4) is addressed by minimizing aircraft physical size. Since large designs are more visible, this result would be expected to be relatively lightweight. The parameter used to quantify size (or visiblity) is the root-mean-square sum of squares of plan area, side area and frontal area of the aircraft. It is called the Visibility Index. An additional constraint is the requirement that power setting be less than miliary power.

Together with the figures-of-merit just described, several additional constraints on the optimizations were also used. The above criteria interrogations were subject to the following constraints (except as noted):

- Dash radius of 125 n.mi.

- Dash Mach number ≥ 1.2

- Combat load factor of at least 3.0 (except for size criterion)

These requirements ensured that all optima generally would have a minimnum level of combat maneuver capability, and an equal radius capability.

Each criteria was investigated for the complete parametric range of dash Mach number. Results are presented under Task X below.

I. Results of BEAM/ARES Turbofan Interrogation (Task X - Boeing)

Based on experience in evaluating the turbojet airplane, the turbofan airplanes' performance surfaces were expected to be accurate. However, a validation comparison made following preliminary interrogation of the surfaces (Tables 9 and 10) proved otherwise. Four turbofan optima identified in the preliminary interrogation were analyzed in BEAM (Table 9).

A number of constraints was used in this analysis. They are described below.

The criterion for Minimum Weight was minimum take-off gross weight for a radius of 125 n.mi. The only other constraint was that dash Mach number be ≥ 1.2. The criterion for Economy required the minimizing of mission fuel. Constraints applied were: subsonic combat load factor ≥ 3.0, dash Mach number ≥ 1.2, dash radius = 125 n.mi., and in certain cases supersonic combat load factor ≥ 7.0. The Stealth criterion had several constraints; dash radius = 125 n.mi., subsonic combat load factor ≥ 3.0, supersonic combat load factor ≥ 7.0 (in certain cases only), dash Mach number ≥ 1.2, and dash power setting $\leq$ Military. Agility criterion had several constraints; dash radius = 125 n.mi., dash Mach number ≥ 1.2, dash power setting $\leq$ Military, supersonic load factor $\geq$ 7.0, and various levels of subsonic load factor.

The BEAM validation result is compared to the initial ARES interrogation result, designated ARES No. 1, on Table 10. The interrogation results are not accurate in many cases. Only the "agile" optimum (i.e., maximum subsonic maneuver load factor) is generally validated. Thus, the necessity of including validation as part of an ARES application study is emphasized.

In an effort to improve accuracy of the regression surface fits, data from the three validation points run on BEAM were added to the data bases. This augmented data base (called ARES No. 2) was then fitted and interrogated. Regression statistics were quite good and some interrogation results are compared to BEAM results on Table 10.

The modified set of surfaces (i.e., ARES No. 2) was interrogated to yield the results discussed in the following paragraphs. Variations of size, design and performance of optima for four figures-of-merit and varying dash Mach number are presented. Designs are identified for maximum combat load factor (MAXMAN), minimum mission fuel (MINFUEL), minimum TOGW (MINGWT), and minimum visibility index (MINVIS) in Figures 17 through 21. As previously mentioned, all designs were required to have a dash radius of 125 mi. Other constraints were similar to those discussed in connection with Table 10.

The variation of airplane size (gross weight) is illustrated on Figure 17. The extraordinary weight penalty for high maneuverability at low dash Mach number is obvious and is also reflected in Figures 17 to 20. Mission

Table 9. Optimal RSTEP/ARM Fighters, GE16/F17 Study A Turbofan, Dash Radius 125 n.mi., BEAMS/ARES No. 1 Output.

	Minimum Weight	Economy	Stealth	Agility
Takeoff Gross Weight, lb.	37,900	35,800	39,200	68,000
Takeoff Wing Loading, psf	120*	120*	120*	86
Aircraft Thrust-to-Weight Ratio	0.63	0.86	0.74	1.20*
Wing Aspect Ratio	1.5*	1.5*	1.5*	3.67
Wing Leading Edge Sweep Angle, deg	60*	60*	60*	30*
Wing Thickness-to-Chord Ratio	0.03*	0.03*	0.03*	0.03*
Dash Mach Number	1.20*	1.20*	1.50	1.20*
Mission Fuel, lb	12,100	9,400	12,700	24,500
Visibility Index, ft^2	333	309	337	850*
Combat Load Factor	2.87	3.00*	3.07	5.40
Dash Load Factor	4.7	5.1	6.1	7.0*
Dash Power Setting, as Percent of Military Power	1.00	0.60	1.00*	0.84

*Study Limit

Table 10. Validation Comparison - Turbofan BEAM Output Vs. BEAM/ARES Output.

Parameter	Minimum TOGW			Minimum Mission Fuel			Minimum Visibility			Maximum Subsonic Load Factor		
	BEAM	ARES No. 1	ARES No. 2	BEAM	ARES No. 1	ARES No. 2	BEAM	ARES No. 1	ARES No. 2	BEAM	ARES No. 1	ARES No. 2
Mission Fuel, lb	12,700	12,100	12,700	10,200	9,400	10,200	13,000	12,700	13,000	24,800	24,500	24,500
Visibility Index, A^2	287	333	290	267	309	277	295	337	300	851	850	855
Subsonic Combat Load Factor	1.94	2.87	1.93	2.11	3.00	2.11	2.07	3.07	2.05	4.43	5.40	4.49
Supersonic Combat Load Factor	3.92	4.7	3.94	4.05	5.1	4.12	4.92	6.1	5.01	8.23	7.0	5.86
Power Setting-Dash - as Fraction of Military Power	1.32	1.00	1.22	0.91	0.60	0.89	1.11	1.00	1.07	0.73	0.84	0.72
Dash Radius, n.mi.	69	125	66	42	125	53	73	125	71	137	125	128

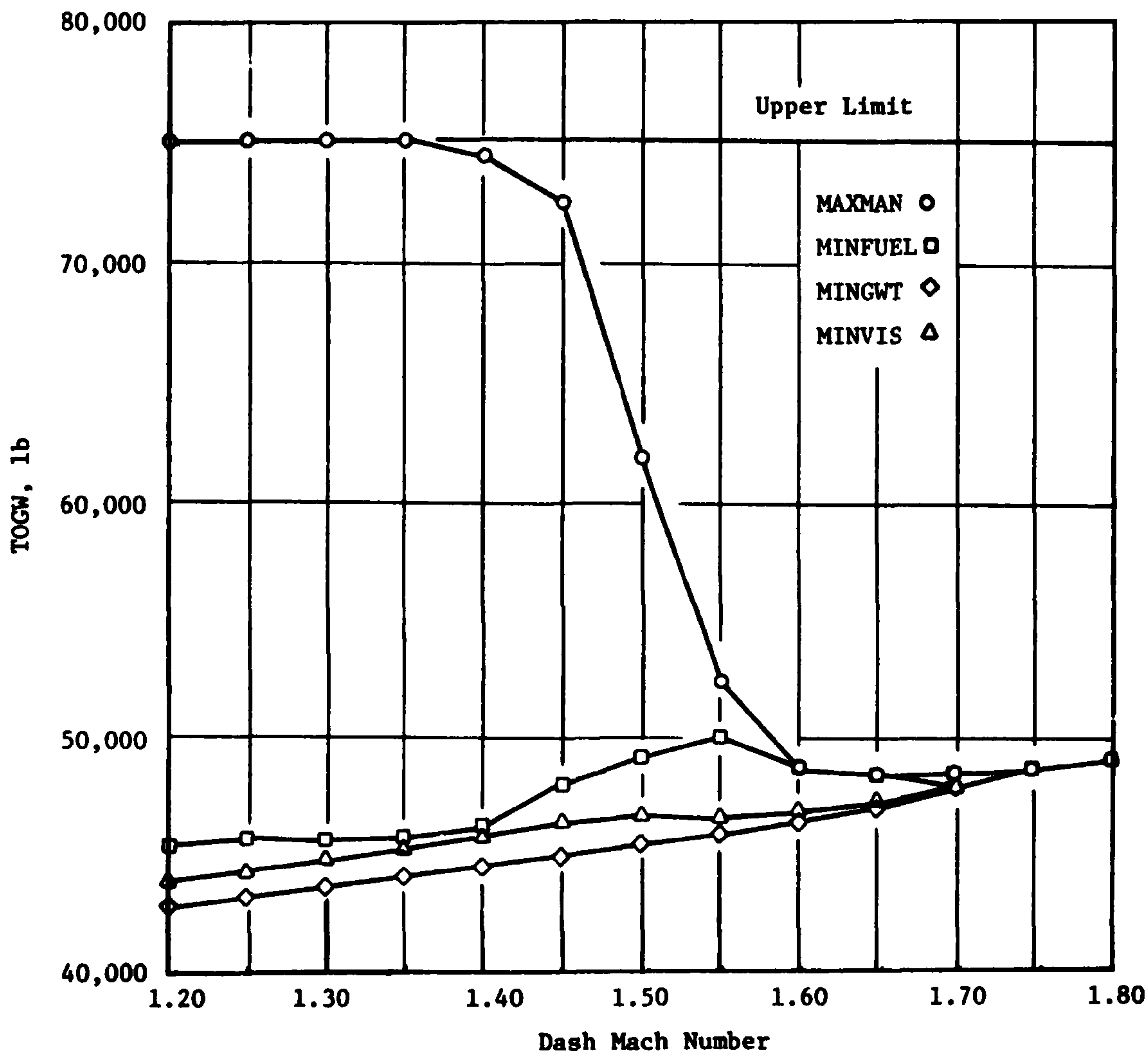


Figure 17. TOGW Sensitivity to Dash Mach Number and Figure of Merit, BEAM/ARES Interrogation Results - Turbofan.

fuel variations are shown in Figure 18. Visibility Index variations are presented in Figure 19. Note that Visibility Index generally varies with either Mach number or figure-of-merit. Figure 20 shows that most optima are constrained by the requirement that combat load factor be at least 3.0. The superior combat capability of the heavy "agile" optima is, once again, obvious. Penetration power settings are illustrated in Figure 21.

Ten candidate optima were selected from the BEAM/ARES No. 2 interrogation results. Their characteristics are tabulated in Table 11. Two designs selected for economy are listed. The first of these is the minimum mission fuel design and occurs at a dash Mach number of 1.2. The second was selected at Mach 1.35. In total economy it should be competitive when TOGW, wing and engine size, planform, speed, and mission fuel trades are made. Two designs optimized for stealth are also presented. Once again the first is the minimum visibility design which also occurs at Mach 1.2. The second would be expected to benefit, stealthwise, from its higher dash Mach number (1.7) while sacrificing just 10% in higher visibility. A group of "agile" optima are shown to illustrate the possible trade of maneuverability for size and dash speed. The last column on the table entitled "Speed" represents the design which occurs at the maximum Mach number of 1.8.

J. Results of RSTEP/ARM Turbofan Interrogation (Task X - G.E.)

After the RSTEP/ARM computer program was delivered to the General Electric Company it was modified so as to be compatible with the computer language of the General Electric computer. Trial runs were made and some minor problems resolved. Several test interrogations were made using cases already utilized by The Boeing Company. Reasonably good results were obtained and it appears that the RSTEP/ARM version in the General Electric computer is essentially the same as that in the Boeing computer.

It should be noted that the computer package delivered to General Electric contained only the RSTEP/ARM routines plus a mission routine. The package did not include the Boeing ARES program or the Boeing powerplant installation loss subroutine.

The final test, the use of RSTEP/ARM by an engine preliminary design group, was incorporated in Task X. Results of the Boeing BEAM/ARES analysis (Table 11) were selected for the test. Five cases taken from Table 11 were run on the General Electric RSTEP/ARM computer program. The results are tabulated and compared to the Boeing results in Table 12.

The comparison is somewhat disappointing, as it does not show as close a correlation of the answers as had been expected. Radius variations show no definite pattern. Values of mission fuel are generally higher for the RSTEP/ARM solutions. In some cases values of load factor are close; in other cases values are not close. The Visibility Index does correlate well, due largely to the fact that it is a direct function of the input variables themselves.

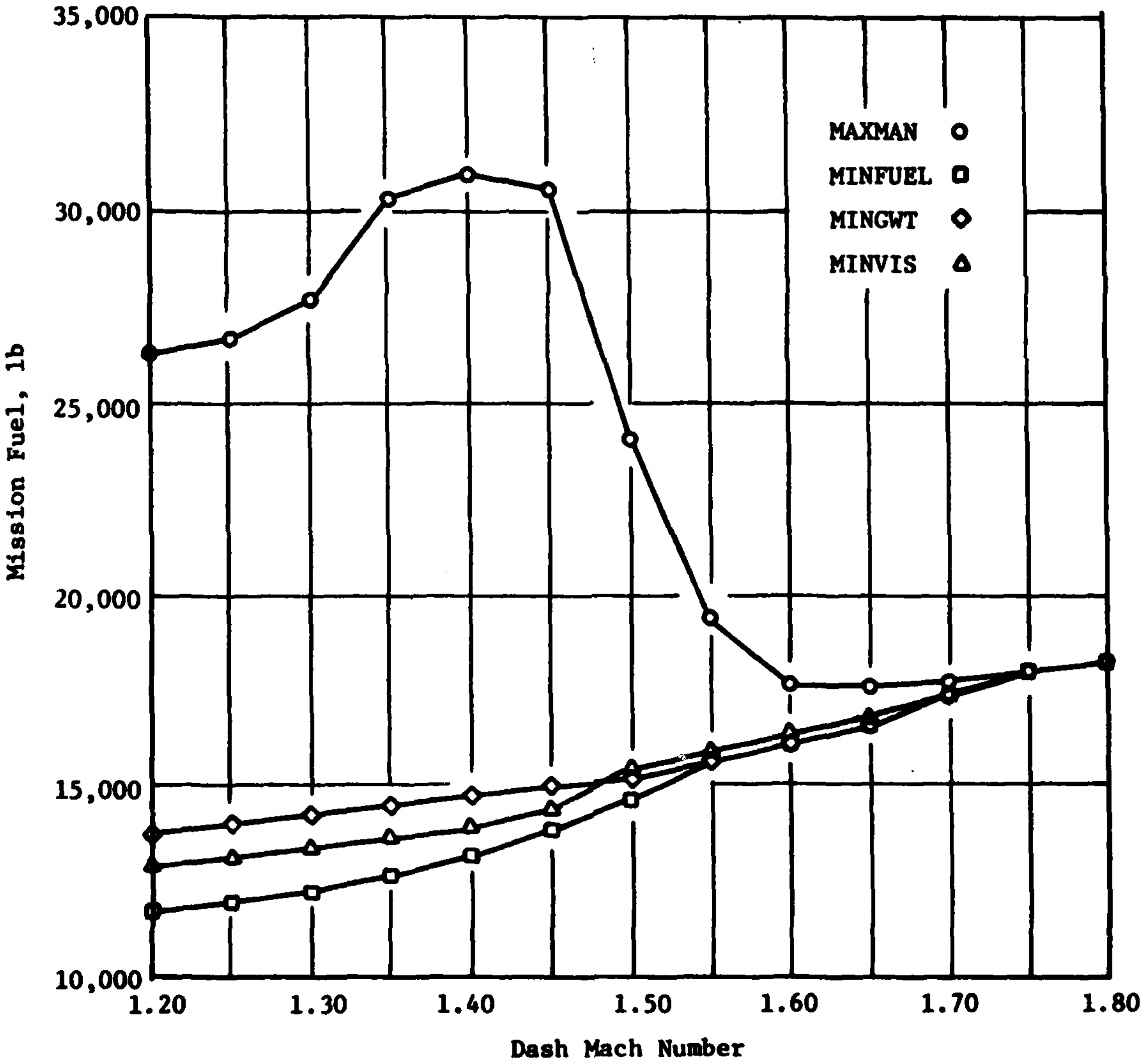


Figure 18. Mission Fuel Sensitivity to Dash Mach Number and Figure of Merit, BEAM/ARES Interrogation Results - Turbofan.

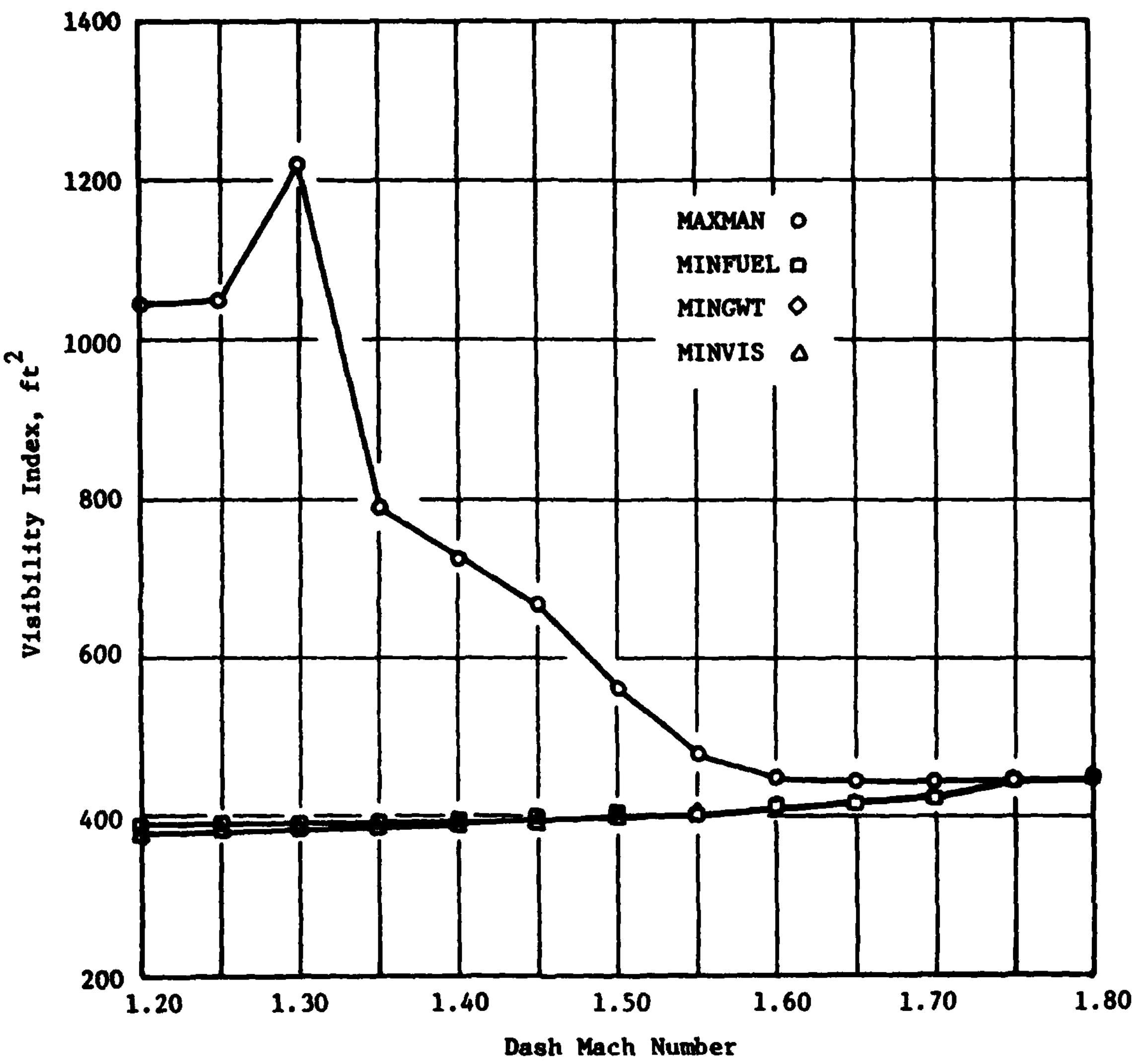


Figure 19. Visibility Sensitivity to Dash Mach Number and Figure of Merit, BEAM/ARES Interrogation Results - Turbofan.

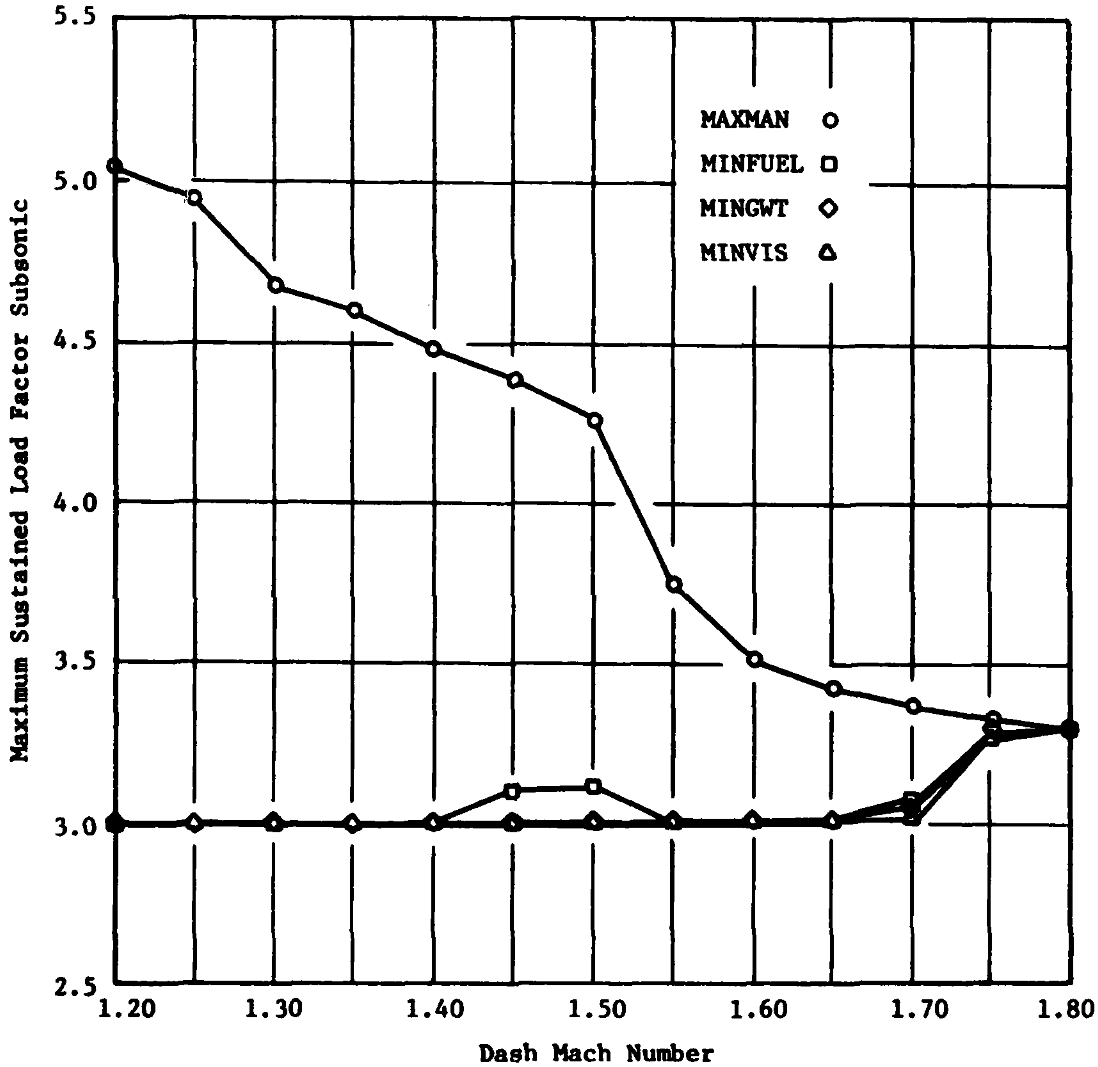


Figure 20. Combat Load Factor Sensitivity to Dash Mach Number and Figure of Merit, BEAM/ARES Interrogation Results - Turbofan.

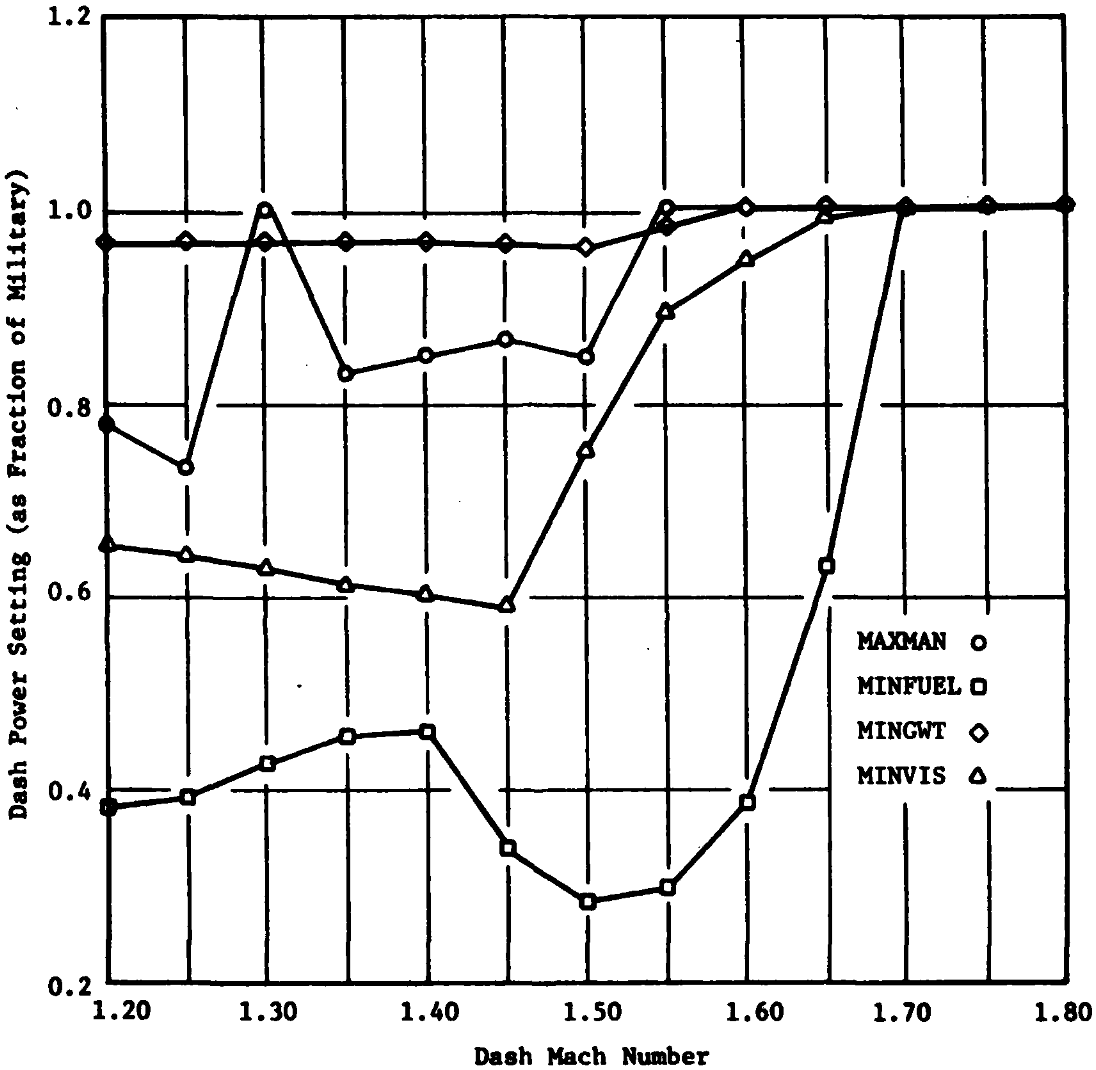


Figure 21. Dash Power Setting Sensitivity to Dash Mach Number and Figure of Merit, BEAM/ARES Interrogation Results - Turbofan.

Table 11. Optimal Fighter Design Solutions, GE16/F17 Study A Turbofan, Dash Radius 1.25 n.mi., BEAM/ARES No. 2.

Parameter	Minimum TOGW	Economy		Stealth		Agility				Speed
Takeoff Gross Weight, lb	42,700	45,300	45,600	43,800	47,700	75,000*	61.700	52,200	48,600	48,900
Takeoff Wing Loading, psf	120*	120*	120*	120*	120*	80.0	120*	120*	120*	120*
Aircraft Thrust-to-Weight Ratio	0.80	1.11	1.08	0.98	0.78	1.18	1.20*	1.03	0.88	0.76
Wing Aspect Ratio	5.12	5.04	4.36	4.07	4.08	5.20	5.39	4.74	5.39	5.43
Wing Leading Edgw Sweep Angle, deg	45.2	60.0*	60.0*	54.8	43.6	30.0*	30.0*	30.0*	30.0*	30.0*
Wing Thickness-to-Chord Ratio	0.035	0.03*	0.03*	0.03*	0.03*	0.03*	0.058	0.048	0.038	0.03*
Dash Mach No.	1.20*	1.20*	1.35	1.20*	1.70	1.20*	1.50	1.55	1.60	1.90*
Mission Fuel, lb	13,700	11,700	12,600	12,900	17,200	26,200	24,000	19,200	17,500	18,000
Visibility Index, ft.^{2}	383	389	388	377	416	1040	558	476	444	443
Combat Load Factor	3.00*	3.00*	3.00*	3.00*	3.00*	5.04	4.24	3.73	3.50	3.28
Dash Load Factor	6.25	6.60	7.00*	6.02	7.00*	6.96	7.00*	7.00*	7.00*	7.00*
Dash Power Setting - As Percent of Military Power	0.97	0.38	0.46	0.65	1.00*	0.78	0.84	1.00*	1.00*	1.00*

*Study Limit

Table 12. RSTEP/ARM Validation, Optimal Fighter Cases, GE16/F17 Study A Turbofan.

	Minimum TOGW		Economy		Stealth		Agility		Dash Speed	
	BEAM/ARES	RSTEP	BEAM/ARES	RSTEP	BEAM/ARES	RSTEP	BEAM/ARES	RSTEP	BEAM/ARES	RSTEP
Takeoff Gross Weight, lb	$\boxed{42,700}$	$\boxed{42,700}$	45,300	45,300	43,800	43,800	75,000*	75,000	48,900	48,900
Takeoff Wing Loading, psf	120*	120*	120*	120*	120*	120*	80.0	80.0	120*	120*
Aircraft Thrust-to-Weight Ratio	0.80	0.80	1.11	1.11	0.98	0.98	1.18	1.18	0.76	0.76
Wing Aspect Ratio	5.12	5.12	5.04	5.04	4.07	4.07	5.20	5.20	5.43	5.43
Wing Leading Edge Sweep Angle, deg	45.2	45.2	60.0*	60.0*	54.8	54.8	30.0*	30.0*	30.0*	30.0*
Wing Thickness-to-Chord Ratio	0.035	0.035	0.03*	0.03*	0.03*	0.03*	0.03*	0.03*	0.03*	0.03*
Dash Mach Number	1.20*	1.20*	1.20*	1.20*	1.20*	1.20*	1.20*	1.20*	$\boxed{1.80*}$	$\boxed{1.80*}$
Dash Radius, n.mi.	125	142	125	83	125	115	125	145	125	146
Mission Fuel, lb	13,700	14,583	$\boxed{11,700}$	12,413	12,900	13,774	26,200	26,117	18,000	19,083
Visibility Index, ft^2	383	390	389	397	$\boxed{377}$	386	1040	1041	443	446
Combat Load Factor	3.00*	3.27	3.00*	3.73	3.00*	3.39	$\boxed{5.04}$	5.08	3.28	3.29
Dash Load Factor	6.25	5.28	6.60	6.49	6.02	5.97	6.96	8.06	7.00*	7.32

*Study Limit

Based on currently available data, it is believed that the poor validation was caused by several factors:

a) Poor simulation of the data base, particularly at or near the "corners" of the design space.

b) Errors in drag-due-to-lift modeling.

In order to check the General Elecric RSTEP/ARM computer program's accuracy, Boeing has run several turbofan cases on their own RSTEP/ARM program. Output of these Boeing runs indicate that the General Electric RSTEP/ARM program still is accurately reproducing the Boeing program results.

SECTION IV

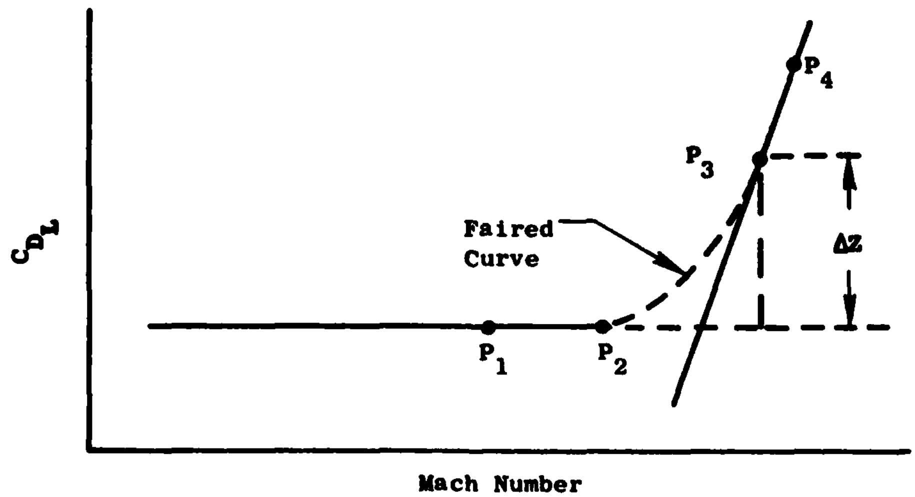
DISCUSSION

An objective of the RSTEP/ARM effort was to explore the feasibility of providing the Air Force and industry with a mission performance computer program which is simplified by using regression models for airframe geometry, weights, and drags. The program was to be adequate for application to conceptual and preliminary design phase screening of engine cycles. Such a computer program was developed and tested. Results indicate that the approach is feasible.

The computer program is operational in the Air Force and at General Electric. Apparently it yields good parametric trends even though the levels of its results are at variable accuracy. Some errors in level of results are greater than had been anticipated. Some of these discrepancies can be attributed to known causes, such as the problem with drag-due-to-lift modeling.

Many of the RSTEP/ARM models were developed with no problems. However, it became quickly apparent that modeling drag-due-to-lift with sufficient precision was a difficult task. This difficulty stems from the complex nature of nonelliptic components of drag-due-to-lift at higher lift coefficients. Several approaches were attempted in an effort to minimize this problem and the best of them was incorporated in the program. Its inaccuracy is responsible for some of the drag differences already mentioned.

At present the drag due to lift representation appears to be fairly good in the subsonic, supersonic, and upper transonic regions. However in the lower transonic region the mathematical formulas predict values of drag-due-to-lift which are too low. It is expected that the best near term solution to this problem is to ignore the equation in the lower transonic region and fill in with a good fairing procedure as schematically illustrated below:



This fairing procedure is presently being applied to the induced drag estimating procedure and yields results which seem acceptable.

Another algorithm, which is being considered, holds some promise for solving the drag-due-to-lift modeling problem and had the form,

$$C_{D_L} = K_1 C_L^2 + K_2 C_L^4,$$

where K_1 is approximately the reciprocal of (π AR) and K_2 is a function of several of the RSTEP independent variables. The difficulty with this algorithm is the definition of K_2. However, the existence of a data base such as that developed in RSTEP/ARM may allow a definition as follows:

$$K_2 = \frac{\left[C_{D_L} \text{ (from the data base) } - \frac{C_L^2}{\pi AR}\right]}{C_L^4}$$

yielding a discrete K_2 for each case in the data base. Then, a function for K_2 in terms of the RSTEP variables is derived in regression analysis.

Further study of drag-due-to-lift modeling technique is required in order that accuracy be improved.

The modeling of transonic and supersonic pressure drag requires additional refinement to reduce errors (presently as high as 5-12%).

A problem related to modeling is the use of quadratic regression equations to model a technical interrelation of technical parameters whose character may be definitely nonquadratic.

Use of a limited number of cases for regression analysis raises the question of the accuracy of the resultant model when it is required to represent certain "corners" of the modeling space. There is no guarantee that the modeling accuracy is constant or consistent over the complete matrix being modeled. A good example of this problem is mentioned in Section III. I. in connection with Table 10. Early checks on the accuracy of the RSTEP/ARM modeling for turbojet engines (see Table 7) showed close correlation between RSTEP/ARM output results and the output of the parent BEAM program. However, when ARES optimization subroutines were used to seek optimum design cases for the turbofan engine case, results did not check as close as anticipated.

The reason for the problem just described is not well known. Most likely it has to do with a relatively poorly defined region in design space, a shortcoming of "design selection". It is notable that the three poor validation points are up against a limit of at least four of the seven independent variables; W/S, AR, λ_{LE} and t/c (See Table 9). Two are upper limits and two, lower; a combination that was never approached in the parametric family while the Latin Square set was developed. Similar "holes" in design space have been identified in past applications of ARES. However, none have been of this magnitude or affected a result quite as much. When additional cases (i.e., the very cases which came out as optima) were added to the original cases and a second regression fit was obtained, the results were definitely improved (see Table 10).

Thus, it would appear that the accuracy of any regression fit is variable. To ensure best results it appears necessary to make two "passes". The first pass will identify the regions where optima are to be expected. The second pass will include in the raw input several cases close to the optima in the set being modeled.

Three sets of independent variables and their ranges were used during the RSTEP/ARM effort (Tables 2, 5, and 8). The set of parameters in Table 2 was used in the development of the RSTEP/ARM performance program. The ranges of variation listed in Table 2 define the range of applicability of the RSTEP/ARM performance program. Extension of the program via extrapolation beyond these ranges is strongly discouraged. Due to the quadratic nature of the regression models, extrapolation can yield very misleading results.

Initial runs of the RSTEP/ARM program were disappointing in that the running time and running costs exceeded those of the parent BEAM program. This was a surprise inasmuch as the RSTEP/ARM program was intended to be a much simpler procedure. Boeing computer specialists checked over the RSTEP/ARM logic and have suggested a number of changes related primarily to iteration procedures to reduce running time and to improve running efficiency. These changes have been incorporated in the Boeing RSTEP/ARM program and the latest check of running costs indicates that the RSTEP/ARM program running cost is approximately half of BEAM running costs with little or no reduction in accuracy. It is expected that further investigation will identify additional changes which can reduce running costs still further.

The Boeing Company has extended the usefulness of RSTEP/ARM by combining the RSTEP/ARM program modules with ARES optimization subroutines and using the combination to seek optimal aircraft design solutions (see Section III). The resulting combination represents a powerful tool for use in engine cycle selection and optimization, as well as a tool for possible use in examining sensitivity of engine cycle selection to variations in aircraft chartacteristics and mission requirements.

At present the use of RSTEP/ARM is limited to the analysis of problems involving only one type of aircraft (advanced tactical aircraft-twin engine). It would considerably enhance the usefulness of RSTEP/ARM if the engine designer had at his disposal additional stand-alone modules which represent other type of aircraft, such as:

- Single-engine, lightweight fighters
- Subsonic V/STOL fighters

- Supersonic V/STOL fighters
- Multimission, variable geometry attack or bomber aircraft
- Subsonic tanker/cargo aircraft
- Subsonic close support aircraft

Other types of aircraft undoubtedly should be considered for possible modeling candidates. Further efforts are indicated along these lines if RSTEP/ARM application is to be extended to problems involving other aircraft (or all aircraft) types.

The RSTEP/ARM computer program presently requires engine data which include installation losses. RSTEP/ARM would be more flexible and easier to use if uninstalled engine data could be utilized. This feature would require the addition of a subroutine to estimate the installation losses and to convert uninstalled data into installed data.

It is felt that the RSTEP/ARM program's inaccuracies can be alleviated. Assuming that problem areas can be corrected, it is expected that trends out of a program like RSTEP/ARM would be adequate for engine design screening in preliminary design.

Development of the regression simulation of aircraft characteristics should continue. The current capability should be improved and the approach should be extended to other aircraft types and mission profiles. Much has been learned in the accomplishment of this effort and in succeeding analyses. This accumulation of experience would be most beneficial to additional applications of the RSTEP/ARM approach by engine designers. A plan for improvement of RSTEP/ARM accuracy and for extending RSTEP/ARM usefulness should be prepared and follow-on work to implement such a plan should be identified.

It is expected that engine designers will find RSTEP/ARM a useful tool in cycle selection studies. Some of the many possible problems or problem areas to which RSTEP/ARM can be applied are:

- Cycle selection for optimal performance-single mission
- Cycle selection for multimission aircraft (where a compromise is required)
- Analysis of effects of changes in aircraft characteristics
- Analysis of tradeoffs and effects of changes in military requirements (both combat and mission)
- Analysis of effects of changes in engine size on aircraft and/or mission performance

- Analysis and evaluation of payoffs of new technology

- Preliminary evaluation of unconventional engine or propulsion concepts

It is expected that General Electric mission analysis and engine preliminary design activities will make use of RSTEP/ARM procedures. Several alternate possibilities are envisioned; the aircraft ARM's can be "lifted" out of the present RSTEP/ARM program and can be incorporated in any of General Electric's mission analysis programs; or, the RSTEP/ARM program can be kept intact and then expanded by making changes (such as making possible evaluation of more complex mission profiles); or, the RSTEP/ARM program can be coupled with other routines, such as an optimization routine similar to ARES. At present it is premature to state which of these possible alternates will be utilized.

It is considered that the original goals of the RSTEP/ARM study have been met, i.e., the creation of a tool which de-couples the aircraft from the engine cycle and which is simple and flexible and relatively low cost. This tool appears to be potentially useful to engine designers. The original concept of such a computer tool appears to be feasible.

Mission performance programs like RSTEP/ARM can act as a strong and credible link between an engine company and an airframe company. Additionaly, this capability can short-circuit the iterative process of engine cycle screening in preliminary design. Thus, conceptual and preliminary design analyses conducted by engine and airframe companies can be made more efficient and more productive.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

As a result of the work completed under this RSTEP/ARM contract several conclusions may be drawn:

- The technical and philosophical goals set prior to the commencement of this program have been met.

- An analytic tool has been created in which the airplane characteristics are "decoupled" from engine performance characteristics.

- The design of the RSTEP/ARM computer program permits the user to conduct propulsion studies without the need for being overly concerned with airframe configuration details and second-order airframe-propulsion interactions. The details and interactions are accounted for within the program automatically.

- The RSTEP/ARM analysis tool has been used extensively by Boeing and in a limited fashion by General Electric. Boeing has been successful in combining RSTEP with certain other subroutines to conduct optimization studies.

- The RSTEP/ARM analysis tool should permit engine preliminary design groups as well as USAF/USN evaluation groups to conduct engine selection studies more easily.

- Some problems exist in the operation and use of RSTEP/ARM. Further effort is required in some areas:

  - Reworking certain program logic to reduce errors

  - Making additional changes to further reduce running time

- Specific modifications to RSTEP/ARM which would enhance or expand its usefulness have been identified and are presented below in Paragraph B.

B. Recommendations

Based on evaluation of the results of this study, follow-on effort is highly recommended to improve accuracy and to expand the scope and area of application of RSTEP/ARM. Several areas of follow-on effort are outlined below:

- Those areas of program logic or modeling which produce unacceptable error should be identified; program equations should be examined to identify the changes necessary to reduce the errors to acceptable levels.
- The program logic should be studied, especially in the area of iterative processes, so that changes which will further reduce running time can be identified.
- RSTEP/ARM program modules and analysis procedures should be combined with additional surface-fitting routines and an optimization routine to permit the resulting combination to be used in optimization studies.
- Additional "stand-alone" modules (which would represent other types of airframe types or families) should be devised to permit RSTEP/ARM techniques to be used in a broader range of applications.
- A procedure for converting uninstalled engine data into installed engine data should be developed and incorporated into the RSTEP/ARM computer program.
- Mission profile modeling capability should be expanded to permit simulation of other type missions, thus increasing the flexibility of RSTEP/ARM procedures.
- Changes in program logic should be made in order to provide capability to easily change RSTEP regression model coefficients.

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