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HYPERSONIC RAMJET EXPERIMENT PROJECT

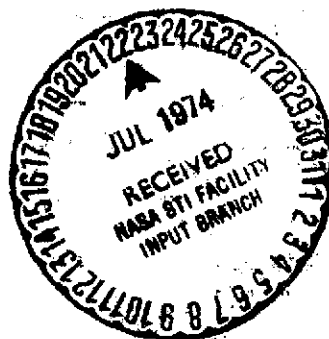
PHASE I

COMPUTER PROGRAM DESCRIPTION
RAMJET AND SCRAMJET CYCLE PERFORMANCE

By: Robert J. Jackson
Tennyson T. Wang

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Prepared under Contract No. NAS1-5116
AiResearch Manufacturing Company, Division of
The Garrett Corporation

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This computer program description is submitted by the AiResearch Manufacturing Company, Los Angeles, California, a Division of the Garrett Corporation in compliance with Part IV; paragraph A of NASA Contract NAS1-5116 and paragraphs 6.4.6 and 5.4.1 of NASA Statement of Work L-4947.

This report is one in a series of several computer program description reports that will be forwarded to NASA in compliance with contractual requirements. This report will be identified at AiResearch by AiResearch Report Number AP-1001-1.

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PHASE I.

COMPUTER PROGRAM DESCRIPTION

RAMJET AND SCRAMJET CYCLE PERFORMANCE

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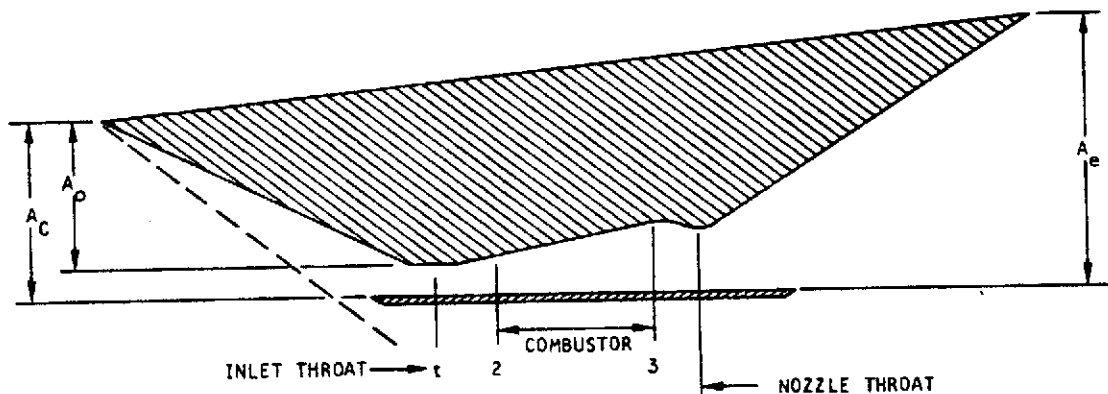
SUMMARY

The Ramjet and Scramjet Cycle Performance Program performs one-dimensional calculations of the equilibrium, real-gas internal flow properties and of pertinent engine performance parameters. This program is a modified version of the NASA program developed by L. Franciscus.

The program can be used (1) for preliminary design calculations, i.e., the sizing of critical flow areas in the engine to comply with stipulated internal flow properties and (2) for design analysis, i.e., determination of internal flow properties corresponding to stipulated flow areas. Only the combustion of hydrogen in air is considered.

PROBLEM DESCRIPTION

General capabilities and input-data requirements of the program are discussed in the following paragraphs in terms of the major engine components: (1) inlet, (2) combustor, and (3) exhaust nozzle. Pertinent engine stations are shown below.



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Two-Dimensional Schematic of Engine Stations

Inlet calculations. - Flight conditions are specified in terms of flight Mach number, ambient pressure, and ambient temperature.

As shown above, station 2 is the interface between the engine inlet and the combustor. The program calculates the one-dimensional, equilibrium properties of the inlet air at station 2 corresponding to (1) assigned flow area or Mach number, (2) inlet losses, and (3) inlet spillage (mass-flow ratio). Note that station 2 is primarily the combustor inlet, not necessarily the engine-inlet throat (minimum flow area).

The inlet losses are stipulated in terms of the kinetic energy efficiency, η_{KE} , or the rise in enthalpy, $\Delta H'$, from conditions corresponding to free-stream pressure and entropy to conditions corresponding to free-stream pressure and combustor-inlet entropy.

The inlet spillage is given as the ratio of capture area to cowl area.

Data printed out at station 2 include pressure, temperature, enthalpy, entropy, molecular weight, c_p , γ , Mach number, ratio of flow area to inlet capture area, velocity, total pressure recovery, vacuum specific impulse, and fuel port area. Also, the equilibrium Mol fractions of the working-fluid constituents are printed.

Combustor calculations.- The combustor calculations yield the one-dimensional, equilibrium properties of the combustor-exit flow, engine station 3. The following conditions and data must be input:

- a. Mode of combustion, supersonic or subsonic.
- b. Fuel equivalence ratio.
- c. Fuel storage temperature and fuel temperature at injection ports.
- d. Fuel injection velocity.
- e. Ratio of combustor wall area to inlet flow area.
- f. Combustor wall-friction drag coefficient.
- g. Assigned combustor exit condition (pressure, Mach number, or area).
- h. Combustion chemical efficiency, the ratio of reacted fuel to fuel supplied.

The input provision for two values of fuel temperature is necessary for analysis of regeneratively-cooled combustors. For energy calculations, the fuel enthalpy must be based on the temperature of the fuel prior to its introduction into the cooling circuits; however, sizing of fuel injection ports must be based on the actual fuel injection temperature and velocity.

The equilibrium thermodynamic properties of the combustion products are calculated by the procedure described in ref. 1.

Calculation of combustor exit momentum requires, for cases other than constant-area or constant-pressure combustion, evaluation of combustor-wall pressure forces. In general, this is done by assuming that the effective combustor static pressure is the average of the combustor inlet and discharge static pressures. However, where appropriate, the effective combustor static pressure can be taken to be:

$$\bar{P}_s = \frac{P_2 + KP_3}{K + 1} \quad (1)$$

By formula (1), the effective combustor static pressure can be made to approach the combustor exit pressure, P_3 , as K is allowed to increase. Use of this procedure would be based on detailed investigation of the combustor pressure distribution.

The combustor wall-friction drag coefficient, C_D , is defined by:

$$F_D = C_D A_w \bar{q} \quad (2)$$

where F_D is the wall-friction drag force, A_w the wall area, and \bar{q} the average of combustor inlet and discharge dynamic pressures.

The flow properties printed out at station 3 include the parameters printed for station 2, the area ratio, A_3/A_2 , plus engine performance parameters: Net internal thrust, thrust per unit of capture area, fuel specific impulse, and thrust coefficient.

Nozzle calculations.- An isentropic, equilibrium, real-gas expansion from the combustor exit to the nozzle exit is calculated. For subsonic combustion, the first line of output subsequent to the combustor exit refers to the nozzle sonic throat (this is omitted for supersonic combustion). Subsequent lines of output correspond to assigned values of combustor-exit-to-nozzle pressure ratio, to full expansion to ambient pressure, and finally, to the assigned nozzle exit condition (assigned area or pressure). For supersonic combustion, the ratio of nozzle area to combustor exit area is printed; for subsonic combustion, the ratio of nozzle area to nozzle sonic throat is printed out.

Nozzle losses are accounted for by a velocity or stream-thrust coefficient, C_S :

$$C_S = \frac{I_{vac}}{I_{vac, ID}} = \frac{\frac{V}{g} + \frac{RT}{V}}{\left(\frac{V}{g} + \frac{RT}{V}\right)_{ID}} \quad (3)$$

where the ideal values are calculated for isentropic, equilibrium nozzle expansion. The coefficient, C_S , is evaluated from detailed nozzle investigations to account for kinetic, friction, and divergence losses.

To calculate the net thrust for flight conditions where inlet spillage must be considered, an additive drag coefficient, C_{DA} , is employed. This drag coefficient is defined as follows:

$$F_{DA} = C_{DA} q_o A_C \quad (4)$$

where F_{DA} is the drag force caused by inlet spillage, q_o is the free-stream dynamic pressure, and A_C is the cowl area. Values of C_{DA} have been correlated with flight Mach number and inlet mass-flow ratio.

OPERATING INSTRUCTIONS

Hardware requirements.-

- a. IBM 7090 or 7094 computer with 32K core.
- b. Data Channels and tape units for the software.

- c. No on-line printer and punch.
- d. Peripheral equipment for card-to-tape, tape-to-printer, and tape-to-punch as required by standard IBM system.
- e. It is assumed that standard keypunch and verifier machines, card readers, and printers are used; therefore, these have not been specified.

Software requirements.-

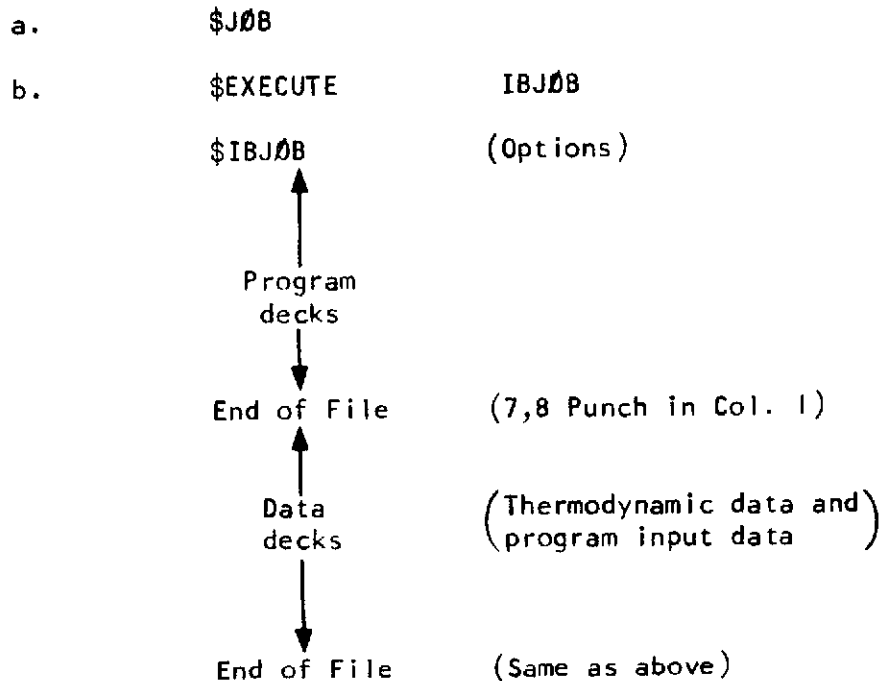
- a. IBSYS Operating System Tape Version 12
 - (1) Basic Monitor (IBSYS) Version 4
 - (2) Processor (IBJOB) Version 4
 - (3) Assembly Language (MAP) Version 4
 - (4) Assembly Language (FTC) Version 4
 - (5) Loader (IBLDR) Version 4
- b. The Fortran IV I/O Library Subroutines

Tape usage.- The standard Fortran input/output configuration, as described in IBM 7090/7094 IBSYS Operating System: IBJOB Processor, Form C28-6275, is used for the logical tape unit designation and the file specifications are as follows.

UNIT01 FILE, UT1, READY, INOUT, BLK = 256, BIN
 UNIT02 FILE, UT2, READY, INOUT, BLK = 256, BIN
 UNIT03 FILE, UT3, READY, INOUT, BLK = 256, BIN, NOLIST
 UNIT04 FILE, UT4, READY, INOUT, BLK = 256, BIN, NOLIST
 UNIT05 FILE, IN, READY, INPUT, BLK = 14, MULTIREEL, BCD, NOLIST
 UNIT06 FILE, OU, READY, OUTPUT, BLK = 110, MULTIREEL, BCD, NOLIST
 UNIT07 FILE, PP, READY, OUTPUT, BLK = 28, MULTIREEL, BIN, NOLIST
 UNIT08 FILE, , MOUNT, INOUT, BLK = 22, BCD

The logical tape unit 5 and 6 are used as input and output, respectively. No intermediate storage tape is used.

Deck set-up.-

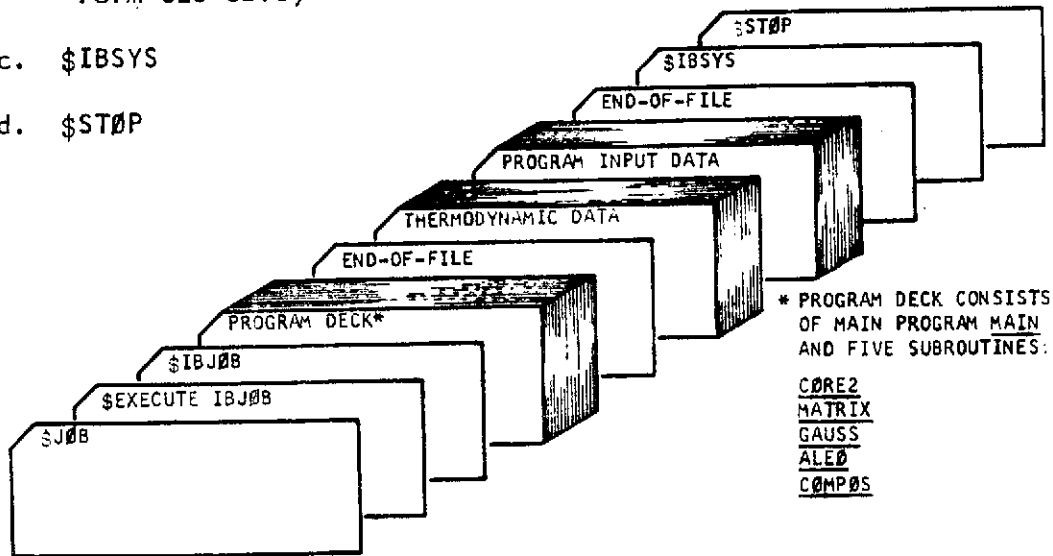


For a description of these control cards see:

(IBM 7090/7094 Operation Systems Basic Monitor (IBSYS),
Form C28-6248)

(IBM 7090/7094 IBSYS Operating System IJOB Processor,
Form C28-6275)

- c. \$IBSYS
- d. \$STOP



Deck Set-up

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Timing.- The computer time for each case depends upon the number of iterations. It takes approximately one minute per case.

Multiple cases.- The cases may be stacked for one computer run.

Input Description

Format.-

<u>Card</u>	<u>Field</u>	<u>Description</u>
1	1	Reference case number (usually "1")
914	2	"0" means subsonic combustion; "1" means supersonic combustion.
	3	Blank
	4	Blank
	5	Number of nozzle stations for which data are printed out.
	6	Number (0 to 25) of nozzle pressure ratios for schedule of assigned nozzle pressure ratios.
	7	Blank
	8	"0" means normal printout. "1" means "debug printout".
	9	Number of cases (1 to 15).
<hr/>		
2	1	"0." means specified combustor pressure ratio. "-1." means specified combustor exit Mach number. "1." means specified combustor area ratio.
8F10.0	2	Ae/AC, ratio of nozzle exit area to cowl area. Blank if nozzle pressure ratio is specified.
	3	A2/AC, ratio of combustor inlet area to cowl area. Blank if combustor inlet Mach number is specified.

<u>Card</u>	<u>Field</u>	<u>Description</u>
2 8F10.0	4	M2, combustor inlet Mach number. Blank if A2/AC is specified.
	5	Pe/P0, ratio of nozzle exit pressure to ambient pressure. Blank if A /AC is specified.
3 8F10.0	1	cos of fuel injection angle
	2	AC, cowl area, sq ft
4	1	Aw/A2, ratio of combustor wall area to combustor inlet area.
5 8F10.0	1	Ambient pressure, atm.
	2	Ambient temperature, °K
	3	Flight Mach number
	4	Blank
	5	Additive drag coefficient
6 8F10.0	1	η_{KE} , inlet kinetic energy efficiency, or (by pre-fixing a minus sign) the enthalpy rise between free-stream pressure, entropy conditions and conditions corresponding to free-stream pressure and combustor-inlet entropy.
	2	A_0/AC , ratio of inlet capture area to cowl area (i.e., mass-flow ratio).
	3	$A_{e, geom}/AC_{eff}$, ratio of geometric nozzle exit area to effective nozzle exit area (to account for boundary-layer growth).
	4	C_S , nozzle velocity coefficient, ratio of I_{vac} to I_{vac} calculated with no nozzle losses.

<u>Card</u>	<u>Field</u>	<u>Description</u>
6	5	Temperature of fuel at fuel-injection nozzles, °K.
7	1	ϕ , equivalence ratio
8F10.0	2	η_c , combustor chemical efficiency, ratio (by weight) of reacted fuel to fuel supplied.
	3	V_f , fuel inlet velocity, ft per sec.
	4	Temperature of fuel corresponding to storage conditions.
	5	Assigned combustor pressure ratio, area ratio, or exit Mach number, as applicable.
	6	Combustor wall-friction drag coefficient.

Cards 8-10
(Optional)
8F10.0

Up to 25 values of nozzle pressure ratio, P_N/P_3 .
Used when sixth field of card 1 is non-zero.

The "reference case" comprises a complete set of the above seven data cards. Up to 14 additional cases, representing changes in any or all of the variables entered on Cards 5, 6, and 7, can be handled for constant values of the data on cards 1 to 4. For each of these additional cases, a set of cards 5, 6, and 7 is added to the input-card deck. However, only the values which differ from those of the reference case are punched. For example, to run a range of M3, two blank cards and a card punched with the appropriate value in the fifth field are added to the input-card deck for each new value of M3.

Any number of the above input-data-card decks can be stacked for a computer run.

Table I presents a computer input data format with program internal symbols.

Definitions.-

$$\text{Additive Drag} = C_{DA} (1/2 \rho_0 V_0^2) A_C$$

$$\text{Combustor Wall-Friction Drag} = C_d \bar{q} A_w$$

$$\text{where } \bar{q} = 1/2 [(1/2 \rho_2 V_2^2) + (1/2 \rho_3 V_3^2)]$$

$$A_w = \text{Combustor internal wetted area}$$

Output Description

Input data.- The input data values for a run are printed out prior to and separate from the calculated results.

Inlet calculations.- First line (below headings):

- P0 - Free stream pressure, atm
- T0 - Free stream temperature, °K
- ETA KE - η_{KE}
- MACH0 - Flight Mach number
- MACH2 - Assigned combustor inlet Mach number (if applicable)
- PHI - Equivalence ratio
- A2/AC - Assigned ratio of combustor inlet area to cowl area (if applicable)
- V0 - Flight velocity
- H01 - Enthalpy (cal per gm) corresponding to free stream pressure and combustor inlet entropy.
- A0/AC - Ratio of capture area to cowl area.
- A0 - Capture area, sq ft

The second and subsequent lines of printout (excluding the composition data) are the values calculated for each iteration to the applicable combustor inlet condition. The converged values are presented in the last such line of data. Units of enthalpy and entropy are cal per gm and cal per gm-°K, respectively, where enthalpy is assigned the value of zero at 298.15°K.

- P0/P - Ratio of free-stream pressure to combustor inlet pressure.
- P ATM - Combustor inlet pressure, atm
- MACHNO - Combustor inlet Mach number
- A/A0 - Ratio of combustor inlet area to capture area

The composition data are the mol fractions of each constituent.

Finally, the inlet total pressure recovery is the calculated ratio of combustor inlet total pressure to the free-stream total pressure; fuel inlet port area is given in sq ft; and IVAC is the momentum parameter, vacuum specific impulse, $\frac{V}{g} + \frac{PA}{W}$, sec.

Combustor exit calculations.- The heading stipulates the type of nozzle calculation; the second line gives the amount of fuel in terms of three parameters: (1) the air-to-fuel mass ratio, (2) the equivalence ratio, and (3) the fuel-to-mixture mass ratio.

Combustor exit data are printed in two lines. Parameters not already identified are the following:

- A/A2 - Ratio of combustor exit area to combustor inlet area.
- T/A0 - Net thrust per unit of capture area, lb per sq ft.
- SP IMP - Net thrust per unit of fuel flow, sec
- THRUST - Net thrust, lb
- IVAC - Vacuum specific impulse, sec
- CT - Thrust coefficient, $\frac{THRUST}{q_0 A_c}$

The second line of output (following composition data), in the case of subsonic combustion, is the nozzle throat calculation. Subsequent lines of output comprise (1) stipulated nozzle pressure ratios (per word 5 on card 1) and (2) results of each iteration to the specified nozzle exit condition. For subsonic combustion, the area ratios, A/A3, are actually ratios of nozzle area to throat area. In the case of supersonic combustion, there is no nozzle throat calculation, and A/A3 is actually the ratio of nozzle area to combustor exit area.

Test Case

The following test cases are used to illustrate the input and the output of the program:

- a. Subsonic combustion with assigned combustor exit Mach number.
- b. Supersonic combustion with assigned combustor exit Mach number.
- c. Supersonic combustion with assigned combustor area ratio.

The IBM input forms for these cases are presented in tables II, III, and IV.

The outputs of the test cases are forwarded under separate cover.

REFERENCE

1. Zeleznik, Frank J., and Fordon, Sanford, "A General IBM 704 or 7090 Computer Program for Computation of Chemical Equilibrium Composition, Rocket Performance, and Chapman-Jouget Detonations", NASA TN D-1454 (1962).

December, 1965
AirResearch Manufacturing Company
Division of the Garrett Corporation
Los Angeles, California

Reference: (1) - AikResearch Report AP-1001-1, Computer
Program Description, Ramjet and Scramjet
Cycle Performance conducted under NASA
Contract NAS1-5116

Revised Cycle Performance Program (from Reference one) including:

- (a) Computer tape
- (b) Program listing
- (c) Sample calculation
- (d) Input format/instructions
- (e) Sample input cards

The revised cycle performance from the referenced report incorporates the following modifications:

1. The program was modified in order to more accurately account for the pressure distribution along the multi-staged combustor walls. This can now be accomplished by stacking the input data for each stage, specifying the combustor area ratio and equivalent pressure, and weighting constant K for each stage. The program will execute the multi-stage problem as a single-stage problem by using the results from previous stages.
2. The momentum-continuity equation in this program was modified to a third order algebraic equation in order to more accurately solve for the velocity at the combustor exit.
3. Because the dynamic pressure distribution is not linear along the multi-stage combustor, the viscous drag calculation was modified by using the averaged value of q of each stage rather than using the averaged value of q for the overall combustor as done previously.

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AIR RESEARCH MANUFACTURING COMPANY

A DIVISION OF THE GARRETT CORPORATION

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TELEPHONE: (213) 770-1010, 670-0131 • CABLE: GARRETTAIR LOS ANGELES

In reply refer to:
SRJD-9267-0510

10 May 1968

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23365

Attention: Mr. K. D. Albert
Contract Administrator

Subject: Hypersonic Research Engine Project
NASA Contract NAS1-6666
Submittal of Computer Tape

Reference: (1) AIR Research Report AP-1001-1, Computer
Program Description, Ramjet and Scramjet
Cycle Performance conducted under NASA
Contract NAS1-5116

Gentlemen:

The following information is submitted as requested in telecon of
May 3, 1968 between H.F. Potthast and K.D. Albert.

Revised Cycle Performance Program (from Reference one) including:

- (a) Computer tape
- (b) Program listing
- (c) Sample calculation
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equivalent pressure, and weighing constant K for each stage.
The program will execute the multi-stage problem as a single-
stage problem by using the results from previous stages.

NASA Langley Research Center
Attention: Mr. K. D. Albert

SRJD-8267-0510
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2. The momentum-continuity equation in this program was modified to a third order algebraic equation in order to more accurately solve for the velocity at the combustor exit.
3. Because the dynamic pressure distribution is not linear along the multi-stage combustor, the viscous drag calculation was modified by using the averaged value of q at each stage rather than using the averaged value of q for the overall combustor as done previously.

Very truly yours,

AIRESEARCH MANUFACTURING COMPANY
A Division of The Garrett Corporation

R. J. Dunn
Program Administrator
Advanced Propulsion Engines Sales

RJD/lk
Enclosure

CC: D. Arganbright - DCASO
M. Craig - Garrett Sales Hampton

INPUT DESCRIPTION

<u>Card</u>	<u>Field</u>	<u>Description</u>
1	1	Reference case number "1" for first stage "15" for subsequent stages
(9I4)	2	"0" means subsonic combustion; "1" means supersonic combustion
	3	Blank
	4	Blank
	5	Number of nozzle stations for which data are printed out
	6	Number (0 to 25) of nozzle pressure ratios for schedule of assigned nozzle pressure ratios
	7	Blank
	→ 8	"0" or "1" means normal printout "2" chemical equilibrium calculation "3" thermodynamic data for species "4" iteration for combustor exit velocity and skin friction coefficient "5" means both "3" and "4" "6" means all "2", "3" and "4"
	9	Number of cases (1 to 15)
2	1	"0" means specified combustor pressure ratio "-1" means specified combustor exit Mach No. "1" means specified combustor area ratio
(8F10.0)	2	A_e/A_c , ratio of nozzle exit area to cowl area. Blank if nozzle pressure ratio is specified
	3	A_2/A_c , ratio of combustor inlet area to cowl area. Blank if combustor inlet Mach number is specified

INPUT DESCRIPTION (Continued)

<u>Card</u>	<u>Field</u>	<u>Description</u>
2 (8F10.0)	4	M_2 , combustor inlet Mach number. Blank if A_2/A_c is specified
	5	P_e/P_o , ratio of nozzle exit pressure to ambient pressure. Blank if A_2/A_c is specified <i>2...? A_e/A_c AWE 1944</i>
3 (8F10.0)	1	$\cos \theta$, θ is the fuel injection angle with respect to the horizontal axis. (e.g., "0." for normal injection)
	2	A_c , cowl area, sq. ft
4 (8F10.0)	1	A_w/A_2 , ratio of combustor wetted area to combustor inlet area
	2	K_1 , constant for evaluating the average pressure acting on the first stage combustor walls. $\bar{P} = (P_2 + K_1 P_3)/(1 + K_1)$
5 (8F10.0)	1	Ambient pressure, atm
	2	Ambient temperature, °K
	3	Flight Mach number
	4	Blank
	5	Additive drag coefficient
6 (8F10.0)	1	η_{KE} , inlet kinetic energy efficiency, or (by pre-fixing a minus sign) the enthalpy rise between freestream pressure, entropy conditions and conditions corresponding to freestream pressure and combustor-inlet entropy
	2	A_o/A_c , ratio of inlet capture area to cowl area (i.e., mass flow ratio)
	3	A_e , geom/ A_c , eff., ratio of geometric nozzle exit area to effective nozzle exit area (to account for boundary layer growth) <i>A A_e/A_c, eff. AWE 1944</i>

INPUT DESCRIPTION (Continued)

<u>Card</u>	<u>Field</u>	<u>Description</u>
6 (8F10.0)	4	C_s , nozzle velocity coefficient, ratio of I_{vac} to the I_{vac} calculated with no nozzle losses
	5	Temperature of the fuel at fuel-injection nozzle, °K
7 (8F10.0)	1	ϕ , equivalence ratio
	2	η_c , combustor chemical efficiency, ratio (by weight) of reacted fuel to fuel supplied
	3	V_f , fuel inlet velocity, ft per sec.
	4	Temperature of fuel corresponding to storage conditions, °K
	5	Assigned combustor area ratio, pressure ratio, or exit Mach number, as applicable
	6	Combustor skin-friction coefficient (a guessed value for multi-stage run)
8 (8F10.0)	1	K_2 , constant determining the effective pressure acting on the second stage combustor wall
	2	The ratio of the first stage exit area to the first stage combustor entrance area <i>A₃/A₂</i>
	3	The ratio of the first stage exit pressure to the first stage combustor entrance pressure
	4	Skin-friction drag force acting on the first stage, lb_f
	5	Ratio of the first stage combustor wetted area to the first stage combustor entrance area (Blank for third stage run)
	6	Second stage combustor skin-friction coefficient (Blank for third stage run)

INPUT DESCRIPTION (Continued)

<u>Card</u>	<u>Field</u>	<u>Description</u>
	7	The dynamic head of the flow at the exit of the first stage, psia (Blank for third stage run)
9 (8F10.0)	1	K_3 , constant determining the effective pressure acting on the third stage combustor wall
	2	The ratio of the second stage exit area to the first stage combustor entrance area <i>2.7/1.2</i>
	3	The ratio of the second stage exit pressure to the first stage combustor entrance pressure
	4	Skin-friction drag force acting on the second stage combustor, lb_f
	5	Ratio of the first and second stage combustor wetted area to the first stage combustor entrance area
	6	Third stage combustor skin-friction coefficient
	7	The dynamic head of the flow at the exit of the second stage, psia

Note:

Card 8 and 9 are blank for first stage run
Card 9 is blank for second stage run