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I am submitting herewith a thesis written by Muftah Taher Abujelala entitled "Mathematical Modeling of Hydrogen Fuel for Advanced Airbreathing Jet Propulsion Simulations." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

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MATHEMATICAL MODELING OF HYDROGEN FUEL FOR ADVANCED AIRBREATHING JET PROPULSION SIMULATIONS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Muftah Taher Abujelala

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ABSTRACT

The versatile QNEP (Quick Navy Engine Program) has been extended to allow treatment of advanced airbreathing jet propulsion engines using hydrogen or hydrocarbon fuels. This modification of the engine code has been exercised for turbofan, augmented turbofan, and ramjet engines using both hydrogen and hydrocarbon fuels.

Examination of modified QNEP (denoted MNEP) thermodynamic routine performance and comparison of this performance with other standard references have been presented. This includes combustion temperature rise for air-hydrogen combustion, air-hydrocarbon fuel combustion, and air thermodynamic properties.

This code can include or preclude the effect of dissociation in the engine cycle performance evaluation. It can also treat the gas mixture as frozen or equilibrium flow through the nozzle. A listing of the MNEP program is included.

Recommendations have been included for the study of the overall merits of hydrogen and hydrocarbon fueled engines and incorporation of analytical models of additional turboaccelerator features in the MNEP code.

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NOMENCLATURE

ACAP	Captured area
ATM	Atmosphere
CD	Discharge coefficient
C_p	Constant pressure specific heat ratio
CV	Velocity coefficient
DELP	Pressure drop
EFF	Efficiency
ER	Ratio of bleed flow to main flow
FAR1	Main flow fuel air ratio
FAR1B	Bleed flow fuel air ratio
FN	Net thrust
F( )	Function represents thermodynamic routine, THERMO
f	Fuel air ratio
f( )	An empirical function to reduce number of iteration
H	Absolute enthalpy
HF	Fuel absolute enthalpy
$H°_f$	Heat of formation
h_i	Sensible enthalpy per unit mass
h_a	Air sensible enthalpy per unit mass
$h°_i$	Species heat of formation per unit mass
$h°_{fa}$	Air heat of formation per unit mass
h_{fu}	Fuel sensible enthalpy per unit mass
$h°_{fu}$	Fuel enthalpy of formation per unit mass

h_i	Species sensible enthalpy per unit mass
m_a	Air mass flow
m_R	Mass of reactants
m_p	Mass of products
P_r	Relative pressure
Q	Total heat transfer
QNEP	Quick Navy Engine Program
R	Gas constant
RCH	Carbon to hydrogen mole ratio
REQ	Equivalence ratio
TSFC	Thrust specific fuel consumption
T1	Main flow entrance total temperature
T1B	Bleed flow entrance total temperature
TP1	Main flow entrance total pressure
TP1B	Bleed flow entrance total pressure
W	Extracted work
WBIN	Entrance mass flow of the bleed stream
WB1	Bleed flow entrance weight flow
WTF	Total mass flow
WTFB	Bleed total mass flow
WT1	Entrance mass flow of the main stream
X_i	Species composition
$( )_p$	Products
$( )_R$	Reactants
$( )_1$	Inlet
$( )_2$	Exit

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

Most of the airbreathing engines that are currently in use have been designed to use hydrocarbon fuels. The availability of these fuels and their storage safety are the main factors encouraging the manufacturers of these engines to design their products for these fuels. The increase in price of hydrocarbon fuels, the increase of air pollution and other factors have caused these manufacturers to look for other fuels to replace the hydrocarbon fuels. Many researchers have recommended hydrogen fuel for the airbreathing engines of the future.

Recent studies have shown that the relatively higher heating values of hydrogen (about 2.7 times that of JP fuels) reduces the take-off gross weight by 10% for short range airplanes and 14% for long-range aircraft [1]. The selection of hydrogen fuel would also minimize the environmental impact of aircraft operation, *vis-à-vis* the next generation of supersonic transportation, by eliminating CO, CO_2, hydrocarbons, and reducing NO_x, and also reducing noise for the same thrust class [2].

Hydrogen fuel could also provide for a technically superior aircraft in terms of performance and operating

capability. Its use could result in the same range/payload performance at lower direct operating cost, depending upon the cost of the hydrogen fuel [2]. For aircraft designs using hydrogen on the design range mission, the direct operating cost improvement is nearly 10% and, associated with this, there is a gain in payload of over 15% when compared with JP-fueled aircraft [3].

The increased interest in space discovery has produced the challenge of transporting large quantities of payload into orbit. The high energy of hydrogen could provide the high thrust required for most turboaccelerator engines [4].

The previous information provides some of the current research results that support the introduction of hydrogen-fueled turbine engines. For preliminary as well as in-depth studies, it is often necessary to examine a broad range of engines operating at both design and off-design conditions in order to find an efficient air frame/engine combination. The spectrum of flight conditions through which an engine must operate will strongly affect the optimum design parameters for that engine. Previous engine developments have shown that it is very important to develop a mathematical model for engine simulations in order to assist the development process. Most of the current models are restricted to hydrocarbon-fueled engine simulations;

therefore, it was desirable to modify one of the current computer codes to use hydrogen fuel for engine simulations. A literature survey of the most important engine simulation codes was conducted and is described below.

1.2. Literature Review

Numerous computer codes for airbreathing engine cycle calculations currently exist, including NASA 1967, CARPET, SMOTE, TRISPL, GENENG I, GENENG II, NEPCOMP, QNEP and NNEP. A brief summary of the capabilities of these codes is presented below.

a. NASA--1967. This computer program provides calculation of the design-point performance of turbojet and simple turbofan engine cycles [5]. The thermodynamic properties of the gas mixture are expressed as a function of temperature and fuel-air ratio. The effect of dissociation is not incorporated.

b. CARPET. CARPET is a computer program that simulates a basic parametric turbojet or turbofan [6]. It can also be used to analyze the performance of a specific engine at discrete operating points if the total airflow is input along with the component characteristics of the engine. The program does not provide component balancing, a feature which is necessary for off-design analysis. The thermodynamic routine is a polynomial equation that

calculates air and fuel/air mixture properties along the temperature range of 300-4000° Rankine and fuel/air ratio range of 0.-0.67623 for JP-fuel. The dissociation effect is not included.

c. SMOTE, GENENG I, GENENG II. (i) SMOTE. This program is capable of calculating turbofan engine design and off-design performance using specific component performance maps [7]. It can easily be expanded to include additional engine features. (ii) GENENG I. This NASA program is a computer code derived from the SMOTE program. It uses component performance maps for the calculation of steady-state design and off-design turbofans, and one- and two-spool turbojet engine performance [8]. Either convergent or convergent-divergent nozzles may be used. (iii) GENENG II. This is a derivative program from GENENG I. It was developed to provide the capability of calculating two or three spool turbofan engine cycles for design and off-design points, with as many as three nozzles (or air-streams) [9].

The thermodynamic routine for these three codes calculates the thermodynamic properties of air and fuel-air mixture (based on JP-4) by using curve fits of the Keenan and Kaye's tables [10]. These results ignore the dissociation effect.

d. TRISPL. TRISPL is a computer program (derived from SMOTE) that simulates steady-state design and off-design performance of triple-spool turbofan engines [11]. This program uses performance maps of the major engine components. It uses the CARPET thermodynamic routine for the calculation of air and fuel/air mixture properties. Hence, the effect of dissociation is not included.

e. NEPCOMP. The NEPCOMP program calculates both design performance of gas turbine and ramjet engines [12]. NEPCOMP can be used with or without component characteristic maps. The program consists of modules representing engine components that may be interconnected to simulate the performance of various gas turbine engine configurations. The thermodynamic subroutine has built-in data tables representing cubic spline curve fits for air, stoichiometric combustion products (for hydrogen to carbon mass ratio = 0.16) and water vapor. The thermodynamic properties are assumed to be functions of two variables (fuel-air ratio and other thermodynamic properties). The dissociation effect is not included in this code.

f. NNEP. This computer code is capable of simulating almost any conceivable turbine and ramjet engine [13]. This code uses stacked component maps and

multiple flow paths to simulate variable cycle engines with variable component geometry. It is capable of design and off-design calculations and can optimize free variables such as nozzle areas to minimize specific fuel consumption. The thermodynamic routine has built-in data tables representing cubic spline curve fits for air and stoichiometric combustion products for JP-5. These data were taken from tables of Reference [10], which ignores the effect of dissociation.

g. QNEP. This program is a derivative of the NEPCOMP and NNEP codes. This code is capable of simulating various gas turbine and ramjet cycles by using component characteristics [14]. It is capable of calculating design and off-design points. It can also be used with or without component characteristic maps. This permits very rapid trade-off examination of an engine, which is very important for preliminary design activity. The thermodynamic routine has built-in data tables representing cubic spline curve fits for air and stoichiometric combustion products based on JP-5. The dissociation effect is not treated.

1.3. Problem Statement

An examination of the previously discussed codes shows the following:

a. These codes have ignored dissociation effects and the extremes of frozen and equilibrium flow in the calculation of the gas mixture properties.

b. It is not possible to exceed the stoichiometric fuel-air ratio.

c. Thermodynamic data is only incorporated for JP fuels.

1.4. Objectives

The current interest in supersonic and hypersonic vehicles has emphasized the need for an accurate yet convenient method of calculating the performance of advanced engine cycles. To achieve this requirement, the dissociation effect must be included in the thermodynamic routine. In addition, it is desirable to incorporate the capability of frozen and equilibrium flow calculations, control of fuel-air ratio, control of maximum combustion temperature, and also the capability to use both typical hydrocarbon fuels and hydrogen fuel.

The purpose of this effort was to incorporate these features in a current engine code. The approach followed was in two steps: (i) Modification of a versatile, flexible engine code to include the cited capabilities. (ii) Use of this modified code for the study of some hydrogen-fueled engine configurations.

CHAPTER II

QNEP MODIFICATION

Advanced engine studies require the capability of examining hydrogen-fueled propulsion cycles. To achieve a high degree of accuracy, the dissociation effect must also be included in the thermodynamic routine of advanced gas turbine models. In addition, thrust losses due to the lack of recombination of dissociated products in the exhaust nozzle are of considerable interest in evaluating the performance of hypersonic vehicles [15].

The review of recent turbine engine codes discussed in Chapter I reveals that the QNEP code is a very flexible code with which to treat both standard turbomachinery cycles and ramjet cycles. Additionally, this code is a current one and is under continuing development at the Naval Air Development Center (NADC), Arnold Engineering Development Center (AEDC), and several other research centers. (References [12] and [13] are generally available references on the construction of this code.)

The QNEP thermodynamic routine does not include the capability of treating hydrogen fuels or the dissociation effect; therefore, this routine has been replaced with one which includes these capabilities. The other component routines have also been modified to be compatible with the

new thermodynamic routine. The following two sections present a brief summary of the capabilities of the modified routines.

2.1. Subroutine THERMO

THERMO is the new QNEP thermodynamic routine. This routine is a combination of an iterative routine and the NASA-Simplified Combustion Gas Model [16]. This NASA program includes the effect of dissociation and allows a wide range of fuel-air ratio (FAR) and carbon to hydrogen mole ratio (RCH) values. This model also allows treatment of hydrogen-air combustion, hydrocarbon-air combustion, and dissociating air. The model uses tabulations of the thermodynamic properties of the individual species in order to calculate gas properties. The composition of a given mixture is determined by specifying the gas pressure (ATM), temperature (°R), FAR and RCH. The model is applicable over the pressure range of .001-100 atmospheres and for temperatures up to 7000°R . The gas model is simplified by neglecting the formation of species containing atomic nitrogen. This is permissible because for the above temperature and pressure ranges the formation of this species occurs in negligible amounts and therefore has a very small effect on the thermodynamic properties of combustion gas mixture [16, 17].

An iterative routine has been added to the NASA program to allow the THERMO routine to accept four main variable inputs that are required for various cycle calculations. Appendix B presents the method of iteration for each of the five following combinations of the input variables.

1. FAR, RCH, temperature, and pressure (IDD = 5)
2. FAR, RCH, pressure, and enthalpy (IDD = 6)
3. FAR, RCH, entropy, and enthalpy (IDD = 4)
4. FAR, RCH, entropy, and temperature (IDD = 3)
5. FAR, RCH, entropy, and pressure (IDD = 1)

FAR is the fuel-air ratio, RCH is the carbon-to-hydrogen mole ratio of the given fuel, and IDD is a switch number which is used to specify the input condition. Since the THERMO routine uses the equivalence ratio for gas properties calculation, fuel-air ratio will be divided by stoichiometric fuel-air ratio as it is input.

The first iteration combination calculates the thermodynamic properties for a given point. The second combination determines the temperature by an iterative technique. The iteration is performed by assuming an initial temperature value and computing the enthalpy. When the calculated value and the given value differ by less than .001%, the iteration is halted. The third combination calculates pressure and temperature by two

iterative loops. Initial pressure and temperature values are assumed. Then, keeping the pressure value constant, an iterative loop similar to the previous one is used to determine the temperature for the known enthalpy value. Keeping this temperature constant, the pressure is calculated by another iterative loop. When the calculated entropy and the given entropy differ by less than .001%, the iteration is halted. From these pressure and temperature values, the enthalpy is determined. If the calculated value is in the previous limit, the overall iteration is stopped; otherwise, the iteration will be repeated for both temperature and pressure until the successive temperatures differ by less than .01%, and pressure less than 1%. The cycle is not as sensitive to pressure as it is to temperature.

The fourth case is to calculate the pressure of a gas mixture. An initial pressure value is assumed and then the entropy is computed. When the calculated value and the given value differ by less than .001%, the iteration is stopped. The last iterative computation is to determine the gas mixture temperature. From the assumed temperature, the entropy is calculated. When the calculated and the given values differ by less than .001%, the iteration is halted.

The computer logic of the previous five combinations is presented in Appendix B, where each of the iterative loops is discussed in more detail.

The reference temperature for the combustion calculation has been chosen to be 0°R. This selection made the calculation of combustion temperature possible for equivalence ratios both greater than and less than one, as is described in Appendix A. The THERMO routine performance, in comparison with the other approaches, is one of the subjects of the next chapter.

2.2. QNEP Code Modification

The QNEP program consists of 17 subroutines and a main program. These routines are performance routines, input routines, output routines, and data arrangement routines. The QNEP performance routines, which have been modified in order to be compatible with the new thermodynamic routine, are summarized in the following paragraphs. The main computer logic for these subroutines is contained in Appendix B.

2.2.1. Subroutine COMPRS. Subroutine COMPRS performs the calculations for all compressor type engine components. Compressor characteristics may be input as constant values or as table look-up functions of referred RPM and "R." "R" is an arbitrary number representing the general shape

of surge and choke lines. The compressor pressure ratio and efficiency may be input as constants or as a table look-up function of corrected RPM and "R."

Bleed flow may be extracted from the compressor at any compressor stage location. The amount of bleed flow is determined by specifying a bleed flow fraction of the compressor entrance weight flow. The general source of the compressor bleed flow extraction is defined by an energy ratio (bleed flow energy to the main flow energy) which is input as a constant.

The portion of the subroutine which determines the main and bleed flow horsepower has been modified to be compatible with the new thermodynamic routine.

2.2.2. Subroutine DBURNR. Subroutine DBURNR is used for three types of engine component calculations. The first type calculation is for a duct pressure drop. A duct total pressure drop is either input as a constant or as a table look-up function of duct entrance corrected flow. In the duct type component, a duct entrance bleed flow and a duct exit bleed flow may be used. If the duct entrance bleed flow option is used, the fuel to air ratio of the gas mixture is computed along with a weighted enthalpy of the gas mixture. The duct exit total temperature is then calculated from the enthalpy, fuel-air ratio, and total pressure.

The second and third types of engine component calculation are for burner and afterburner components. The calculations for both of these components are almost the same. These components have the same duct total pressure drop option as provided in the duct type component. In addition, the combustion efficiency and fuel enthalpy (fuel heat of formation plus fuel enthalpy at fuel inlet temperature) are input as constants. Either exit total temperature or exit fuel-air ratio of the burner or afterburner can be input as a constant. In addition to the duct total pressure drop option in the burner and afterburner type components, calculations are provided for Rayleigh type momentum total pressure drop whenever the duct cross-section is specified.

Most of the DBURNR routine has been modified to incorporate the new thermodynamic routine (THERMO) requirements. Additionally, some parts of this routine have been rewritten to provide the more accurate and more extensive capability of calculating either fuel-air ratio or temperature rise of a gas mixture through the burner or afterburner components. The mathematical representation of this capability is presented in Appendix A. The new technique of calculating combustion temperature rise maintains the capability of controlling the maximum combustion temperature. Typical results for this technique will be discussed in the next chapter.

2.2.3. Subroutine HEATXC. Subroutine HEATXC, which performs the calculations for heat exchanger components, has two flow entrances and two flow exits. The function of this component is to transfer heat from the secondary flow stream to the main stream. A duct total pressure drop for each flow stream is either input as a constant or as a table look-up function of each respective entrance corrected flow.

The modification in this routine involves the calculation of the specific heat ratio and the gas constant of primary and secondary entrance streams. A description of this modification is also presented in Appendix B.

2.2.4. Subroutine INLET. This routine computes the air flow conditions of the inlet entrance and exit. It also calculates the installation effects on the airflow properties [4]. The free-stream static pressure and temperature is either input or computed from the geometrical altitude input. The inlet recovery is either input as a constant or a table look-up function of inlet referred flow and inlet Mach number.

Ram recovery and the referred flow calculation in this subroutine have been modified in order to use the new thermodynamic routine. Appendix B presents a description of this modification.

2.2.5. Subroutine MIXER. Subroutine MIXER performs the calculation for mixing two gas streams into a single stream. The cross-sectional area of each mixer entrance is specified as an input. Using each cross-sectional area, the pressure across each flow entrance is iterated until each actual entrance corrected flow and each calculated entrance corrected flow differ by less than .01%. If, during the iteration, the entrance Mach number increases above the sonic value, then the iteration for that entrance is halted at the sonic conditions. The ideal enthalpy and ideal velocity of the mixed gas are computed on a flow weighted basis. The mixer exit enthalpy is then computed from the ideal enthalpy and actual mixed velocity. Total temperature and total pressure are then found from the mixed exit enthalpy. The entrance flow weighted entropy is compared with the entropy of the mixed gases at the mixer exit. If the entropy at the exit is greater than the entrance flow weighted entropy, the exit total pressure is recomputed assuming exit entropy equal to the flow weighted entropy.

Most of this subroutine has been modified in order to be compatible with the new thermodynamic routine. This modification is described in Appendix B.

2.2.6. Subroutine NOZZLE. This routine performs the calculations for convergent and convergent-divergent

type nozzles. The gas mixture can be treated for either equilibrium or frozen flow. The discharge and velocity coefficient can be input as constant or a table look-up as a function of pressure ratio across the nozzle.

The static temperature for sonic conditions in the nozzle throat is calculated by an iterative technique. The critical pressure and pressure ratio at the nozzle throat are then computed. In the case of a convergent-divergent nozzle, full expansion to the ambient pressure is assumed. The actual velocity is calculated from the nozzle exit condition, inlet condition, and velocity coefficient. The nozzle weight flow is computed using the cross-sectional area, discharge coefficient and gas properties at the nozzle throat. Alternatively, the cross-sectional area is calculated if the other factors are known. The net thrust is then calculated from flow velocity, weight flow, area, and pressure difference at the nozzle exit.

The thermodynamic portion of this routine has been modified according to the requirements of the new thermodynamic routine. To account for thrust losses in cycle performance due to dissociated gas in the exhaust nozzle, the subroutine NOZZLE has also been modified to calculate the nozzle thrust for both frozen and equilibrium flow. In the case of frozen flow, the gas mixture composition was kept constant at the nozzle throat condition

for the convergent-divergent nozzle. The frozen flow condition is assumed at this nozzle section, since the downstream expansion process occurs so quickly the dissociated gas cannot recombine. Appendix B presents a description of this routine.

2.2.7. Subroutine TURBIN. Subroutine TURBIN performs all the calculations for turbine-type engine components. Weight flow may enter the turbine by a main entrance and a bleed flow entrance. Turbine characteristics, such as referred flow and efficiency, may be input as constant values or as a table look-up function of corrected RPM and turbine pressure ratio.

Turbine entrance bleed flow is mixed with main entrance flow on a flow weighted enthalpy and entropy basis. The total pressure and temperature used for the turbine entrance calculation are then determined using the flow weighted entropy and enthalpy.

The turbine work calculation is based on the actual enthalpy decrease, turbine main entrance flow, and turbine entrance bleed flow. The turbine exit bleed flow is not credited with any turbine work.

For calculation of the mixed streams and the exit stream, thermodynamic properties have been modified to satisfy the requirements of the new thermodynamic routine. Appendix B presents the description of this modification.

2.2.8. Function THERM. It was mentioned before that the basic QNEP thermodynamic routine does not allow calculations for hydrogen fuel or include the effect of dissociation; therefore, function THERM of QNEP has been replaced with a new thermodynamic subroutine, THERMO, which was described in Section 2.1.

In summary, subroutine THERMO has been constructed from the NASA-Simplified Combustion Gas Model program and an iterative routine. In order to include the calculation of hydrogen-air combustion and include the dissociation effect in cycle performance calculations, this routine has replaced the QNEP thermodynamic routine. Most of the other QNEP routines have been modified to be compatible with the THERMO routine. The Modified QNEP has been renamed MNEP, which is an abbreviation of Modified Navy Engine Program. Several cases were run with both QNEP and MNEP to evaluate the matching of THERMO with the other QNEP routines. The result of these evaluations is presented in the next chapter.

CHAPTER III

RESULTS AND DISCUSSION

This effort has included major modifications to the thermodynamic routines of the QNEP code, exercise of typical cycles to evaluate these modifications, and evaluation of nozzle flow characteristics on typical cycle performance. These results will be discussed in the following paragraphs.

3.1. Subroutine THERMO Performance

The thermodynamic routine of MNEP, THERMO, was evaluated for several input cases. The output values of function THERM (the original QNEP thermodynamic routine [14]) and the tabulated values of Keenan and Kaye [10] and Browne and Warlike [17] were all used for comparison with the modified thermodynamic routine. The results of comparing these routines are documented in Appendix C, where the percentage error is defined as follows:

$$\% \text{ Error} = \frac{\text{Reference Data} - \text{THERMO Data}}{\text{Reference Data}}$$

Figure 1* shows an average percentage error of about 0.15 in the enthalpy values calculated by THERMO for air

*All figures are included in Appendix C.

over a temperature range of 600-2800° Rankine. Due to the effect of dissociation, which begins at approximately 2800°R and which is ignored by References [10] and [14], the percentage error is higher beyond this temperature. The THERMO routine shows, however, good agreement in the dissociation range with Reference [17], which includes this effect. The temperature range of 600-3600°R is the applicable range for air for most aircraft gas turbine and ramjet engines and good agreement with appropriate references is shown over this range.

Within a temperature range of 600-2000°R, a maximum percentage error of 0.2 in the values of specific heat ratio calculated by THERMO for air is shown in Figure 2. Beyond this temperature, the average percentage error of THERMO values is less than 0.2 compared to References [10] and [14] and about 1.25 at 3200°R with respect to Reference [17]. This error exists for References [10] and [14], and even for Reference [17], in the temperature range where the dissociation effect is not present (2000-2800°R). The cause for this error among the accepted references is unknown. The error which is present in the dissociation range is due to the method of calculation of specific heat ratio where THERMO calculates frozen specific heat ratio (C_p = F [Temperature and Pressure] and Reference [17] calculates equilibrium specific heat ratio (C_p = F [Enthalpy]). In the case of dissociated gas, the equilibrium specific heat ratio is more representative than the frozen one.

Figure 3 shows the effect of pressure on the air enthalpy values along a temperature range of 600-4000°R . For example, the percentage deviation of the enthalpy values at pressures of 0.1 and 40 atmosphere is 0.34 at 3600°R . This error is also shown in the tabulated values of Reference [17].

The turbine engine fuels, JP-4 and JP-5 (RCH = .5 and 0.52456) are the 2 hydrocarbon fuels which were chosen to evaluate the combustion product properties calculated by THERMO. The representative temperate range of 1000-4000°R was selected for this evaluation. The THERMO output was compared with the tabulated data of Reference [10] (RCH = .5) and the output data of Reference [14] (RCH = .52456).

Figure 4 shows an average enthalpy percentage error of less than ±0.1 in the values calculated by the THERMO routine compared to Reference [14] over a temperature range of 1000-3000°R . Beyond this range, the error increases. The reason for this increase will be discussed below. In addition, Figure 5 presents a comparison between enthalpy values calculated by subroutine THERMO and the tabulated data of Reference [10]. It shows the same error range as Figure 4.

To show the effect of dissociation, the THERMO routine was used to calculate dissociated and nondissociated gas properties. This was accomplished by changing the

nondissociation range to higher values than the maximum temperature. Figure 6 displays the high error noted in the values shown in Figures 4 and 5 beyond the temperature of 3000°R . Here the percentage error was defined as:

$$\% \text{ Error} = \frac{\text{Dissociated Values} - \text{Nondissociated Values}}{\text{Dissociated Values}} \times 100$$

The effect of dissociation produces a high error beyond that temperature. Both the previous references have ignored this effect. This figure shows that the effect of dissociation on the absolute enthalpy values for a given temperature is also increased by increasing fuel-air ratio. This is because at a given temperature the energy required for dissociation is high for high dissociated mass.

Figure 7 shows good agreement between the specific heat values calculated by THERMO and Reference [14]. It shows a maximum percentage error of less than 0.5 at high fuel-air ratio. The comparison of specific heat ratio values calculated by THERMO and the tabulated data of Reference [10] is also presented in Figure 8. A maximum percentage error of 1.0 is shown. This large difference is due to ignoring real gas effects in calculating specific heat ratio in Reference [10]. In this reference, the specific heat ratio is based up $\gamma = C_p/(C_p - R)$, whereas in

the THERMO routine it is calculated from the species specific heat ratio values (i.e., $\gamma = \frac{C_{p_i}}{C_{p_i} - R}$).

One of the new features in MNEP that was mentioned in Chapter II is that it allows calculation of the maximum combustion temperature that can be obtained for a given fuel-air ratio, including the effects of dissociation. The subroutines DBRNR and THERMO have been modified to work together for calculation of combustion temperature. These modifications are described in Appendices A and B. The results of this modification were compared with the tabulated data of Reference [18] for JP-4 air combustion. This latter data was calculated by the NASA One-Dimensional Equilibrium (ODE) thermodynamic computer program [19]. The result of this evaluation is presented in Figures 9 and 10. These figures show good agreement between the two codes for two representative values of combustor inlet temperature. A maximum error of ±.5% is shown in the calculation of combustion temperature and 0.6% is the maximum error in the molecular weight values over a typical equivalence ratio range.

Figures 11 and 12 show combustion temperature rise results for JP-5 fuel with air at different inlet temperatures and 1 atmosphere pressure. Figure 11 presents these results assuming a nondissociated gas mixture. The result shows an increase of combustion temperature with fuel-air ratio; however, when the mixture ratio exceeds

stoichiometric, CO and possibly H_2 and unburned fuel are present in the exhaust products, resulting in the combustion temperature decreasing with increasing fuel-air ratio. The figures also show that for a given amount of energy release, the final combustion temperature increases with initial inlet temperature. These results are significantly altered when the effect of dissociation is included. This is illustrated in Figure 12. The difference between non-dissociated and dissociated gas combustion temperature as the mixture ratio approaches stoichiometric is due to the presence of significant CO and H_2 concentrations at high temperature. In addition, note that dissociation causes the peak combustion temperature to occur at slightly higher fuel-air ratio conditions.

Figure 13 presents the change of gas mixture molecular weight of the combustion gases with fuel-air ratio. Dissociation causes the molecular weight to decrease sharply as the mixture exceeds the stoichiometric temperature.

Additional evaluation of the THERMO routine was done to check the matching of THERMO with the modified QNEP routines. Several cases were evaluated with both THERM and THERMO routines after they were configured similarly to eliminate non-relevant sources of error such as dissociation. These cases examined isentropic processes near standard sea level conditions. The outputs of these

two routines were compared and the results of comparison are discussed in the following paragraphs.

Several values of air enthalpy and JP-5-air combustion gas mixture enthalpy were input to both routines. Figures 14 and 15 present the deviation of THERMO output values from the THERM ones. A very good agreement has been achieved in calculating temperature and constant pressure specific heat, where ±0.4% is the maximum error value shown in these figures, while the maximum percent error in pressure values is about ±2. This error is due to the fact that the two routines calculate the pressure in two different ways. THERM calculates the pressure from relative pressure, P_r , values that are tabulated in Reference [10] as shown below:

$$\log P_r = \phi/R \tag{1}$$

$$P_2 = P_1 \times \frac{P_{r2}}{P_{r1}} \tag{2}$$

where ϕ is equal to $\int^{T} \frac{C_p}{T}\, dt$; C_p is constant pressure specific heat and R is the gas constant. For tabulation purposes, values of the relative pressure have been truncated. This means that the tabulated data do not represent the exact values and an error occurs in the pressure calculation of Eq. (2). Since the THERMO routine calculates the pressure directly, its pressure calculation is more accurate than the THERM one.

Figure 16 presents the output deviation for the input of several pressure values to THERMO and THERM routines. It shows a very good agreement between the enthalpy, specific heat and temperature values calculated by these routines. Except at very low pressure, the maximum error is about 0.2%.

The performance of the THERMO routine for hydrogen-air combustion was compared with the tabulated data of Reference [17]. Except at near zero enthalpy (temperature of approximately 1100 and 3200°R), Figure 17 shows an enthalpy percentage error of less than ±2.0 in the values calculated by THERMO for the temperature range of 1000-4000°R. The high error, about 3.7%, which occurs at near zero enthalpy evolves from the definition of percent error, defined previously, when very small values exist in the denominator. At a temperature higher than 4000°R and high equivalence ratio, the maximum percentage error is approximately 4. It is suspected that this error is due to the different approach of calculating gas thermodynamic properties by THERMO and Reference [17]. Also due to the high degree of dissociation at these temperatures, it is suspected that a portion of this error is due to formation of species containing the nitrogen atom, which has been ignored in THERMO. Reference [17] shows that the percentage of species containing the nitrogen atom (NH_3, NH) in the gas mixture at 4200°R and

stoichiometric fuel-air ratio is about 7.43×10^{-6} . This percentage value is increased by temperature.

Figure 18 illustrates the result of comparing the specific heat ratio for hydrogen-air combustion calculated by THERMO and those calculated from the tabulated data of Reference [17]. It shows a maximum percentage error of about 1.6 along the temperature range of 1000-3000°R. Beyond this temperature, the error is sharply increased by increasing temperature, where a 7% error is shown at 4000°R and stoichiometric fuel-air ratio. This error occurs because THERMO calculates frozen specific heat ratio [i.e., $C_p = F(T,P)$] while Reference [17] calculates the equilibrium specific heat ratio [i.e., $C_p = F(h)$]; in addition, the latter is the isentropic specific heat ratio. In case of dissociated gas, the equilibrium specific heat ratio is more representative than the frozen one. The isentropic specific heat ratio does not represent the real gas specific heat ratio; therefore, the range error shown in Figure 18 does not represent the exact error between Reference [17] and the THERMO specific heat ratio values.

The combustion temperature rise for hydrogen-air combustion for different inlet temperatures and one atmosphere pressure is presented in Figure 19. It shows the same trends for hydrogen-air combustion which was displayed in Figure 12 for hydrocarbon-air combustion. Comparing Figure 19 with Figure 12 also shows that the

maximum temperature achieved by the combustion of hydrogen-air is larger than that obtained by hydrocarbon-air. This difference is due to the hydrogen heating value, which is about 2.7 times the hydrocarbon value.

Figure 20 presents the variation of hydrogen-air combustion gas mixture molecular weight with the change of equivalence ratio. It shows a rapid decrease of molecular weight (compared with that of the hydrocarbon) as the equivalence ratio is increased. This rapid change occurs because of the small value of the hydrogen molecular weight, where the hydrogen content is increased in the combustion products by increasing fuel-air ratio.

Figure 21 illustrates the relation between the limiting pressure (beyond which ammonia will be formed) and the equivalence ratio (REQ). Up to an equivalence ratio of one, ammonia will not be formed at any pressure, while beyond this value the limiting pressure varies with the inlet temperature. In cases where a high degree of cycle accuracy is needed, the input pressure should not exceed the limiting value.

3.2. MNEP Performance

To illustrate the use of MNEP, and to evaluate its performance against QNEP, several engine configurations were exercised using both of these codes. This includes design-point and off-design-point performance for typical

twin-spool turbofan, twin-spool aft fan, augmented turbofans, and ramjets. Schematics of these building block cycles, showing the flow station and component identification numbers, are displayed in Figures 22-24. The two codes were configured similarly to eliminate the differences due to dissociation. The outputs of the two models were compared and these results are also documented in Appendix C.

Typical results of cycle calculations for an aft fan engine fueled with JP-5 are shown in Table 1*. This data tabulates the percentage error encountered in thrust and thrust specific fuel consumption for calculations using MNEP and QNEP codes. The values of error are given by:

$$\% \text{ Error} = \frac{\text{QNEP Output} - \text{MNEP Output}}{\text{QNEP Output}} \times 100$$

A very good agreement is demonstrated between the values calculated from the 2 models with a maximum discrepancy in thrust of approximately 2.4%. The maximum discrepancy in thrust specific fuel consumption is about 1.6%.

Table 2 shows comparable calculations for an augmented aft fan engine. Again, a very good agreement is shown between the output values of the two models. A maximum discrepancy in thrust of about 2.4% is revealed.

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*All tables are included in Appendix C.

The maximum discrepancy in thrust specific fuel consumption is about 1.6%.

To further evaluate MNEP code performance, it was used to obtain data for comparable high altitude and Mach number conditions with the ramjet cycle. This data, which is displayed in Table 3, reveals excellent agreement for the performance parameters. Though the differences are not large, the differences shown are due to differences in the pressure calculations by the two models. This difference was previously shown in Figure 14.

The excellent agreement between the results of the MNEP and QNEP codes for hydrocarbon-fueled airbreathing engines gave high confidence in the validity of MNEP calculation and the accuracy of its thermodynamic routine (THERMO). Also, the good agreement between THERMO and the tabulated data of Brown and Warlike [17] for hydrogen-air combustion encouraged extending MNEP to the previous engine configurations fueled by hydrogen. These results demonstrate the difference between the hydrocarbon and hydrogen fuels in airbreathing engine applications. Results for the 2 fuels were compared and tabulated in Tables 4, 5 and 6. This data tabulates the percentage increase in thrust (FN) and the percentage decrease in thrust specific fuel consumption (TSFC) for cycles using these fuels. The percentage increase and decrease is defined as:

$$\% \text{ FN Increase} = \frac{\text{Hydrogen fuel - JP-5 fuel}}{\text{JP-5 fuel}} \times 100$$

$$\% \text{ TSFC Decrease} = \frac{\text{JP-5 fuel - Hydrogen fuel}}{\text{JP-5 fuel}} \times 100$$

Table 4 shows a high percentage increase in thrust and it also shows a large decrease in the thrust specific fuel consumption for an aft fan engine fueled by hydrogen rather than JP-5. The average percentage decrease in TSFC is about 63 and the average increase in the FN is about 7%.

Tables 5 and 6 show almost the same results for both augmented aft fan and ramjet engines.

3.3. Effect of Dissociation and Frozen Flow on Ramjet Engine Performance

Table 7 presents typical results of the effect of dissociation on ramjet engine performance when the fuel is a hydrocarbon (JP-5) and the engine is operated at 60,000 feet altitude. The exit combustion temperature was assumed to be 4100°R. This table tabulates the percentage error in thrust and thrust specific fuel consumption due to the dissociation effect. The error is defined as:

$$\% \text{ Error} = \frac{\text{Dissociation Values - Non-dissociation Values}}{\text{Dissociation Values}} \times 100$$

With the assumption of non-dissociated gas flow, Table 7 shows a maximum error of 4.85% in the thrust. The maximum error in thrust specific fuel consumption is about .55%.

This result shows that for an engine which operates on fixed exit combustion temperature, the thrust is higher by assuming dissociated gas flow rather than non-dissociated gas flow. This result is true because to compensate for the energy which is absorbed in dissociation, more fuel is added to achieve the given temperature. From Table 7, it can be seen that the minimum fuel mass increase is about 1.9%.

For the same engine, the combustor fuel-air ratio was assumed to be 0.01 and the combustor exit temperature was calculated for hydrogen fuel. Figure 25 presents the effect of assuming frozen flow through the nozzle. The net thrust percentage error was defined as

$$\frac{\text{Equilibrium Flow Thrust - Frozen Flow Thrust}}{\text{Equilibrium Flow Thrust}} \times 100$$

Compared with the assumption of equilibrium flow, this figure shows a percentage error in the range of 0.0 to 0.8 in the thrust values. This error is increased with Mach number. This occurs because the inlet combustion temperature is increased with increasing Mach number, yielding high combustor exit temperature for the given amount of heat released. Therefore, the higher the Mach number, the higher the degree of dissociation. Thus, at high Mach number, a large amount of energy is frozen in the nozzle, which reduces the nozzle thrust.

In summary, THERMO performance shows excellent agreement with References [10] and [14] in the calculation of both air and hydrocarbon-air combustion thermodynamic properties along the non-dissociating temperature range. Due to dissociation effect which was ignored by the previous references, THERMO shows relatively high disagreement. However, it also shows very good agreement with Reference [17], which includes the effect of dissociation in calculating hydrogen-air combustion and air thermodynamic properties. The comparison of MNEP with QNEP performance revealed good agreement in calculating the turbojet and ramjet engine performances. Also, up to 4.85% disagreement was shown by including dissociation effect in the cycle performance calculation. Both a significant increase in thrust and decrease in thrust specific fuel consumption were achieved by using hydrogen fuel for the airbreathing cycles. Finally, the errors which have been shown due to effect of dissociation and frozen flow reveals that these effects must be taken into consideration in the cycle performance calculation.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

This effort has included the modification of the QNEP thermodynamic routine using the Simplified Combustion Gas Model [16], modification of other QNEP routines in order to be compatible with the new thermodynamic routine, evaluation of the THERMO routine and the modified QNEP code (MNEP), and studying MNEP code performance by using both hydrocarbon and hydrogen fuels for some engine configurations.

4.1. Conclusions

The evaluation which was conducted for the MNEP thermodynamic routine (THERMO) revealed excellent agreement between this routine and References [10] and [14] in calculating thermodynamic properties for air along the non-dissociating temperature range. The average percentage errors of .15 and .2 were shown in the enthalpy and specific heat ratio values, respectively, calculated by THERMO for air over the previous range. Within the dissociating temperature range, a higher error in the enthalpy values was shown due to ignoring the dissociation effect in References [10] and [14]. However, the THERMO routine shows good agreement in the dissociation range with

Reference [17] which includes this effect. The maximum error is less than 0.2% in the enthalpy values calculated by THERMO for air in this region. Comparing specific heat ratio values calculated by THERMO for air with the tabulated values of Reference [17] shows a maximum error of 1.8% at 3600°R.

The result of comparing THERMO calculations for hydrocarbon-air combustion gas properties with the ones of References [10] and [14] shows almost the same results as have been achieved for air thermodynamic property calculations. The result of comparing THERMO calculation for hydrogen-air combustion gas enthalpy values with the ones tabulated in Reference [17] also shows good agreement. Except at some critical points (near zero enthalpy), the results show an average percentage error of ±2. For the previous reaction and within a temperature range of 1000-3600°R, the maximum percentage error in the specific heat ratio calculated by THERMO is about 2%. Beyond this temperature, the error is higher. The reason for the appearance of this error has been discussed in Chapter III.

The results of evaluating the MNEP code performance give confidence in MNEP calculations for turboaccelerator cycle performance. This result shows a maximum discrepancy in the thrust of approximately 2.39% compared to the QNEP code for aft fan engine cycle and about 2.36% for the augmented aft fan cycle. It is less than 2.1% for the

ramjet cycle thrust calculation. The maximum discrepancy in thrust specific fuel consumption among all the previous engine configurations is about 2.3%. Generally, this result shows a very good agreement between these codes.

The result which was obtained for the ramjet engine with fixed combustion exit temperature of 4100°R and operated at 60,000 feet altitude shows an average percentage increase of 1.6 in the thrust values due to the assumption of dissociated flow in calculating cycle performance. For the same engine at the same altitude and with a combustor fuel-air ratio of .011, the results also show about 0.8% decrease in thrust values due to assuming frozen flow through the nozzle.

Using hydrogen fuel rather than hydrocarbon fuels in the cycle performance calculations give a higher thrust (FN) and decreased thrust specific fuel consumption (TSFC). The average percentage decrease in TSFC is about 63% and the maximum increase in FN is about 11% at high altitude and high Mach number. However, in order to achieve higher thrust, a larger vehicle size is required due to the small hydrogen density values.

4.2. Recommendations for Future Work

To determine the trade-off factor between hydrocarbon and hydrogen fueled transports, it is important to make a system study for the total impact of hydrogen fuel use.

This includes fuel production, safety, storage, and engine cost, among other factors. The result of comparing hydrogen fuel costs with hydrocarbon fuel cost, together with the results which were obtained in this work, will influence the decision for airbreathing engine fuel selection.

In order to increase the fidelity of the simulation in the engine calculation, it is important to incorporate other turboaccelerator features which have not been considered in MNEP code. Chief among these features are regeneratively-cooled nozzles, pre-compressive cooling, and turbo-expander energy extraction [4].

It is also recommended that this code be modified to simulate variable cycle engines with variable component geometry, and to incorporate optimization routines to treat, for example, variable geometry setting to minimize the specific fuel consumption or to maximize the thrust.

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APPENDICES

APPENDIX A

MATHEMATICAL REPRESENTATION FOR CALCULATION OF FUEL-AIR RATIO AND COMBUSTION TEMPERATURE

MATHEMATICAL REPRESENTATION FOR CALCULATION OF FUEL-AIR RATIO AND COMBUSTION TEMPERATURE

A.1 Combustion Temperature Rise Calculation

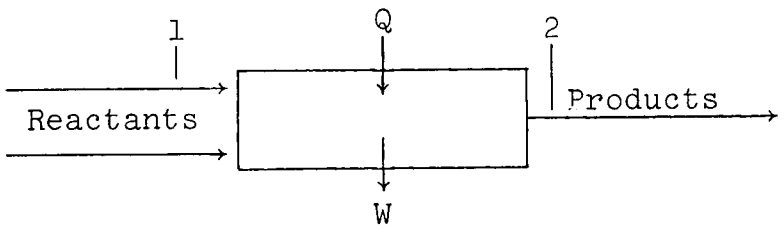
The first law of thermodynamics may be applied to a generalized steady-flow system with chemical reaction, as shown below. Neglecting the change in potential energy, the first law for steady-flow is

$$Q = H_{P2} - H_{R1} + W \quad , \tag{A-1}$$

where

H_{P2} = total enthalpy of products at state 2,

H_{R1} = total enthalpy of reactants at state 1.



The enthalpy data needed for the evaluation of $(H_{P2} - H_{R1})$ are conveniently based upon absolute values. This means that the enthalpy values must include both sensible enthalpy and heat of formation values, i.e.,

$$H = H_i + H^\circ_f \quad ,$$

where

H°_f = heat of formation,

H_i = sensible enthalpy,

H = absolute enthalpy;

therefore, Eq. (A-1) can be rewritten as:

$$Q = (H^\circ_f + H_i)_p - (H^\circ_f + H_i)_R + W \quad .$$

For adiabatic combustion without work extraction, $Q = 0$, $W = 0$, thus

$$(H^\circ_f + H_i)_p = (H^\circ_f + H_i)_R \quad . \qquad \text{(A-2)}$$

On a mole basis, Eq. (A-2) may be written as:

$$m_p \sum_p X_i(h_i + h^\circ_f) = m_R \sum_R X_i(h_i + h^\circ_f) \quad , \qquad \text{(A-3)}$$

where

m_p = mass of the products,

m_R = mass of the reactants = m_p ,

h°_f = species heat of formation,

h_i = species sensible enthalpy.

If the reactants are assumed to be air and fuel, Eq. (A-3) may be rewritten as:

$$m_p\left[\sum_p X_i(h_i + h^\circ_p)\right] = m_f\left[h^\circ_{fu} + h_{fu}\right] + m_a(h_a + h^\circ_{fa})$$

where

h°_{fu} = fuel enthalpy of formation,

h_{fu} = fuel sensible enthalpy,

h_a = air sensible heat,

h°_{fa} = air heat of formation,

m_a = air mass flow,

m_f = fuel mass flow.

Since m_p is equal to $m_a + m_f$ and h°_{fa} is equal to zero, the previous equation can be rewritten as:

$$h_a + f(h^\circ_{fu} + h_{fu}) = (1 + f)\left[\sum_p X_i(h_i + h^\circ_f)\right] \qquad \text{(A-4)}$$

where

$$f = m_f/m_a \ .$$

In case the reactants are gas and fuel, this equation can be rewritten as:

$$m_p\left[\sum_p X_i(h_i + h^\circ_f)\right] = m_{f2}(h^\circ_{fu} + h_{fu}) + m_1 h_1 \quad ,$$

where

m_1 = inlet gas mass flow = $m_{f1} + m_a$,

h_1 = inlet gas enthalpy.

Since $m_{f2} = m_p - m_1$, then

$$m_p\left[\sum_p X_i(h_i + h^\circ_f)\right] = (m_p = m_1)\ (h^\circ_{fu} + h_{fu}) + m_1 h_1 \quad .$$

If this equation is divided by the air mass flow, then it can be rewritten as:

$$(f_1 + 1)h_1 + (f_2 - f_1)\ (h^\circ_{fu} + h_{fu}) = (1 + f_2)\ \left[\sum_p X_i(h_i + h^\circ_f)\right]$$

where

$(f_1 + 1) = m_1/m_a$, $(f_2 + 1) = m_p/m_a$;

f_1 is the inlet fuel air ratio,

f_2 is the exit fuel air ratio, and

h_1 is the inlet gas enthalpy.

For each specie, a table of $(h_i + h^\circ_f)$ vs. temperature can be constructed. This is the basis which is used in Reference [16], which has been incorporated in subroutine THERMO. The left-hand side of Eq. (A-4) is calculated from the combustor inlet conditions. Therefore, the unknown values are X_i and the temperature of reaction. This information is provided by the THERMO routine as:

$$X_i = F(\text{Temperature, Pressure}) \quad .$$

A.1.1. Method of calculation

1. From the combustor inlet conditions, the left-hand side of Eq. (A-4) can be calculated by using the

THERMO routine and the fuel properties. The fuel properties consist of fuel heat of formation at absolute zero degrees and fuel sensible heat. For example, the JP-5 and H_2 fuel property calculations are given below.

JP-5 heat of formation at 298°K is given in Reference [18] equal to -5390 cal/gram mole. The THERMO routine uses 0°R as reference temperature; therefore, the heat of formation should be calculated at this temperature using the following formulation:

$$H^\circ_{f0} = H^\circ_{f\ 298} + (H_0 - H_{298})_{comp} - (H_0 - H_{298})_{elements} \quad .$$

The result is H°_{f0} = -668 BTU/lb. This value was obtained by assuming fuel specific heat equals .47 BTU/lb and solid carbon used in formation of JP-5. Therefore, the absolute enthalpy at a typical fuel temperature, 536.3°F, is equal to:

$$HF = -668 + .47\ (536.3 - 0)$$
$$= -416 \text{ BTU/lb} \quad .$$

By the same process, the absolute enthalpy of hydrogen fuel can be calculated. Since the hydrogen heat of formation is equal to zero, the absolute enthalpy is equal to the sensible enthalpy. The hydrogen sensible enthalpy at 536.3°R is approximately equal to 1830 BTU/lb.

2. The value of the left-hand side of Eq. (A-4) and the combustion exit pressure are input to the THERMO routine. By an iterative technique, the combustion temperature is calculated. This technique assumes a combustion temperature, calculates the enthalpy, and then compares this value with the left-hand side of Eq. (A-4). Another temperature is assumed if the two values do not agree. This technique is further described in Appendix B under subroutine THERMO option, IDD = 6.

A.2. Calculation of Fuel-Air Ratio

The method which is currently used in most engine codes in the calculation of fuel-air ratio has been derived from Eq. (A-3) above.

Eq. (A-3) can be rewritten as:

$$m_p \sum_p X_i h_i = m_R \sum_R X_i h_i + m_R \left(\sum_R X_i h^\circ_f + \sum_p X_i h_f \right)$$

or

$$m_p \sum_p X_i h_i = m_R \sum_R X_i h_i + \Delta H \quad , \qquad \text{(A-5)}$$

where ΔH is called the standard enthalpy of reaction. If the reactants and products are both at the same temperature (usually at 536.3°R), it is known as the heating value of the fuel. This value is assumed to be constant for all the reaction temperatures. If the

reactants are assumed to be air and fuel, Eq. (A-5) may be rewritten as:

$$m_p \sum X_i h_i = m_a h_a + m_f \Delta H' \quad ,$$

where

$$m_f \Delta H' = \Delta H + m_f h_{fu} \quad , \text{ or}$$

$$h_a + f \Delta H' = (1 + f) \sum_p X_i h_i \quad . \tag{A-6}$$

There are 2 errors in the application of Eq. (A-6). They are as follows:

1. Assuming ΔH as a constant for various reaction temperature implies that $(X_i)_p$ is constant.

2. Using the sensible enthalpy instead of the absolute one also implies that $(X_i)_p$ is constant.

As a result of these 2 points, Eq. (A-6) precludes the effect of dissociation. To include this effect in the calculation of fuel-air ratio, a new technique has been developed for the MNEP code. This technique is as follows:

1. As a result of several calculations, an empirical equation was developed to calculate the initial assumption of fuel-air ratio. This initial value reduces the numbers of iteration required for convergence. Substitute this value into Eq. (A-4).

2. By using Eq. (A-4), the technique described in the previous section is used to calculate the combustion temperature.

3. If the result of comparing this value with the combustion exit temperature does not agree, a new fuel-air ratio is assumed. This technique is further described in Appendix B.

Using Eq. (A-4) in MNEP code rather than Eq. (A-6), this allows the calculation for both dissociated and non-dissociated gases. The error, due to using both sensible enthalpy and fuel heating value, has also been eliminated.

APPENDIX B

SUBROUTINES ANALYSIS

B.1. Subroutine DBURNR

Statement	Description
TP2=TP1(1-DLEP)	Exit total pressure calculated from entrance pressure and pressure drop
1.1.	DUCT COMPONENT CALCULATION
A1=WT1/(1+FAR1)	MAin air flow
A2=WBIN/(1+FAR1B)	Bleed air flow
WT2=WT1+WBIN	Total weight flow
FARG=(FAR1*A1+FAR1B*A2)/(A1+A2)	Exit fuel air ratio
H1M=F(T1,TP1,FAR1)	Inlet main stream enthalpy
H2M=F(T1B,TP1B,FAR1B)	Bleed stream enthalpy
HM12=(WT1*H1M+WBIN*H2M)/WT2	Mixed stream enthalpy
T2=F(TP2,HM12,FARG)	Duct exit total temperature
1.2.	BURNER COMPONENT CALCULATION
1.2.1.	Calculation for exit fuel/air
FARG=f(T2,T1)	First guess of exit fuel/air (Note this function is described at the end of this Appendix)
AIRR=(1+FAR1)/WT1	Inverse of air flow rate
HIN=F(T1,TP1,FAR1)	Inlet total enthalpy
HSTD=((FSTD-FAR1)*HF1+(FAR1+1)*HIN)/(FSTD+1)	Calculated maximum enthalpy
TSTD=F(TP2,HSTS,FSTD)	Maximum combustion temp.

	If this temp. is less than
	the input combustion temp.,
	the excution is halted
ZX=1.00698*FARG	This is the second guess for
	fuel air ratio
H1=F(T2,TP2,ZX)	First guess of exit enthalpy
**	Beginning of the iteration loop
FAR2=FARG	
H2=((FAR2-FAR1)*HF+(FAR1+1)*	Calculated exit enthalpy
HIN)/(FAR2+1)	
T3=F(TP2,H2,FAR2)	Calculated exit temp.. If this
	temp. equales the input one the
	iteration is halted
FARG=f(FAR2,T2,T3,H1,H2)	New calculated fuel/air
**	End of iteration loop
FARG=FARG/EFF	Actual fuel/air
1.2.2.	Calculation of exit temp.
FARG=FARG*EFF	Ideal fuel air ratio
HOUT=((FARG-FAR1)*HF+(FAR1+1)	Exit enthalpy
*HIN)/(FARG+1)	
T2=F(TP2,HOUT,FARG)	Exit total temrerature
FARG=FARG/EFF	Actual fuel air ratio
FUEL=(FARG-FAR1)/AIRR	Burner fuel flow
WT2=WT1+FUEL	Total flow rate
1.3.	MOMENTUM PRESSURE DROP CALC.
1.3.1.	Design point calculation
GAM,R1M=F(T1,TP1,FARG)	Entrance specific heat ratio

CONST=AREA/(R1M*778.2)*TP2/TP1	and gas constant
FLOWG=WT2*√(R1M*778.2)/(AREA* TP2)	Not essential parameters
FOURAC=4*FLOWG**2/(32.2*GAM)	
ROOT=√1-FOURAC	
TDEL=(1-ROOT)*.25*(GAM-1)	Temperature difference
T2M=T1(1-TDEL)	Inlet static temperature
P2,H2M=F(T1,TP1,T2M,FARG)	Inlet static pressure and exit enthalpy
V1=223.78*√(HIN-H2M)	Inlet velocity
CON1=WT1*T2M*TP1/(P2*TP2*V1)	
AREA=CON1*R1M*778.2	Burner cross_sectional area
TOTM1=(1+GAM*VM1S)**2	
TOTM=TOTM1/((GAM+1)*VM1S*(2+ (GAM-1)*VM1S)	Optimum temp. ratio which decides the flow status
1.3.2.	**Off_design point calculation**
GAM3,HIN=F(T1,TP1,FARG)	Entrance specific heat ratio and enthalpy
T2M=T1(1+.2*VM1S)	A guess for inlet static temp.
**	Beginning of iteration
R1M,GAM,H2M=F(T1,TP1,T2M,FARG)	Static gas cons., sp. heat ratio and enthalpy
VMSC=2(HIN-H2M)/(GAM*R1M*T2M)	Calculated Mach number
DM=VM1S-VMSC	The error in the calculated Mach number
T2M=F(GAM,DM,VMSC)	New guess for the inlet static

	temperature
**	end of iteration loop
*** H2M,GAM,R1M=F(T1,TP1,T2M, FARG)	
V1=223.7*√(HIN-H2M)	Inlet calculated velocity
WT2G=P2*CONST*V1/T2M	Total gas flow
VM1S=2(HIN-H2M)/(GAM*R1M*T2M)	Flow Mach number
1.4.	CALCULATION FOR BOTH DESIGN AND OFF_DESIGN POINTS
1.4.1.	Calculation for sonic exit velocity
PTOM1=(GAM+1)/(1+GAM*VM1S)	
PTOM=(PTOM1*((2+(GAM-1)*VM1S /(GAM+1) **(GAM/GAM-1))	Optimum pressure ratio
DELMP=TP2(1-1/PTOM)	Momentum pressure drop
1.4.2.	Calculation for non_sonic exit velocity
PS1=TP2*P2/P1	
CON=WT2/(32.2*AREA)	
TS2=TM2*T2/T1	Exit static temperature
PS,GAM,R1M,HS2=F(T2,TP2,TS2, FARG)	Static pressure, sp.heat ratio gas constant and enthalpy
V2=223.8*√(HOUT-H2S)	Exit velocity
PS2=PS1-(V2-V1)*CON	Exit static pressure
VM2S=2*(HOUT-HS2)/(GAM*R1M*TS2)	Exit Mach no. which decides the flow status

1.4.3.	Calculation for subsonic cond.
DELMP=(1-PS2/PS1)*TP2	Momentum pressure drop
1.4.4.	Calculation for supersonic flow. The flow is set to sonic flow and the new static temp.is calculated as followings
TSMIN=.83*T2	First guess for minimum static temperature
**	Beginning of iteration loop
TS=TSMIN	
R1M,GAM,HCRI,PS=F(T2,TP2,TS, FARG)	
VM3S=2(HOUT-HCRI)/(GAM*R1M*TS)	Calculated Mach number
DM=(1-VM3S)	Deviation of Mach no. from 1
Z=.5(GAM-1)*VM3S	
TSMIN=f(TSMIN,Z,DM,VM3S)	New guess for the static temp
**	End of iteration loop
T2M=TSMIN+.005	This new static temp. is substituted back in 1.3.2. at *** sign

B.2. Subroutine NOZZLE

Statement	Description

PTOPA=TP1/SPE	Overall pressure ratio
H1=F(T1,TP1,FAR1)	Inlet total enthalpy
2.1.	CRITICAL PRESSURE RATIO
TS1=.83*T1	First guess of static temp. at nozzle min. area assuming Mach no. =1 at min. area
***	Beginning of iteration loop
TS=TS1	
GAM,R1=F(T1,TP1,TS,FAR1)	Sp. heat ratio and gas cons.
TS1=T1/(1+GAM-1)*.5)	New value of the static temp. assuming Mach no.=1 at min. area
***	End of iteration loop
PCRIT=(2/(GAM-1)**GAM/(1-GAM)	Critical pressure ratio
2.2.	CONVERGENT NOZZLE CALCULATION
TP2=TP1/PTOPA	Unchoked nozzle } Exit static pressure
TP2=TP1/PCRIT	Ckoked nozzle } Exit static pressure
H2,R1,GAM=F(T1,TP1,FAR1,TP2)	Static enthalpy, gas cons. and specific heat ratio
$V1=223.8\sqrt{(H1-H2)}$	
SPVL=778.2*R1*T2/TP2	Specific volume
AREA=WT1R*SPVL/(V1*CD)	Nozzle area
$CORFR=WT1R*\sqrt{T1}/TP1$	Corrected flow
$VM1=\sqrt{(T1/T2-1)*2/(GAM-1)}$	Exit Mach no.
VE=V1/VM1 VS=VE	Exit sound velocity
2.3.	CONVERGENT DIVERGENT NOZZLE

TP4=TP1/PTOPA	Exit static pressure
T4,GAM4,H4=F(T2,TP2,T1,TP1, TP4,FAR1,N)	T2,TP2 are used only for frozen flow (N=10). N=1 for eq.
VIDEAL=223.8$\sqrt{(H1-H4)}$	Exit ideal velocity
VE=VS*$\sqrt{(GAM4*T4/(GAMS*TS))}$	Exit velocity
2.4.	CALCULATION FOR BOTH NOZZLES
VACT=VIDEAL*CV	Actual exit velocity
FG=WT1R*VACT/32.2+AREA(TP2-SPE)	Nozzle gross thrust
DRAGN=QC*Q*AREA/144	Q,QC are inlet drag and scale factor

B.3. Subroutine THERMO

Statement	Description
3.1.	IDD=6
	Calculation of temp. from the enthalpy and pressure
T1=HZ/CP	First guess for the temp.
TI=T1	
***	Beginning of iteration loop
T=T1	
H=F(T,P)	Calculated enthalpy
T1=T1+(HZ-H)/CP	New guess for the temp.
ERROR=(HZ-H)/HZ	Test of the deviation
T1=(T1+TI)/2	
TI=T1	

	of the calculated value from the input one. It should be less than .001 percent
3.2.	IDD=1 Calculation of temp. from entropy and pressure
T2=T1*(P/P1)**(GAM-1)/GAM	First guess of temp. value calculated from pressure ratio and the inlet temp.
***	Beginning of iteration loop
T=T2	
S=F(T,P)	Entropy
ERROR=(S1-S)/S1	Test of deviation of the calculated entropy from the input one. This error should be less than .001 percent
T2=T2*EXP((S1-S)/CP)	New guess for temp.
***	End of iteration loop
3.3.	IDD=3 Calculation of pressure from entropy and temperature
P2=P1*(T1/T2)**(GAM/(GAM-1)	First guess from input pressure and temperature ratio
***	Beginning of iteration loop
P=P2	

R1,S=F(T,P)	Gas constant and entropy
ERROR=(S1-S)/S1	Test of deviation of calculated entropy from the input one . This should be less than .001%
P2=P1*EXP((S-S1)/R+LOG(P/P1))	New guess for pressure
**	End of iteration loop
3.4.	IDD=4 Calculation of temp. from enthalpy and entropy
P=P1	First guess pressure= inlet pressure
3.1.	Using loop 3.1. to calculate temperature
3.3.	Using loop 3.3. to calculate pressure The iteration will be stopped when the deviation between two successive temp. is less than .01 percent and the pressure is less than 1 percent

B.4. Subroutine COMPRS

Statement	Description
4.1.	MAIN FLOW HORSEPOWER CAL.
H1,H2=F(T1,TP1,FAR1,P2)	Inlet and exit enthalpy

DHA=(H2-H1)/EFF	Actual enthalpy increase
H3=H1+DHA	Exit actual enthalpy
T2=F(P2,H3,FAR1)	Exit actual temperature
HP=1.415*WTF*DHA	Main flow horsepwoer
4.2.	BLEED FLOW HORSEPOWER CAL.
H4I=(H2-H1)*ER+H1	Ideal exit bleed enthalpy
PRB=F(T1,TP1,FAR1,H4I)	Bleed total pressure
H4=DHA*ER+H1	Actual bleed exit enthalpy
TB=F(PRB,H4,FAR1)	Bleed total temperature
HPB=1.415*WTFB*DHA*ER	Bleed horsepower

B.5. Subroutine HEATXC

Statement	Description
GAM1,R1=F(T1,TP1,FAR1)	Specific heat ratio and gas constant of primary stream
GAM2,R2=F(T2,TP2,FAR2)	Specific heat ratio and gas constant of secondary stream

B.6. Subroutine INLET

Statement	Description
6.1.	RAM RECOVERY CALCULATION
H1=F(T1,P1,FAR1)	Inlet static enthalpy

H2=H1+VEL**2*1.99E-05)	Total enthalpy
TP2=F(T1,P1,FAR1,H2)	Total pressure
RAMP=TP2/P1	Ram recovery
6.2.	REFERRED FLOW CALCULATION
RINF=F(T1,P1,FAR1)	Gas constant of inlet flow
REF2=WTF*RINF/(P1*VEL*ACAP) *778.2	

B.7. Subroutine TURBIN

Statement	Description
H1,S1=F(T1,TP1,FAR1)	Inlet enthalpy and entropy of the main flow
HB,S2=F(T2,TP2,FAR2)	Inlet enthalpy and entropy of the bleed flow
H2=(WT1*H1+WB1*HB)/(WT1+WB1)	Mass weighted mixed enthalpy
S3=(WT1*S1+WB1*S2)/(WT1+WT2)	Mass weighted mixed entropy
FUEL=FAR1*WT1/(1+FAR1)	Fuel flow of the main stream
FUEL=FUEL+FAR2*WB1/(1+FAR2)	Total fuel flow
AIR1=WB1/(1+FAR2)	Air flow of the bleed stream
AIR1=AIR1+WT1/(1+FAR1)	Total air flow
FAR3=FUEL/AIR1	Exit fuel/air
P3,TB3=F(S3,H2,FAR3)	Total pressure and temperature of the mixed flow
TP3=P3/PR	Exit total pressure
H3=F(S3,TP3,FAR3)	Exit total enthalpy
HPT=1.415*WIN*(H3-H2)*EFF	Turbine horsepower

HOUT=H2+(H3-H2)*EFF	Actual exit enthalpy
P2=TP1/PR	Exit total pressure of the exit main flow
TOUT=F(P2,HOUT,FAR)	Exit total temperature
	FAR calculation is similar to FAR3 calculation except the bleed flow values are replaced by exit bleed flow ones

B.8. Subroutine MIXER

Statement	Description
8.1.	DESIGN POINT, PRIMARY STREAM
H1=F(T1,TP1,FAR1)	Inlet enthalpy
8.1.1.	Subsonic or sonic flow
TS=T1/(1+.2*VM1S)	First guess of static temp.
***	Beginning of iteration loop
GAM,R1,H2=F(T1,TP1,FAR1,TS)	
VMSC=2*(H1-H2)/(GAM*R1*TS)	Calculated Mach number
DM=VM1S-VMSC	Deviation of Mach no. from the input one. If the percentage dev. is less than .001 the iteration is halted
TS=f(TS,GAM,VM1S)	New guess for the static temp.
***	End of iteration loop

8.1.2.	Supersonic flow
PS=TP1/PR	Static pressure
TS,H2,GAM,R1=F(T1,TP1,FAR1,PS)	Gas static properties
8.1.3.	Calculation for all flow types
V1=223.77*$\sqrt{(H1-H2)}$	Inlet velocity
AREA=WT1R*TS*R1*778/(PS*V1)	Cross_sectional area of mixer entrance
PR=TP1/PS	
SPMIX=PS	entrance stream static pressure
SP1=SPMIX	Storage parameters
HS=H1	Storage parameters
WT1=WT1R	Storage parameters
H12=H1*WT1R	Mass weighted enthalpy
SIN=S2*WT1R	Mass weighted entropy
VID=V1*WT1R	Mass weighted velocity
AIR12=WT1R/(1+FAR1)	
FAR12=FAR1*AIR12	Fuel flow of the primary stream
8.2. Same as 8.1.2.	DESIGN POINT, SECONDARY STREAM
V1=223.77*$\sqrt{(H1-H2)}$	Inlet velocity of the secondary stream
AREA=WT1R*TS*R1*778.2/(PS*V1)	
AIR2=WT1R/(1+FAR1)	Air flow of the sec. stream
8.3.	CALCULATION FOR BOTH STREAMS

SPAVG=.5(SPMIX+SP1)	Average static pressure
W12=W12+WT1R	Total flow rate
H12=.5(H1+HS)	Average total enthalpy
AIR12=AIR12+AIR2	Total air flow
FAR12=(FAR12+FAR1*AIR2)/AIR12	Mixed stream fuel/air
SIN=(SIN+S2*WT1R)/W12	Average mass weighted entropy
H12=(H12+H1*WT1R)/W12	Average mass weighted enthalpy
VID=(VID+V1*WT1R)/W12	Average mass weighted velocity
H3I=H12-VID**2*1.997E-05	Ideal static enthalpy
P12,T12=F(SIN,FAR12,H12)	Total temp.,, pressure
V12=VID*CV	Actual exit velocity
H32=H12-V12**2*1.997E-05	Actual exit enthalpy
P32,T32=F(SIN,FAR12,H3I)	Exit static pressure and temp
SOUT=F(SPMIX,FAR12,H32)	Calculated exit entropy
PMIX=SPMIX*P12/P32	Total exit pressure ,"SOUT"
	greater than 'SIN"
PMIX=P12	For "SOUT" less than "SIN"
8.4.	OFF-DESIGN POINT, BOTH STREAMS
H1,GAM,R1=F(T1,TP1,FAR1)	Inlet gas properties
CONST=AREA/(R1*778.2)	Not essential parameters
FLOWG=WT1R*√(R1*778.2*T1)/(AREA*TP1)	
FOURAC=4*FLOWG**2/(32.2*GAM)	
ROUT=√(1-FOURAC)	
TDEL=(1-ROUT)*.25*(GAM-1)	
TS=T1(1-TDEL)	Inlet stream static temp.

H2,GAM,R1=F(T1,TP1,FAR1,TS)	Gas static properties
V1=223.77*$\sqrt{(H1-H2)}$	Inlet velocity
VM1S=2.(H1-H2)/(GAM*R1*TS)	Inlet Mach number
WT1G=PS*CONST*V1/TS	Calculated flow rate
8.4.1.	Subsonic or sonic flow
WTERR=(WT1R-WT1G)/WT1R	Deviation of calculated flow from the input one
FAC=-WTERR*(GAM-1)*VM1S/(1-VM1S)	
TS=TS(1+FAC)	This new value is used to recalculate V1,VM1S and WT1G. When the flow percentage deviation is less than .01, the iteration is halted
8.4.2.	Supersonic flow
TSMIN=.83*T1	Initial static temp. value
***	Beginning of iteration loop
TS=TSMIN	
HCRIT,GAM,R1=F(T1,TP1,TS)	Critical gas properties
VM3S=2(H1-HCRIT)/(GAM*R1*TS)	Calculated Mach number
Z= .5(GAM-1)*VM3S	
DM=1-VM3S	Deviation of calculetd Mach no. from the sonic value. 'DM' should be less than .001%
TSMIN=f(TSMIN,Z,DM,VM3S)	V1,VM1S,WT1G and 8.4.1. are recalculated using this new static temp. value

8.5. The same as 8.1.3.	PRIMARY STREAM CALCULATION
8.6. The same as 8.3.	SECONDARY AND PRIMARY STREAMS

B.9.

Computer time is the most important factor in any computing work; therefore, the iteration loops should be kept as small as possible. To achieve this, empirical functions, denoted f( ), have been derived to reduce the number of iterations to minimum values. Among these functions is the function which calculates first guess of fuel-air ratio which was shown earier in Section 1.2.1. This function is as follows:

For H_2:

```
FARG = .7937944 D - 05 * (T2 - T1) + .6189714 D01 * (TT2 - TT1) -
                0.2269739D04 * (TT2 ** 2 - TT1 ** 2)
```

For Hydrocarbons:

```
FARG = .2043573 D - 04 * (T2 - T1) + .1251456 D02 * (TT2 - TT1) -
                0.4195694D04 * (TT2 ** 2 - TT1 ** 2)
```

where

$$TT1 = \frac{1}{T1}$$

$$TT2 = \frac{1}{T2}$$

APPENDIX C

DATA REPRESENTATION

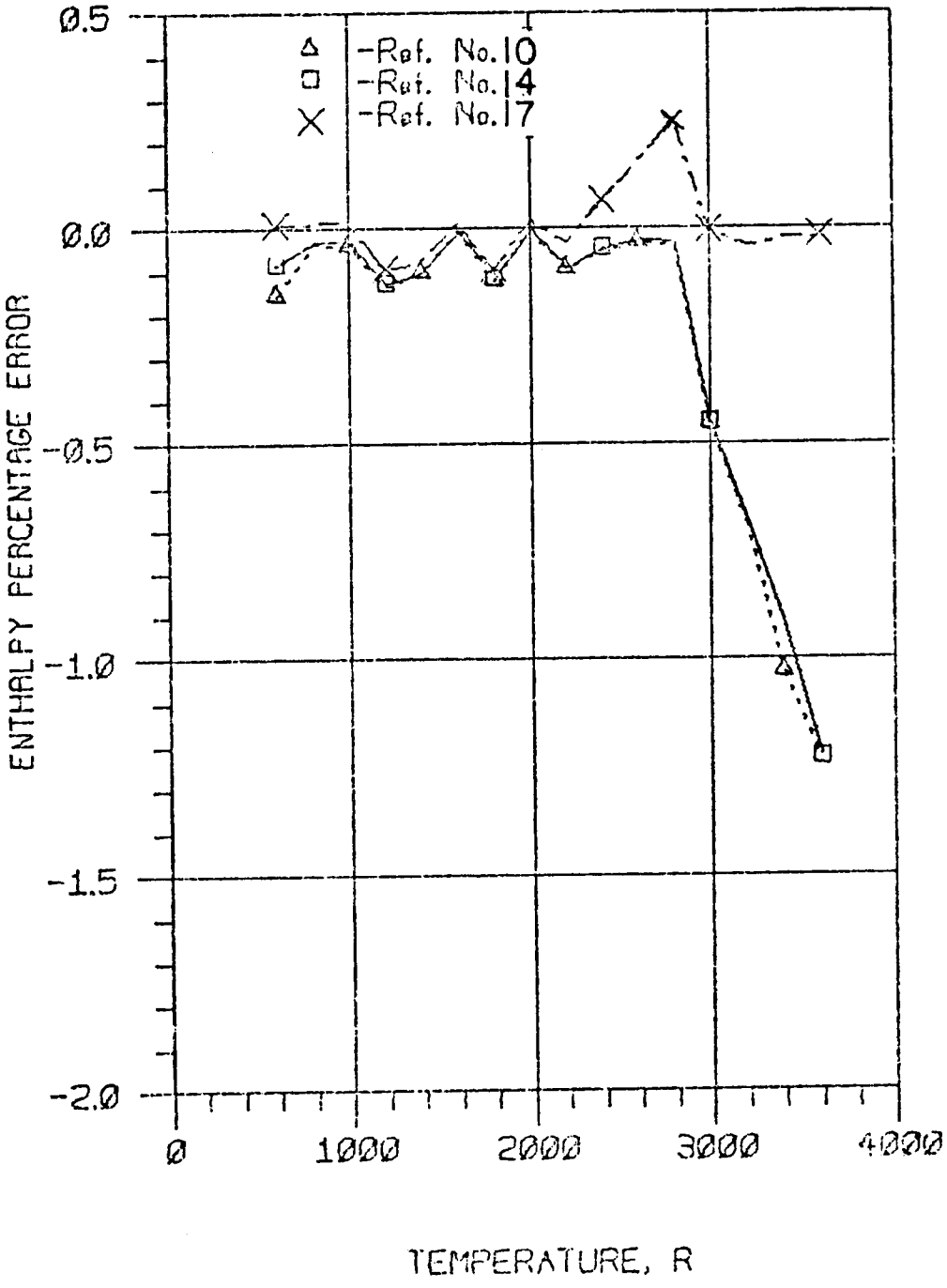


Figure 1. Enthalpy Percentage Error from Comparison of Data from THERMO and References [10], [14], and [17]; P = 1 ATM; Air.

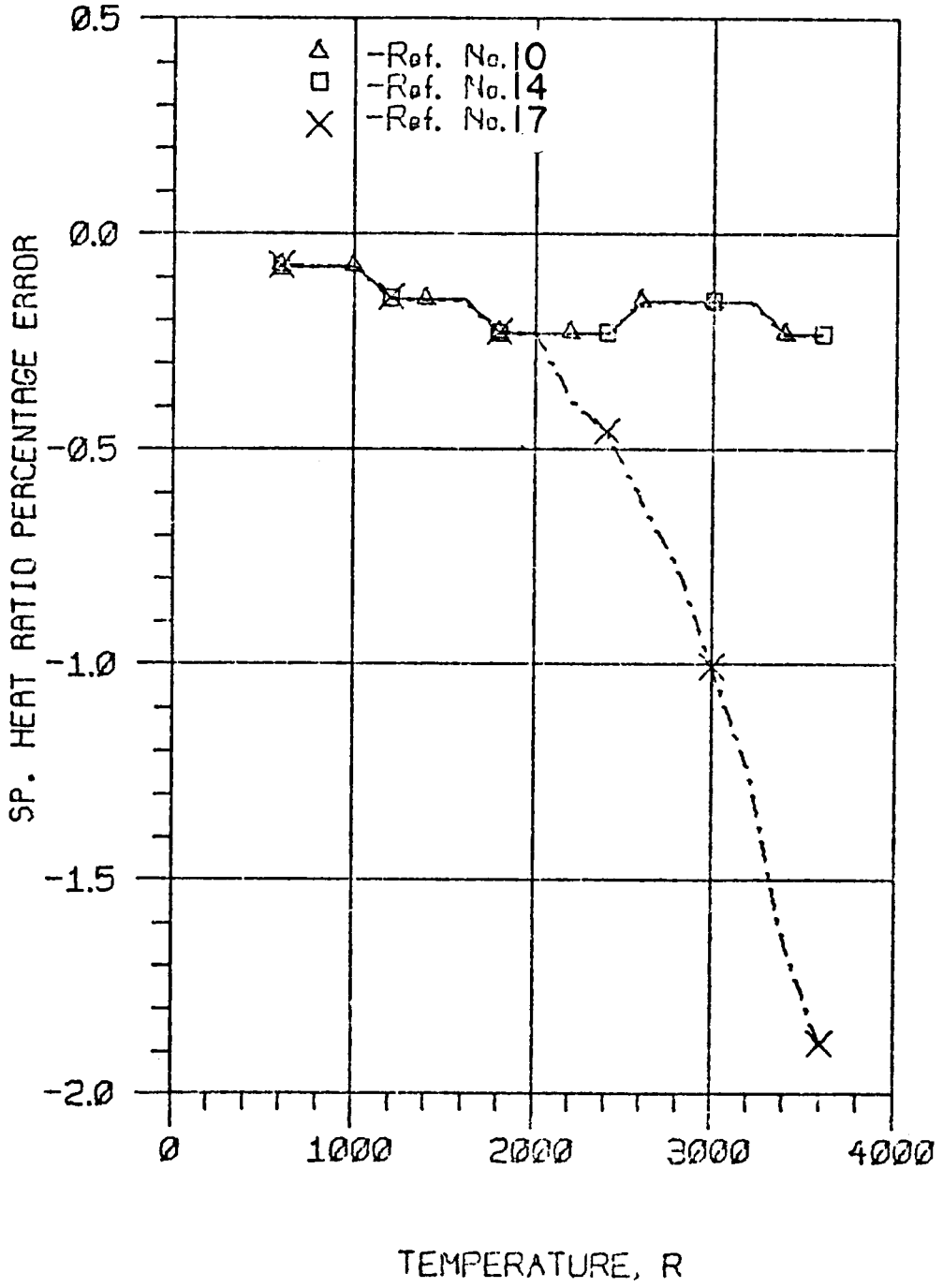


Figure 2. Specific Heat Ratio Percentage Error from Comparison of Data from THERMO and References [10], [14], and [17]; P = 1 ATM; Air.

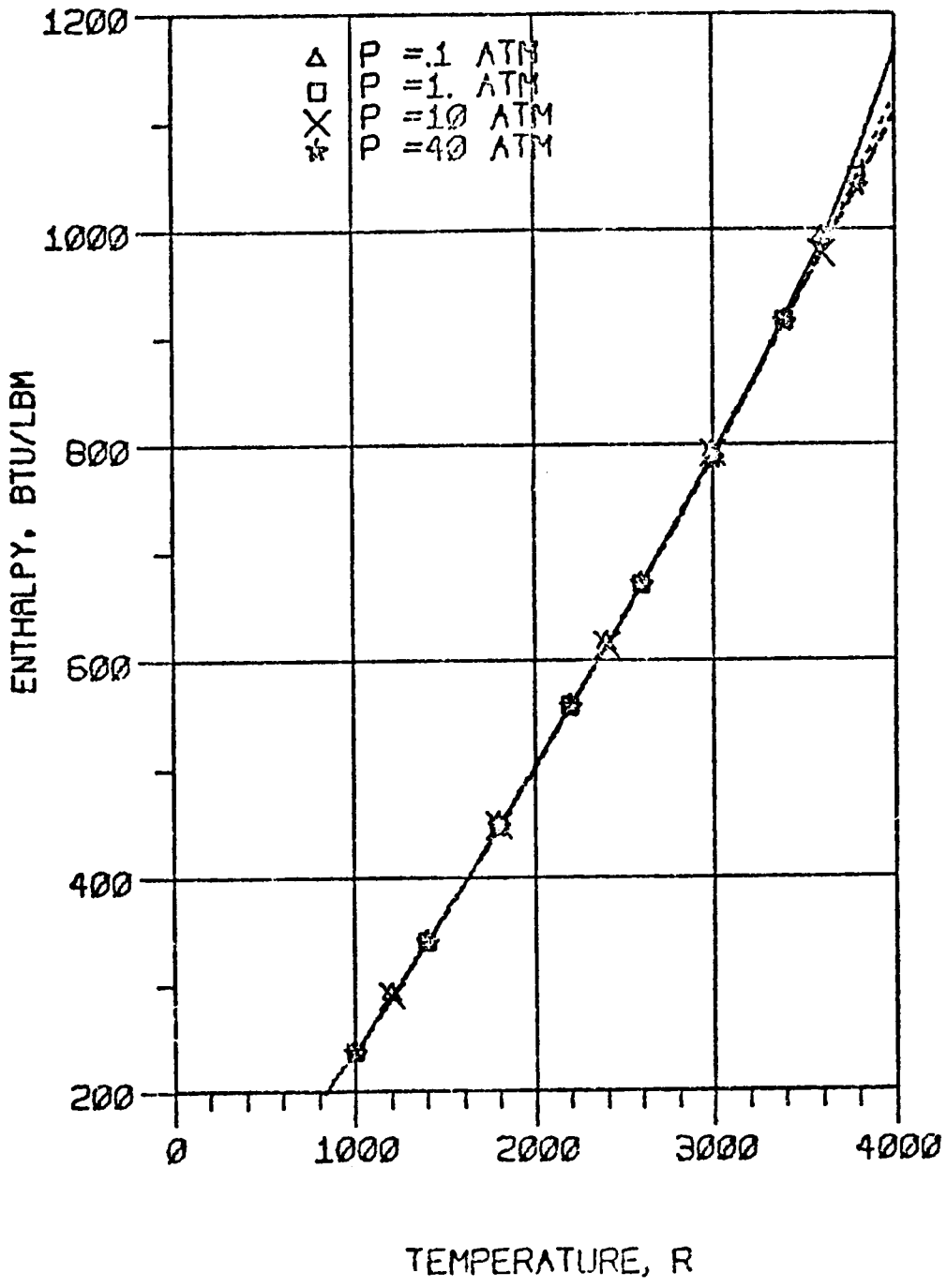


Figure 3. Effect of Pressure on the Enthalpy Values of Air; Data from THERMO.

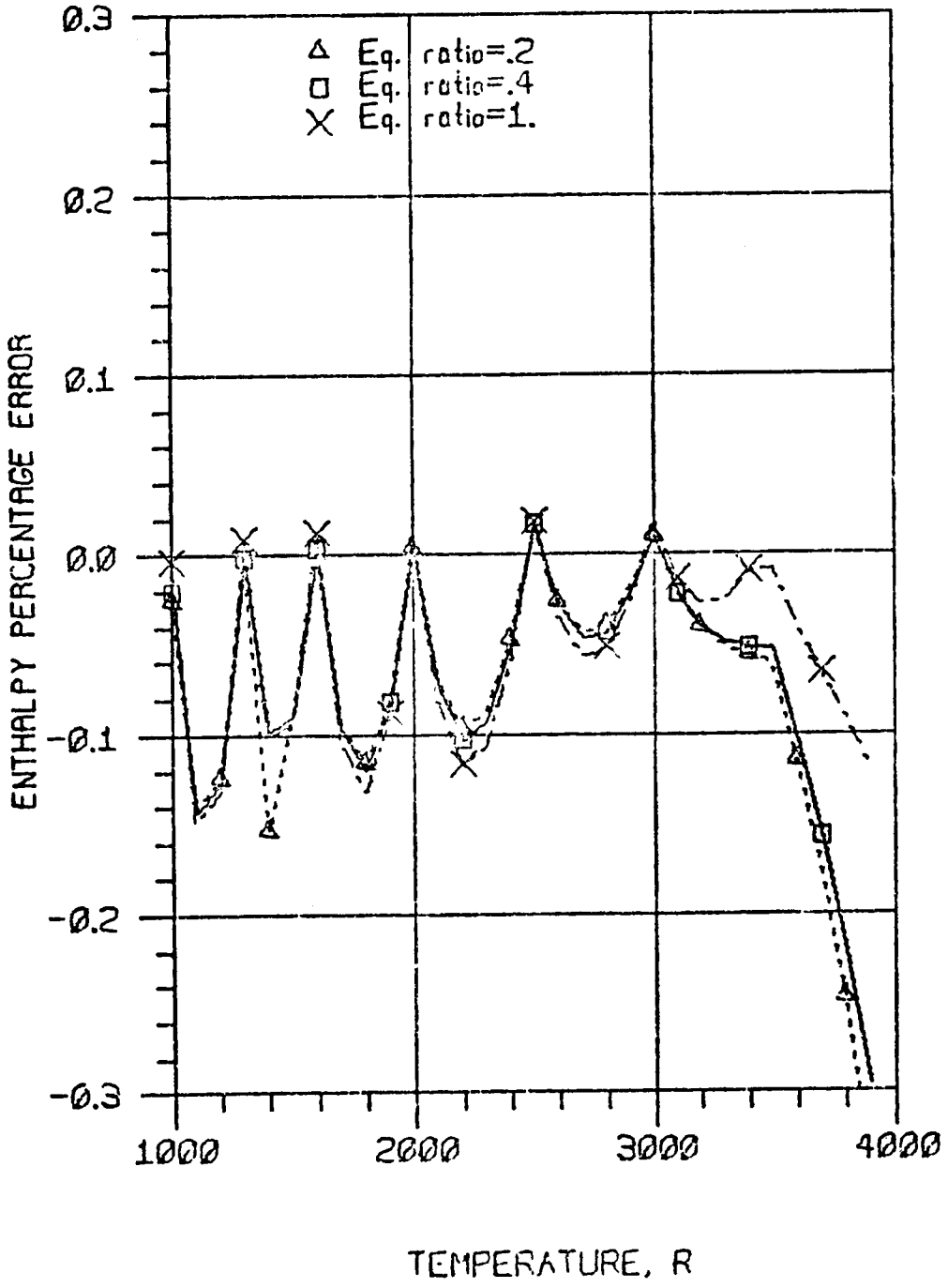


Figure 4. Enthalpy Percentage Error from Comparison of Data from THERMO and THERM [14]; P = 1 ATM; RCH = .52456.

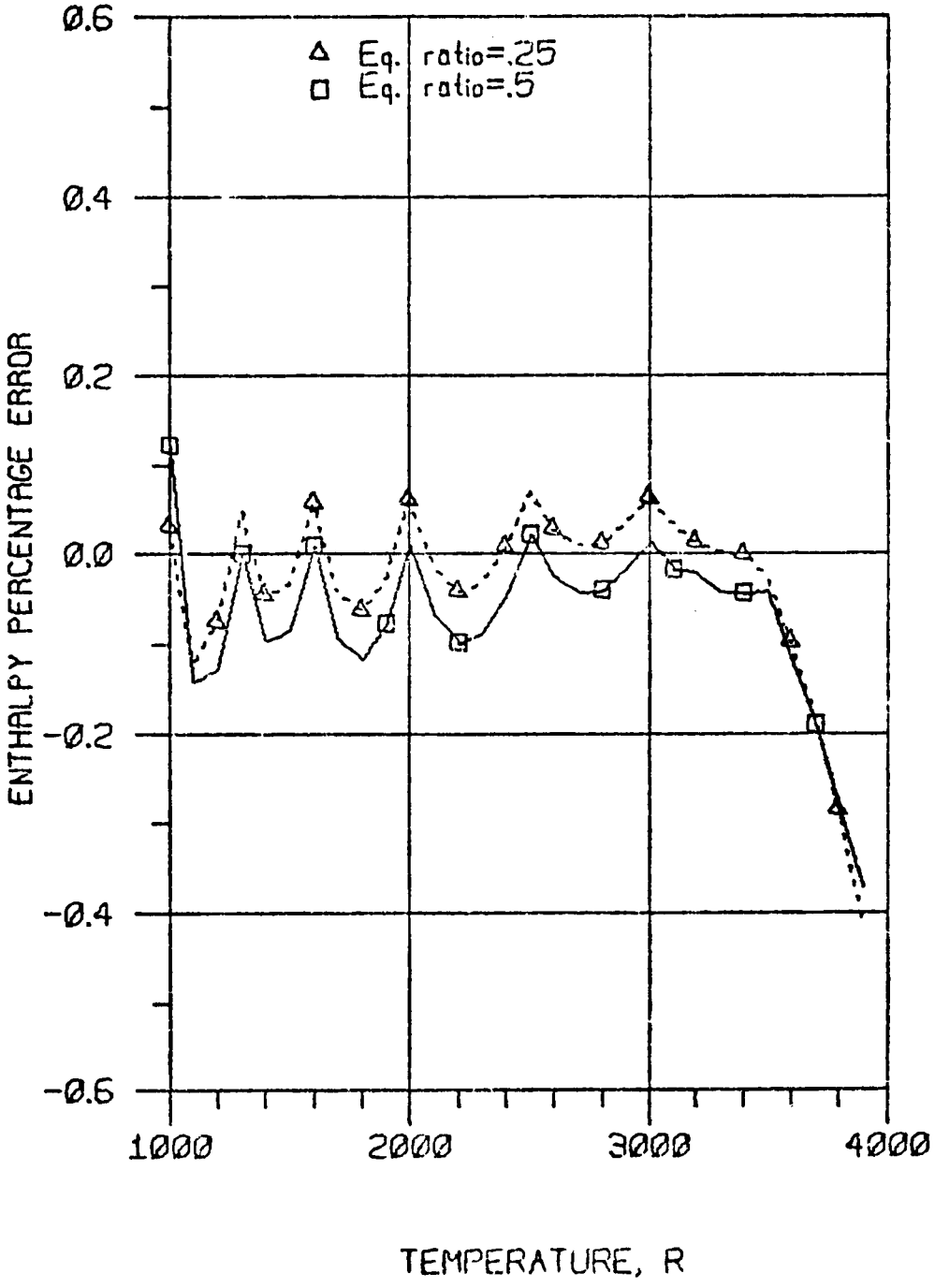


Figure 5. Enthalpy Percentage Error from Comparison of Data from THERMO and Reference [10]; P = 1 ATM; RCH = .5 .

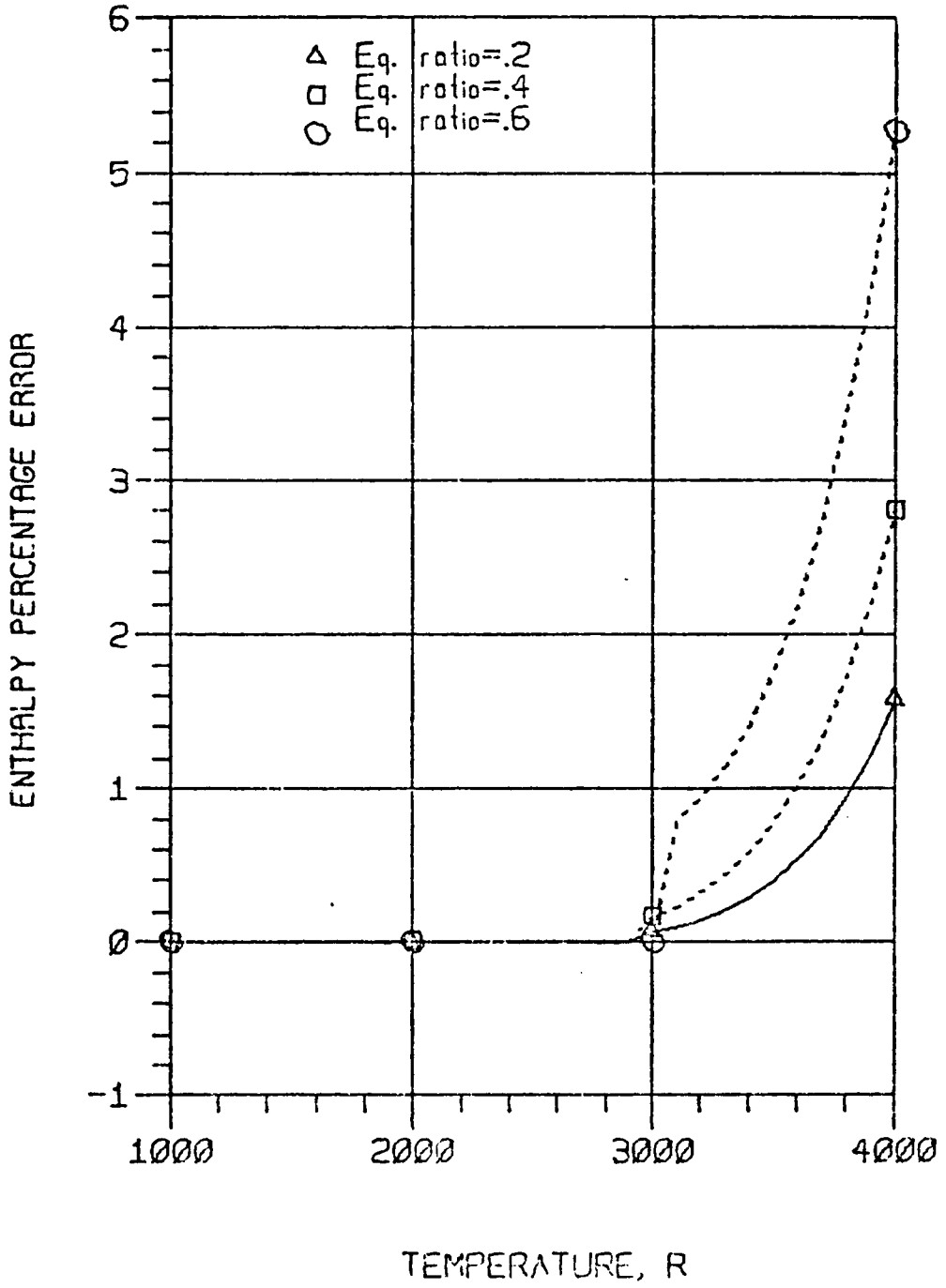


Figure 6. Enthalpy Percentage Error from Comparison of Data from THERMO for Dissociated and Non-dissociated Gases; P = 1 ATM; RCH = .52456.

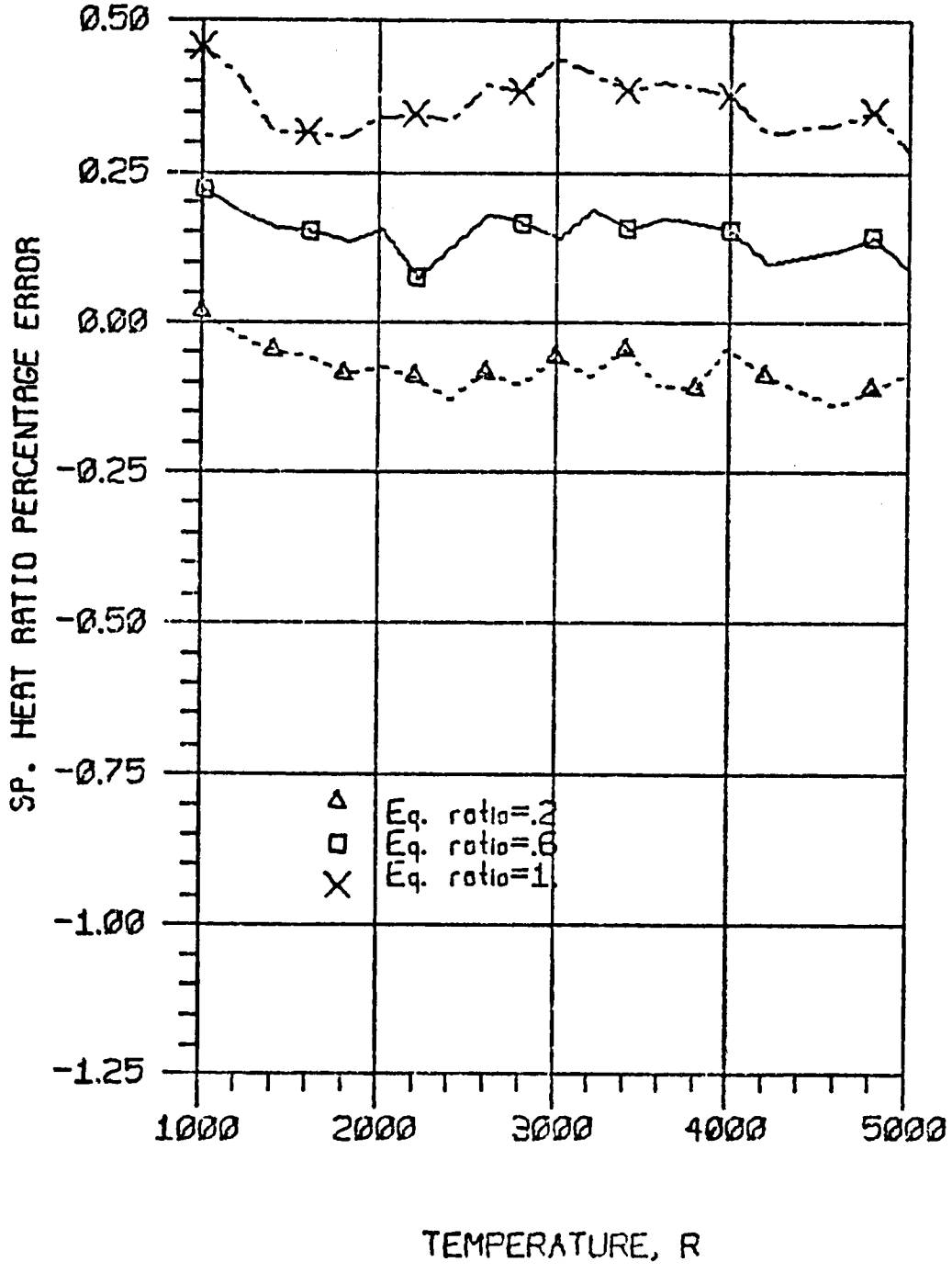


Figure 7. Specific Heat Ratio Percentage Error from Comparison of Data from THERMO and THERM [14]; P = 1 ATM; RCH = .52456.

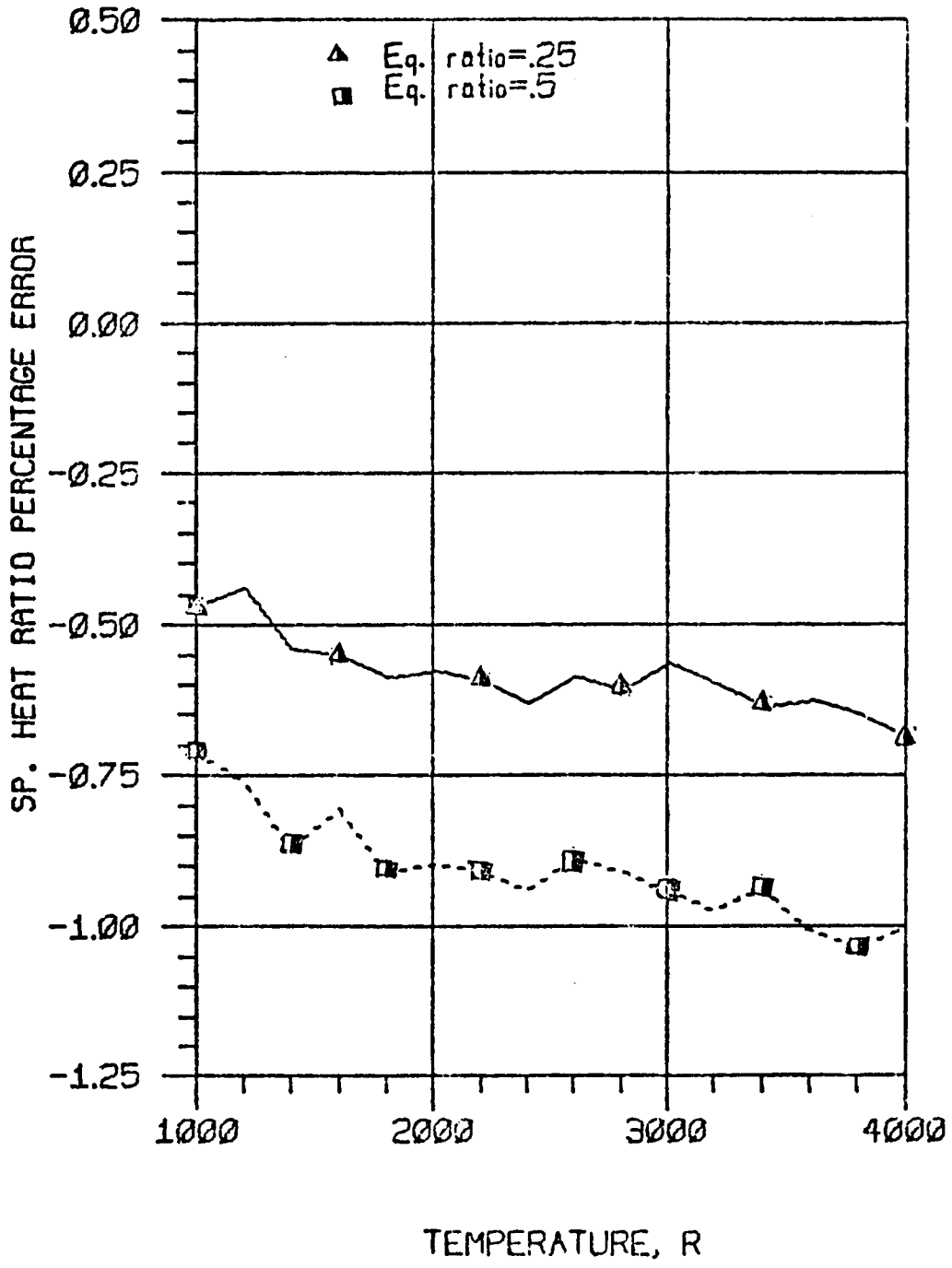


Figure 8. Specific Heat Ratio Percentage Error from Comparison of Data from THERMO and Reference [10]; P = 1 ATM; RCH = .5... .

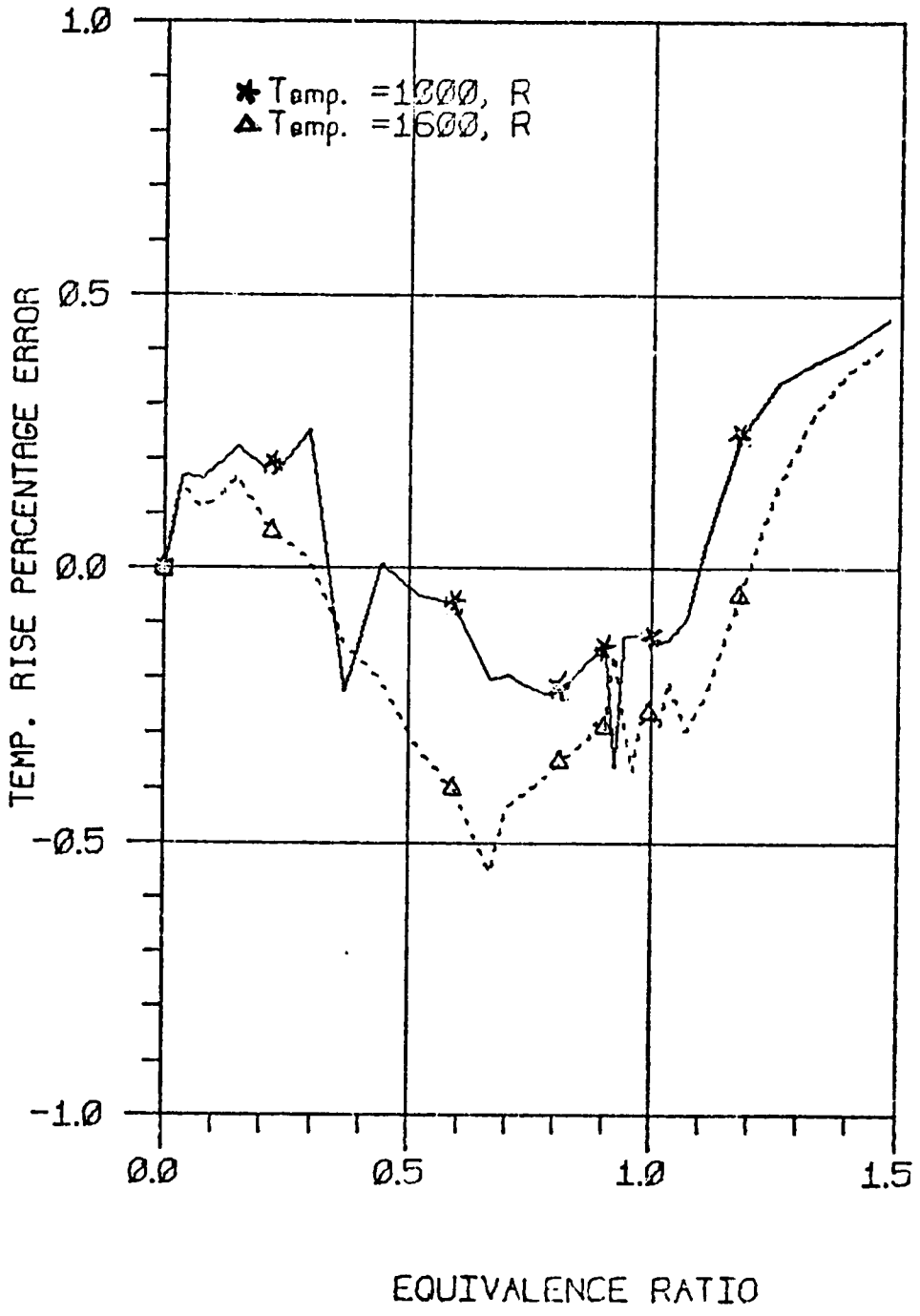


Figure 9. Combustion Temperature Rise Percentage Error from Comparison of Data from THERMO and Reference [18]; JP-4 Fuel; P = 1 ATM.

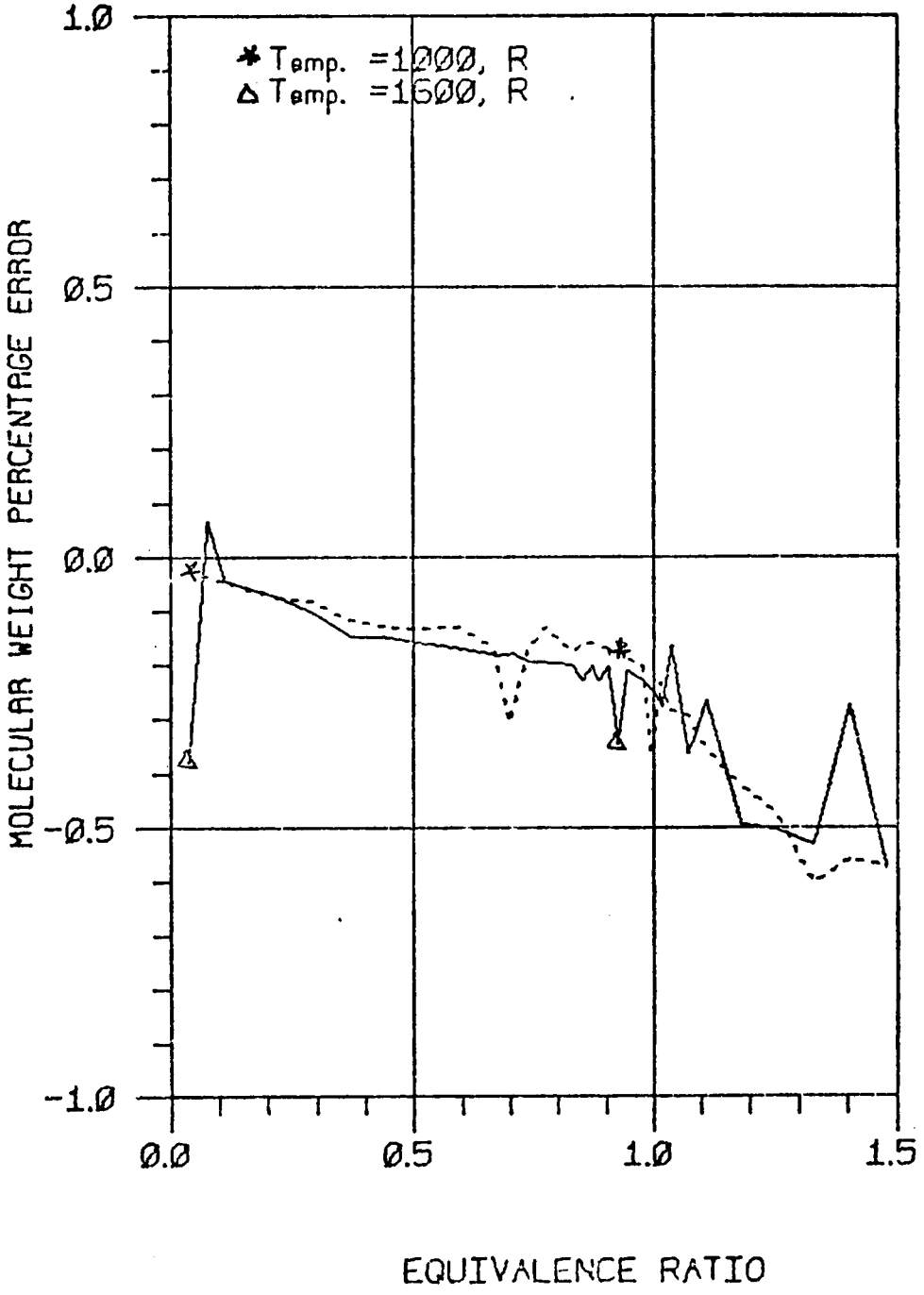


Figure 10. Molecular Weight Percentage Error from Comparison of Data from THERMO and Reference [18]; JP-4 Fuel; P = 10 ATM.

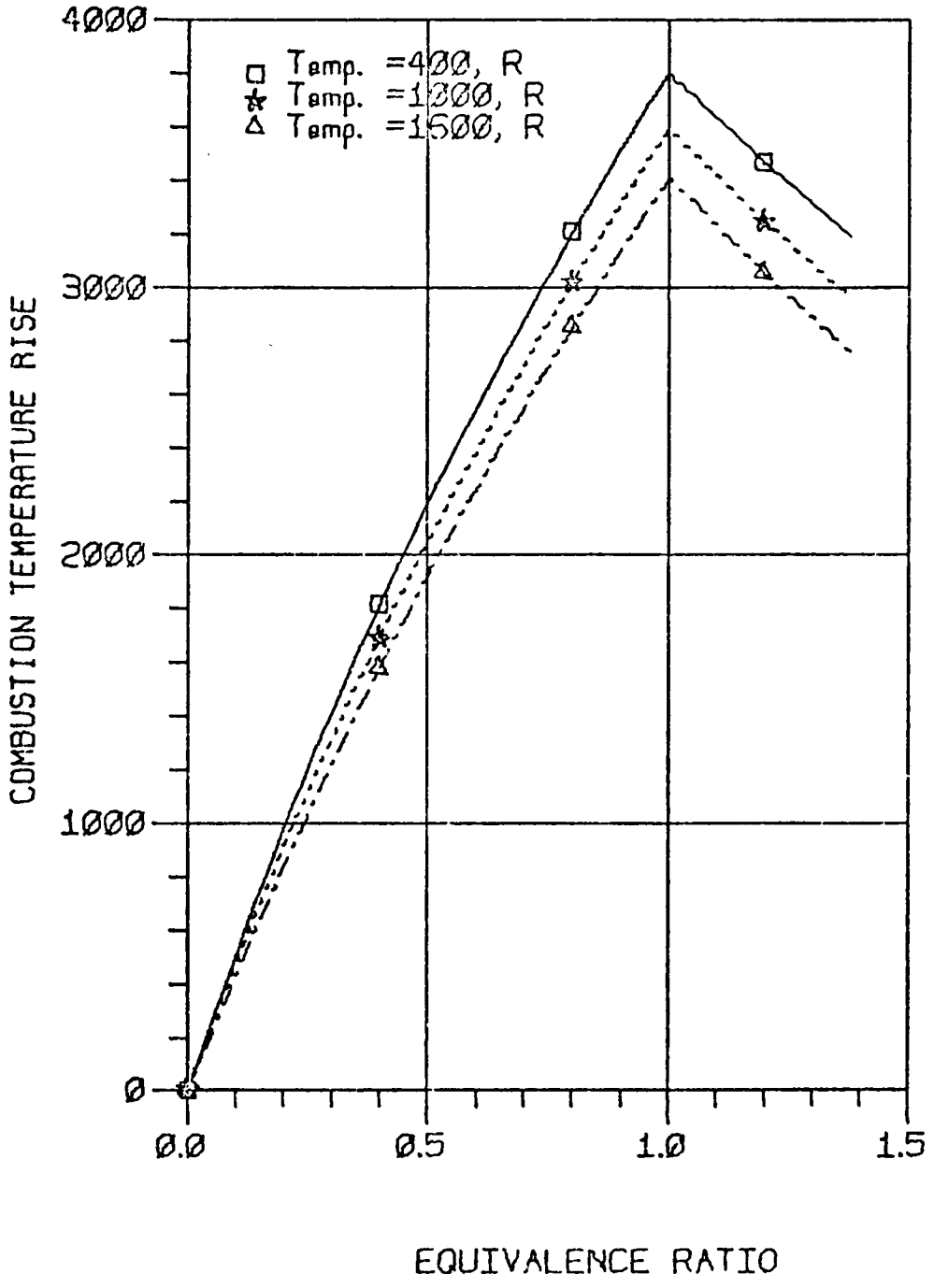


Figure 11. Combustion Temperature Rise for Different Inlet Temperatures; P = 1 ATM; RCH = .52456; Non-dissociation Was Assumed.

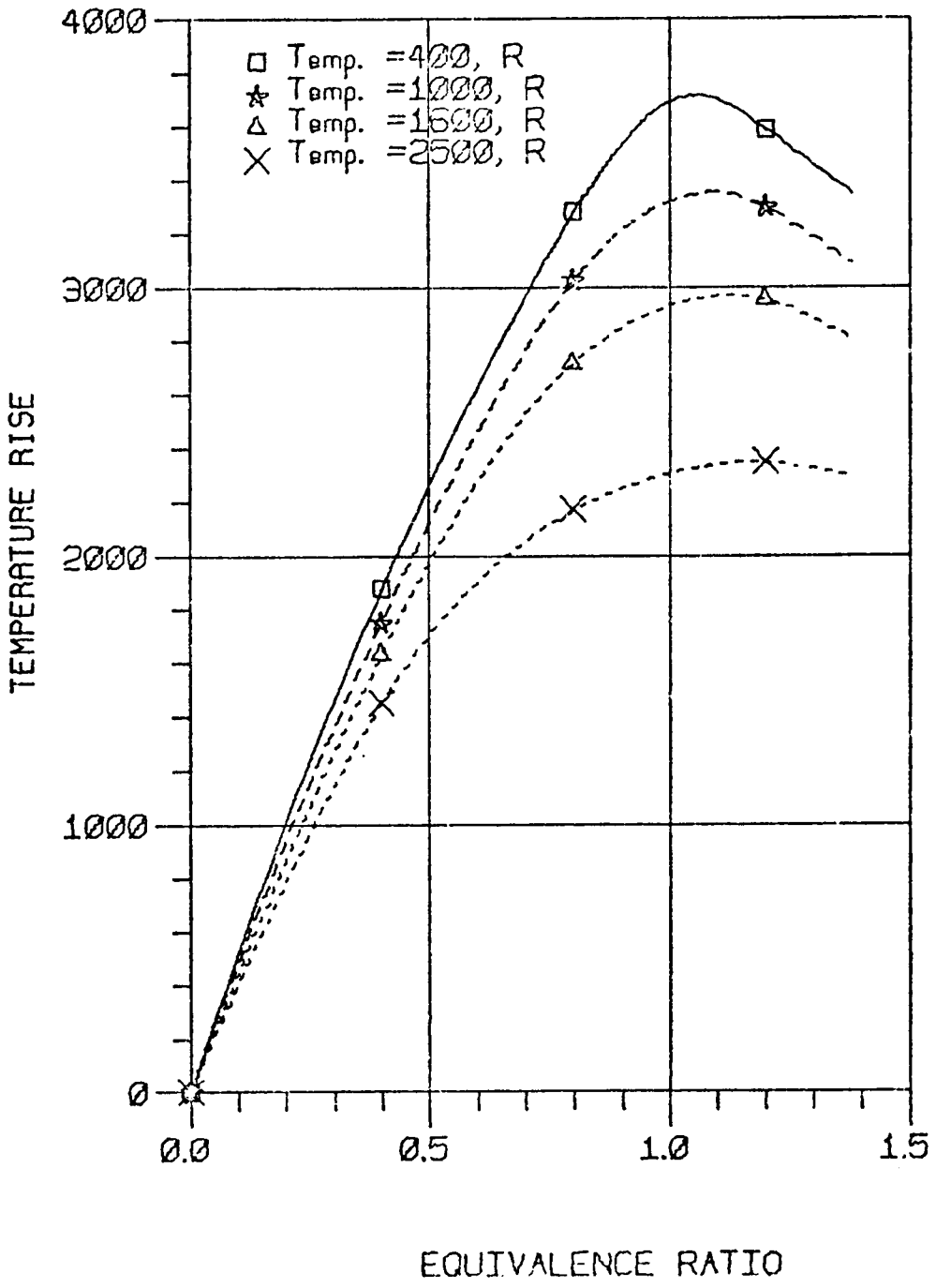


Figure 12. Combustion Temperature Rise for Different Inlet Temperatures; P = 1 ATM; RCH = .52456; Dissociation Was Assumed.

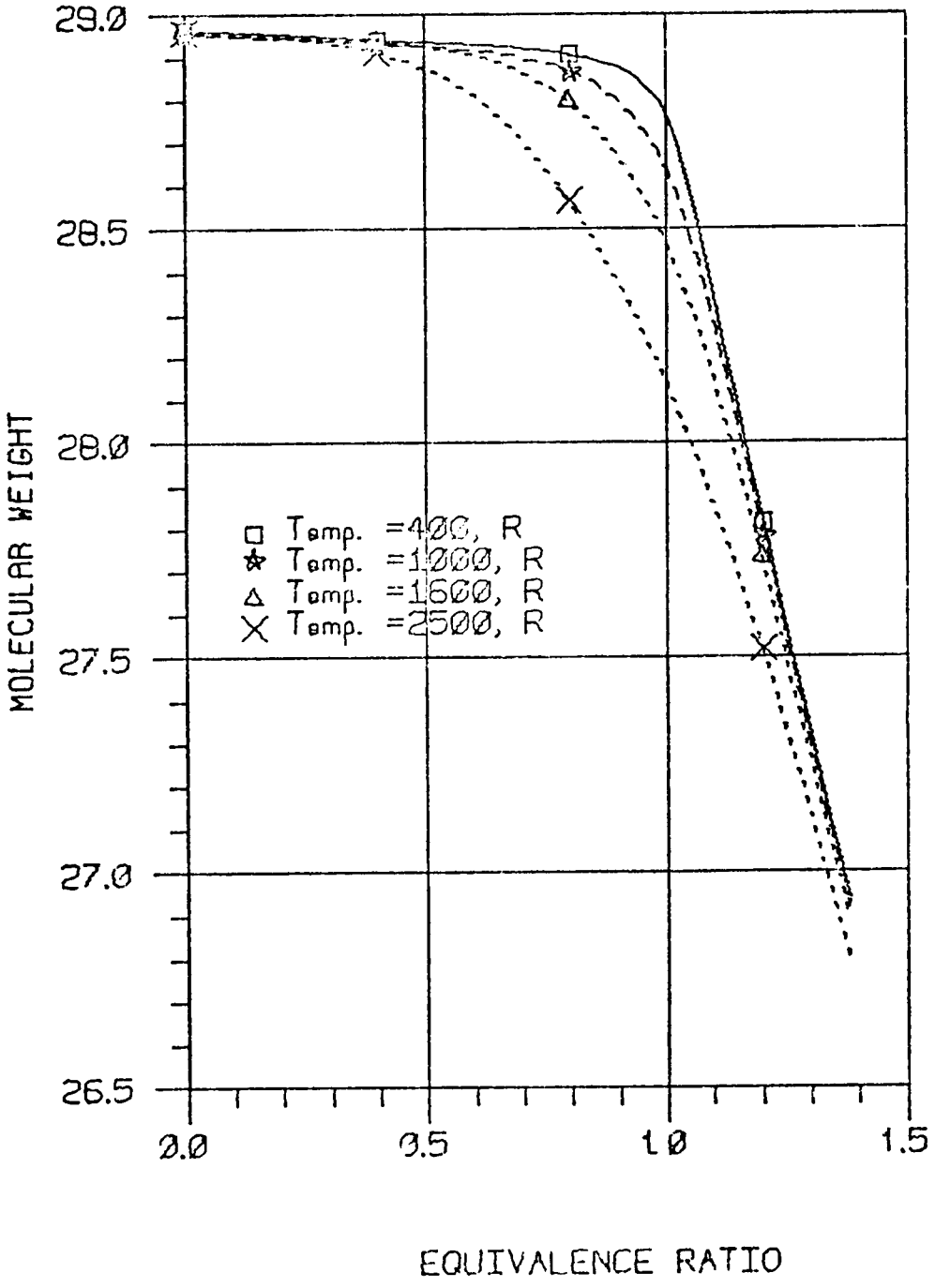


Figure 13. Molecular Weight Change for JP-5 Fuel-Air Combustion for Different Inlet Temperatures; P = 1 ATM; RCH = .52456.

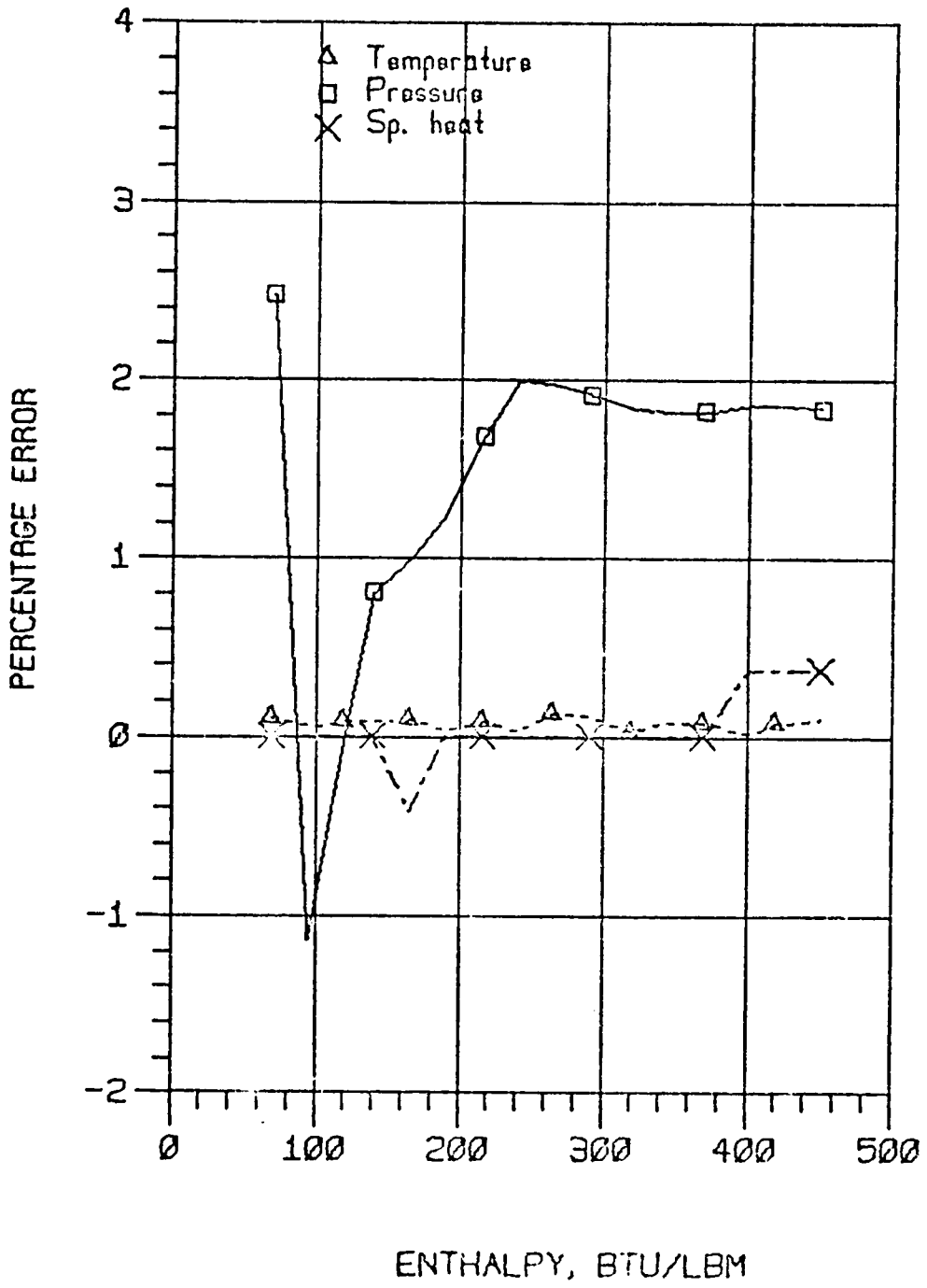


Figure 14. Percentage Error of THERMO Performance Compared to THERM [14]; Air.

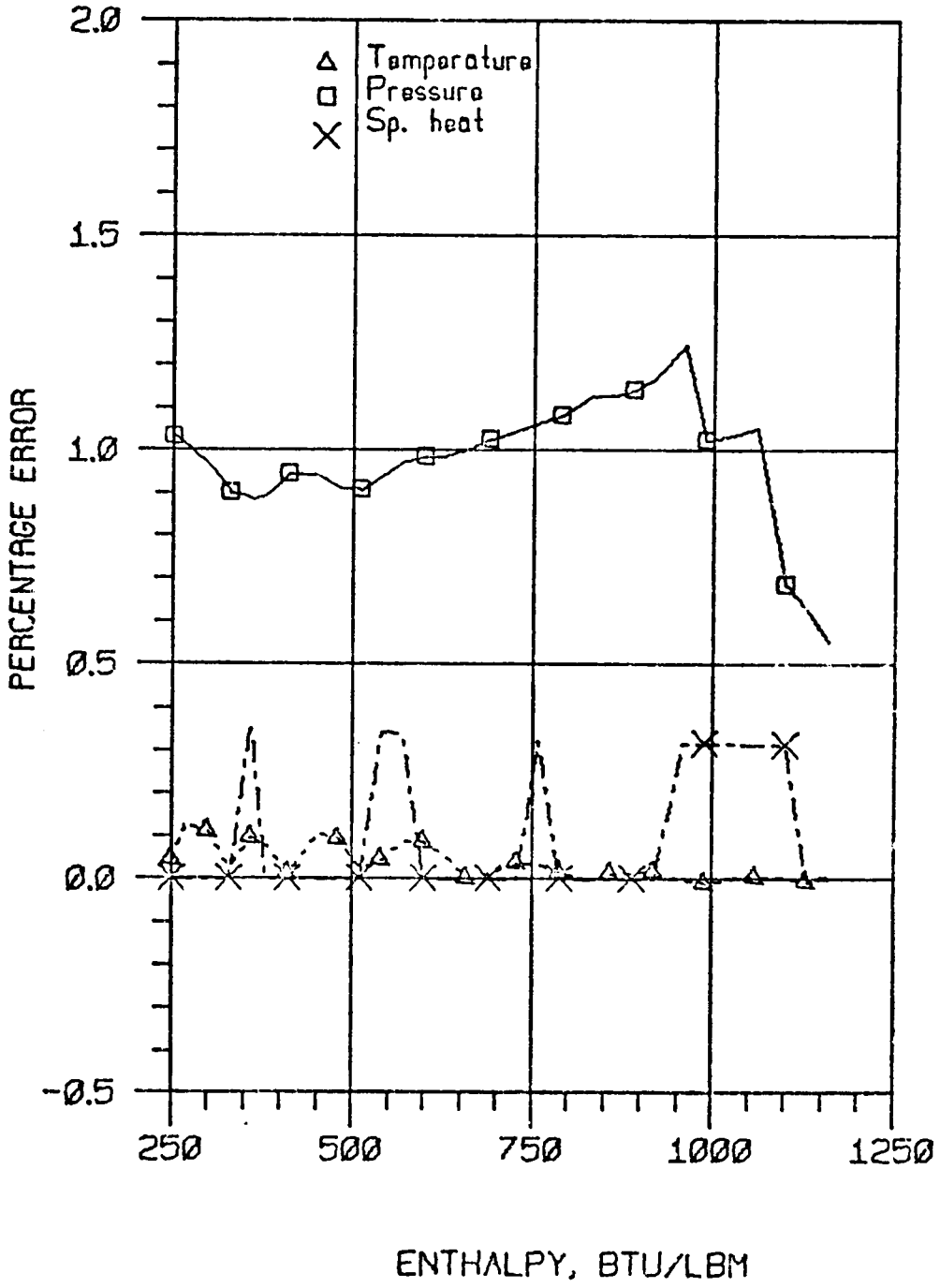


Figure 15. Percentage Error of THERMO Performance Compared to THERM [14]; RCH = .52456.

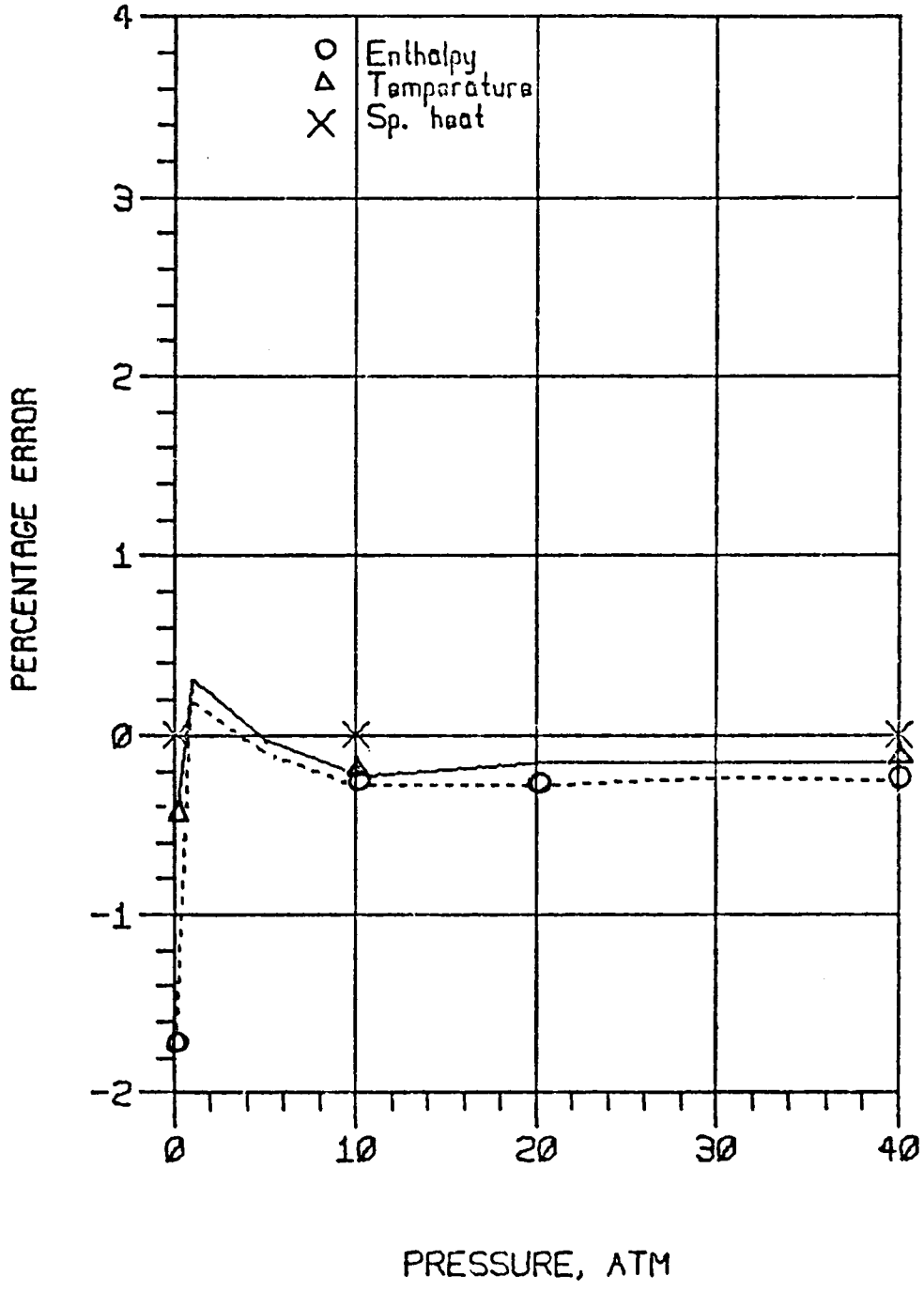


Figure 16. Percentage Error from Comparison of Data from THERMO and Reference [14]; P = 1 ATM; RCH = .52456.

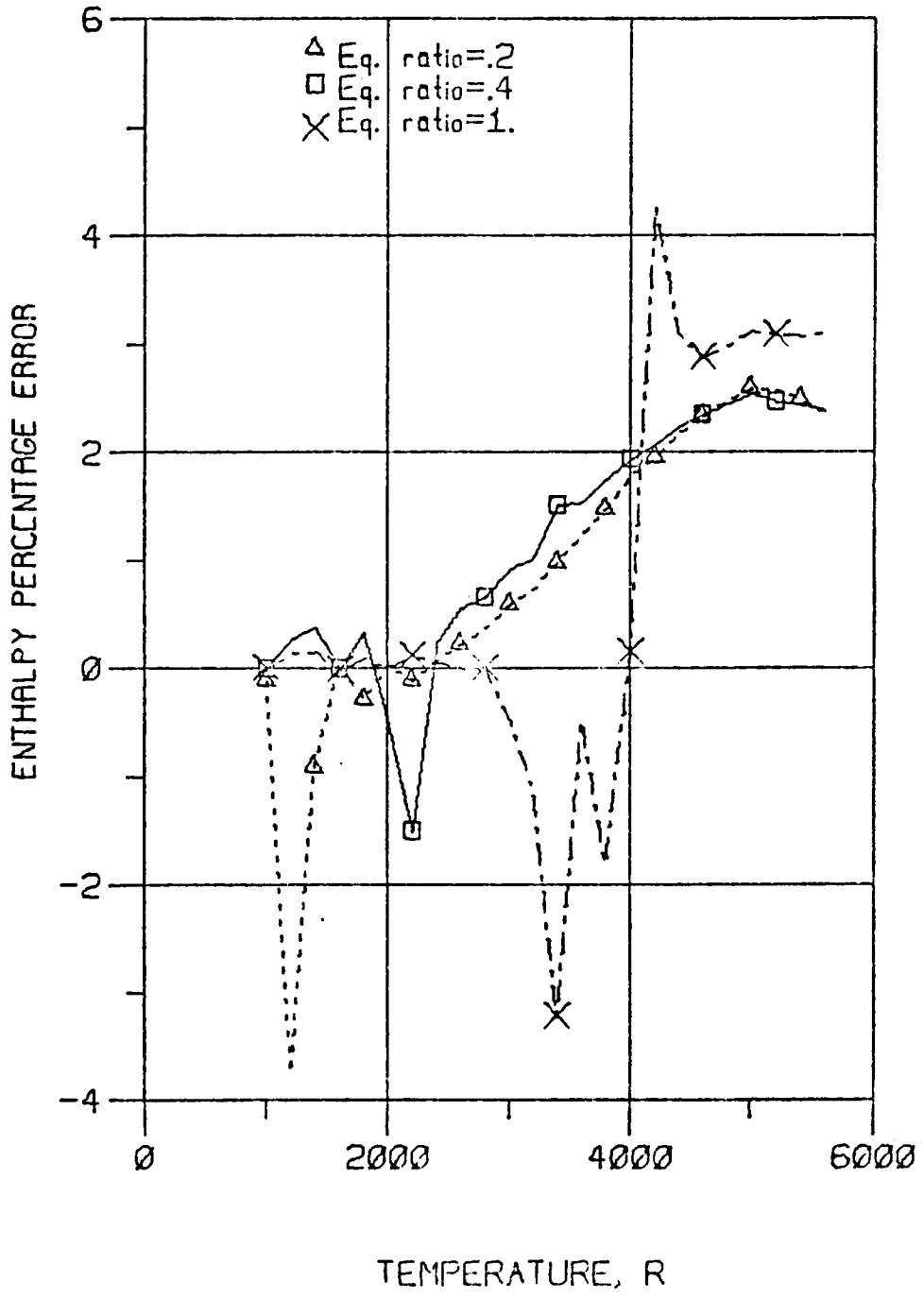


Figure 17. Enthalpy Percentage Error from Comparison of Data from THERMO and Reference [17]; P = 1 ATM; RCH = 0.0 .

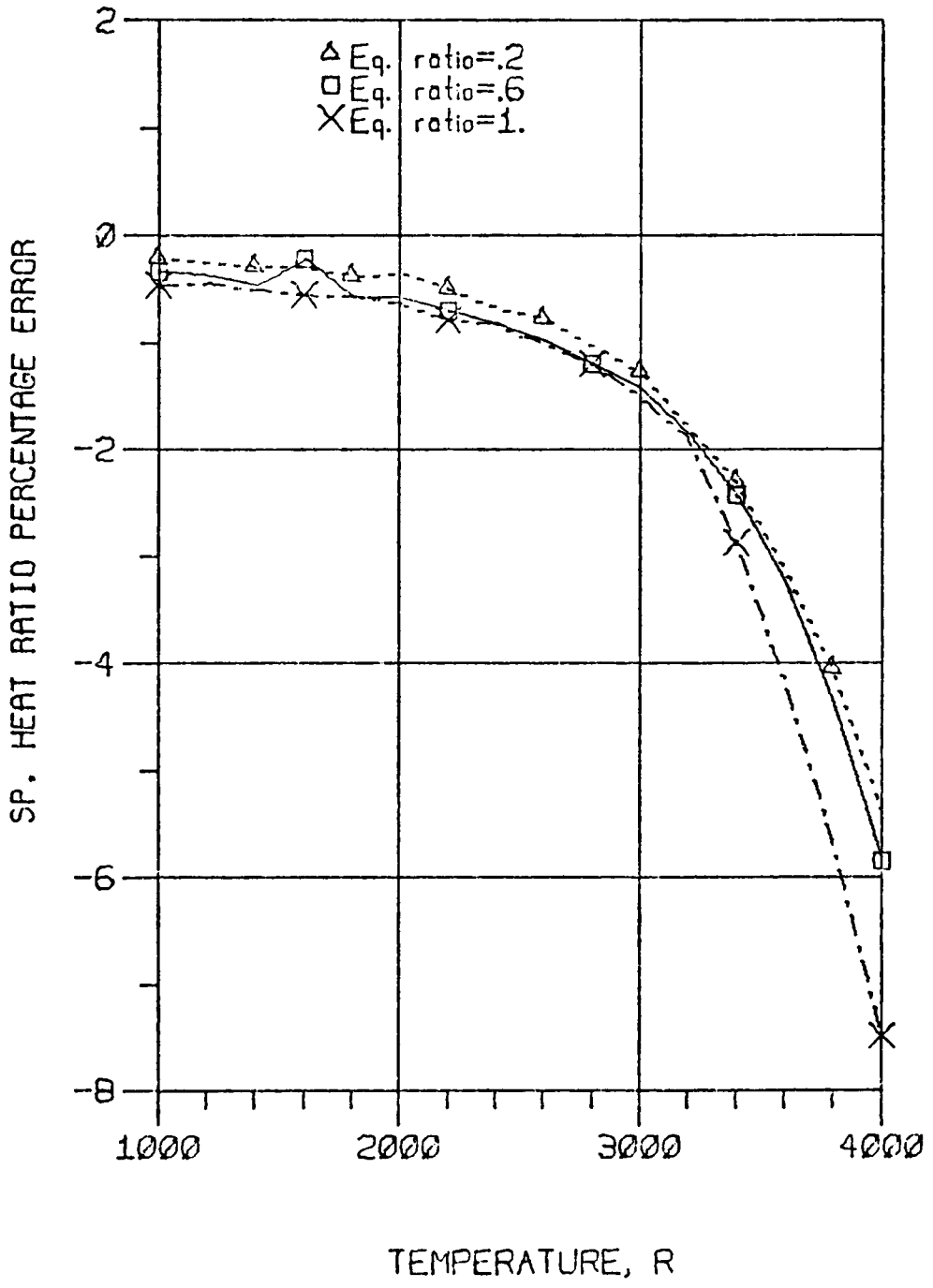


Figure 18. Specific Heat Ratio Percentage Error from Comparison of Data from THERMO and Reference [17]; P = 1 ATM; RCH = 0.0 .

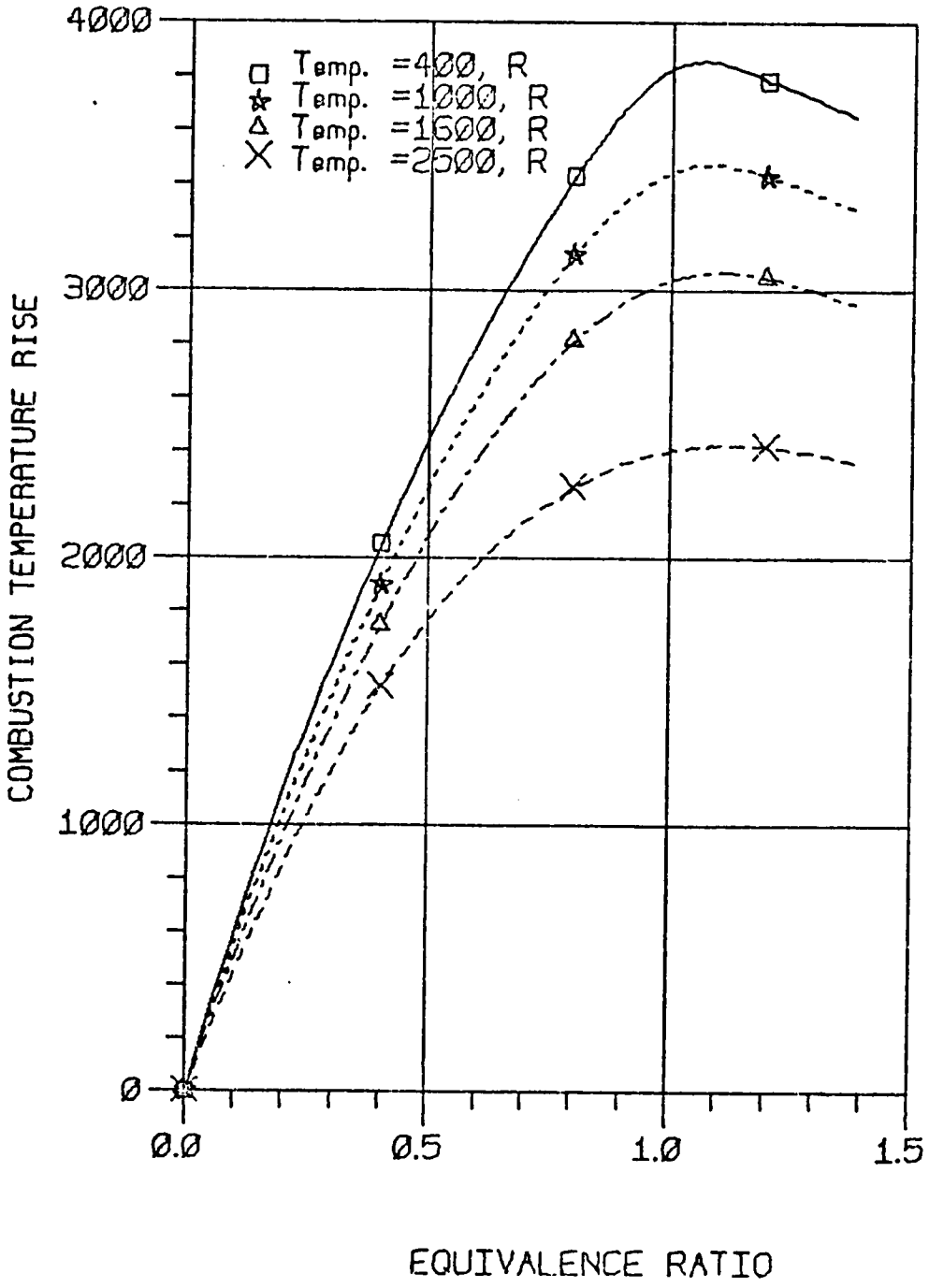


Figure 19. Combustion Temperature Rise for Hydrogen-Air Combustion for Different Inlet Temperatures; P = 1 ATM.

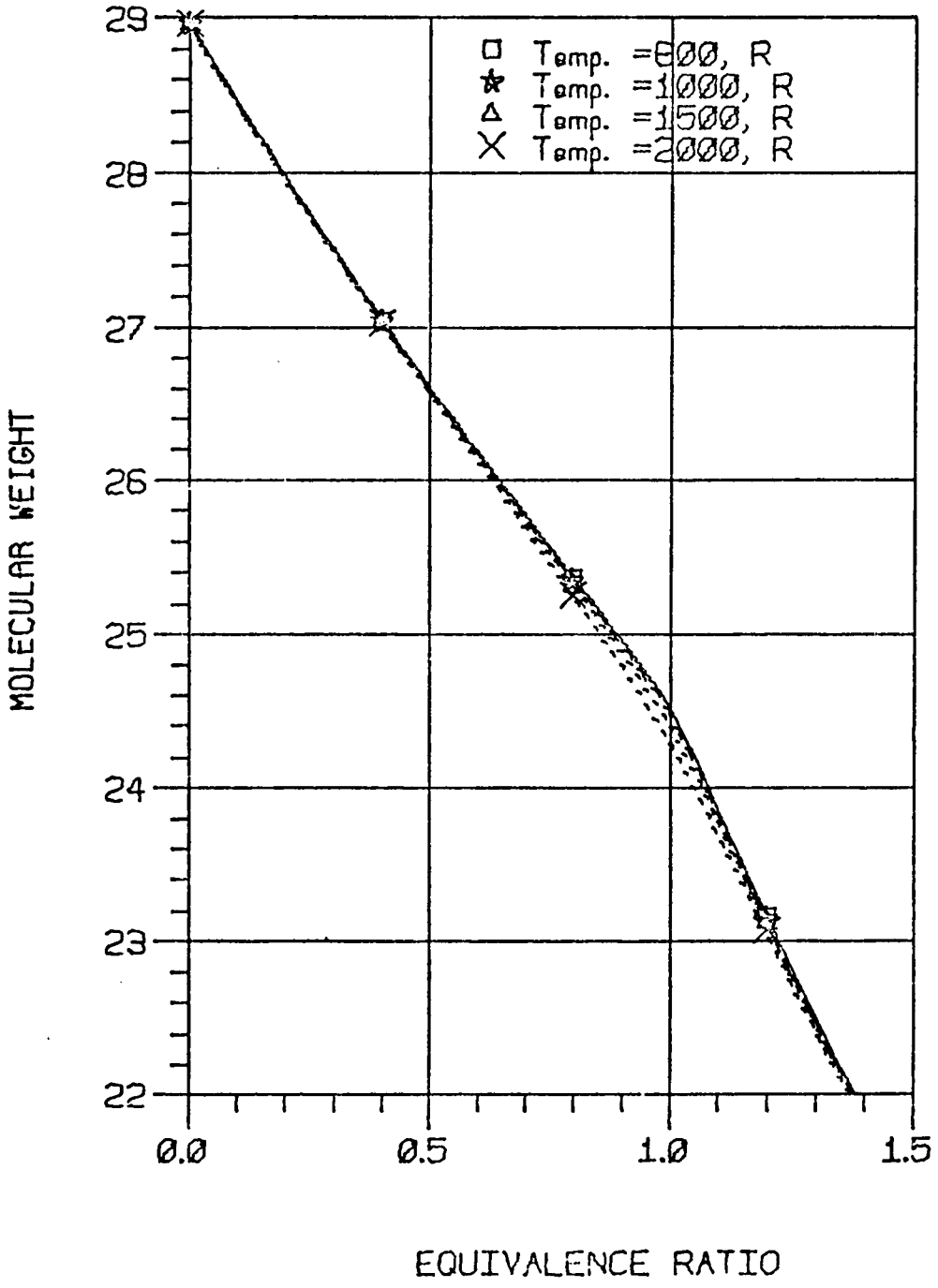


Figure 20. Molecular Weight Change for Hydrogen-Air Combustion for Different Inlet Temperatures; P = 1 ATM.

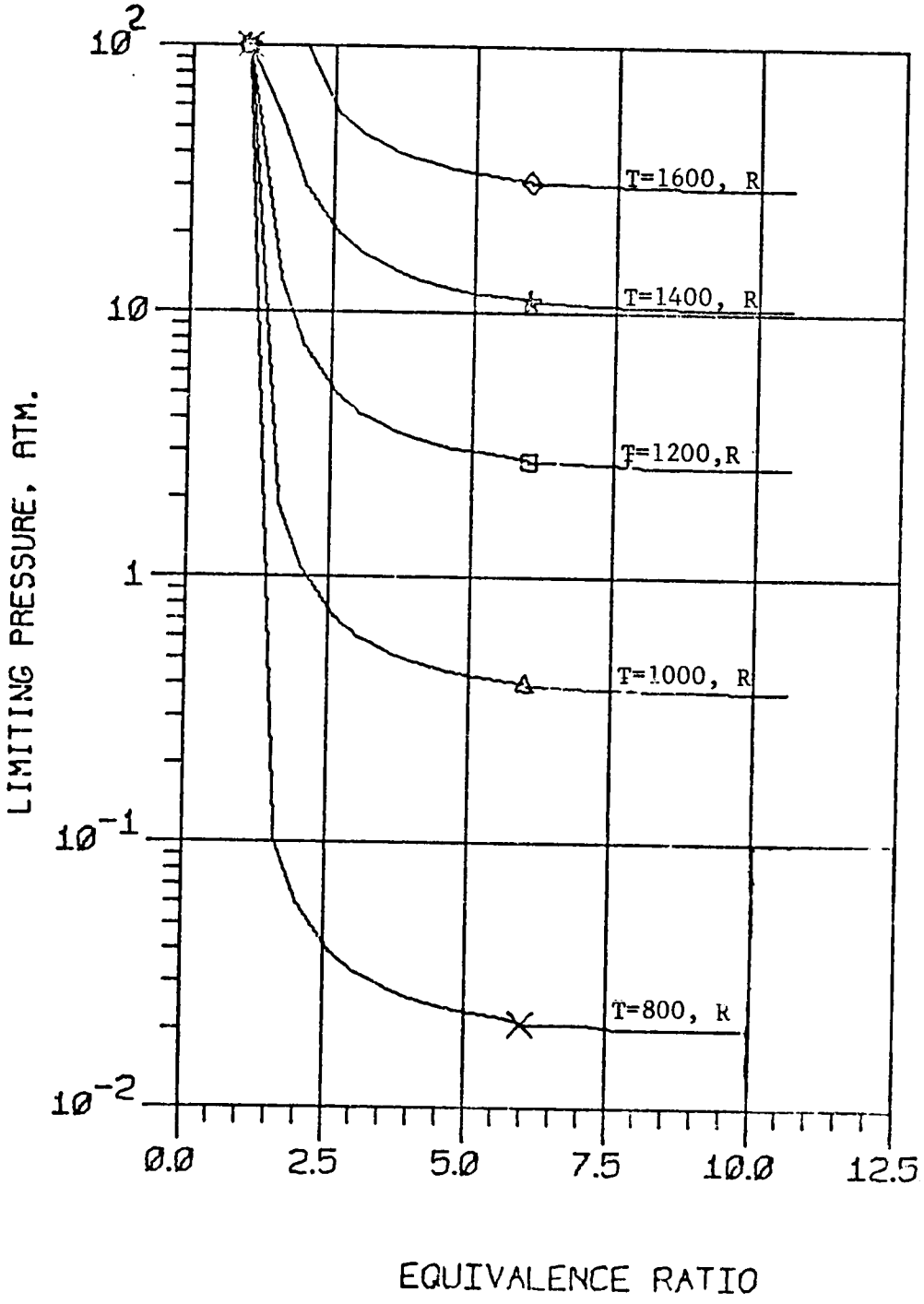


Figure 21. Limiting Pressure; RCH = 0.0, Data from THERMO.

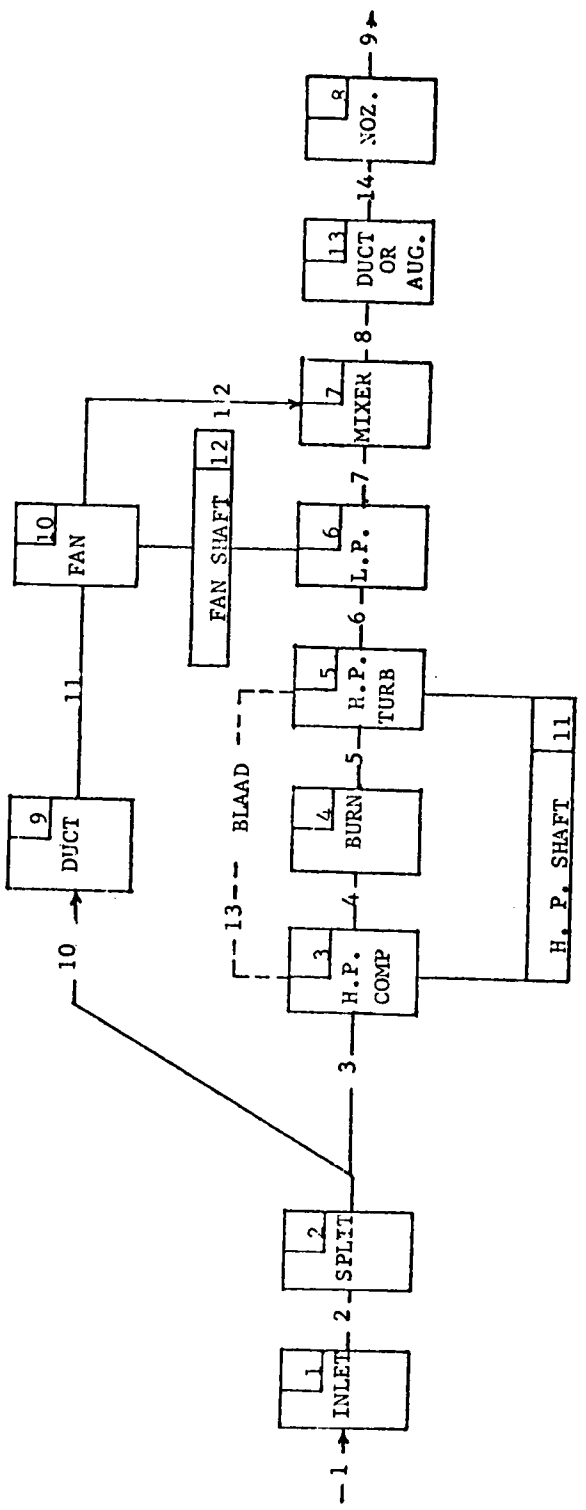


Figure 22. Engine Schematic, Mixed Flow, Dry Turbofan.

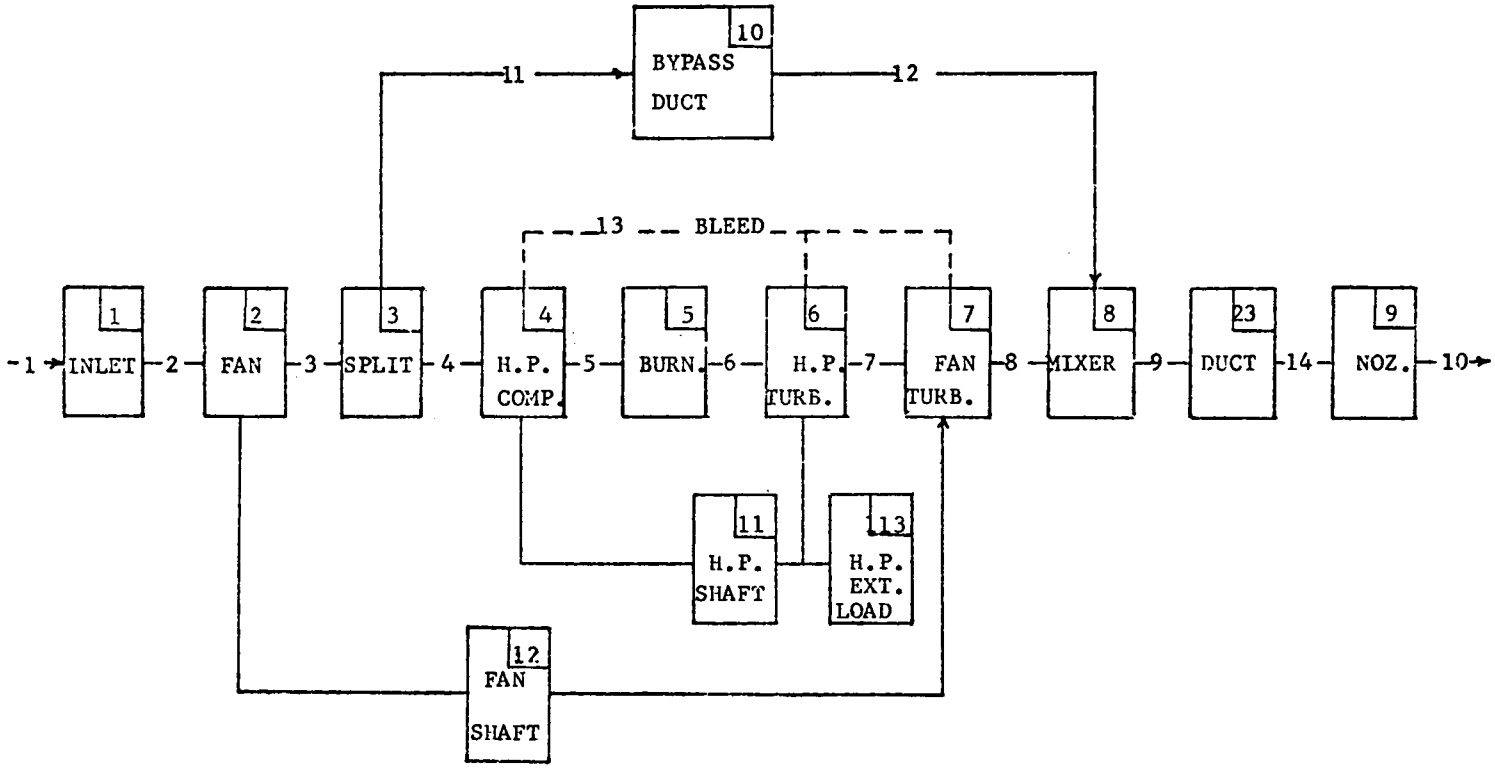


Figure 23. Engine Schematic, Mixed Flow, Aft, Dry or Augmented.

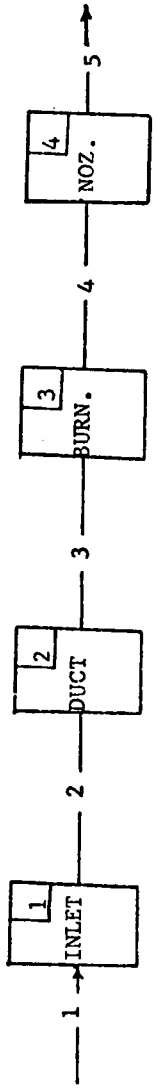


Figure 24. Engine Schematic, Ramjet.

TABLE 1

MNEP, QNEP PERFORMANCE COMPARISON, AFT FAN ENGINE FOR DIFFERENT INLET TURBINE TEMPERATURE, JP-5 FUEL

Mach	QNEP Model		MNEP Model		% Error*	
	FN	TSFC	FN	TSFC	FN	TSFC
ALTITUDE = 0., FT						
0.0	61244	0.699	60906	0.688	0.55	1.57
0.2	54626	0.795	54269	0.783	0.65	1.51
0.4	48067	0.937	47679	0.924	0.81	1.39
0.6	41245	1.149	40803	1.136	1.07	1.13
0.8	32448	1.553	32042	1.545	1.25	0.83
0.9	25091	2.062	24799	2.047	1.16	0.73
ALTITUDE = 10000., FT						
0.2	40461	0.788	40453	0.780	0.02	1.02
0.4	37382	0.926	37012	0.913	0.99	1.40
0.6	33869	1.106	33633	1.092	0.70	1.27
0.8	28525	1.426	28099	1.411	1.49	1.05
0.9	24233	1.740	23760	1.737	1.95	0.63
1.0	20317	2.174	19831	2.172	2.39	0.09

TABLE 1 (Continued)

Mach	QNEP Model FN	QNEP Model TSFC	MNEP Model FN	MNEP Model TSFC	% Error* FN	% Error* TSFC
			ALTITUDE = 30000., FT			
0.2	18442	0.738	18528	0.730	-0.47	1.08
0.4	17221	0.865	17335	0.856	-0.66	1.04
0.6	16467	1.034	16151	1.023	1.92	1.06
0.8	16134	1.285	15852	1.270	1.75	1.17
0.9	15809	1.439	15611	1.432	1.25	0.49
1.0	16442	1.535	16166	1.534	1.68	0.07
			ALTITUDE = 36000., FT			
0.2	13998	0.717	14161	0.709	-1.16	1.12
0.4	13113	0.841	13342	0.830	-1.75	1.31
0.6	12707	1.011	12850	0.996	-1.13	1.48
0.8	12326	1.246	12425	1.229	-0.80	1.36
0.9	12376	1.378	12383	1.372	-0.06	0.44
1.0	13130	1.465	13069	1.455	0.46	0.68

*$\%\ \text{Error} = \dfrac{\text{QNEP Model} - \text{MNEP Model}}{\text{QNEP Model}} \times 100$.

TABLE 2

MNEP, QNEP PERFORMANCE COMPARISON, AUGMENTED AFT FAN ENGINE, INLET TURBINE TEMPERATURE = 3150°R, JP-5 FUEL

Mach	QNEP Model FN	QNEP Model TSFC	MNEP Model FN	MNEP Model TSFC	% Error* FN	% Error* TSFC
ALTITUDE = 0., FT						
0.0	101186	1.622	100968	1.597	0.22	1.54
0.1	98069	1.683	97836	1.658	0.24	1.49
0.2	95813	1.754	95315	1.730	0.52	1.37
0.3	93414	1.843	92853	1.817	0.60	1.41
0.4	91493	1.944	90843	1.919	0.71	1.29
0.5	89988	2.058	89252	2.033	0.82	1.21
ALTITUDE = 40000., FT						
0.8	23630	2.265	23588	2.229	0.18	1.59
1.0	27649	2.295	27300	2.274	1.26	0.92
1.1	30753	2.292	30193	2.239	1.82	0.58
1.8	58627	1.935	57520	1.926	1.89	0.52
2.4	93510	1.802	91961	1.784	1.66	1.00
2.8	120167	1.733	118376	1.710	1.49	1.33

TABLE 2 (Continued)

Mach	QNEP Model FN	QNEP Model TSFC	MNEP Model FN	MNEP Model TSFC	% Error* FN	% Error* TSFC
			ALTITUDE = 60000., FT			
1.1	11758	2.252	11553	2.239	1.74	0.58
1.6	21308	1.858	20832	1.850	2.23	0.43
2.2	26176	1.986	25548	1.978	2.40	0.40
2.8	45953	1.733	45268	1.710	1.49	1.33
3.0	55514	1.681	54299	1.660	2.19	1.25
3.2	67102	1.648	65540	1.625	2.33	1.40
			ALTITUDE = 85000., FT			
1.0	3118	2.318	3048	2.309	2.25	0.39
1.6	5966	1.924	5844	1.916	2.04	0.42
2.0	6658	2.063	6501	2.057	2.36	0.29
2.8	13301	1.754	13074	1.732	1.71	1.25
3.2	19719	1.657	19278	1.634	2.24	1.39
3.5	25372	1.661	24836	1.635	2.11	1.57

*$\%\ \text{Error} = \frac{\text{QNEP Model} - \text{MNEP Model}}{\text{QNEP Model}} \times 100$.

TABLE 3

MNEP, QNEP PERFORMANCE COMPARISON, RAMJET ENGINE, EXIT COMBUSTION TEMPERATURE 4100°R, JP-5 FUEL

Mach	QNEP Model FN	QNEP Model TSFC	MNEP Model FN	MNEP Model TSFC	% Error* FN	% Error* TSFC
ALTITUDE = 50000., FT						
2.5	13873	4.124	13625	4.120	1.79	0.10
3.0	36962	2.855	36504	2.829	1.24	0.91
4.0	137764	2.185	137440	2.153	0.25	1.46
5.0	332626	1.960	333900	1.928	-0.38	1.63
6.0	483826	2.011	489101	1.975	-1.09	1.79
6.5	449843	2.102	458096	2.061	-1.83	1.95
ALTITUDE = 70000., FT						
3.0	14 72	2.862	13897	2.838	1.24	0.84
3.5	29220	2.410	29077	2.377	0.49	1.37
4.5	85253	2.053	85402	2.021	-0.17	1.56
5.0	126357	1.962	126898	1.930	-0.43	1.63
6.0	161648	2.022	164342	1.975	-1.37	2.32
6.5	167630	2.109	170776	2.069	-1.88	1.90

TABLE 3 (Continued)

Mach	QNEP Model FN	QNEP Model TSFC	MNEP Model FN	MNEP Model TSFC	% Error* FN	% Error* TSFC
			ALTITUDE = 90000., FT			
3.0	5359	2.895	5307	2.865	0.97	1.04
3.5	11121	2.432	11096	2.396	0.22	1.48
4.5	32304	2.066	32429	2.033	-0.39	1.60
5.5	60772	1.967	61254	1.936	-0.79	1.58
6.0	65936	2.043	66688	2.008	-1.14	1.71
6.5	57370	2.148	58531	2.106	-2.02	1.96
			ALTITUDE = 100000., FT			
3.0	3339	2.911	3311	2.879	0.84	1.10
3.5	6927	2.443	6921	2.406	0.09	1.51
4.5	20076	2.072	20173	2.039	-0.48	1.59
5.0	29513	1.976	29728	1.943	-0.73	1.67
5.5	37374	1.975	37677	1.944	-0.81	1.57
6.0	40012	2.054	40482	2.019	-1.17	1.70

*$\%\ \text{Error} = \frac{\text{QNEP Model} - \text{MNEP Model}}{\text{QNEP Model}} \times 100$.

TABLE 4

JP-5, HYDROGEN FUELED ENGINE PERFORMANCE COMPARISON, AFT FAN ENGINE, FOR DIFFERENT INLET TURBINE TEMPERATURES

Mach	Hydrogen Fuel FN	Hydrogen Fuel TSFC	JP-5 Fuel FN	JP-5 Fuel TSFC	% Inc. FN	% Dec.* TSFC
			ALTITUDE = 0., FT			
0.0	62975	0.251	60906	0.688	3.40	63.52
0.2	56360	0.284	54269	0.783	3.87	63.73
0.4	49821	0.333	47679	0.924	4.49	63.96
0.6	43087	0.405	40803	1.136	5.60	64.35
0.8	34403	0.541	32042	1.545	7.37	64.98
0.9	27155	0.701	24799	2.047	9.50	65.75
			ALTITUDE = 10000., FT			
0.2	41776	0.282	40453	0.780	3.27	63.85
0.4	38640	0.330	37012	0.913	4.40	63.86
0.6	35228	0.391	33633	1.092	4.74	64.19
0.8	29964	0.498	28099	1.411	6.64	64.71
0.9	25756	0.603	23760	1.737	8.40	65.28
1.0	22043	0.734	19831	2.172	11.15	66.21

TABLE 4 (Continued)

Mach	Hydrogen Fuel FN	Hydrogen Fuel TSFC	JP-5 Fuel FN	JP-5 Fuel TSFC	% Inc. FN	% Dec.* TSFC
			ALTITUDE = 30000., FT			
0.2	19149	0.264	18528	0.730	3.35	63.84
0.4	18002	0.307	17335	0.856	3.85	64.14
0.6	17240	0.365	16517	1.023	4.38	64.32
0.8	16912	0.447	15852	1.270	6.69	64.80
0.9	16909	0.494	15611	1.432	8.31	65.50
1.0	17684	0.523	16166	1.534	9.39	65.91
			ALTITUDE = 36000., FT			
0.2	14646	0.256	14161	0.709	3.42	63.89
0.4	13851	0.299	13342	0.830	3.82	63.98
0.6	13427	0.356	12850	0.996	4.49	64.26
0.8	13190	0.432	12425	1.229	6.16	64.85
0.9	13410	0.473	12388	1.372	8.25	65.52
1.0	14154	0.497	13069	1.455	8.30	65.84

*$\%\ \text{FN Increase} = \frac{\text{Hydrogen Values} - \text{"JP-5" Values}}{\text{"JP-5" Values}} \times 100$.

$\%\ \text{TSFC Decrease} = \frac{\text{"JP-5" Values} - \text{Hydrogen Values}}{\text{"JP-5" Values}} \times 100$.

TABLE 5

JP-5, HYDROGEN FUELED ENGINE PERFORMANCE COMPARISON, AUGMENTED AFT FAN ENGINE, INLET TURBINE TEMPERATURE = 3150°R

Mach	Hydrogen Fuel FN	Hydrogen Fuel TSFC	JP-5 Fuel FN	JP-5 Fuel TSFC	% Inc. FN	% Dec.* TSFC
			ALTITUDE = 0., FT			
0.0	104784	0.586	101019	1.599	3.73	63.35
0.1	101663	0.608	97887	1.660	3.86	63.37
0.2	99243	0.633	95365	1.732	4.07	63.45
0.3	97288	0.662	92902	1.820	4.72	63.63
0.4	95408	0.697	90892	1.922	4.97	63.74
0.5	94040	0.737	89301	2.035	5.31	63.78
			ALTITUDE = 10000., FT			
0.4	71525	0.689	68492	1.891	4.43	63.56
0.6	70125	0.767	66919	2.115	4.79	63.74
0.8	70924	0.859	66835	2.393	6.12	64.10
1.0	69928	0.975	63931	2.793	9.38	65.09
1.2	70256	1.071	63931	3.137	9.89	65.86
1.4	69624	1.166	61871	3.449	12.53	66.19

TABLE 5 (Continued)

Mach	Hydrogen Fuel FN	Hydrogen Fuel TSFC	JP-5 Fuel FN	JP-5 Fuel TSFC	% Inc. FN	% Dec.* TSFC
			ALTITUDE = 60000., FT			
1.1	12472	0.792	11578	2.242	7.72	64.67
1.6	22427	0.642	20893	1.851	7.34	65.32
2.2	27260	0.705	25629	1.978	6.36	64.36
2.8	46668	0.626	45373	1.711	2.85	63.41
3.0	56162	0.609	54407	1.661	3.23	63.34
3.2	67956	0.599	65645	1.626	3.52	63.16
			ALTITUDE = 85000., FT			
1.2	3940	0.800	3642	2.276	8.18	64.85
1.8	6560	0.713	6082	2.016	7.86	64.63
2.2	7605	0.733	7135	2.063	6.59	64.47
2.4	10347	0.665	9947	1.834	4.02	63.74
2.8	13529	0.634	13108	1.734	3.21	63.44
3.0	16468	0.613	15921	1.675	3.44	63.40

*$\%\ \text{FN Increase} = \dfrac{\text{Hydrogen Values} - \text{"JP-5" Values}}{\text{"JP-5" Values}} \times 100$.

$\%\ \text{TSFC Decrease} = \dfrac{\text{"JP-5" Values} - \text{Hydrogen Values}}{\text{"JP-5" Values}} \times 100$.

TABLE 6

JP-5, HYDROGEN FUELED ENGINE PERFORMANCE COMPARISON, RAMJET ENGINE, INLET TURBINE TEMPERATURE = 4100°R

Mach	Hydrogen Fuel FN	Hydrogen Fuel TSFC	JP-5 Fuel FN	JP-5 Fuel TSFC	% Inc. FN	% Dec.* TSFC
ALTITUDE = 50000., FT						
3.0	41149	1.034	37486	2.839	9.77	63.58
3.5	83126	0.874	77944	2.383	6.65	63.32
4.0	149011	0.796	139919	2.160	6.50	63.15
5.0	361096	0.715	338932	1.933	6.54	63.01
6.0	532705	0.730	495314	1.985	7.55	63.22
7.0	303319	0.843	275823	2.340	9.97	63.97
ALTITUDE = 60000., FT						
3.0	24892	1.037	23276	2.846	6.94	63.56
3.5	51540	0.876	48352	2.383	6.59	63.24
4.0	92353	0.796	86742	2.162	6.47	63.18
5.0	223775	0.715	210004	1.934	6.56	63.03
6.0	330313	0.730	306957	1.986	7.61	63.24
7.0	188700	0.848	171384	2.339	10.10	63.75

TABLE 6 (Continued)

Mach	Hydrogen Fuel FN	Hydrogen Fuel TSFC	JP-5 Fuel FN	JP-5 Fuel TSFC	% Inc. FN	% Dec.* TSFC
			ALTITUDE = 80000., FT			
3.0	9540	1.047	8942	2.879	6.69	63.63
3.5	19696	0.883	18508	2.407	6.42	63.32
4.0	35227	0.802	33089	2.177	6.46	63.16
5.0	84761	0.719	79487	1.943	6.64	63.00
6.0	121910	0.736	118071	2.001	3.25	63.22
7.0	56921	0.900	51887	2.462	9.70	63.44
			ALTITUDE = 100000., FT			
3.0	3744	1.062	3531	2.925	6.03	63.69
3.5	7705	0.893	7253	2.436	6.23	63.34
4.0	13734	0.810	12911	2.199	6.37	63.17
5.0	32710	0.723	30648	1.955	6.73	63.02
6.0	45241	0.744	41854	2.023	8.09	63.22
7.0	14036	1.024	12624	2.813	11.19	63.60

*$\%\ \text{FN Increase} = \frac{\text{Hydrogen Values} - \text{"JP-5" Values}}{\text{"JP-5" Values}} \times 100$.

$\%\ \text{TSFC Decrease} = \frac{\text{"JP-5" Values} - \text{Hydrogen Values}}{\text{"JP-5" Values}} \times 100$.

TABLE 7

DISSOCIATION EFFECT ON THE PERFORMANCE OF RAMJET, EXIT COMBUSTION TEMPERATURE = 4100°R, JP-5 FUEL

Mach	Diss. Model FN	Diss. Model TSFC	Nondiss. Model FN	Nondiss. Model TSFC	% Error* FN	% Error* TSFC
ALTITUDE = 60000., FT						
3.0	23276	2.846	22559	2.832	3.08	0.49
3.5	48352	2.365	47208	2.373	2.37	0.50
4.0	86742	2.162	84992	2.153	2.02	0.42
4.5	141338	2.025	138801	2.019	1.79	0.30
5.0	210004	1.934	206481	1.928	1.68	0.31
5.5	273058	1.923	268629	1.917	1.62	0.31
6.0	306957	1.986	302456	1.975	1.47	0.55
6.5	289156	2.064	283283	2.061	2.03	0.15
7.0	171384	2.339	163 73	2.354	4.85	-0.64

*$\%\ \text{Error} = \dfrac{\text{Diss. Model} - \text{Nondiss. Model}}{\text{Dissociated Model}} \times 100$.

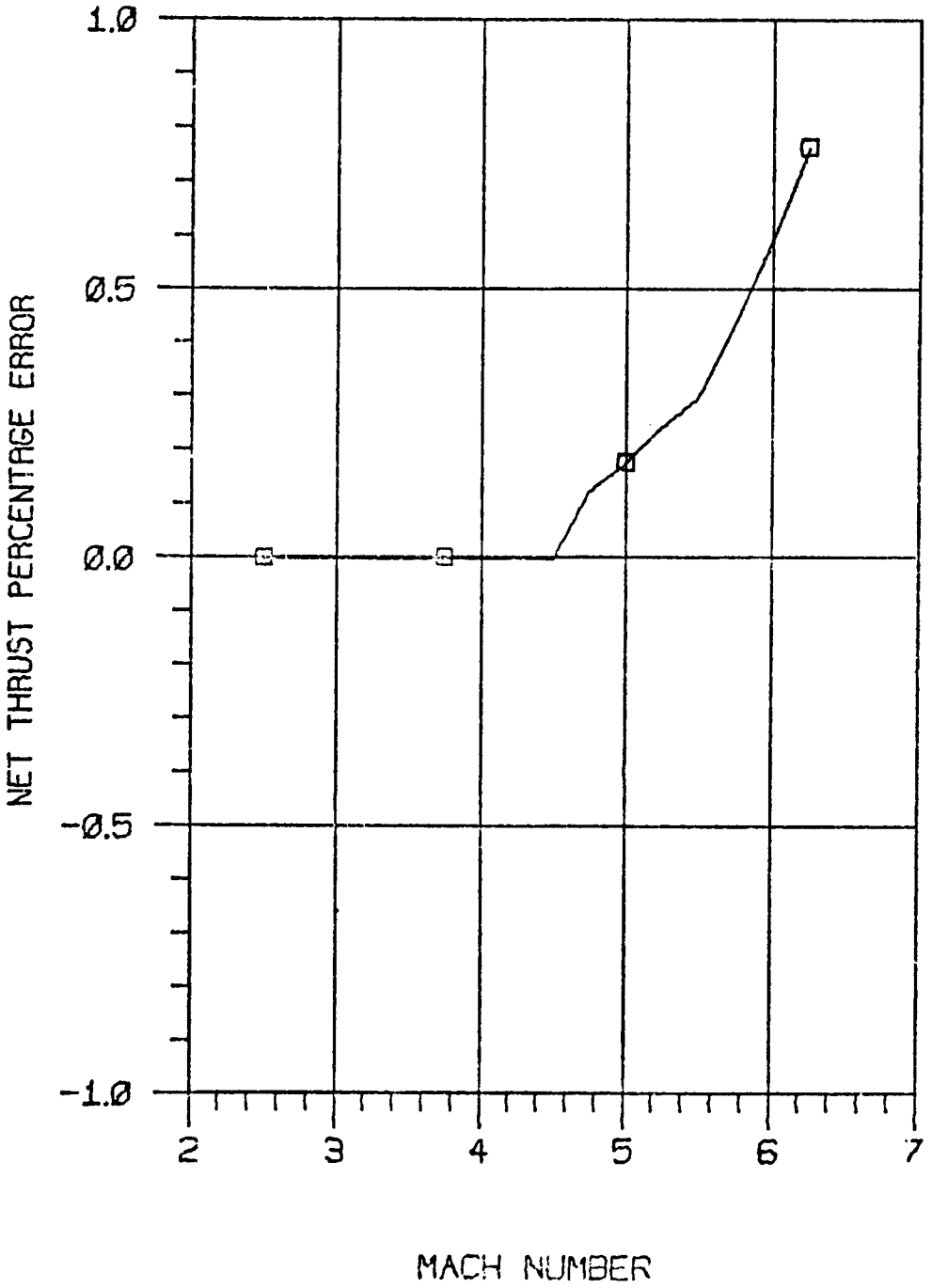


Figure 25. Net Thrust Percentage Error from Comparison of Data from MNEP for Frozen and Equilibrium Flow Through the Nozzle; Hydrogen Fuel; f/a = .011 .

APPENDIX D

PROGRAM LISTING

```
C***  NON VARIABLE GEOMETERY
C****
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER AWD,BWD
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
      COMMON /ARAB/ SHOCK,ABU,TAH
      DIMENSION SAVE(15,2)
      DIMENSION XMA(16),TDEL(7),ERR(15)
      COMMON/NEPOPT/SELAST,DD,NDSET,NPARTS,IOPTP,NPASSO,NVOPT,NJOPT,
     1TOLOPT,NUPT
      COMMON/QIN/TDEL,XMA,ALT,WMAX,PUNCHO,TIT,JCB,JN1,JN2,IDESN,IPRINT,
     2 JCAB2,JCAB1,NP,NM
      DIMENSION THR(7),WFD(7)
      DATA IPS,TIT /0,.002D0/
      DATA AWD,BWD /'TSFC','BSFC'/
C
C***  TABLE 1 IS NON-DIMENSIONAL REFERRED FLOW LIMIT VS THETA2
C
C     DO 7 I=1,7
C  7  TDEL(I)=0.0D0
C     TIT=0.0D0
C     PUNCHO=0.0D0
      CALL NEPSUB
      NPLUS=NCOMP+1
      IDESN=1
      SELAST=0.0D0
      RCH=DATINP(11,JCB)
      CALL GUNEP
      WMAXD=CORFLO(2)/1.549695676D0
C*** SET PRESSURE DROPS AS FUNCTIONS OF C FLOW**2
      N=KKINDS(2,1)
      DO 10 I=1,N
      JCX=KKINDS(2,I+1)
      IF(JCX.NE.JCB)  DATINP(5,JCX)=0.
      JS=JFIG(2,JCX)
      DATINP(3,JCX)=DATOUT(2,JCX)/CORFLO(JS)**2.0D0
      DATINP(1,JCX)=0.0D0
      DATINP(2,JCX)= 0.0D0
   10 CONTINUE
C*** ACTIVATE ALL CONTROLS
      N=KKINDS(12,1)
      DO 20 I=1,N
      JCX=KKINDS(12,I+1)
   20 DATINP(1,JCX)=1.0D0
C*** CALL IN THE INPUT PRINT
C*** SET TIT TO DESIGN INPUT VALUE
      TID=DATINP(4,JCB)
C*** SET UNUSED COMPONENTS TO ZERO FOR PRINTING PURPOSES
```

```
      IF(JN2.NE.0) GO TO 30
      JN2=NPLUS
      JSN2=NOSTAT+1
      IF(JBPR.EQ.0) JBPR=NPLUS
   30 JSN2=JFIG(2,JN2)
      JBPR=KKINDS(7,2)
      JSN1=JFIG(2,JN1)
      JSB=JFIG(4,JCB)
      IA=0
      CALL FINPRT
      IDESN=0
      PRINT 40,IDEDAP
   40 FORMAT(1H1,20A4,/)
   50 CALL  NPREAD
      IF(WMAX.LE.0.0D0) WMAX=1.0D10
C     IF(DABS(WMAX-WMAXD).LE.1.0D-4) WMAXD=WMAX
      IF(WMAX.LT.WMAXD)  PRINT 51
   51 FORMAT(' WARNING INPUT VALUE WMAX IS LESS THAN DESIGN')
      IF(JCAB1.EQ.0) JCAB1=NPLUS
      IF(JCAB2.EQ.0) JCAB2=NPLUS
      EFF1=DATINP(5,JCAB1)
      EFF2=DATINP(5,JCAB2)
      IF(TIT.LE.0.0D0) TIT=TID
      IPS=IPS+5
      IF((IPS+NP+1).LT.40) GO TO 60
      IPS=0
      PRINT 40,IDEDAP
   60 IPS=IPS+NP+1
      ISFC=AWD
      IF(PERPF(2).NE.0.0D0) ISFC=BWD
      PRINT 70,ISFC
   70 FORMAT (1X,'ALTITUDE  MACH      FN      BSHP     WF      ',A4,
     1'  REF FLOW  BPR     BOT      T19   PR19    A19   T9        PR9',
     2'      A9       RR     NIT')
      IA=IA+1
      IF(PUNCHO.EQ.0.0D0)  GO TO 72
      MP=NM
      IF(NM.GT.7) MP=7
      PUNCH 301  ,NM,(XMA(I),I=1,MP)
  301 FORMAT('MACH',4X, I2,7(1X,F9.4))
      IF(NM.GT.7) PUNCH 302,(XMA(I),I=8,NM)
  302 FORMAT(10X,7(1X,F9.4))
   72 DO 230 IM=1,NM
      TB1=DATINP(4,JCAB1)
      TB2=DATINP(4,JCAB2)
      IF(IM*IA.EQ.1) GO TO 90
      DO 80 ISS=1,N
      JCX=KKINDS(12,ISS+1)
      IF(JFIG(4,JCX).EQ.1.AND.DATINP(4,JCX).EQ.1.0D0) JJJ=JCX
      ISV=1
      IF(IM.EQ.1.AND.IA.NE.1) ISV=2
   80 DATOUT(1,JCX)=SAVE(ISS,ISV)
            JM1=1
                  JP1=2
      JCX=1
      DATINP(9,1)=ALT
```

```
      DATINP(5,1)=XMA(IM)
C*** SAVE SCALE FACTOR ON RECOVERY TABLE REFERRED FLOW
      RFC=DATINP(4,1)
      DATINP(4,1)=.00001D0
      CALL INLET
      DATINP(4,1)=RFC
      DATOUT(1,JJJ)=CSAVE*TOPRES(2)/DSQRT(TOTEMP(2))
C*** RESET ALTITUDE AND SET MACH NO.
   90 DATINP(9,1)=ALT
      DATINP(5,1)=XMA(IM)
      T=TIT
C*** SET A/B EFF OFF....
      IT=1
      DATINP(5,JCAB1)=0.0D0
      DATINP(5,JCAB2)=0.0D0
      NN=0
  100 DATINP(4,JCB)=T
      DT=-100.0D0
      SELAST=0.0D0
  110 CALL GONEP
      IF(NIT.EQ.50) GO TO 140
      THET2=DATOUT(8,1)
      IF(WMAX.EQ.1.0D10)  GO TO 140
      REFMAX=WMAX
      IF(THET2.GE.1.0D0) GO TO 120
      CALL TABLU(1,THET2,Y,0.0D0,RATIO)
      REFMAX=REFMAX*RATIO
  120 REF =CORFLO(2)/1.549695676D0
      IF(NN.NE.0) GO TO 130
      IF(REF.LT.REFMAX) GO TO 140
  130 DY=(REF-REFMAX)/REFMAX
      CALL SNESI (NN,DY,DATINP(4,JCB),DT,TTT,ABDS,DYL,ABB,XCK,
     1 10HFLOW SCHED  )
      IF(NN.NE.0) GO TO 110
  140 IF(IPRINT.EQ.1) CALL FINPRT
      IF(IT.NE.1) GO TO 160
      CSAVE=CORFLO(2)
      DO 150 ISS=1,N
      JCX=KKINDS(12,ISS+1)
      IF(IM.EQ.1) SAVE(ISS,2)=DATOUT(1,JCX)
  150 SAVE(ISS,1)=DATOUT(1,JCX)
      IF((EFF1+EFF2).GT.0.0D0) GO TO 190
  160 T=DATINP(4,JCB)
      T=T    -TDEL(IT)
  170 T9=TOTEMP(JSN1)
      T19=TOTEMP(JSN2)
      PR9=DATOUT(9,JN1)
      PR19=DATOUT(9,JN2)
      REF =CORFLO(2)/1.549695676D0
      BPR     =DATOUT(1,JBPR)
      FN      =PERPF(1)
      SFC=PERPF(4)
      IF(PERPF(2).NE.0.0D0) SFC=PERPF(5)
      IF (SHOCK.EQ.0.D0)PRINT 96
       IF(ABU.EQ.600.D0) PRINT 600
       IF(ABU.EQ.601.D0) PRINT 601
```

```
      IF(TAH.EQ.500.D0) PRINT 602
  600  FORMAT(10X,'***** SOLID CARBON HAS FORMED ****')
  601  FORMAT(10X,'***** AMMONIA HAS FORMED ****')
  602 FORMAT( 10X,'*** WARNING BECAUSE THE CONVERGENCE HAS GONE',
     1' TO INFINITY, 0.3% ERROR IN ENTHALPY HAS BEEN ASSUMED ***')
   96  FORMAT(/,20X,'***** DETACHED SHOCK, DEFLECTION =0 IS',
     1' ASSUMED *****',/)
      PRINT 180,DATOUT(9,1),DATINP(5,1),FN,PERPF(2),PERPF(6),SFC,REF,
     1 DATOUT(1,JBPR),TOTEMP(JSB),T19,PR19,DATOUT(5,JN2)
     2,T9,PR9,DATOUT(5,JN1),DATOUT(7,1),NIT
  180 FORMAT(2X,F7.0,2X,F5.3,1X,F8.0,1X,F4.0,2X,F7.0,2X,F5.3,2X,F7.1,
     12X,F5.3,3X,F5.0,2X,F5.0,2X,F5.3,2X,F5.0,2X,F5.0,2X,F7.2,2X,F5.0
     2,2X,F5.3,2X,I3)
      IF(FN.LE.0.0D0.OR.NIT.EQ.50) GO TO 609
      THR(IT)=FN
      WFD(IT)=PERPF(6)
      IP=IT
  609 IT=IT+1
      IF(IT.LE.NP.AND.NIT.NE.50.AND.FN.GT.0.0D0) GO TO 189
      IF(PUNCHO.EQ.0.0D0)  GO TO 230
      PUNCH 611      . ,IP,(THR(I),I=1,IP)
  611 FORMAT('THR ',4X,I2, 7(1X,F9.1))
      PUNCH 621       ,IP,(WFD(I),I=1,IP)
  621 FORMAT('WFD ',4X,I2, 7(1X,F9.1))
      GO TO 230
  189 IF((EFF1+EFF2).LE.0.0D0) GO TO 100
  190 JCAB=JCAB1
      JN=JN1
      EFF=EFF1
      TB=TB1
  200 IF(EFF.LE.0.0D0) GO TO 210
      DATINP(5,JCAB)=EFF
      TBS=DATINP(4,JCAB)
      DATINP(4,JCAB)=TB
      DATINP(7,JN)=1.0D0
      CALL FLOCAL(JCAB,SS,ERR)
      IF(IPRINT.NE.0) CALL FINPRT
      DATINP(7,JN)=0.0D0
      DATINP(4,JCAB)=TBS
  210 IF(EFF.EQ.EFF2) GO TO 220
      EFF=EFF2
      JCAB=JCAB2
      JN=JN2
      TB=TB2
      GO TO 200
  220 TB1=TB1-TDEL(IT)
      TB2=TB2-TDEL(IT)
      JSUB=JFIG(2,JCAB1)
      IF(EFF1.GT.0.0D0.AND.TB1.LT.TOTEMP(JSUB          ))GO TO 230
      JSUB=JFIG(2,JCAB2)
      IF(EFF2.GT.0.0D0.AND.TB2.LT.TOTEMP(JSUB          ))GO TO 230
      GO TO 170
  230 CONTINUE
      GO TO 50
      END
CCOMPR
```

```
      SUBROUTINE COMPRS
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
C      *****   MODIFIED BY M.T. ABUJELALA      2/79  *****
      FAR1=FAR(JM1)
      T1=TOTEMP(JM1)
      TP1=TOPRES(JM1)
      FAR(JP1)=FAR1
      FAR(JP2)=FAR1
      NCOR=LOCTBL(4,JCX)
      NEFF=LOCTBL(6,JCX)
      NPR=LOCTBL(8,JCX)
      RT=DATINP(1,JCX)
      VGP=DATINP(10,JCX)
      SQT1=1.0D0/DSQRT(T1)
      CRPM=DATOUT(2,JCX)*22.77432765D0*SQT1
      IF(IWAY.EQ.0) GO TO 10
      CRPMT=DATINP(14,JCX)
      DATINP(3,JCX)=CRPM/CRPMT
      GO TO 20
   10 CRPMT=CRPM/DATINP(3,JCX)
   20 CORFT=DATINP(4,JCX)
      IF(NCOR.GT.0) CALL TABLU(NCOR,RT,CRPMT,VGP,CORFT)
      CORFT=CORFT*1.54969567600
      PRT=DATINP(8,JCX)
      IF(NPR .GT.0) CALL TABLU(NPR ,RT,CRPMT,VGP,PRT)
      EFFT=DATINP(6,JCX)
      IF(NEFF.GT.0) CALL TABLU(NEFF,RT,CRPMT,VGP,EFFT)
      IF(IWAY.EQ.0) GO TO 30
      COREF=CORFLO(JM1)
      DATINP(5,JCX)=COREF/CORFT
      EFF=DATINP(12,JCX)
      DATINP(7,JCX)=EFF/EFFT
      PR=DATINP(13,JCX)
      DATINP(9,JCX)=(PR-1.0D0)/(PRT-1.0D0)
      GO TO 40
   30 PR=DATINP(9,JCX)*(PRT-1.0D0)+1.0D0
      EFF=EFFT*DATINP(7,JCX)
      COREF=CORFT*DATINP(5,JCX)
   40 WT1=COREF*TP1*SQT1
      WTF(JP2)=WT1*DATINP(2,JCX)
      WTF(JP1)=WT1-WTF(JP2)
      ER=1.0D0-DATINP(11,JCX)
      P2=TP1*PR
      CALL THERMO (T1,TP1,H1,S1,1,RCH,FAR1,T2,H2,P2,0,GAM,RR)
      DH1=H2-H1
      DHA=DH1/EFF
      H3=H1+DHA
       CALL THERMO (T2,P2,H3,SS,6,RCH,FAR1,ZERO,ZERO,ZERO,0,GAM,RR)
```

```
      TOTEMP(JP1)=T2
      IF(WTF(JP2).LE.0.0D0) GO TO 70
      IF(ER.LT.1.0D0) GO TO 50
      TB=TOTEMP(JP1)
      DHBLD=DHA
      PRB=PR*TP1
      GO TO 60
   50 H41=DHI*ER+H1
      CALL THERMO (T1,TP1,H1,S1,4,RCH,FAR1,T4I,H4I,PRB,4,GAM,RR)
      DHBLD=DHA*ER
      H4=H1+DHBLD
      CALL THERMO (TB,PRB,H4,SS,6,RCH,FAR1,ZERO,ZERO,ZERO,0,GAM,RR)
   60 HPB=-1.415D0*WTF(JP2)*DHBLD
      GO TO 80
   70 HPB=0.0D0
      TB=0.0D0
      PRB=0.0D0
   80 HPC=-1.415D0*WTF(JP1)*DHA+HPB
      TOTEMP(JP2)=TB
      TOPRES(JP2)=PRB
      WTF(JM1)=WT1
      CORFLO(JM1)=COREF
      TOPRES(JP1)=TP1*PR
      CORFLO(JP1)=WTF(JP1)*DSQRT(TOTEMP(JP1))/TOPRES(JP1)
      DATOUT(1,JCX)=HPC
      DATOUT(3,JCX)=VGP
      DATOUT(4,JCX)=RT
      DATOUT(5,JCX)=DATINP(3,JCX)
      DATOUT(6,JCX)=CRPMT
      DATOUT(7,JCX)=DATINP(5,JCX)
      DATOUT(8,JCX)=EFF
      DATOUT(9,JCX)=PR
      RETURN
      END
CCONFIG
      SUBROUTINE CONFIG
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERFF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
      DIMENSION JCUS(30),JCDS(30),JPASS(25),JPASS1(25),JHEATX(25)
C     ASSEMBLE NUMBERS AND KINDS OF COMPONENTS
      DO 10 IC=1,15
      DO 10 JC=1,25
   10 KKINDS(IC,JC)=0
      DO 30 IC=1,NCOMP
      JT=JFIG(1,IC)
      IF(JT.GT.15.OR.JT.LT.1) PRINT 20,IC
   20 FORMAT(' CONFIGURATION DATA, JFIG(1,',I2,') IS IN ERROR')
      JNO=KKINDS(JT,1)
      KKINDS(JT,1)=JNO+1
```

```
      JNO=JNO+2
   30 KKINDS(JI,JNO)=IC
C     OBTAIN ARRAY OF ALL COMPONENTS WHICH ARE IN FLOW
      JCC=0
      NS=KKINDS(11,1)
      DO 60 I=1,NCOMP
C*** CHECK FOR SHAFT CONNECTION TO ALL ROTATING COMPONENTS
      JT=JFIG(1,I)
      IF(JT.NE.4.AND.JT.NE.5.AND.JT.NE.10) GO TO 70
      IF(NS.EQ.0) GO TO 50
      DO 40 J=1,NS
      JCX=KKINDS(11,J+1)
      DO 40 K=2,5
      IF(JFIG(K,JCX).EQ.I) GO TO 70
   40 CONTINUE
   50 PRINT 60,I,(KKINDS(11,M+1),M=1,NS)
   60 FORMAT(' WARNING COMPONENT ',I3,' MUST HAVE A CONNECTION TO ONE OF
     1 THE FOLLOWING SHAFTS ',10(I2,' OR '))
   70 IF(JT.GT.9.OR.JT.LE.0) GO TO 80
      JCC=JCC+1
      JCOMP(JCC)=I
   80 CONTINUE
C     GET ALL COMPONENTS IN TERMS OF THEIR STATION
      DO 110 I=1,NOSTAT
      JCUS(I)=0
      JCDS(I)=0
      DO 90 J=1,JCC
      JJ=JCOMP(J)
      IF(JFIG(4,JJ).EQ.I.OR.JFIG(5,JJ).EQ.I) JCUS(I) = JJ
      IF(JFIG(2,JJ).NE.I.AND.JFIG(3,JJ).NE.I) GO TO 90
      JCDS(I)=JJ
      IF(JCUS(I).NE.0) GO TO 110
   90 CONTINUE
      IF((JCDS(I)+JCUS(I)).EQ.0) PRINT 100,I
  100 FORMAT(' WARNING, FLOW STATION ',I3,' HAS NO CONNECTION')
  110 CONTINUE
C     BEGIN AT FIRST INLET IN CONFIGURATION
      JINLET=1
      JC=0
C     INITIALIZE COUNTERS
      JSET=0
      JSET1=0
      JHEAT=0
      JH=0
      GO TO 240
C     STORE COMPONENT IN FLOW ARRAY
  120 IF(JCX.EQ.0) GO TO 280
      JC =JC+1
C*** CHECK FOR OVERFLOW ** LOOPING AROUND IN CONFIG DATA
      IF(JC.GT.50) GO TO 290
      JFLOW(JC)=JCX
C     GET MAIN DOWNSTREAM STATION
      JP1=JFIG(JH+4,JCX)
      IF(JP1.LE.NOSTAT) GO TO 140
      PRINT 130,JCX,JCX
  130 FORMAT(' CONFIGURATION DATA, JFIG(4,',I2,') OR JFIG(5,',I2,')
```

```
     1N ERROR')
        GO TO 290
  140 JH=0
C       GET NEXT COMPONENT JCX DOWN STREAM OF STATION JP1  NOW JM1
        JCX=JCDS(JP1)
C       CHECK TO SEE IF THIS IS THE END OF A FLOW PATH
        IF (JCX.EQ.0) GO TO 260
  150 JT=JFIG(1,JCX)
C       CHECK COMPONENT TYPE FOR SPLITTER OR MIXER
C *** AND HEAT EXCHANGER
        IF(JT-6)120,160,200
C *** PROCESS FIRST PASS IN HEAT EXCHANGER
  160 IF(JHEAT.EQ.0) GO TO 180
        DO 170 JX=1,JHEAT
        IF(JCX.EQ.JHEATX(JX)) GO TO 190
  170 CONTINUE
  180 JHEAT=JHEAT+1
        JHEATX(JHEAT)=JCX
        GO TO 120
  190 JH=1
        JHEATX(JX)=JHEATX(JHEAT)
        JHEAT=JHEAT-1
        GO TO 120
C       CHECK FOR SPLITTER
  200 IF (JT.EQ.7) GO TO 250
        IF (JT.NE.8) GO TO 120
C       HAS THIS MIXER ALREADY BEEN PROCESSED
        IF (JSET.EQ.0) GO TO 230
        DO 210 JX=1,JSET
        IF (JCX.EQ.JPASS(JX)) GO TO 220
  210 CONTINUE
        GO TO 230
  220 JPASS(JX)=JPASS(JSET)
        JSET=JSET-1
        GO TO 120
  230 JSET=JSET+1
        JPASS(JSET)=JCX
        IF(JSET1.NE.0) GO TO 270
C       CHECK FOR MORE INLETS
  240 IF(JINLET.GT.KKINDS(1,1)) GO TO 280
        JINLET=JINLET+1
        JCX=KKINDS(1,JINLET)
        GO TO 120
  250 JSET1=JSET1+1
        JSPT=JFIG(5,JCX)
        JPASS1(JSET1)=JCDS(JSPT)
        GO TO 120
  260 IF (JSET1.EQ.0) GO TO 240
C       ARE THERE ANYMORE FLOW PATHS FROM SPLITTERS NOT PROCESSED YET
  270 JCX=JPASS1(JSET1)
C       YES CHECKEM OFF
        JSET1=JSET1-1
        GO TO 150
  280 IF(JC.GE.JCC) GO TO 340
  290 PRINT 300
  300 FORMAT(//,39H WARNING * CHECK LOGIC IN CONFIGURATION,/,
```

```
     160H THE FOLLOWING FLOW COMPONENTS DO NOT LIE IN ANY FLOW STREAM )
      DO 330 I=1,JCC
      L=JCOMP(I)
      DO 310 J=1,JC
      IF(L.EQ.JFLOW(J)) GO TO 330
  310 CONTINUE
      PRINT 320,I
  320 FORMAT(1X,I3)
  330 CONTINUE
  340 CONTINUE
      DO 350 KJ=1,50
  350 JCOMP(KJ)=0
      DO 360 K=1,JC
      L=JC+1-K
      JCX=JFLOW(L)
  360 JCOMP(JCX)=L
      JCC=JC
C     SET CONTROL ORDER FOR OPTIMUM PASS MODE
      NCTS=KKINDS(12,1)
      NM1=NCTS-1
      IF(NCTS.LE.1) GO TO 390
  370 NOTYET=0
      DO 380 I=1,NM1
      JCX1=KKINDS(12,I+1)
      JCX2=KKINDS(12,I+2)
      JIN1=JFIG(4,JCX1)
      JIN2=JFIG(4,JCX2)
      IC1=JCOMP(JIN1)
      IC2=JCOMP(JIN2)
      IF (IC1.GE.IC2) GO TO 380
      NOTYET=1
      JCXS=JCX1
      KKINDS(12,I+1)=JCX2
      KKINDS(12,I+2)=JCXS
  380 CONTINUE
      IF (NOTYET.EQ.1) GO TO 370
  390 CALL INPRT
      RETURN
      END
CDUCTB
      SUBROUTINE DBURNR
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
C      *****   MODIFIED BY M.T. ABUJELALA      2/79   *****
      FAR1=FAR(JM1)
      TP1=TOPRES(JM1)
      T1=TOTEMP(JM1)
      T2=DATINP(4,JCX)
      HF=DATINP(6,JCX)
```

```
      EFF=DATINP(5,JCX)
      NCE=LOCTBL(5,JCX)
      NHCF=LOCTBL(6,JCX)
      NDP=LOCTBL(1,JCX)
      G=CORFLO(JM1)
      WT1=WTF(JM1)
C***
C***DRY PRESSURE DROP CALCULATIONS
C***
      DELP=  DATINP(1,JCX)+DATINP(3,JCX)*G*G
      CALL TABLU (NDP,G,0.0D0,0.0D0,DELP)
      IF (DELP.GT..8D0) DELP=.8D0
      TP2=TP1*(1.0D0-DELP)
      IF (EFF.GT.0.0D0) GO TO 30
      FWR=0.0D0
      FUEL=0.0D0
      DELMP=0.0D0
      VM1=0.0D0
      T2=T1
      WT2=WT1
      FARG=FAR1
      IF(JM2.GE.30) GO TO 10
      FAR1B=FAR(JM2)
      WBIN=DATINP(8,JCX)*WTF(JM2)
      IF(WBIN.LE.0.0D0) GO TO 10
      A1=WT1/(1.0D0+FAR1)
      CALL THERMO (T1,TP1,H1M,S1,5,RCH,FAR1,ZERO,ZERO,ZERO,0,
     1ZERO,ZERO)
      A2=WBIN/(1.0D0+FAR1B)
      CALL THERMO (TOTEMP(JM2),TOPRES(JM2),H2M,S1,5,RCH,FAR1B,ZERO,
     1ZERO,ZERO,0,ZERO,ZERO)
      WT2=WT1+WBIN
      FARG=(FAR1*A1+FAR1B*A2)/(A1+A2)
      HM12=(WT1*H1M+WBIN*H2M)/WT2
      CALL THERMO (T2,TP2,HM12,S1,6,RCH,FARG,ZERO,ZERO,ZERO,0,
     1ZERO,ZERO)
   10 IF(JP2.GE.30) GO TO 20
      WTFBO=WT2*DATINP(9,JCX)
      WT2=WT2-WTFBO
      WTF(JP2)=WTFBO
      TOTEMP(JP2)=T2
      FAR(JP2)=FARG
   20 IF(IWAY.NE.0) GO TO 70
      GO TO 290
   30 IF (WT1.LE.0.0D0) GO TO 50
      AIRR=(1.0D0+FAR1)/WT1
      IF(DATINP(12,JCX).GE.0.D0) GO TO 42
      FSTD=.028931D0*(1.008D0+12.01D0*RCH)/(1.D0+4.D0*RCH)
      CALL THERMO (T1,TP1,HIN,S1,5,RCH,FAR1,ZERO,ZERO,ZERO,0,
     1ZERO,ZERO)
      IF (T1.GT.3400.D0) GO TO 27
       HSTD=((FSTD-FAR1)*HF+(FAR1+1.D0)*HIN)/(1.D0+FSTD)
      CALL THERMO (TSTD,TP2,HSTD,S1,6,RCH,FSTD,ZERO,ZERO,ZERO,0,
     1ZERO,ZERO)
   27 IF(T1.GT.3400.D0) TSTD=7000.D0
      IF(T2.LT.TSTD.AND.T2.GT.T1) GO TO 23
```

```
      WRITE(6,24)T1,T2,ISTD
      STOP
   24 FORMAT(//,10X,'*** INPUT ERROR  ***',/,10X,'INLET COMBUSTIN'
     1' TEMP.=',F8.1,' , EXIT TEMP.=',F8.1,' AND MAX. TEMP.=',
     2 F8.1,//,10X,'***                    ***')
   23 CALL TABLU (NCE,G,FAR1,0.0D0,EFF)
      CALL TABLU (NHCF,T2,TP1,0.0D0,HCF)
      TT1=1.D0/T1
      TT2=1.D0/T2
      FARG=.7937944D-05*(T2-T1)+.6189714D01*(TT2-TT1)-0.2269739D04
     1*(TT2**2-TT1**2)
      IF(RCH.GT.0.D0)FARG=.2043573D-04*(T2-T1)+.1251456D02*(TT2-TT1)
     1-.4195694D04*(TT2**2-TT1**2)
       ZX=1.00698823D0*FARG
      CALL THERMO (T2,TP2,H1,S1,5,RCH,ZX,ZERO,ZERO,ZERO,0,CP,CM)
C     IF(HCF.GT.25000.D0) GO TO 35
C     EFFHCF=EFF*HCF+128.27D0
C     GO TO 40
C  35 EFFHCF=EFF*(HCF+1.75D0*(DATINP(10,JCX)-37.0D0))
      JH=0
   41 FAR2=FARG
      H2=((FAR2-FAR1)*HF+(FAR1+1.D0)*HIN)/(1.D0+FAR2)
      CALL THERMO (T3,TP2,H2,S1,6,RCH,FAR2,ZERO,ZERO,ZERO,0,CP,CM)
      FARG=FAR2+1.65D0*(T2-T3)/T2*FAR2+(H1-H2)*FAR2/H1
       H1=H2
      IF(DABS(T2-T3).LE..00025D0*T2) GO TO 9
         JH=JH+1
         IF(JH.LE.45) GO TO 41
      WRITE(6,12)
      WRITE(6,13)TP1,TP2,HIN,FAR2,T2,T1
   13 FORMAT(10X,6(F10.4,4X),'TP1,TP2,HIN,FAR2,T2,T1')
      STOP
   12 FORMAT(20X,'**** 45 ITERATIONS ARE NOT ENOUGH SUB...DB STAT. 9')
    9 FAR2=FAR2/EFF
      CALL THERMO (T2,TP2,HOUT,S1,5,RCH,FAR2,ZERO,ZERO,ZERO,0,
     1ZERO,ZERO)
      FARG=FAR2
      FWR=(FARG-FAR1)/(WT1*AIRR)
      GO TO 50
   42 FARG=DATINP(12,JCX)*EFF
      CALL THERMO (T1,TP1,HIN,S1,5,RCH,FAR1,ZERO,ZERO,ZERO,0,
     1ZERO,ZERO)
       HOUT=((FARG-FAR1)*HF+(FAR1+1.D0)*HIN)/(1.D0+FARG)
      CALL THERMO (T2,TP2,HOUT,S1,6,RCH,FARG,ZERO,ZERO,ZERO,0,
     1ZERO,ZERO)
      DATINP(4,JCX)=T2
       FARG=FARG/EFF
      FWR=(FARG-FAR1)/(WT1*AIRR)
   50 FUEL=FWR*WT1
      WT2=WT1+FUEL
      DELMP=0.0D0
      VM1=0.0D0
C ***
C *** MOMENTUM PRESSURE DROP CALCULATION
C ***
      MDESN=0
```

```
      IF(IWAY.NE.0) GO TO 70
   60 AREA=DATINP(7,JCX)
      IF(AREA*EFF.EQ.0.0D0) GO TO 290
C***
C*** CHECK FOR LOW FLOW CONDITIONS,  IF MACH IS GREATER THAN .0001 GO
C***
      IF(G/AREA.LT..0001D0) GO TO 290
      GO TO 80
   70 VM1S=DATINP(2,JCX)
      IF(VM1S.LE.0.0D0) GO TO 60
      VM1S=VM1S*VM1S
      MDESN=1
   80 CALL THERMO (T1,TP1,HIN,S1,5,RCH,FARG,ZERO,ZERO,ZERO,0,
     1GAM3,R1M)
      TSMIN=0.0D0
      TPB=TP2
      IF(MDESN.NE.1) GO TO 100
      T2M=T1/(1.0D0+.2D0*VM1S)
   90 CALL THERMO (T1,TP1,ZERO,ZERO,3,RCH,FARG,T2M,H2M,ZERO,
     10,GAM,R1M)
      VMSC=2.0D0*(HIN-H2M)/(GAM*R1M*T2M)
      DM=VM1S-VMSC
      T2M=T2M*(1.0D0-.5D0*(GAM-1.0D0)*DM/(1.0D0+.5D0*(GAM-1.0D0)*VMSC))
      IF(DABS(DM/VM1S).GT..00001D0) GO TO 90
      GO TO 110
  100 CON1=AREA/(R1M*778.161D0)
      CONST=CON1*TP2/TP1
C***
C *** COMPUTE INLET MACH NO. BASED ON FLOW AFTER DRY PRESSURE LOSS
C *** MACH NO. IS COMPUTED WITH FUEL ADDED INTO FLOW
C***
      NM=0
C***
C*** FIRST GUESS AT STATIC TEMPERATURE - DUCT ENTRANCE
C***
      FLOWG=WT2*DSQRT(R1M*778.161D0*T1)/(AREA*TP2)
        GAM=GAM3
      FOURAC=4.0D0*FLOWG/32.174D0*FLOWG/GAM
      ROOT=0.0D0
      IF(FOURAC.LT.1.0D0) ROOT=DSQRT(1.0D0-FOURAC)
      TDEL=(1.0D0-ROOT)*.25D0*(GAM-1.0D0)
      T2M=T1*(1.0D0-TDEL)
      CX=0.0D0
  110 CALL THERMO (T1,TP1,ZERO,S1,3,RCH,FARG,T2M,H2M,P2,0,
     1GAM,R1M)
      V1=223.7702D0*DSQRT(HIN-H2M)
      IF(MDESN.EQ.0) GO TO 120
      CON1=WT2/P2*T2M/V1*TP1/TP2
      AREA=CON1*R1M*778.161D0
      DATINP(7,JCX)=AREA
      IF(EFF.LE.0.0D0) GO TO 290
      GO TO 180
C***
C*** COMPUTE  FLOW FOR CHECK WITH INCOMING FLOW
C***
  120 WT2G=P2*CONST*V1/T2M
```

```
      VM1S=2.0D0*(HIN-H2M)/(GAM*R1M*T2M)
      IF(VM1S.LE.1.0D0) GO TO 140
C***
C***  ITERATION HAS GONE SONIC -FIND STATIC TEMP FOR MACH=1.
C***
      TSMIN=.8333D0*T1
  130 TS=TSMIN
      CALL THERMO (T1,TP1,ZERO,S1,3,RCH,FARG,TS,HCRIT,PS,0,
     1GAM,R1M)
      VM3S=2.0D0*(HIN-HCRIT)/(GAM*R1M*TS)
      Z=.5D0*(GAM-1.0D0)*VM3S
      DM=1.0D0-VM3S
      TSMIN=TSMIN*(1.0D0-Z/(1.0D0+Z)*DM/VM3S)
      IF(DABS(DM).GT..00001D0 ) GO TO 130
      T2M=TSMIN+.005D0
      CX=1.0D0
      GO TO 110
  140 WTERR=(WT2-WT2G)/WT2
      NM=NM+1
      IF(NM.GT.25) GO TO 160
      IF(DABS(WTERR).LT..0001D0) GO TO 180
C***
C*** UPDATE STATIC TEMP USING INFLUENCE COEFFICIENT
C***
      FAC=-WTERR*  (GAM-1.0D0)*VM1S/(1.0D0-VM1S)
      IF(CX*WTERR.GT.0.0D0) GO TO 200
      CX=0.0D0
      AFAC=DABS(FAC)
      IF(AFAC.GT..01D0) FAC=.01D0*FAC/AFAC
      TOLD=T2M
      T2M=T2M*(1.0D0+FAC)
      IF(T2M.GT.TSMIN) GO TO 150
      T2M=.5D0*(TSMIN+TOLD)
      GO TO 110
  150 IF(T2M.GT.T1) T2M=.99D0*T1+.01D0*TOLD
      GO TO 110
  160 PRINT 170,JCX
  170 FORMAT(' MACH NUMBER ITERATION HAS FAILED  '' COMPONENT ',I2)
      GO TO 280
C***
C*** COMPUTE MAX ALLOWABLE TEMP RATIO FOR THERMAL CHOKING
C***
  180 TOTM=((1.0D0+GAM*VM1S)**2.0D0)/((GAM+1.0D0)*VM1S*(2.0D0+(GAM-1.0D0
     1)*VM1S))
      IF(T2/T1.LT.TOTM) GO TO 220
C***
C***  FLOW AT EXIT IS SONIC SET DROP TO MAX
C***
  190 POTM=((GAM+1.0D0)/(1.0D0+GAM*VM1S))*((2.0D0+(GAM-1.0D0)*VM1S)/(GAM
     1+1.0D0))**(GAM/(GAM-1.0D0))
      TP2=TP2/POTM
  200 PRINT 210,JCX
  210 FORMAT(10X,46HWARNING *** EXIT VELOCITY IS SONIC *COMPONENT ,I2)
      GO TO 280
  220 IF(T2.LT.T1) GO TO 290
C***
```

```
C*** LOOP FOR COMPUTING EXIT STATIC TEMP,P TOTAL ,MACH NO, AND FLOW
C***
      TSMIN=0.0D0
      PS1=TP2*P2/TP1
      CON=WT2/(32.174D0*AREA)
      TS2=T2M*T2/T1
      CK=0.0D0
  230 CALL THERMO (T2,TP2,ZERO,S1,3,RCH,FARG,TS2,HS2,PS,0,
     1GAM,R1M)
      V2=223.7702D0*DSQRT(HOUT-HS2)
C***
C*** STATIC PRESSURE CALCULATION CONSIDERING MOMENTUM CONSERVATION
C***
      PS2=PS1-(V2-V1)*CON
      WT2G=PS2*CON1*V2/TS2
      VM2S=2.0D0*(HOUT-HS2)/(GAM*R1M*TS2)
      IF(VM2S.LE.1.0D0) GO TO 250
      TSMIN=.8333D0*T2
  240 TS=TSMIN
      CALL THERMO (T2,TP2,ZERO,S1,3,RCH,FARG,TS,HCRIT,PS,0,
     1GAM,R1M)
      VM3S=2.0D0*(HOUT-HCRIT)/(GAM*R1M*TS)
      Z=.5D0*(GAM-1.0D0)*VM3S
      DM=1.0D0-VM3S
      TSMIN=TSMIN*(1.0D0-Z/(1.0D0+Z)*DM/VM3S)
      IF(DABS(DM).GT.1.0D-5) GO TO 240
      TS2=TSMIN+.005D0
      CK=1.0D0
      GO TO 230
  250 WTERR=(WT2-WT2G)/WT2
      IF(WTERR*CK.GT.0.0D0) GO TO 190
      IF(DABS(WTERR).LT..0001D0) GO TO 270
      FAC=-WTERR*  (GAM-1.0D0)*VM2S/(1.0D0-VM2S)
      AFAC=DABS(FAC)
      IF(AFAC.GT..01D0) FAC=.01D0*FAC/AFAC
      TS2=TS2*(1.0D0+FAC)
      IF(TS2.GT.TSMIN) GO TO 260
      TS2=TSMIN+.05D0
      GO TO 230
  260 IF(TS2.GT.T2) TS2=.5D0*(T2+TS2/(1.0D0+FAC))
      GO TO 230
  270 CALL THERMO (T2,TP2,ZERO,S1,3,RCH,FARG,TS2,ZERO,PS,0
     1,ZERO,ZERO)
      TP2=PS2*TP2/PS
C***
C*** MOMENTUM PRESSURE DROP
C***
  280 DELMP=(TPB-TP2)/TPB
      VM1=DSQRT(VM1S)
  290 FAR(JP1)=FARG
       CORFLO(JP1)=WT2*DSQRT(T2)/TP2
      TOTEMP(JP1)=T2
      TOPRES(JP1)=TP2
      WTF(JP1)=WT2
      DATOUT(1,JCX)=DELMP
      DATOUT(2,JCX)=DELP
```

```
      DATOUT(3,JCX)=DATINP(2,JCX)
      DATOUT(5,JCX)=DATINP(7,JCX)
      DATOUT(4,JCX)=FWR
      DATOUT(6,JCX)=FUEL*3600.0D0
      DATOUT(7,JCX)=VM1
      DATOUT(8,JCX)=HF
      DATOUT(9,JCX)=EFF
      RETURN
      END
CFLOCAL
      SUBROUTINE FLOCAL(IGET,SS,EROR)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NrINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
      DIMENSION SPROP(30,8),EROR(15)
      EQUIVALENCE(SPROP,WTF)
      JWAY=IWAY
      IF (NPASS) 10,10,20
   10 N1=KKINDS(1,1)
      N2=KKINDS(9,1)
      N3=KKINDS(2,1)
      N10=KKINDS(10,1)
      NSHAFT=KKINDS(11,1)
C
C     SET SHAFT RPMS
   20 IF (NSHAFT) 90,90,30
   30 DO 80 IS=1,NSHAFT
      JSC=KKINDS(11,IS+1)
      RPM=DATINP(1,JSC)
      DATOUT(2,JSC)=RPM
      DO 80 KJ=2,5
      JCX=JFIG(KJ,JSC)
      IF (JCX.LE.0) GO TO 80
C*** CHECK FOR A ZERO SHAFT GEAR RATIO
      KL=2+(KJ-2)*2
      GR=DATINP(KL,JSC)
      IF(GR.EQ.0.0D0) GR=1.0D0
      RPMS=RPM*GR
      DATOUT(2,JCX)=RPMS
C***** SHAFT MOD ..IF  SHAFT THEN SET SHAFT INPUT..MJC 6/9/78
      IF(JFIG(1,JCX).EQ.11) DATINP(1,JCX)=RPMS
      DATOUT(KJ+1,JSC)=RPMS
C *** SET LOAD OR MOTOR HORSEPOWER
      IF(JFIG(1,JCX).NE.10) GO TO 80
   40 NHP=LOCTBL(1,JCX)
      IF(NHP)60,60,50
   50 CALL TABLU(NHP,DATOUT(2,JCX),0.0D0,0.0D0,HP)
      GO TO 70
   60 HP=DATINP(1,JCX)
   70 DATOUT(1,JCX)=HP
```

```
   80 CONTINUE
   90 JSPLIT=0
      JHP=0
      NPASS=NPASS+1
      IF(IGET.LE.0 ) GO TO 100
      I=JCOMP(IGET)
      IF(I.GT.0) GO TO 110
  100 I=1
      INLAST=JCC
  110 IN=I
  120 JCX=JFLOW(I)
      JT=JFIG(1,JCX)
      JM1=JFIG(2,JCX)
      JM2=JFIG(3,JCX)
      JP1=JFIG(4,JCX)
      JP2=JFIG(5,JCX)
      IF(JM2.LE.0) JM2=30
      IF(JP2.LE.0) JP2=30
      CORJM1=CORFLO(JM1)
      GO TO (130,140,150,160,180,190,200,210,220), JT
C     COMPONENT TYPE 1
  130 CALL INLET
      CORJM1=CORFLO(JM1)
      GO TO 240
C     COMPONENT TYPE 2
  140 CALL DBURNR
      GO TO 240
C     COMPONENT TYPE 3
  150 CONTINUE
      GO TO 240
C     COMPONENT TYPE 4
  160 CALL COMPRS
C*** QUICK EXIT DESIGN POINT MODE 1ST PASS
      IF(IGET.GT.0) GO TO 170
      IWAYE=I
      GO TO 240
  170 IF(IWAY.GE.0) GO TO 240
      IF(IWAYE.EQ.I)GO TO 250
      GO TO 240
C     COMPONENT TYPE 5
  180 CALL TURBIN
      GO TO 240
C     COMPONENT TYPE 6
  190 CONTINUE
      CALL HEATXC(I)
      JCXL=JFLOW(I-1)
      JHP=JHP-1
      IF(JFIG(4,JCXL).EQ.JM1.OR.JFIG(5,JCXL).EQ.JM1) JHP=JHP+2
      GO TO 240
C     COMPONENT TYPE 7
  200 CALL SPLITR
      JSPLIT=JSPLIT+1
      GO TO 240
C     COMPONENT TYPE 8
  210 CONTINUE
      CALL MIXER
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```
      JSPLIT=JSPLIT-1
      GO TO 240
C     COMPONENT TYPE 9
  220 CALL NOZZLE
      DENO=.50D0*DATOUT(5,JCX)
      GO TO 241
  240 DENO=.500*(CORJM1+CORFLO(JM1))
  241 ERROR(JM1)=(CORJM1-CORFLO(JM1))/DENO
      CORFLO(JM1)=CORJM1
      IF(JT.NE.9) GO TO 243
      IF(JSPLIT.LE.0) GO TO 242
      JSPLIT=JSPLIT-1
      GO TO 243
  242 IF(JHP.GT.0) GO TO 243
      IF(I.EQ.JCC.OR.I.GT.INLAST) GO TO 250
  243 I=I+1
      GO TO 120
  250 CONTINUE
C     COMPUTE SHAFT HORSEPOWERS
      HPT=0.0D0
      IF(NSHAFT.LE.0) GO TO 340
C**** MOD TO REVERSE HP SUM ON SHAFTS TO PERMIT SHAFTS CONNECTED TO
C**** SHAFTS   MJC   6/8/78
      NSR=NSHAFT+2
      DO 330 IS=1,NSHAFT
      JSC=KKINDS(11,NSR-IS)
      HP=0.0D0
      HPA=0.0D0
      DO 300 KJ=2,5
      JCX=JFIG(KJ,JSC)
      IF (JCX) 300,300,260
  260 HPC=DATOUT(1,JCX)
      KL=3+(KJ-2)*2
      FAC=DATINP(KL,JSC)
      IF (HPC) 280,300,270
  270 IF (IWAY.GE.0) GO TO 290
      IF(JFIG(1,JCX).EQ.5) GO TO 300
      GO TO 290
  280 FAC=1.0D0/FAC
  290 HPFAC=HPC*FAC
      HP=HP+HPFAC
      HPA=HPA+DABS(HPFAC)
  300 CONTINUE
      IF(IWAY.GE.0) GO TO 320
      DO 310 KJ=2,5
      JCX=JFIG(KJ,JSC)
      IF(JCX.LE.0) GO TO 310
      IF(JFIG(1,JCX).NE.5) GO TO 310
      KL=3+(KJ-2)*2
      DATOUT(1,JCX)=-HP*DATINP(13,JCX)/DATINP(KL,JSC)
  310 CONTINUE
C**** HP=0.       ********DELETE THIS CARD FOR SHAFT MOD
  320 DATOUT(1,JSC)=HP
      DATOUT(8,JSC)=HP*2.0D0/HPA
      HPT=HPT+HP
  330 CONTINUE
```

```
  340 IF(IWAY.GE.0) GO TO 350
      IWAY=1
      GO TO 90
C     SET AIR FLOW AND DRAG
  350 AIR=0.0D0
      DRAG=0.0D0
      DO 360 I1=1,N1
      JCX=KKINDS(1,I1+1)
      DRAG=DRAG+DATOUT(1,JCX)
  360 AIR=AIR+DATINP(1,JCX)
C     SET NOZZLE NET THRUST
      FG=0.0D0
      DO 370 I2=1,N2
      JCX=KKINDS(9,I2+1)
      DRAG=DRAG+DATOUT(8,JCX)
  370 FG=FG+DATOUT(1,JCX)
      FNET=FG-DRAG
C     SET FUEL USED
      FUEL=0.0D0
      IF (N3.LE.0) GO TO 390
      DO 380 I3=1,N3
      JCX=KKINDS(2,I3+1)
  380 FUEL=FUEL+DATOUT(6,JCX)
C     SET BSHP
  390 BSHP=0.0D0
      IF (N10.LE.0) GO TO 410
      DO 400 I4=1,N10
      JCX=KKINDS(10,I4+1)
      IF(DATINP(2,JCX).NE.0.0D0) BSHP=BSHP-DATOUT(1,JCX)
  400 CONTINUE
  410 BSFC=0.0D0
      IF(BSHP.NE.0.0D0) BSFC=FUEL/BSHP
      PERPF(1)=FNET
      PERPF(2)=BSHP
      PERPF(3)=AIR
      PERPF(4)=FUEL/FNET
      PERPF(5)=BSFC
      PERPF(6)=FUEL
      PERPF(7)=FNET/AIR
      PERPF(8)=BSHP/AIR
      PERPF(9)=DRAG
      IWAY=JWAY
C *** COMPUTE CONTROL ERRORS
      S=0.0D0
      NFINIS=0
      IF(NCTS.EQ.0) GO TO 470
      DO 460 I=1,NCTS
      NJCXD=JCDEP(I)
      NDEP=JCVDEP(I)
      IF (KDTYP(I))430,420,440
  420 VCAL=DATOUT(NDEP,NJCXD)
      GO TO 450
  430 VCAL=SPROP(NJCXD,NDEP)
      GO TO 450
  440 VCAL=PERPF(NDEP)
  450 ER=DEPV(I)-VCAL
```

```
      S=S+ER*ER
      EROR(I)=ER
      IF(DABS(ER).GT.DTOL(I)) NFINIS=1
  460 CONTINUE
  470 SS=S
      INLAST=IN
      RETURN
      END
CHEATXC
      SUBROUTINE HEATXC(I)
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTI
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
C       *****   MODIFIED BY M.T. ABUJELALA      2/79   *****
      JI=JM1
      JO=JP1
      K=1
      JCXL=JFLOW(I-1)
C ** CHECK FOR ENTERING CONDITION 1)HEATED FLOW 2)HEATER FLOW
      IF(JFIG(4,JCXL).EQ.JM1.OR.JFIG(5,JCXL).EQ.JM1) GO TO 10
      K=2
      JI=JM2
      JO=JP2
   10 DELP=DATINP(K,JCX)
      NDP=LOCTBL(K,JCX)
      IF(NDP.EQ.0) GO TO 20
      G=CORFLO(JI)
      CALL TABLU(NDP,G,0.0D0,0.0D0,DELP)
   20 TOPRES(JO)=TOPRES(JI)*(1.0D0-DELP)
      DATOUT(K,JCX)=DELP
      IF(JI.NE.JM1) GO TO 30
      TOTEMP(JO)=TOTEMP(JI)+DATINP(3,JCX)
C *** END OF HEATED FLOW PASS
      GO TO 40
C *** HEATER FLOW PASS BEGIN
   30 EFF=DATINP(4,JCX)
      NEF=LOCTBL(4,JCX)
      WR=WTF(JM2)/WTF(JM1)
      IF(NEF.NE.0) CALL TABLU(NEF,WTF(JM1),WR,0.0D0,EFF)
      EFF=EFF*DATINP(5,JCX)
      FAR1=FAR(JM1)
      FAR2=FAR(JM2)
      TJM2=TOTEMP(JM2)
      PJ2=TOPRES(JM2)
      PJ1=TOPRES(JM1)
      TJM1=TOTEMP(JM1)
      CALL THERMO (TJM1,PJ1,HJ,SJ,5,RCH,FAR1,ZERO,ZERO,ZERO,0,GA,RA)
      CALL THERMO (TJM2,PJ2,HJ,SJ,5,RCH,FAR2,ZERO,ZERO,ZERO,0,GG,RG)
      RA=RA*GA
      RG=RG*GG
```

```
      WCPA=WTF(JM1)*RA/(GA-1.0D0)
      WCPG=WTF(JM2)*RG/(GG-1.0D0)
      WCPR=1.0D0
      IF(WCPG.LT.WCPA) WCPR=WCPG/WCPA
      DELT=EFF*WCPR*(TJM2-TJM1)
      TOTEMP(JP2)=TJM2-WCPA*DELT/WCPG
      DATOUT(4,JCX)=EFF
      DATOUT(5,JCX)=DATINP(5,JCX)
      DATOUT(6,JCX)=DELT
      DATOUT(7,JCX)=DELT/(TJM2-TJM1)
      DATOUT(8,JCX)= DATINP(3,JCX)/DELT-1.0D0
   40 FAR(JO)=FAR(JI)
      WTF(JO)=WTF(JI)
      CORFLO(JO)=WTF(JO)*DSQRT(TOTEMP(JO))/TOPRES(JO)
      RETURN
      END
CINLET
      SUBROUTINE INLET
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
      COMMON /ARAB/ SHOCK,ABU,TAH
C      *****   MODIFIED BY M.T. ABUJELALA      2/79   *****
      DIMENSION HB(10),TMB(10),DELTAB(10),ALM(10)
      DATA HB/-5.0D0,0.0D0,11.0D0,20.0D0,32.0D0,47.0D0,52.0D0,61.0D0,79.
     10D0,88.743D0/
      DATA TMB/320.65D0,288.15D0,216.65D0,216.65D0,228.65D0,270.65D0,270
     1.65D0,252.65D0,180.65D0,180.65D0/
      DATA DELTAB/1.75363D0,1.0D0,2.23361D-1,5.40328D-02,8.56663D-03,1.0
     19455D-03,5.82289D-04,1.79718D-04,1.02410D-05,1.6223D-06/
      DATA ALM/-6.5D0,-6.5D0,0.0D0,1.0D0,2.8D0,0.0D0,-2.0D0,-4.0D0,0.0D0
     1,0.0D0/
      DATA  REFT59/2.0855531D07/, GZ    /9.80665D0/,
     2      AMZ   /28.9644D0      /, RSTAR /8.31432D0/,
     3      FTTOKM/3.048D-04    /, CAZ   /1116.45D0/
      T1=TOTEMP(JM1)
      TP1=TOPRES(JM1)
      SHOCK=1.D0
      HFT=DATINP(9,JCX)
      IF(HFT) 10,30,20
   10 T1=DATINP(2,JCX)
      TP1=DATINP(3,JCX)
      DELTA=TP1/14.696D0
      DATOUT(9,JCX)=-1.0D-20
      GO TO 90
   20 IF(HFT.EQ.DATOUT(9,JCX)) GO TO 90
   30 DATOUT(9,JCX)=HFT
      DATOUT(7,JCX)=1.0D0
C***  CONVERT  ALTITUDE FROM GEOMETERIC(INPUT) TO GEOPOTENTIAL
      IF(DATINP(11,JCX).EQ.0.0D0) HFT=(REFT59/(REFT59+HFT))*HFT
```

```
      H = FTTOKM*HFT
      TMZ=TMB(2)
      DO 40 M=1,10
      IF (H-HB(M)) 50,60,40
   40 CONTINUE
   50 M = M-1
   60 DELH = H-HB(M)
      IF (ALM(M).EQ.0.0D0)  GO TO 70
      TMK = TMB(M)+ALM(M)*DELH
      DELTA = DELTAB(M)*((TMB(M)/TMK)**(GZ*AMZ/(RSTAR*ALM(M))))
      GO TO 80
   70 TMK = TMB(M)
      DELTA = DELTAB(M)*DEXP(-GZ*AMZ*DELH/(RSTAR*TMB(M)))
   80 THETA = TMK/TMZ
      T1=1.8D0*TMK
      TP1=14.696D0*DELTA
   90 DATINP(3,JCX)=TP1
      THETA=T1*1.9280081.74D-3
      XM=DATINP(5,JCX)
      CA = CAZ*DSQRT(THETA)
      TOTEMP(JM1)=T1
      TOPRES(JM1)=TP1
C*** CALCULATION OF FOREBODY EFFECT
      DANG=DATINP(15,JCX)
      IF(DANG.LE.0.0D0) GO TO 98
      IF(XM.LE.1.0D0) GO TO 98
      G=1.4D0
      G1=G+1.0D0
      G2=G1/2.0D0
      G3=G1/4.0D0
      G4=G1/16.0D0
      G5=(G-1.0D0)/2.0D0
      RAD=57.295779SD0
      SM=XM**2
C*** CHECK FOR DETATCHED SHOCK WAVE
      EX=DARSIN(DSQRT((G3*SM-1.0D0+DSQRT(G1*(1.0D0+G5*SM+G4*SM**2D0)))
     1/(G*SM)))
      DX=DATAN((SM*DSIN(EX)**2.0D0-1.0D0)/((G2*SM-SM*DSIN(EX)**2D0+1.D0)
     1*DTAN(EX)))*RAD
      IF(DANG.GT.DX-.3D0) GO TO 95
C*** OBTAIN FIRST ESTIMATE FOR SHOCK WAVE ANGLE
      SLOPE=.77D0
      IF(XM.LT.1.5D0) SLOPE=1.50D0
      EE=DARSIN(1.0D0/XM)+(DANG*SLOPE)/RAD
C*** CALCULATE SHOCK WAVE ANGLE USING NEWTON RAPHSON ITERATION
   92 TND=DTAN(DANG/RAD)
      A=SM*DSIN(EE)**2.0D0-1.0D0
      B=G2*SM-A
      C=2.0D0*SM*DSIN(EE)*DCOS(EE)
      H=1.0D0/((TND*B)**2.0D0+A**2.0D0)
      FE=EE-DATAN(A/(B*TND))
      FEP=1.0D0-C*H*TND*(A+B)
      DE=-FE/FEP
      EE=EE+DE
      IF(DABS(DE).GT.0.00001) GO TO 92
      SHANG=EE*RAD
```

```
C*** FIND CONDITIONS DOWNSTREAM OF SHOCK
      U1N=XM*DSIN(SHANG/RAD)
      U1NS=U1N*U1N
      U2NS=(U1NS+2.0D0/.4D0)/(7.0D0*U1NS-1.0D0)
      U2N=U2NS**.5D0
      T1=T1*(1.0D0+.2D0*U1NS)/(1.0D0+.2D0*U2NS)
      TP1=TP1*(1.0D0+1.4D0*U1NS)/(1.0D0+1.4D0*U2NS)
      IF (DATINP(14,JCX).GT.0.5D0) GO TO 94
      DATINP(3,JCX)=TP1
   94 CONTINUE
      XM=U2N/DSIN((SHANG-DANG)/RAD)
      THETA=T1*1.928008174D-3
      CA=CAZ*DSQRT(THETA)
      VEL=XM*CA
      DELTA=TP1/14.696D0
      GO TO 98
   95 SHOCK=0.D0
 98   WTF(JM1)=DATINP(1,JCX)
      CORFLO(JM1)=WTF(JM1)*DSQRT(T1)/TP1
      WTF(JP1)=WTF(JM1)
      FAR1=DATINP(10,JCX)
      FAR(JM1)=FAR1
      VEL=CA*XM
      RAMP=1.0D0
      T2=T1
      IF(VEL.LE.0.0D0) GO TO 100
      CALL THERMO (T1,TP1,H1,SS,5,RCH,FAR1,ZERO,ZERO,ZERO,0,GAM,ZERO)
      H2=H1+VEL*VEL*1.99708012D-5
      CALL THERMO (T1,TP1,H1,SS,4,RCH,FAR1,T2,H2,TP2,1,GAM,ZERO)
      RAMP=TP2/TP1
  100 R=DATINP(6,JCX)
C*** IF RECOVERY =0 USE AIAA RECOVERY
      IF(R.NE.0.0D0) GO TO 130
  110 IF(XM.GT.1.0D0) GO TO 120
      R=1.0D0
      GO TO 170
  120 IF(XM.GT.5.0D0)GO TO 125
      R=1.0D0-.075D0*((XM-1.0D0)**1.35D0)
      GO TO 130
 125  R=800.D0/(XM**4.0D0+935.0D0)
  130 N1=LOCTBL(6,JCX)
C*** LOOP ON RECOVERY AS A FUNCTION OF EXIT REFERRED FLOW AND MACH
      IF(N1.EQ.0) GO TO 170
      R=DATOUT(7,JCX)
      IF(R.LE.0.0D0) R=1.0D0
      RFMAX=DATINP(7,JCX)
      IF(RFMAX.EQ.0.0D0)RFMAX=1.0D+10
      RFSCAL =DATINP(8,JCX)
      IF(RFSCAL .EQ.0.0D0) RFSCAL =1.0D0
      CONST=RFSCAL *WTF(JP1)*DSQRT(T2)/(TP1*RAMP*1.549695676D0)
      NM=0
  140 RL=R
      CF=CONST/R
C*** CHECK ON MAX REFERRED FLOW INPUT
      IF(CF.GT.RFMAX)CF=RFMAX
      CALL TABLU(N1,CF,XM,0.0D0,R)
```

```
      IF(R.LE.0.0D0) R=.01D0
      NM=NM+1
      IF(NM.LT.20) GO TO 160
      PRINT 150,XM,CF,R
  150 FORMAT(' WARNING RECOVERY HAS FAILED TO CONVERGE  XM= ',D12.5,
     1' CF= ',D12.5,'  R= ',D12.5)
      GO TO 170
  160 IF(DABS(R-RL).GT..0005D0)  GO TO 140
  170 VMACH(JM1)=XM
      TOTEMP(JP1)=T2
      TOPRES(JP1)=RAMP*TP1*R
      FAR(JP1)=FAR1
      CORFLO(JP1)=WTF(JP1)*DSQRT(T2)/TOPRES(JP1)
      DRAG=WTF(JP1)*VEL*3.108099707D-2
      N2=LOCTBL(4,JCX)
      DRAG2=0.0D0
      Q=0.0D0
      IF(XM.EQ.0.0D0) GO TO 180
      Q=1481.354D0*DELTA*XM*XM
      QSF=Q*DATINP(13,JCX)
      DRAG2=QSF*DATINP(4,JCX)
      IF(N2.EQ.0) GO TO 180
      ACAP=DATINP(12,JCX)
      IF(ACAP)175,176,177
  175 CALL THERMO (T1,TP1,H1,SS,5,RCH,FAR1,ZERO,ZERO,ZERO,0,GAM,RINF)
      ACAP=-ACAP
      REF2= WTF(JM1)*RINF*T1*778.161D0/(TP1*VEL*ACAP)
      GO TO 178
  176 ACAP=1.0D0
  177 REF2=CORFLO(JP1)*.6452879849D0/ACAP
  178 CALL TABLU(N2,REF2,XM,0.0D0,DRAG2)
      IF (XM.LT.0.79D0) DRAG2=0.D0
      DRAG2=DRAG2*QSF*ACAP/144.D0
  180 DATOUT(1,JCX)=DRAG+DRAG2
      DATOUT(2,JCX)=VEL
      DATOUT(3,JCX)=Q
      DATOUT(4,JCX)=T2/T1
      DATOUT(5,JCX)=RAMP
      DATOUT(6,JCX)=XM
      DATOUT(7,JCX)=R
      DATOUT(8,JCX)=TOTEMP(JP1)* 1.926008174D-3
      RETURN
      END
CINPRT
      SUBROUTINE INPRT
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JC1ND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
      DIMENSION JCID(2,15)
      REAL*8 IDP(2,9)
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```
      DATA  JC1D/4H  IN,4HLET ,4H DUC,4HT B ,4H  VA,4HLVE ,4HCOMP,4HRESR
     1,4H TUR,4HBINE,4HHEAT,4H EXC,4HSPLI,4HITER,4H  MI,4HXER ,4H NOZ,4H
     2ZLE ,4H  LO,4HAD  ,4H  SH,4HAFT ,4H CON,4HTROL,4HOPT ,4HVAR ,
     3 4HLIMI,4HTER ,4H    ,4H    /
      DATA IDP/
     18HNET THRU,8HST (LBS),8HNET BRAK,8HE SHP       ,
     28HAIRFLOW ,8H(LB/SEC)     ,8HTSFC LB/,8HHR/LB)      ,
     38HBSFC (LB,8H/HR/HP)      ,8HFUEL FLO,8HW(LB/HR)    ,
     48HNT THRUS,8HT/AIRFLW   ,8HNET BSHP,8H/AIRFLOW     ,
     58HINLET DR,8HAG (LBS)     /
      PRINT 130,IDEDAP
      PRINT 10, NOSTAT,NCOMP
   10 FORMAT (10X,20HCONFIGURATION DATA  ,I3,11H STATIONS  ,I3,1X,11HCOM
     1PONENTS ,//,3X,9HCOMPONENT,2X,5HNKIND,1X,9HCOMPONENT,5X,8HUPSTREAM
     2,7X,10HDOWNSTREAM,/,5X,6HNUMBER,11X,4HTYPE,8X,8HSTATIONS,8X,8HSTAT
     3IONS,/)
      DO 30 I=1,NCOMP
      JT=JFIG(1,I)
      PRINT 20, I,JT,(JCID(K,JT),K=1,2),(JFIG(L,I),L=2,5)
   20 FORMAT (6X,I2,7X,I2,3X,2A4,5X,4(I2,6X))
   30 CONTINUE
      IF (NCIS.EQ.0) RETURN
   40 PRINT 50
   50 FORMAT (///,10X,19HCONTROL INFORMATION,/)
      DO 120 I=1,NCIS
      K=KKINDS(12,I+1)
      INDEP=DATINP(4,K)
      IJC=JFIG(4,K)
      DVAL=DATINP(5,K)
      JCV=DATINP(6,K)
      JFIX=JCV/10
      IDEP=JCV-10*JFIX
      IF(JFIX-1)60,80,100
   60 PRINT 70, K,INDEP,IJC,IDEP,JFIG(2,K),DVAL
   70 FORMAT (1X,I2,7X,12HVARY CDAT   ,I2,1X,13HOF COMPONENT ,I2,1X,
     114HSO THAT STATP ,I2,1X,16HOF FLOW STATION ,I2,1X,7HEQUALS ,D12.5)
      GO TO 120
   80 PRINT 90, K,INDEP,IJC,IDEP,JFIG(2,K),DVAL
   90 FORMAT (1X,I2,7X,12HVARY CDAT   ,I2,1X,13HOF COMPONENT ,I2,1X,
     114HSO THAT DATOUT,I2,1X,16HOF COMPONENT    ,I2,1X,7HEQUALS ,D12.5)
      GO TO 120
  100 PRINT 110, K,INDEP,IJC,(IDP(J,IDEP),J=1,2),DVAL
  110 FORMAT (1X,I2,7X,12HVARY CDAT   ,I2,1X,13HOF COMPONENT ,I2,1X,
     1 8HSO THAT ,9X,2A8,9X,7HEQUALS ,D12.5)
  120 CONTINUE
      RETURN
      ENTRY FINPRT
      PRINT 130, IDEDAP
  130 FORMAT (1H1,20A4,//)
      IF(IWAY.EQ.0) GO TO 170
      PRINT 140
  140 FORMAT(1S7,'DESIGN POINT MODE'///)
      DO 160 I=1,NCOMP
      IF(JFIG(1,I).GT.12) GO TO 160
      PRINT 150,I,( DATINP(J,I),J=1,8),1,( DATINP(J,I),J=9,15)
  150 FORMAT(' CDAT(',I2,',1-8 )',3X,8D13.5,/' CDAT(',I2,',9-15)',3X,
```

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     1 7D13.5)
  160 CONTINUE
      PRINT 130,IDEDAP
  170 PRINT 180
  180 FORMAT (50X,28HSTATION PROPERTY OUTPUT DATA,//,5X,4HFLOW,7X,6HWEIG
     1HT,8X,5HTOTAL,8X,5HTOTAL,6X,8HFUEL/AIR,5X,9HREFERRED ,6X,4HMACH,8X
     2 ,6HSTATIC,2X,19HINTERFACE RELATIVE ,/,4X,7HSTATION,6X
     3 ,4HFLOW,7X,8HPRESSURE,4X,11HTEMPERATURE,5X
     4 ,5HRATIO,8X,4HFLOW,8X,6HNUMBER,6X,8HPRESSURE
     5 ,5X,10HFLOW ERROR)
      PRINT 190, ((J),J=1,8)
  190 FORMAT (13X,8(3X,5HSTATP,I1,4X))
      DO 210 I=1,NOSTAT
      REFF=CORFLO(I)*.645287984900
      PRINT 200, I,WTF(I),TOPRES(I),TOTEMP(I),FAR(I),REFF      ,VMACH(I),
     1STATP(I),ERROR(I)
  200 FORMAT (6X,I2,5X,9(D12.5,1X))
  210 CONTINUE
      PRINT 220, ((J),J=1,9)
  220 FORMAT (//,52X,21HCOMPONENT OUTPUT DATA,/,2X,9HCOMPONENT,/,2X,3HNO
     1.,2X,4HTYPE,2X,9(3X,6HDATOUT,I1,3X))
      DO 240 I=1,NCOMP
      JT=JFIG(1,I)
      IF(JT.EQ.12) GO TO 240
      PRINT 230, I,(JCID(L,JT),L=1,2),(DATOUT(K,I),K=1,9)
  230 FORMAT (1X,I2,1X,2A4,1X,9(D12.5,1X))
  240 CONTINUE
      PRINT 250,((J,(IDP(K,J),K=1,2),PERPF(J)),J=1,9)
  250 FORMAT(//,T54,'PERFORMANCE OUTPUTS',/
     1 /,  3X,'(',I1,') ',2A8,F15.2,    3X,'(',I1,') ',2A8,F15.2,
     2     3X,'(',I1,') ',2A8,F15.2,/,  3X,'(',I1,') ',2A8,F15.4,
     3     3X,'(',I1,') ',2A8,F15.4,    3X,'(',I1,') ',2A8,F15.2,
     4 /,  3X,'(',I1,') ',2A8,F15.4,    3X,'(',I1,') ',2A8,F15.2,
     5     3X,'(',I1,') ',2A8,F15.2)
      PRINT 260, NIT,NPASS
  260 FORMAT (//,40X,I3,12H ITERATIONS ,2X,I3,7H PASSES)
      IF (NFINIS.NE.0) PRINT 270
  270 FORMAT(//,10X,30HERROR PRINT *** NO CONVERGENCE)
      RETURN
      END
CMINV
      SUBROUTINE MINV(A,N,DM,L,M)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(225),L(15),M(15)
      NK=-N
      DM=1.0D0
      DO 190 K=1,N
      NK=NK+N
      LB=K
      MB=K
      KK=NK+K
      BIGA=A(KK)
      DO 30 J=K,N
      IZ=N*(J-1)
      DO 30 I=K,N
      IJ=IZ+I
```

```
10 IF(DABS(BIGA)-DABS(A(IJ))) 20,30,30
20 BIGA=A(IJ)
   LB=I
   MB=J
30 CONTINUE
   L(K)=LB
   M(K)=MB
   J=LB
   IF(J-K) 60,60,40
40 KI=K-N
   JI=J-N
   DO 50 I=1,N
   KI=KI+N
   HOLD=-A(KI)
   JI=JI+N
   A(KI)=A(JI)
50 A(JI) =HOLD
60 I=MB
   IF(I-K) 90,90,70
70 JI=N*(I-1)
   JK=NK
   DO 80 J=1,N
   JK=JK+1
   JI=JI+1
   HOLD=-A(JK)
   A(JK)=A(JI)
80 A(JI) =HOLD
90 IF(BIGA) 110,100,110
100 DM=0.0D0
   RETURN
110 BIGAR=1.0D0/BIGA
   DO 130 I=1,N
   IF(I-K) 120,130,120
120 IK=NK+I
   A(IK)=-A(IK)*BIGAR
130 CONTINUE
   IK=NK
   DO 160 I=1,N
   IK=IK+1
   HOLD=A(IK)
   IJ=I-N
   KMI=K-I
   DO 160 J=1,N
   IJ=IJ+N
   IF(I-K) 140,160,140
140 IF(J-K) 150,160,150
150 KJ=IJ+KMI
   A(IJ)=HOLD*A(KJ)+A(IJ)
160 CONTINUE
   KJ=K-N
   DO 180 J=1,N
   KJ=KJ+N
   IF(J-K) 170,180,170
170 A(KJ)=A(KJ)*BIGAR
180 CONTINUE
   DM=DM*BIGA
```

```
      A(KK)=BIGAR
  190 CONTINUE
      K=N
  200 K=(K-1)
      IF(K) 270,270,210
  210 I=L(K)
      IF(I-K) 240,240,220
  220 JK=N*(K-1)
      JI=N*(I-1)
      DO 230 J=1,N
      JK=JK+1
      HOLD=A(JK)
      JI=JI+1
      A(JK)=-A(JI)
  230 A(JI) =HOLD
  240 J=M(K)
      IF(J-K) 200,200,250
  250 KI=K-N
      DO 260 I=1,N
      KI=KI+N
      HOLD=A(KI)
      JI=KI-K+J
      A(KI)=-A(JI)
  260 A(JI) =HOLD
      GO TO 200
  270 RETURN
      END
CMIXER
      SUBROUTINE MIXER
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DIOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCIBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCIS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
C      *****   MODIFIED BY M.T. ABUJELALA      2/79   *****
   10 K=1
      J=JM1
   20 AREA=DATINP(K,JCX)
      TP1=TOPRES(J)
      FAR1=FAR(J)
      T1=TOTEMP(J)
      CALL THERMO (T1,TP1,H1,S1,5,RCH,FAR1,ZERO,ZERO,ZERO,0,GAM3,R1)
      WT1R=WTF(J)
      IF(IWAY.EQ.0) GO TO 50
      IF(K.EQ.2) GO TO 40
      PR=DATINP(J,JCX)
      VM1S=PR*PR
      IF(VM1S.GT.1.0D0) GO TO 40
      TS=T1/(1.0D0+.2D0*VM1S)
   30 CALL THERMO (T1,TP1,ZERO,S1,3,RCH,FAR1,TS,H2,PS,3,GAM,R1)
      VMSC=2.0D0*(H1-H2)/(GAM*R1*TS)
      DM=VM1S-VMSC
```

```
      TS=TS*(1.0D0-.5D0*(GAM-1.0D0)*DM/(1.0D0+.5D0*(GAM-1.0D0)*VM1S))
      IF(DABS(DM/VM1S).GT..00001D0) GO TO 30
      GO TO 60
   40 PS=TP1/PR
      CALL THERMO (T1,TP1,ZERO,S1,1,RCH,FAR1,TS,H2,PS,1,GAM,R1)
      IF(TS-T1)61,62,62
   62 TS=.99999D0*T1
      GO TO 60
   50 CONST=AREA*TP1/(R1*TP1*778.161D0)
      TSMIN=0.0D0
      VM1S=0.0D0
      PS=TP1
      NM=0
      FLOWG=WT1R*DSQRT(R1*778.161D0*T1)/(AREA*TP1)
      IF(FLOWG.LT.1.0D-6) GO TO 150
      GAM=GAM3
      FOURAC=4.0D0*FLOWG/32.174D0*FLOWG/GAM
      ROOT=0.0D0
      IF(FOURAC.LT.1.0D0) ROOT=DSQRT(1.0D0-FOURAC)
      TDEL=(1.0D0-ROOT)*.25D0*(GAM-1.0D0)
      TS =T1*(1.0D0-TDEL)
      CX=0.0D0
   60 CALL THERMO (T1,TP1,ZERO,S1,3,RCH,FAR1,TS,H2,PS,3,GAM,R1)
   61 V1=223.7702D0*DSQRT(H1-H2)
      VM1S=2.0D0*(H1-H2)/(GAM*R1*TS)
      IF(1WAY.EQ.0) GO TO 70
      AREA=WT1R/PS*TS/V1*R1*778.161D0
      IF(AREA.LE.0.0D0) AREA=1.0D20
      DATINP(K,JCX)=AREA
      GO TO 150
C***
C*** COMPUTE  FLOW FOR CHECK WITH INCOMING FLOW
C***
   70 WT1G=PS*CONST*V1/TS
      IF(VM1S.LE.1.0D0) GO TO 90
C***
C***  ITERATION HAS GONE SONIC -FIND STATIC TEMP FOR MACH=1.
C***
      TSMIN=.8333D0*T1
   80 TS=TSMIN
      CALL THERMO (T1,TP1,ZERO,S1,3,RCH,FAR1,TS,HCRIT,ZERO,3,GAM,R1)
      VM3S=2.0D0*(H1-HCRIT)/(GAM*R1*TS)
      Z=.5D0*(GAM-1.0D0)*VM3S
      DM=1.0D0-VM3S
      TSMIN=TSMIN*(1.0D0-Z/(1.0D0+Z)*DM/VM3S)
      IF(DABS(DM).GT..00001D0 ) GO TO 80
      TS=TSMIN+.005D0
      CX=1.0D0
      GO TO 60
   90 WTERR=(WT1R-WT1G)/WT1R
      NM=NM+1
      IF(NM.GT.25) GO TO 110
      IF(DABS(WTERR).LT..0001D0) GO TO 150
C***
C*** UPDATE STATIC TEMP USING INFLUENCE COEFFICIENT
C***
```

```
      FAC=-WTERR*  (GAM-1.0D0)*VM1S/(1.0D0-VM1S)
      IF(CX*WTERR.GT.0.0D0) GO TO 130
      CX=0.0D0
      AFAC=DABS(FAC)
      IF(AFAC.GT..01D0) FAC=.01D0*FAC/AFAC
      TOLD=TS
      TS=TS*(1.0D0+FAC)
      IF(TS .GT.TSMIN) GO TO 100
      TS =.5D0*(TSMIN+TOLD)
      GO TO 60
  100 IF(TS .GT.T1) TS =.99D0*T1+.01D0*TOLD
      GO TO 60
  110 PRINT 120,JCX
  120 FORMAT(' MACH NUMBER ITERATION HAS FAILED  '' COMPONENT ',I2)
      GO TO 150
  130 PRINT 140,J
  140 FORMAT(10X,41HWARNING *** VELOCITY IS SONIC AT STATION ,I2)
  150 PR=TP1/PS
      SPMIX=TP1/PR
      VMACH(J)=DSQRT(VM1S)
      STATP(J)=SPMIX
      DATOUT(K,JCX)=AREA
      DATOUT(K+2,JCX)=PR
      DATOUT(K+4,JCX)=V1
      S2=S1
      IF(K.EQ.2) GO TO 160
      K=2
      SP1=SPMIX
      J=JM2
      PR=TOPRES(J)/SPMIX
      W12=WT1R
      VID=WT1R*V1
      H12=H1*WT1R
      AIR12=WT1R/(1.0D0+FAR1)
      FAR12=FAR1*AIR12
      HS=H1
      SIN=S2*WT1R
      GO TO 20
  160 SPAVG=.5D0*(SPMIX+SP1)
      DATOUT(8,JCX)=(SPMIX-SP1)/SPAVG
      SPMIX=SPAVG
      W12=W12+WT1R
      IF(W12.GT.0.0D0) GO TO 170
      H12=.5D0*(H1+HS)
      GO TO 180
  170 AIR2=WT1R/(1.0D0+FAR1)
      AIR12=AIR12+AIR2
      FAR12=(FAR12+FAR1*AIR2)/AIR12
      W12R=1.0D0/W12
      SIN=(SIN+S2*WT1R)*W12R
      H12=(H12+H1*WT1R)*W12R
      VID=(VID+V1*WT1R)*W12R
      H31=H12-VID*VID*1.99708D-5
  180 CALL THERMO (T1,TP1,ZERO,SIN,4,KCH,FAR12,T12,H12,P12,1,GAM,R1)
      V12=VID*DATINP(4,JCX)
      H32=H12-V12*V12*1.99708D-5
```

```
      CALL THERMO (T12,P12,ZERO,SIN,4,RCH,FAR12,T32,H31,P32,1,GAM,R12)
      CALL THERMO (T32,SPMIX,H32,SOUT,6,RCH,FAR12,ZERO,ZERO,ZERO,0,GAM,
     1R12)
      PMIX=SPMIX*P12/P32
      IF(SOUT.LT.SIN) PMIX=P12
      DATOUT(9,JCX)=PMIX/SPMIX
      DATOUT(7,JCX)=V12
      TOTEMP(JP1)=T12
      TOPRES(JP1)=PMIX
      CORFLO(JP1)=W12*DSQRT(T12)/PMIX
      FAR(JP1)=FAR12
      WTF(JP1)=W12
      RETURN
      END
CNEPSUB
      SUBROUTINE NEPSUB
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER CWD,DWD
      COMMON/NEPOPT/SELAST,DD,NDSET,NPARTS,IOPTP,NPASSO,NVOPT,NJOPT,
     1TOLOPT,NOPT
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
      COMMON/TABLE/ITAB(50),NTBL
      DIMENSION F1(15),F2(15),CR2(15),CR3(15),T(225),V(15),XSA(15)
      DIMENSION IDCK(8),IDCE(8),IDCC(32),LMINV(15),MMINV(15),ICARD(15)
      DIMENSION JCACT(15)
      DIMENSION CDAT(15,40)
      DIMENSION ISET(74),IBUG(14)
      EQUIVALENCE(DATINP(1,1),CDAT(1,1))
C*** SPECIAL COMMON FOR INSTALLATION
      COMMON/QIN/TDEL,XMA,ALT,WMAX,PUNCHO,TIT,JCB,JN1,JN2,IDESN,IPRINT,
     2 JCAB2,JCAB1,NP,NM
      DIMENSION XMA(16),TDEL(7)
      NAMELIST/D/NCOMP,NOSTAT,IDESN,IPRINT,TITLE,TABLES,FIGSET,ENDRUN,
     1 JFIG,CDAT,NP,TDEL,XMA,NM,ALT,JCB,JN1,JN2,JCAB1,JCAB2,WMAX,TIT,
     2 IOPTP,NVOPT,NJOPT,TOLOPT,PUNCHO
      DATA IDCK /1,4,5,6,8,9,11,12/
      DATA IDCE / 1,11,21,24,27,29,30,32/
      DATA IDCC /1,3,4,5,6,7,8,9,12,13,14,1,3,4,5,6,7,8,11,12,13,
     1  3,4,5,1,2,4,1,5,1,4,6/
      DATA CWD,DWD /'D E',' S'/
C     TITLE=0.0D0
C     TABLES=0.0D0
C     FIGSET=1.0D0
C     ENDSET=0.0D0
C     NVOPT=0
C     IDESN=0
C     NJOPT=0
C     IOPTP=0
C     IPRINT=0
```

```
C       TOLOPT=.0002D0
C       ENDRUN=0.0D0
C1      READ (5,100,ERR=5,END=5)(ICARD(K),K=1,15)
C       WRITE(6,100)(ICARD(K),K=1,15)
C       GO TO 1
C5      REWIND 5
C***    CLEAR INPUT,OUTPUT WITH NEW CONFIGURATION READ IN
        PRINT 10
   10   FORMAT(1H1,////////////,50X,'NAVAL AIR DEVELOPMENT CENTER',//)
        PRINT 40
   40   FORMAT(//,41X,'MNEP       NAVY ENGINE PERFORMANCE COMPUTER CODE',
       1/52X,'VERSION II IBM 360  ')
        DO 15 I=1,15
        DO 15 J=1,40
        CDAT(I,J)=0.0D0
   15   DATINP(I,J)=0.0D0
        DO 20 I=1,9
        DO 20 J=1,40
        DATOUT(I,J)=0.0D0
   20   LOCTBL(I,J)=0
        DO 25 I=1,5
        DO 25 J=1,40
   25   JFIG(I,J)=0
        DO 30 I=1,15
        DO 30 J=1,25
   30   KKINDS(I,J)=0
        DO 45 I=1,50
        JCOMP(I)=0
   45   JFLOW(I)=0
        DO 50 I=1,30
        WTF(I)=0.0D0
        TOPRES(I)=0.0D0
        TOTEMP(I)=0.0D0
        FAR(I)=0.0D0
        CORFLO(I)=0.0D0
        VMACH(I)=0.0D0
        STATP(I)=0.0D0
   50   ERROR(I)=0.0D0
        DO 60 K=1,12
   60   PERPF(K)=0.0D0
        IWAY=0
        TOL=0.0D0
        TOLT=0.0D0
        TOLTT=0.0D0
        XSCM=.10D0
        TOL=.0005D0
        TOLTT=.001D0
        NTBL=0
        ENTRY  NPREAD
        SELAST=0.0D0
    70  IR=0
        PRINT 80
    80  FORMAT(/,      ' NAMELIST INPUT CARDS FOR NEXT SOLUTION')
C100    FORMAT(A2,A3,A3,12A6)
  140   READ (5,D)
        PRINT 160
```

```
  160 FORMAT(1X)
      IF(ENDRUN.EQ.1.0D0) STOP
      IF(TITLE.EQ.1.0D0) READ (5,170)IDEDAP
  170 FORMAT(20A4)
      TITLE=0.0D0
      ITPRT=TABLES-1.0D0
      IF(TABLES.NE.0.0D0) CALL TABRD(ITPRT,XD,YD,ZD,FXYZ)
      IF(FIGSET.EQ.0.0D0) GO TO 230
      TABLES=0.0D0
      CALL CONFIG
      FIGSET=0.0D0
C****    QUICK CHECK OF CDAT INPUTS
      IS=1
      DO 210 I=1,8
      JT=IDCK(I)
      NT=KKINDS(JT,1)
      IE=IDCE(I)
      IF(NT.EQ.0) GO TO 210
      DO 200 J=1,NT
      JCX=KKINDS(JT,J+1)
      CK=1.0D0
      DO 180 K=IS,IE
      IDCCK=IDCC(K)
  180 CK=CK*DATINP(IDCCK  ,JCX)
      IF(CK.EQ.0.0D0) PRINT 190,JCX
  190 FORMAT(' WARNING ONE OR MORE NORMALLY NON ZERO CDAT INPUTS TO COMP
     1ONENT ',I2,' IS ZERO')
  200 CONTINUE
  210 IS=IE+1
      DO 215 I=1,9
      DO 215 J=1,40
      DATOUT(I,J)=0.0D0
  215 LOCTBL(I,J)=0
      DO 220 I=1,30
      WTF(I)=0.0D0
      TOPRES(I)=0.0D0
      TOTEMP(I)=0.0D0
      FAR(I)=0.0D0
      CORFLO(I)=0.0D0
  220 VMACH(I)=0.0D0
  230 RETURN
      ENTRY GOMEP
      IF(NTBL.EQ.0) GO TO 260
      DO 250 J=1,NCOMP
      DO 250 I=1,9
      LOCTBL(I,J)=0
      DATIN=CDAT(I,J)
      DO 240 N=1,NTBL
      TABL=ITAB(N)
      IF(TABL.EQ.DATIN) LOCTBL(I,J)=N
  240 CONTINUE
  250 CONTINUE
  260 IWAY=IDESN
      IF(IWAY.NE.0.) IWAY=-1
      NCTS=KKINDS(12,1)
      N=0
```

```
      IF(NCTS.LE.0) GO TO 290
      DO 280 I=1,NCTS
      JCX=KKINDS(12,I+1)
      ETOL=CDAT(1,JCX)
      IF(ETOL.LE.0.0D0) GO TO 270
      N=N+1
      JCIND(N)=JFIG(4,JCX)
      JCDEP(N)=JFIG(2,JCX)
      JCVIND(N)=DATINP(4,JCX)
      DEPV(N)=DATINP(5,JCX)
      IF(ETOL.EQ.1.0D0) ETOL=TOL
      DTOL(N)=ETOL
      JCV=CDAT(6,JCX)
      JFIX=JCV/10
      KDTYP(N)=JFIX-1
      JCVDEP(N)=JCV-10*JFIX
      JCACT(N)=JCX
      NI=JCVIND(N)
      NJ=JCIND(N)
      IF(DATOUT(1,JCX).NE.0.0D0) DATINP(NI,NJ)=DATOUT(1,JCX)
      GO TO 280
  270 DATOUT(1,JCX)=0.0D0
  280 CONTINUE
  290 NCTS=N
      NPASS=0
      NIT=0
      SE=0.0D0
C*** MOD
      SE=SELAST
      GO TO 520
  300 IF(SELAST) 430,430,310
  310 SRATIO=SE/SELAST
      IF(SRATIO.GT.,6D0)GO TO 330
  320 NSET=0
      GO TO 470
  330 IF(NIT)340,470,340
  340 IF(SRATIO.GT.1.0D0)GO TO 350
      GO TO 370
  350 IF(NSET.EQ.1)GO TO 360
      GO TO 370
  360 NSET=0
      GO TO 430
  370 CT=0.0D0
      NSET=1
      IF(IPRINT .GT.1) PRINT 380
  380 FORMAT(32H BROYDEN'S METHOD NOW BEING USED)
      DO 390 I=1,NCTS
      NI=JCVIND(I)
      NJ=JCIND(I)
  390 V(I)=(DATINP(NI,NJ)-XSA(I))/SCM
      DO 410 I=1,NCTS
      C1=0.0D0
      C2=0.0D0
      K=I-NCTS
      L=NCTS*(I-1)
      DO 400 J=1,NCTS
```

```
      K=K+NCTS
      L=L+1
      C1=C1+T(K)  *(F1(J)-F2(J))
  400 C2=C2+V(J)*T(L)
      CR2(I)=C2
      CR3(I)=V(I)*SCM-C1
  410 CT=CT+C2*(F1(I)-F2(I))
      DO 420 I=1,NCTS
      CONST=CR3(I)/CT
      K=I-NCTS
      DO 420 J=1,NCTS
      K=K+NCTS
  420 T(K)  =CONST*CR2(J)+T(K)
      GO TO 470
  430 JP=0
      DO 450 I=1,NCTS
      NJCXI=JCIND(I)
      NIND=JCVIND(I)
      X1=DATINP(NIND,NJCXI)
      DEL=TOLTT*X1
      IF(DEL.EQ.0.0D0) DEL=TOLTT
      X2=X1+DEL
      DATINP(NIND,NJCXI)=X2
      CALL FLOCAL(NJCXI,SS,F2)
      IF(IPRINT.GT.2) CALL FINPRT
      DATINP(NIND,NJCXI)=X1
      DO 440 II=1,NCTS
      JP=JP+1
  440 T(JP)  =(F2(II)-F1(II))/DEL
C*****SPECIAL PRINTOUT OF PARTIAL MATRIX
C*****
C 440 PRINT 441,II,F2(II),F1(II),T(JP)
  441 FORMAT(I3,3(2X,E20.14))
  450 CONTINUE
      CALL MINV(T,NCTS,DET,LMINV,MMINV)
C***  ADD TO  NEP
      NPARTS=1
      IF(DET.EQ.0.0D0) PRINT 460
  460 FORMAT(' MATRIX NO GO')
  470 DO 490 I=1,NCTS
      DXX=0.0D0
      K=I-NCTS
      DO 480 J=1,NCTS
      K=K+NCTS
  480 DXX=DXX-T(K)  *F1(J)
      F2(I)=F1(I)
  490 V(I)=DXX
      XMAX=0.0D0
      DO 500 J=1,NCTS
      NIND=JCVIND(J)
      NJCXI=JCIND(J)
      XBAR=DATINP(NIND,NJCXI)
      IF(DABS(XBAR).LT.XSCM) XBAR=XSCM
      XMAX1=DABS(V(J)/XBAR)
      IF (XMAX1.GT.XMAX) XMAX=XMAX1
  500 CONTINUE
```

```
      SCM=1.0D0
      IF (XMAX.GT.XSCM) SCM=XSCM/XMAX
      DO 510 K=1,NCTS
      NIND=JCVIND(K)
      NJCXI=JCIND(K)
      XSA(K)=DATINP(NIND,NJCXI)
  510 DATINP(NIND,NJCXI)=DATINP(NIND,NJCXI)+V(K)*SCM
      NIT=NIT+1
  520 SELAST=SE
      ITL=0
      CALL FLOCAL(ITL,SE,F1)
      IF(IPRINT.GT.1) PRINT 530,SE
  530 FORMAT(20H SUM OF (ERRORS**2)=,D12.5)
      IF(IPRINT.NE.3) GO TO 550
      PRINT 540,SELAST,SE,SCM, SRATIO,XMAX
  540 FORMAT(1X,5D12.5)
      CALL FINPRT
  550 IF(NFINIS.EQ.0) GO TO 560
      IF(NIT.LT.50) GO TO 300
  560 IF(IPRINT.GT.1) CALL FINPRT
      IF(NFINIS.NE.0) RETURN
      IF(NCTS.EQ.0) RETURN
      DO 570 I=1,NCTS
      JCX=JCACT(I)
      NI=JCVIND(I)
      NJ=JCIND(I)
  570 DATOUT(1,JCX)=DATINP(NI,NJ)
      RETURN
      END
CNOZZLE
      SUBROUTINE NOZZLE
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
C       *****   MODIFIED BY M.T. ABUJELALA      2/79   *****
      TP1=TOPRES(JM1)
      SPE=DATINP(4,JCX)
      JINL=DATINP(9,JCX)
      IF(JINL.LE.0) JINL=1
      IF(SPE.GT.0.0D0)GO TO 10
      SPE=DATINP(3,JINL)
C** DEFAULT PO IS AT FIRST COMPONENT     MUST BE INLET
   10 T1=TOTEMP(JM1)
      FAR1=FAR(JM1)
      PTOPA=TP1/SPE
      TPOPA=PTOPA
      CD=DATINP(2,JCX)
      IF(CD.LE.0.0D0) CD=1.0D0
      AREA=DATINP(1,JCX)
      TS1=.8333D0*T1
```

```
      IP=0
   20 IP=IP+1
      IF(IP.GT.10) GO TO 30
      TS=TS1
      CALL THERMO (T1,TP1,H1,S1,3,RCH,FAR1,TS,ZERO,ZERO,0,GAM,R1)
      TS1=T1/(1.0D0+(GAM-1.0D0)*.5D0)
      IF (DABS(TS-TS1).GT..01D0) GO TO 20
   30 PCRIT=(2.0D0/(GAM+1.0D0))**(GAM/(1.0D0-GAM))
      CALL THERMO (T1,TP1,H1,S1,5,RCH,FAR1,ZERO,ZERO,ZERO,0,GAM,R1)
      SPT=SPE
      NCD=LOCTBL(2,JCX)
      IF(NCD.GT.0) CALL TABLU(NCD,PTOPA,0.0D0,0.0D0,CD)
      PR=PTOPA
      DRAGN=0.0D0
      SIGN=1.0D0
      IF(PR.GT.1.0D0) GO TO 40
      SPT=TP1*PR
      PR=1.0D0/PR
      SIGN=-1.0D0
      PTOPA=PR
   40 IF (PR.LE.PCRIT)  GO TO 50
      PR=PCRIT
      VM1=1.0D0
      SPT=TP1/PR
   50 TP2=TP1/PR
      MUF=DATINP(12,JCX)
      IF(DATINP(6,JCX).NE.0.D0) MUF=1
      CALL THERMO (T1,TP1,H1,S1,1,RCH,FAR1,T2,H2,TP2,MUF,GAMS,R1)
      V1=223.7702D0*DSQRT(H1-H2)*SIGN
      SPVOL=778.161D0*R1*T2/SPT
      IF(IWAY+DATINP(7,JCX).LE.0.0D0) GO TO 60
      WT1R=WTF(JM1)
      AREA=WT1R*SPVOL/(V1*CD)
      IF(IWAY.NE.0) DATINP(1,JCX)=AREA
      GO TO 70
   60 WT1R=AREA*V1*CD/SPVOL
   70 CORFR=WT1R*DSQRT(T1)/TP1
      IF(PR.EQ.PCRIT)GO TO 80
      VM1=DSQRT((T1/T2-1.0D0)*2.0D0/(GAMS-1.0D0))
   80 VS=V1/VM1
      STATP(JM1)=SPT
      IF(DATINP(6,JCX).NE.0.0D0)GO TO 90
      VIDEAL=V1
      VE=VS
      PROUT=PR
      GO TO 100
C     CD NOZZLE *** FULL EXPANSION
   90 PROUT=PTOPA
      MUF=DATINP(12,JCX)
      TP4=TP1/PROUT
      CALL THERMO (T2,TP2,ZERO,S1,1,RCH,FAR1,T4,H4,TP4,MUF,GAM4,R1)
      VIDEAL=223.7702D0*DSQRT(H1-H4)*SIGN
      VE=VS*DSQRT(GAM4*T4/(GAMS*T2))
      SPT=SPE
  100 CV=DATINP(5,JCX)
      NCV=LOCTBL(5,JCX)
```

```
      NCA=LOCTBL(8,JCX)
      ALATH=DATINP(8,JCX)
      ARAT=AREA/DATINP(1,JCX)
      IF(NCA.GT.0) CALL TABLU(NCA,ARAT,0.0D0,0.0D0,ALATH)
      IF(NCV.GT.0) CALL TABLU(NCV,PROUT,ALATH,0.0D0,CV)
      VACT=CV*VIDEAL
      FG=(WT1R*VACT*3.108099707D-2)*SIGN+AREA*(SPT-SPE)
      Q=DATOUT(3,JINL)
      IF(Q.EQ.0.0D0) GO TO 110
      DRAGN=DATINP(3,JCX)
      NND=LOCTBL(3,JCX)
      IF(NND.GT.0) CALL TABLU(NND,PTOPA,DATOUT(6,JINL),0.0D0,DRAGN)
      DRAGN=DRAGN*Q*DATINP(10,JCX)*DATINP(11,JCX)*AREA/144.D0
  110 VMACH(JM1)=V1/VS
      WTF(JM1)=WT1R
      CORFLO(JM1)=CORFR
      TOTEMP(JP1)=T1
      TOPRES(JP1)=TP1
      WTF(JP1)=WT1R
      CORFLO(JP1)=CORFR
      FAR(JP1)=FAR1
      VMACH(JP1)=VACT/VE
      STATP(JP1)=SPE
      DATOUT(1,JCX)=FG
      DATOUT(2,JCX)=VACT
      DATOUT(3,JCX)=PROUT
      DATOUT(4,JCX)=VIDEAL
      DATOUT(5,JCX)=AREA
      DATOUT(6,JCX)=CD
      DATOUT(7,JCX)=CV
      DATOUT(8,JCX)=DRAGN
      DATOUT(9,JCX)=TPOPA
      RETURN
      END
CSNEST0
      SUBROUTINE SNEST(N,DY,X,DELX,TOL,ABDS,DYL,ABDYL,XCHECK,XLOC)
      IMPLICIT REAL*8(A-H,O-Z)
C** NEW FORM OF SOLVER
C*** MAY BE USED WITH NESTED ITERATIONS
      ABDY=DABS(DY)
      IF(ABDY-TOL)140,140,10
   10 IF(N)30,20,30
   20 ABDS=DABS(DELX)*2.0D0
      GO TO 100
   30 IF(X-XCHECK)40,50,40
   40 DELX=-.5D0*(DELX+X-XCHECK)
      GO TO 100
   50 IF(ABDY-ABDYL)70,100,60
   60 ABDS=ABDS*.5D0
   70 DF=DYL-DY
      IF(DF)80,100,80
   80 DELX=DY*DELX/DF
      ABD=DABS(DELX)
      IF(ABD-ABDS)100,100,90
   90 DELX=ABDS*DELX/ABD
  100 DYL=DY
```

```
      N=N+1
      X=X+DELX
      XCHECK=X
      ABDYL=ABDY
      IF(N-30)110,120,120
  110 RETURN
  120 WRITE (   6   ,130) N,XLOC
  130 FORMAT(1X,25HNO CONVERGENCE IN SOLVER ,I3,19H TRYS**CALLED FROM ,
     1A8)
  140 N=0
      RETURN
      END
CSPLITR
      SUBROUTINE SPLITR
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERPF(12),TOL,TOLT,TOLTT
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
      T1=TOTEMP(JM1)
      TP=TOPRES(JM1)
      TOTEMP(JP1)=T1
      TOTEMP(JP2)=T1
      CF1=CORFLO(JM1)
      DMAIN=DATINP(2,JCX)
      DBYPS=DATINP(3,JCX)
      N2=LOCTBL(2,JCX)
      N3=LOCTBL(3,JCX)
      IF(N2.NE.0) CALL TABLU(N2,CF1,0.0D0,0.0D0,DMAIN)
      TPM=TP*(1.0D0-DMAIN)
      IF(N3.NE.0) CALL TABLU(N3,CF1,0.0D0,0.0D0,DBYPS)
      TPB=TP*(1.0D0-DBYPS)
      FAR(JP1)=FAR(JM1)
      FAR(JP2)=FAR(JM1)
      TROOT=DSQRT(T1)
      B=DATINP(1,JCX)
      IF(B.LT.0.0D0) B=0.0D0
      WTF(JP1)=WTF(JM1)/(B+1.0D0)
      WTF(JP2)=WTF(JM1)-WTF(JP1)
      TOPRES(JP1)=TPM
      TOPRES(JP2)=TPB
      CORFLO(JP1)=WTF(JP1)*TROOT/TPM
      CORFLO(JP2)=WTF(JP2)*TROOT/TPB
      DATOUT(1,JCX)=B
      RETURN
      END
CSPLNQ
      FUNCTION  SPLNQ1     (NLOC,X,XINDEP)
      IMPLICIT REAL*8(A-H,O-Z)
C*** LOCAL CUBIC FIT   8/9/77  M.J. CADDY
      DIMENSION X(1100),QM(3)
      EQUIVALENCE (QM(1),T3),(QM(2),Q2),(QM(3),Q3)
```

```
      XIN=XINDEP
      NS=NLOC
      NOPTS=X(NS)
      ID=NS+NOPTS
      NSP1=NS+1
      NSP2=NS+2
      IF(NOPTS.LE.1) GO TO 130
      IF(NOPTS.GT.2) GO TO 10
      N=ID+NOPTS
      T3=(X(N)-X(N-1))/(X(ID)-X(ID-1))
      M=ID
      NTRAP=1
      GO TO 280
   10 NS2=NOPTS*2+NSP1
      L=X(NS2)
      LSC=NS2+1
      IQMODE=X(LSC)
      K=L+NS
      NL=NSP1
      NH=ID
      NTRAP=-1
C*** BINARY SEARCH FOR INTERVAL
      IF(XIN-X(ID))30,140,20
   20 NTRAP=0
      GO TO 150
   30 IF(XIN-X(NSP1))40,40,60
   40 NTRAP=1
   50 K=NSP2
      GO TO 160
   60 IF(L)120,120,70
   70 IF(XIN-X(K))80,100,100
   80 NH=K
      K=K-1
   90 IF(XIN-X(K))110,100,100
  100 NL=K
      GO TO 120
  110 NH=K
  120 K=(NH-NL)/2+NL
      IF(K-NL)90,140,90
  130 YOUT=X(NSP2)
      GO TO 320
  140 LFAST=L-NH+NS
      X(NS2)=NH-NS
  150 K=NH
  160 M=K
      N=M+NOPTS
      Y3=X(N-1)
      X3=X(M-1)
C*** CHECK FOR FAST MODE AND  EXTRAPOLATION
      IF(NTRAP.GE.0) GO TO 180
      IF(IQMODE*L.EQ.0.OR.LFAST.NE.0) GO TO 180
      DO 170 I=1,3
  170 QM(I)=X(LSC+I)
      GO TO 310
  180 Y4=X(N)
      X4=X(M)
```

```
      A3=X4-X3
      S3=(Y4-Y3)/A3
      IF(M.EQ.NSP2) GO TO 190
      X2=X(M-2)
      Y2=X(N-2)
      S2=(Y3-Y2)/(X3-X2)
      IF(M.EQ.ID) GO TO 200
  190 X5=X(M+1)
      Y5=X(N+1)
      S4=(Y5-Y4)/(X5-X4)
      IF(M.EQ.NSP2)   S2=S3+S3-S4
      GO TO 210
  200 S4=S3+S3-S2
  210 IF(M.LE.(NSP2+1))    GO TO 220
      S1=(Y2-X(N-3))/(X2-X(M-3))
      GO TO 230
  220 S1=S2+S2-S3
  230 IF(M.GE.(ID-1))    GO TO 240
      S5=(X(N+2)-Y5)/(X(M+2)-X5)
      GO TO 250
  240 S5=S4+S4-S3
  250 W2=DABS(S4-S3)
      W3=DABS(S2-S1)
      SW=W2+W3
      IF(SW.NE.0.0D0)     GO TO 260
      W2=0.5D0
      W3=0.5D0
      SW=1.0D0
  260 T3=(W2*S2+W3*S3)/SW
      W3=DABS(S5-S4)
      W4=DABS(S3-S2)
      SW=W3+W4
      IF(SW.NE.0.0D0)    GO TO 270
      W3=0.5D0
      W4=0.5D0
      SW=1.0D0
  270 T4=(W3*S3+W4*S4)/SW
      IF(NTRAP.LT.0) GO TO 290
      IF(NTRAP.EQ.0) T3=T4
  280 IX=M-NTRAP
C*** FAST EXIT FOR 2 POINTS AND LINEAR EXTRAPOLATION
      YOUT=X(IX+NOPTS)+(XIN-X(IX))*T3
      GO TO 320
  290 Q2=(2.0D0*(S3-T3)+S3-T4)/A3
      Q3=(-S3-S3+T3+T4)/(A3*A3)
      IF(IQMODE*LFAST.EQ.0) GO TO 310
      DO 300 I=1,3
  300 X(LSC+I)=QM(I)
  310 DX=XIN-X3
      YOUT=Y3+DX*(T3+DX*(Q2+DX*Q3))
  320 SPLNQ1=YOUT
      RETURN
      END
CTABRD
      SUBROUTINE TABRD (II,X,Y,Z,FXYZ)
      IMPLICIT REAL*8(A-H,O-Z)
```

```
C  REVISED  9/76  MJC,DBK
      INTEGER EWD,FWD
      COMMON /TSIZE/TDATA(3000),NMAX
      COMMON/TABLE/ITAB(50),NTBL
      DIMENSION A(100),IREP (30),IDD(4),LOCTB(30)
      DATA EWD /'    '/
      DATA FWD /'EOT '/
C     NTABL=0
C     NMAX=3000
      MR=0
      IF(NTBL.NE.0) GO TO 20
      LOC=1
      DO 10 M=1,NMAX
   10 TDATA(M)=0.0D0
   20 READ (5,30) IP,ITABNO
   30 FORMAT (I1,I4,70H
     1                    )
      IF(ITABNO.EQ.0) GO TO 100
      NTBL=NTBL+1
      ITAB(NTBL)=ITABNO
      LOCTB(NTBL)= LOC
      IF(NTBL.LE.1) GO TO 150
      DO 40 I=2,NTBL
      IF(ITABNO.EQ.ITAB(I-1))  GO TO 50
   40 CONTINUE
      GO TO 150
   50  MLOC=LOCTB(I-1)
      ILOC=MLOC
      LOCTB(I-1)=LOC
      NTBL=NTBL-1
      MR=MR+1
      IREP(MR)=ITABNO
      LIBLOC=100000
      DO 60 IRK=1,NTBL
      LIBRA=LOCTB(IRK)
      IF((LIBRA.GE.MLOC).AND.(LIBRA.LT.LIBLOC)) LIBLOC=LIBRA
   60 CONTINUE
      LEO=LIBLOC-MLOC
      IF(LEO.EQ.0)  GO TO 89
      IZAR=LOC-1
      DO 70 I=LIBLOC,IZAR
      TDATA(MLOC)=TDATA(I)
   70 MLOC=MLOC+1
      DO 80 I=1,NTBL
      LLOC=LOCTB(I)
      IF(LLOC.GT.ILOC) LOCTB(I)   =LLOC-LEO
   80 CONTINUE
   89 DO 90 I=MLOC,LOC
   90 TDATA(I)=0.0D0
      LOC=MLOC
      GO TO 150
  100 NREM=NMAX-LOC
      IF(II.LE.0) GO TO 135
      PRINT 110,NTBL
  110 FORMAT (1H1,35X,24HTABLE DATA INPUT SUMMARY,1XI2,1X,6HTABLES,//,28
     1X,48HTABLE NUMBER  REFERENCE NUMBER    ARRAY LOCATION )
```

```
      PRINT 120, ((N,ITAB(N),LOCTB(N)),N=1,NTBL)
  120 FORMAT (32X,I2,12X,I5,15X,I5)
      PRINT 130, NMAX,NREM
  130 FORMAT (//,35X,24HDATA STORAGE ALLOCATION ,I5,/35X,24HDATA STORAGE
     1 NOT USED    ,I5,/)
  135 IF(MR.GT.0) PRINT 140,(IREP(IQ),IQ=1,MR)
  140 FORMAT(10X,'THE FOLLOWING TABLES HAVE BEEN REPLACED',10(I5,','))
      RETURN
  150 IF(II.LE.0) GO TO 170
      IP=1
      PRINT 30, IP,ITABNO
      PRINT 160
  160 FORMAT(//////)
  170 ICC=0
      LZ=LOC
      DO 180 ICL=1,4
  180 IDD(ICL)=END
      ID=0
  190 IDL=ID
      READ (5,200)ID,N,(A(I),I=1,N)
  200 FORMAT(A4,I3,3X,(T11,7F10.0))
      IF(ID.EQ.FWD )GO TO 20
      ICC=ICC+1
      IF(ICC.LE.4) IDD(ICC)=ID
      IF(ID.EQ.IDL) GO TO 280
      IF(ID.NE.IDD(4)) GO TO 210
      IF(IDL.EQ.IDD(2)) GO TO 280
      LOC=LE
      L=LX
      GO TO 220
  210 TDATA(LOC)=N
      L=LOC
      IF(ID.EQ.IDD(3)) LX=L
      IF(ID.NE.IDD(2)) GO TO 260
      LY=L
      LZ=LZ+1
      GO TO 260
  220 IF(IP.EQ.0) GO TO 260
      LY=LY+1
      PRINT 230,IDD(1),TDATA(LZ),IDD(2),TDATA(LY)
  230 FORMAT(1X,A4,1H=,D13.5,1X,A4,1H=,D13.5)
      JF=0
      M=N
      LF=LX
  240 NP=M
      IF(M.GT.8)NP=8
      M=M-NP
      LE=LF+NP
      LF=LF+1
      PRINT 250,IDD(3),(TDATA(I),I=LF,LE)
  250 FORMAT(20X,A4,1X,8D13.5)
      LF=LE
      JE=JF+NP
      JF=JF+1
      PRINT 250,IDD(4),(A(I),I=JF,JE)
      JF=JE
```

```
      IF(M.GT.0) GO TO 240
  260 DO 270 I=1,N
      LOC=LOC+1
  270 TDATA(LOC)=A(I)
      LE=LOC
      IF(ID.EQ.IDD(4)) TDATA(LOC+2)=1.0D0
      LOC=L+3*N+3
      IF(LOC.GT.NMAX) GO TO 300
      GO TO 190
  280 TDATA(LOC)=TDATA(LX)
      L=LOC
      DO 290 I=1,N
      LOC=LOC+1
  290 TDATA(LOC)=TDATA(LX+I)
      GO TO 220
  300 PRINT 310, ITABNO
  310 FORMAT (1X,32H**********TABLE OVER FLOW ,TABLE ,I5,11H NOT LOADED)
      GO TO 100
      ENTRY TABLU(II,X,Y,Z,FXYZ)
      IF(II.LE.0) RETURN
      IZ=LOCTB(II)
      INZ=TDATA(IZ)
      IY=3*INZ+IZ+3
      IX=IY
      IZ1=IZ+INZ+1
      IZ2=IZ+2*INZ
      DO 330 IZS=IZ1,IZ2
      INY=TDATA(IY)
      IX=3*INY+IX+3
      IY1=IY+INY+1
      IY2=IY+2*INY
      DO 320 IYS=IY1,IY2
      TDATA(IYS)=SPLNQ1(IX ,TDATA,X)
  320 IX=IX+3*TDATA(IX)+3
      TDATA(IZS)=SPLNQ1(IY,TDATA,Y)
  330 IY=IX
      FXYZ=SPLNQ1(IZ,TDATA,Z)
  340 RETURN
      END
      SUBROUTINE THERMO(TEMP,P,H,S1,IDD,RCH,REQ,T2,HI,P2,MUF,GAM,RR)
C      THERMODYNAMIC PROPERTIES OF HYDROCARBON-AIR COMBUSTION PRODUCTS
C  X(1)    X(2) X(3) X(4) X(5) X(6) X(7) X(8) X(9) X(10) X(11) X(12)
C  H2O     CO2    O2    H2   N2    AR    O     H     CO     OH     NO      N
      IMPLICIT REAL *8(A-H,O-Z)
      COMMON /ARAS/ SHOCK,ABU,TAH
      REAL *8 M,MT,K1,K2,K3,K4,K5,K6,K7,K8,K9,K10
      DIMENSION IT(16),MT(12),X(12),Y(99),F(99),CP1(16,2),CP2(16,10),
     1Z(99),TY(99),TG(31),HT1(16,5),HT2(16,7),ST1(16,5),ST2(16,7)
C    ****  THERMODYNAMIC PROPERTIES OF PURE CONSTITUENTS ******
      DATA MT /18.016D0,44.01D0,32.00D0,2.016D0,28.016D0,
     139.944D0,16.000D0,1.008D0,28.01D0,17.008D0,30.008D0,14.008D0/
      DATA TT /0.D0,200.D0,400.D0,600.D0,800.D0,1000.D0,1300.D0,
     11600.D0,2000.D0,2500.D0,3000.D0,3500.D0,4000.D0,5000.D0,6000.D0,
     27000.D0/
      DATA HT1 /-51727.D0,-51100.D0,-50400.D0,-497
     100.D0,-48900.D0,-47743.D0,-46297.D0,-44939.D0,-42944.D0,-40290.D
```

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20,-37449.D0,-34456.D0,-31354.D0,-24889.D0,-18176.D0,-11296.D0,
3-85117.D0,-84000.D0,-83500.D0,-82801.D0,-81818.D0,-80746.D0,-79
4007.D0,-77147.D0,-74535.D0,-71116.D0,-67595.D0,-63983.D0,
5-60312.D0,-52857.D0,-44500.D0,-37000.D0,0.D0,698.D0,1398.D0,2104
6.D0,2826.D0,3574.D0,4744.D0,5963.D0,7639.D0,9794.D0,11996.D0,142
741.D0,16524.D0,21203.D0,26021.D0,30953.D0,0.D0,751.D0,1356.D0,20
852.D0,2755.D0,3458.D0,4518.D0,5588.D0,7042.D0,8918.D0,10867.D0,
912886.D0,14964.D0,19272.D0,23744.D0,28355.D0,0.D0,699.D0,1398.D0
1,2099.D0,2801.D0,3513.D0,4608.D0,5743.D0,7316.D0,9356.D0,11456.D0
2,13597.D0,15768.D0,20171.D0,24629.D0,29124.D0/
 DATA HT2 /  0.D0,500.D0,1000.D0,1500.D0,2000.D0,2500.D0,
13250.D0,4000.D0,5000.D0,6250.D0,7500.D0,8750.D0,10000.D0,12500.D0
2,15000.D0,17500.D0,53425.D0,54000.D0,54436.D0,54900.D0,55345.D0
3,56165.D0,56801.D0,57600.D0,58594.D0,59855.D0,61110.D0,62356.D0
4,63612.D0,66120.D0,68640.D0,71183.D0,46759.D0,47300.D0,47712.D0
5,48380.D0,48879.D0,49336.D0,49977.D0,50763.D0,51752.D0,53008.D0
6,54261.D0,55503.D0,56756.D0,59255.D0,61758.D0,64257.D0,-24639.
7D0,-24000.D0,-23000.D0,-22540.D0,-21835.D0,-21118.D0,-20009.D0
8,-18856.D0,-17261.D0,-15193.D0,-13073.D0,-10912.D0,-8725.D0,
9-4295.D0,0.D0,3500.D0,
18424.9D0,9098.D0,9750.D0,10455.D0,
11222.D0,11997.D0,13043.D0,14130.D0,15605.D0,17520.D0,19508.D0,
221558.D0,23664.D0,27996.D0,32458.D0,37024.D0,19454.D0,20006.D0,
320567.D0,21427.D0,22220.D0,23091.D0,24248.D0,25445.D0,26992.D0,
429185.D0,31341.D0,33530.D0,35743.D0,40220.D0,44741.D0,49302.D0,
5101922.D0,102000.D0,102000.D0,102156.D0,103312.D0,104590.D0,
6105104.D0,105933.D0,106908.D0,108173.D0,109422.D0,110663.D0,
7111916.D0,114425.D0,116946.D0,119518.D0/
 DATA ST1 /0.D0,18.68D0,21.55D0,23.167D0,
124.338D0,25.273D0,26.434D0,27.400D0,28.505D0,29.691D0,30.725D0,
231.6464D0,32.4745D0,33.9163D0,35.1400D0,36.2003D0,0.D0,21.70D0,
324.550D0,26.20115D0,27.616777D0,28.81060D0,30.32729D0,31.61336D0
4,33.06955D0,34.59469D0,35.87841D0,36.98959D0,37.97138D0,39.6386
51D0,41.0D0,42.19D0,0.D0,21.1538D0,23.6633D0,25.0721D0,26.1033D0
6,26.9292D0,27.9544D0,28.7966D0,29.7306D0,30.6915D0,31.4947D0,
732.1868D0,32.796D0,33.8396D0,34.7178D0,35.4778D0,0.D0,12.5375D0
8,14.7172D0,16.1042D0,17.1073D0,17.8829D0,18.8146D0,19.55D0,
920.3638D0,21.2011D0,21.9103D0,22.5326D0,23.0880D0,24.0484D0,
124.8623D0,25.5747D0,
10.0D0,19.5245D0,22.0313D0,23.430
18D0,24.4362D0,25.2221D0,26.1808D0,26.9656D0,27.8431D0,28.7524D0
2,29.5175D0,30.1789D0,30.758D0,31.74D0,32.55D0,33.25D0/
 DATA ST2 / 0.0D0,
316.11D0,17.90D0,18.90D0,19.61D0,20.16D0,20.82D0,21.341D0,21.899
4D0,22.457D0,22.912D0,23.298D0,23.632D0,24.19D0,24.646D0,25.031
4D0,0.0D0,16.59D0,18.61D0,19.662D0,20.401D0,20.965D0,21.632D0,
522.156D0,22.7177D0,23.2772D0,23.7374D0,24.1205D0,24.4557D0,
625.015D0,25.474D0,25.866D0,0.0D0,11.280D0,13.08D0,14.0D0,14.787
7D0,15.339D0,15.996D0,16.514D0,17.0724D0,17.6301D0,18.087D0,
818.4713D0,18.81D0,19.3632D0,19.8195D0,20.2045D0,0.0D0,20.39D0,
922.80D0,24.19D0,25.21D0,26.007D0,26.98D0,27.773D0,28.66D0,
229.59D0,30.36D0,31.03D0,31.61D0,32.60D0,33.45D0,34.15D0,
1 0.0D0,19.643D0,21.2024D0,
122.4669D0,23.5156D0,24.300D0,25.234D0,25.9813D0,26.8053D0,
227.6588D0,28.3836D0,29.0155D0,29.5779D0,30.54D0,31.36D0,
332.06D0,0.0D0,21.62D0,24.31D0,25.75D0,26.71D0,27.52D0,
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428.5805D0,29.397D0,30.269D0,31.250D0,32.036D0,32.7121D0,
533.3028D0,34.3009D0,35.1249D0,35.8281D0,0.0D0,15.92D0,
617.71D0,18.71D0,19.43D0,19.979D0,20.638D0,21.155D0,
821.713D0,22.272D0,22.727D0,23.1126D0,23.4466D0,24.0055D0,
924.4654D0,24.8616D0/
 DATA CP1/0.D0,4.008D0,4.0143D0,4.0598D0,4.1662D0,4.3064D0,4.5377D
10,4.7867D0,5.1246D0,5.5139D0,5.8394D0,6.1005D0,6.3075D0,6.6056D0
2,6.8048D0,6.9464D0,0.0D0,3.5551D0,4.0041D0,4.6514D0,5.1587D0,
35.5542D0,6.015D0,6.3549D0,6.6777D0,6.9436D0,7.1175D0,7.2391D0,
47.3265D0,7.4473D0,7.5306D0,7.5960D0/
 DATA CP2 / 0.0D0,
13.5001D0,3.5077D0,3.5568D0,3.6698D0,3.8077D0,3.9883D0,
24.1246D0,4.2518D0,4.3610D0,4.4477D0,4.528D0,4.6049D0,4.7523D0,
34.879D0D0,4.9605D0,0.0D0,2.7955D0,3.3547D0,3.4995D0,3.5173D0,
43.5224D0,3.5447D0,3.5885D0,3.6837D0,3.8260D0,3.9703D0,4.100D0,
54.2122D0,4.3956D0,4.5443D0,4.6763D0,0.0000D0,3.5003D0,3.5011D0,
63.5064D0,3.5325D0,3.5911D0,3.7169D0,3.8511D0,4.0048D0,4.1468D0,
84.2454D0,4.3151D0,4.3663D0,4.4351D0,4.4793D0,4.5117D0,0.0000D0,
915*2.4999D0,0.0D0,2.8374D0,2.7107D0,2.6120D0,2.5690D0,2.5471D0,
12.5288D0,2.5195D0,2.5128D0,2.5061D0,2.5057D0,2.5049D0,2.5056D0,
22.5125D0,2.5299D0,2.5562D0,0.0D0,15*2.4999D0,0.0D0,3.5005D0,
33.5015D0,3.5107D0,3.5495D0,3.6255D0,3.7685D0,3.909D0,4.0611D0,
44.1953D0,4.2862D0,4.3496D0,4.3955D0,4.4561D0,4.4993D0,4.5304D0,
50.0000D0,3.7042D0,3.6051D0,3.5823D0,3.5526D0,3.5469D0,3.5719D0,
63.6346D0,3.7500D0,3.9045D0,4.0428D0,4.1590D0,4.2546D0,4.4030D0,
74.5170D0,4.6150D0,0.0000D0,3.8505D0,3.6342D0,3.5665D0,3.6252D0,
83.7173D0,3.8728D0,4.0124D0,4.1523D0,4.2705D0,4.3503D0,4.4022D0,
94.4426D0,4.4997D0,4.5411D0,4.5755D0,0.0D0,10*2.4999D0,2.5005D0,
12.5015D0,2.5117D0,2.5439D0,2.6065D0/
C      *****   MODIFIED BY M.T. ABUJELALA      2/79   *****
 ISW1=1
 S=S1
 TOT1=TEMP
 H1=H
 TP1=P
  P=P/14.696D0
 ICH=0
 IF(IDD.GE.3) P2=0.D0
 P2=P2/14.696D0
  IZ=1
 IDD1=1
 ID=1
 FST=.028931D0*(1.008D0+12.01D0*RCH)/(1.D0+4.D0*RCH)
 REQ1=REQ
 REQ=REQ/FST
 CPP=.321D0
 IF(DABS(H).LT.2.D0)H=2.D0
 IF(DABS(H1).LT.2.D0)H1=2.D0
 IF(IDD.LT.6) GO TO 374
   TEMP=H/.321D0
  IF(DABS(H).LE.100.D0)TEMP=H/.05D0
  IF(DABS(H).LE.20.D0)TEMP=H/.01D0
  IF(REQ.EQ.0D0)TEMP=H/.243D0
 TEMP=DABS(TEMP)
 TZ=TEMP
 HZ=H
```

```
  374  IF(MUF.GT.0)GO TO 486
       GO TO 500
  486  IF(MUF.EQ.10) GO TO 500
       GOTO 487
  500  DO 12 J=1,12
   12  X(J)=0.0D0
C       ************  GAS MODEL CONSTANTS  ********************
       D=4.773384D0
       D1=.0061627D0
       D2=3.727445D0
       D3=(2.0D0*REQ*RCH)/(1.0D0+4.0D0*RCH)
       D4=(2.0D0*REQ)/(1.0D0+4.0D0*RCH)
       ABU=0.D0
        IF(IDD.EQ.4.OR.IDD.EQ.6)TAH=0.D0
       IF(TEMP.GT.(100.0D0*DLOG10(P)+2800.0D0))GO  TO  1
     7 IF(REQ.EQ.1.0D0)GO TO 2
       IF(REQ.GT.1.0D0)GO TO 3
C              ************** NON-DISSOCIATING GAS MODEL , REQ. LT 1
       X(1)=(2.0D0*D4)/(D4+2.0D0*D)
       X(2)=(4.0D0*D3)/(D4+2.0D0*D)
       X(3)=(2.0D0-4.0D0*D3-D4)/(D4+2.0D0*D)
       X(5)=(2.0D0*D2)/(D4+2.0D0*D)
       X(6)=(4.0D0*D2*D1)/(D4+2.0D0*D)
       GO  TO   50
C              ************** NON-DISSOCIATING GAS MODEL ,REQ. EQ. 1
     2 X(1)=(2.0D0*(1.0D0-2.0D0*D3))/(D+(1.0D0-2.0D0*D3))
       X(2)=(2.0D0*D3)/(D+(1.0D0-2.0D0*D3))
       X(5)=D2/(D+(1.0D0-2.0D0*D3))
       X(6)=(2.0D0*D2*D1)/(D+(1.0D0-2.0D0*D3))
       GO TO 50
     3 IF(RCH.EQ..0D0) GO TO 14
       IF(REQ.GE.((1.0D0+4.0D0*RCH)/(2.0D0*RCH))) GO TO 15
C              ************** NON-DISSOCIATING GAS MODEL ,REQ. GT. 1
       K8=10.0D0**(1.747D0-(3415.0D0/TEMP))
       K9=10.0D0**(9.272D0-(16210.D0/TEMP))
       AA=(1.0D0-K8)*(D+D4+2.0D0*D3-1.0D0)**2
       BB=(D-1.0D0+D4+2.0D0*D3)*(2.0D0*(1.0D0-2.0D0*D3)+K8*(D4+6.0D0*D3
      1-2.0D0))
       CC=K8*(2.0D0-D4-4.0D0*D3)*2.0D0*D3
       X(9)=(DSQRT(BB**2.0D0-4.0D0*AA*CC)-BB)/(2.0D0*AA)
       X(2)=(2.0D0*D3/(D+D4+2.0D0*D3-1.0D0))-X(9)
       X(1)=((1.0D0-2.0D0*D3)*X(2)+(1.0D0-D3)*X(9))/D3
       X(4)=X(1)*X(9)/(K8*X(2))
       X(5)=D2*(2.0D0*X(2)+X(9)+X(1))/2.0D0
       X(6)=2.0D0*D1*X(5)
       PLIM=K9*X(2)/(X(9)**2)
       IF(P.LT.PLIM) GO TO 50
    15 ABU=600.D0
       GO TO 50
C              ************** NON-DISSOCIATING GAS MODEL ,REQ. GT. 1
    14 X(1)=(2.0D0*(1.0D0-2.0D0*D3))/(D+D4+2.0D0*D3-1.0D0)
       X(2)=(2.0D0*D3)/(D+D4+2.0D0*D3-1.0D0)
       X(4)=(D4-2.0D0+4.0D0*D3)/(D+D4+2.0D0*D3-1.0D0)
       X(5)=D2/(D+D4+2.0D0*D3-1.0D0)
       X(6)=(2.0D0*D2*D1)/(D+D4+2.0D0*D3-1.0D0)
       K10=10.0D0**((10114.0D0/TEMP)-12.089D0)
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```
      PLIM=0.01D0/(DSQRT(K10*X(5)*(X(4)**3)))
      IF(P.LT.PLIM) GO TO 50
      ABU=601.D0
      GO TO 50
C       ***************   DISSOCIATING COMBUSTION GAS MODEL  ********
    1 K1=10.0D0**((89677.D0/TEMP)-12.7295D0)
      K2=10.0D0**((42387.0D0/TEMP)-6.2325D0)
      K3=10.0D0**((47850.D0/TEMP)-6.9570D0)
      K5=10.0D0**((41612.0D0/TEMP)-5.872D0)
      K6=10.0D0**((90047.0D0/TEMP)-6.9505D0)
      K7=10.0D0**((60437.0D0/TEMP)-6.2915D0)
      IF(REQ.EQ.0.D0) GO TO 4
      IF(RCH.NE.0.D0) GO TO 5
      K4=0.0D0
      GO TO 6
    5 K4=10.0D0**((50173.0D0/TEMP)-7.8785D0)
    6 A22=P**3*K1*K4*(1.0D0-2.0D0*D3+D)
      A21=P**2*(K1*(1.0D0+D)+2.0D0*K2*K4*(1.0D0-2.0D0*D3))
      A20=2.0D0*P*K2*(1.0D0-D3)
      A12=P**2*K4*K5*(1.0D0-2.0D0*D3+D)
      A11=P*(K5*(1.0D0+D)+2.0D0*K4*(1.0D0-2.0D0*D3))
      A10=2.0D0*(1.0D0-D3)
      A03=2.0D0*P**2*D*K3*K4
      A02=P*(K4*(1.0D0-2.0D0*D3+D)+2.0D0*K3*(D3+D))
      A01=1.0D0+D-2.0D0*P*K4*(1.0D0-2.0D0*D3)
      A00=2.0D0*(D3-1.0D0)
      B22=P**3*K1*K4*(2.0D0-4.0D0*D3-D4)
      B21=P**2*(K1*(2.0D0-2.0D0*D3-D4)+2.0D0*K2*K4*(1.0D0-2.0D0*D3))
      B20=2.0D0*P*K2*(1.0D0-D3)
      B12=P**2*K4*K5*(1.0D0-2.0D0*D3-D4)
      B11=P*(K5*(1.0D0-D3-D4)+K4*(1.0D0-2.0D0*D3))
      B10=1.0D0-D3
      B03=2.0D0*D4*P**2*K3*K4
      B02=D4*P*(2.0D0*K3+K4)
      B01=D4
C          ***************** ITERATION FOR CHEMICAL COMPOSITION ******
   21 Y(1)=(1.0D0*DSQRT((1.D0+D)**2+16.D0*D*P*K3)-(1.D0+D))/(4.D0*D
     1*P*K3)
      L=1
      IF(REQ.GT.1.D0) GO TO 25
   16 B=(Y(L)*(Y(L)*B12+B11)+B10)**2+4.D0*(Y(L)*(Y(L)*B22+B21)+B20)
     1*(Y(L)*(Y(L)*(Y(L)*B03+B02)+B01))
      IF(B.LT.0.)GO TO  20
      Z(L)=(DSQRT(B)-1.0D0*(Y(L)*(Y(L)*B12+B11)+B10))/((Y(L)*(Y(L)*B22
     1+B21)+B20)*2.0D0)
      IF((Y(L).LT..00001D0).AND.(REQ.LE.1.D0)) GO TO 7
      F(L)=Z(L)*(Z(L)*(Y(L)*(Y(L)*A22+A21)+A20)+(Y(L)*(Y(L)*A12+A11)+
     1A10))+(Y(L)*(Y(L)*(Y(L)*A03+A02)+A01)+A00)
      IF((F(L).GT.-.0001D0).AND.(F(L).LT..0001D0)) GO TO 8
      DELF=(Z(L)**2)*(2.0D0*A22*Y(L)+A21)+Z(L)*(2.0D0*A12*Y(L)+A11)+3
     1.0D0*A03*Y(L)**2+2.0D0*A02*Y(L)+A01-(2.0D0*(Y(L)*(Y(L)*A22+A21)
     2+A20)*Z(L)+(Y(L)*(Y(L)*A12+A11)+A10))*((Z(L)**2)*(2.0D0*B22*Y(L
     3)+B21)+Z(L)*(2.0D0*B12*Y(L)+B11)-(3.0D0*B03*Y(L)**2+2.0D0*B02*Y
     4(L)+B01))/(2.0D0*(Y(L)*(Y(L)*B22+B21)+B20)*Z(L)+(Y(L)*(Y(L)*B12
     5+B11)+B10))
      Y(L+1)=Y(L)-F(L)/DABS(DELF)
```

```
      L=L+1
      GO TO 16
   20 Y(L)=.1D0*Y(L)
      IF((Y(L).LT..00001D0).AND.(REQ.LE.1.D0)) GO TO 7
      GO TO 16
   25 Z(1)=(1.0D0*DSQRT((2.0D0*D4*(1.0D0-D3)+1.0D0+D)**2+16.0D0*P*K2
     1*D4*(1.0D0-D3)*(D4*(1.0D0-D3)+1.0D0+D))-(2.0D0*D4*(1.0D0-D3)+1
     2.D0+D))/(4.0D0*P*K2*(D4*(1.0D0-D3)+1.0D0+D))
   28 B=(B21*Z(L)**2+B11*Z(L)-B01)**2-4.0D0*(B20*Z(L)*B2+B10*Z(L))*(
     1B22*Z(L)**2+B12*Z(L)-B02)
      KZ=1
      TY(KZ)=(-1.0D0*DSQRT(B)-(B21*Z(L)**2+B11*Z(L)-B01))/(2.0D0*(B22
     1*Z(L)**2+B12*Z(L)-B02))
   27 DEL=(B22*TY(KZ)**2+B21*TY(KZ)+B20)*Z(L)**2+(B12*TY(KZ)**2+B11*
     1TY(KZ)+B10)*Z(L)-(B03*TY(KZ)**3+B02*TY(KZ)**2+B01*TY(KZ))
      IF((DEL.LT..00001D0).AND.(DEL.GT.-.00001D0)) GO TO 26
      TY(KZ+1)=TY(KZ)-DEL/(-3.0D0*B03*TY(KZ)**2+2.0D0*(B22*Z(L)**2+B12
     1*Z(L)-B02)*TY(KZ)+(B21*Z(L)**2+B11*Z(L)-B01))
      KZ=KZ+1
      GO TO 27
   26 Y(L)=TY(KZ)
      F(L)=Z(L)*(Z(L)*(Y(L)*(Y(L)*A22+A21)+A20)+(Y(L)*(Y(L)*A12+A11)+
     1A10))+(Y(L)*(Y(L)*(Y(L)*A03+A02)+A01)+A00)
      IF((F(L).LT..0001D0).AND.(F(L).GT.-.0001D0)) GO TO 8
      IF(Z(L).LT..00001D0) GO TO 7
      IF(L.EQ.1) GO TO 29
      Z(L+1)=Z(L)-F(L)*(Z(L-1)-Z(L))/(F(L-1)-F(L))
      L=L+1
      GO TO 28
   29 Z(2)=.5D0*Z(1)
      L=2
      GO TO 28
    8 X(7)=Y(L)
      IF(REQ.EQ.0.D0) GO TO 22
      X(8)=Z(L)
      X(1)=P**2*K1*X(7)*X(8)**2
      X(3)=P*K3*X(7)**2
      X(10)=P*K5*X(7)*X(8)
      X(9)=(D3*(X(1)+2.0D0*X(3)+X(7)+X(10)))/((1.0D0-2.0D0*D3)*P*K4*
     1X(7)+1.0D0-D3)
      X(2)=P*K4*X(7)*X(9)
      X(4)=P*K2*X(8)**2
      X(5)=(D2/2.0D0)*(2.0D0*X(2)+X(1)+2.0D0*X(3)+X(7)+X(9)+X(10))
      X(6)=2.0D0*D1*X(5)
      GO TO 50
C              ***************** DISSOCITING AIR  ****************
    4 A22=0.D0
      A21=0.D0
      A20=P*K6*(1.0D0+2.0D0*D1)
      A12=0.D0
      A11=P*K7*(1.0D0+D1)
      A10=1.0D0+D1
      A03=0.D0
      A02=P*K3
      A01=1.0D0
      A00=-1.0D0
```

```
      B22=0.0D0
      B21=0.0D0
      B12=0.0D0
      B20=2.0D0*P*K6
      B11=P*K7*(1.0D0-D2)
      B10=1.0D0
      B03=0.0D0
      B02=2.0D0*P*K3*D2
      B01=D2
      GO TO 21
   22 X(12)=Z(L)
      X(11)=P*K7*X(7)*X(12)
      X(3)=P*K3*X(7)**2
      X(5)=(D2*(2.0D0*X(3)+X(7)+X(11))-X(11)-X(12))/2.0D0
      X(6)=D1*(2.0D0*X(5)+X(11)+X(12))
C     ******** CALCULATION OF GAS MIXTURE THERMODYNAMIC PROPERTIES  *****
   50 DO 9 I=1,16
      IF(TEMP-TT(I)) 10,10,9
    9 CONTINUE
   10 DELH=(TEMP-TT(I-1))/(TT(I)-TT(I-1))
      DELS=(DLOG(TEMP/TT(I-1)))/(DLOG(TT(I)/TT(I-1)))
      M=0.0D0
      H=0.D0
      S=0.D0
      GAM=0.D0
      DO 11 IJ=1,12
      J=IJ
      IF(X(J).EQ.0.D0) GO TO 11
      M=M+X(J)*MT(J)
      IF(J.GT.5) GO TO 889
      H=H+X(J)*(HT1(I-1,J)+(HT1(I,J)-HT1(I-1,J))*DELH)
      S=S+X(J)*(ST1(I-1,J)+(ST1(I,J)-ST1(I-1,J))*DELS-DLOG(P*X(J)))
      IF(J.GT.2) GO TO 848
      CPP=CP1(I-1,J)+(CP1(I,J)-CP1(I-1,J))*DELH
       GOTO 883
  848 J=IJ-2
      CPP=CP2(I-1,J)+(CP2(I,J)-CP2(I-1,J))*DELH
      GO TO 883
  889 J=IJ-2
      CPP=CP2(I-1,J)+(CP2(I,J)-CP2(I-1,J))*DELH
      J=IJ-5
      H=H+X(IJ)*(HT2(I-1,J)+(HT2(I,J)-HT2(I-1,J))*DELH)
      S=S+X(IJ)*(ST2(I-1,J)+(ST2(I,J)-ST2(I-1,J))*DELS-DLOG(P*X(IJ)))
  883 GAM=GAM+X(IJ)*CPP/(CPP-1.D0)
   11 CONTINUE
      H=H*1.98588D0/M
      S=S*1.98588D0/M
      RR=1.98588D0/M
      CPP=GAM*RR/(GAM-1.D0)
      ZXC=GAM/(GAM-1.0D0)
C                      ******************  OUT PUT ********************
      GOTO(801,800,900),ISWI
  801 IF(IDD-5)467,894,897
  894  S1=S
       P=TP1
       GOTO 984
```

```
 897 IF(DABS(HZ-H)-.00001D0*DABS(HZ))634,634,635
 634 P=P*14.696D0
     S1=S
     H=HZ
     GO TO 984
 635  CPA=.587D0
      IF(ICH.LT.15)CPA=1.678D0/CPP
     TEMP=TEMP+(HZ-H)*CPA
     TEMP=(TEMP+TZ)/2.D0
     ER1=DABS(TEMP-TZ)/TZ*100.D0
      ER2=(HZ-H)/HZ*100.D0
      IF(ICH.GT.20.AND.DABS(ER2).LT..3D0.AND.ER1.LT..08D0) TAH=500.D0
      IF (TAH.EQ.500.D0) GO TO 634
     TEMP=DABS(TEMP)
     TZ=TEMP
     ICH=ICH+1
     IF(ICH.LE.45)GO TO 500
     WRITE(6,205)TEMP,HZ,P,H,IDD,REQ1
     STOP
 487 S1=S
     T1=TEMP
     P1=P
     H1=H
 800 GOTO(319,325,335,432),IDD
 432 GOTO(301,300,900),ISW1
 301 TEMP=HI/CPP
      IF(DABS(HI).LE.100.D0)TEMP=HI/.05D0
      IF(DABS(HI).LE.20.D0)TEMP=HI/.01D0
       IF(REQ.EQ.0D0)TEMP=HI/.243D0
     TEMP=DABS(TEMP)
     TI=TEMP
     P=P1
     ICI=0
     ISWI=2
     GOTO 500
 300 IF(DABS(H-HI).LE..00001D0*DABS(HI))GO TO 820
      CPA=.587D0
      IF(ICI.LT.15)CPA=1.678D0/CPP
     TEMP=TEMP+(HI-H)*CPA
     TEMP=(TEMP+TI)/2.D0
     ER1=DABS(TEMP-TI)/TI*100.D0
      ER2=(HI-H)/HI*100.D0
      IF(ICI.GT.20.AND.DABS(ER2).LT..3D0.AND.ER1.LT..08D0) TAH=500.D0
      IF(TAH.EQ.500.D0) GO TO 820
     TEMP=DABS(TEMP)
     TI=TEMP
     ICI=ICI+1
     IF(ICI.LE.45)GO TO 500
     WRITE(6,205)S1,HI,P,P1,IDD,REQ1
     STOP
 820 IF(IZ.GE.2)GO TO 117
     P=.8D0*P1*(TEMP/T1)**ZXC
 117 ISW1=3
     P3=P
     IHC=0
      ICI=1
```

```
      GOTO 500
  900 IF(DABS(S-S1)-.00001D0*S1)213,213,201
  201 P=P1*DEXP((S-S1)/RR*DLOG(P/P1))
      IHC=IHC+1
      IF(IHC-45)500,500,203
  203 WRITE(6,205)S1,H1,P1,P,IDD,REQ1
      STOP
  213 IZ=IZ+1
      TG(IZ)=TEMP
      ISWI=2
      IF(IZ.LE.2)GOTO 500
      IF((DABS(P-P3).LE..01D0*P3).AND.(DABS(TG(IZ)-TG(IZ-1)).LE..0001
     1*TG(IZ))) GOTO 127
      IF(IZ.LE.45)GOTO 500
      WRITE(6,205)S1,H1,P1,P,IDD,REQ1
      STOP
  127 T2=TEMP
      H1=H
      P2=P*14.696D0
      P=TP1
      H=H1
      TEMP=TOT1
  205 FORMAT(10X,4(F12.6,3X),I3,5X,F8.6,'  SSSSSSTTTOOPPP')
      GOTO 984
  319 IF(IDD1.GT.1)GOTO 318
      P=P2
      IDD1=2
      TEMP=T1*(P/P1)**(1.D0/ZXC)
      ISWI=2
      IF(MOF.EQ.10) GO TO 50
      GOTO 500
  318 IF(DABS(S-S1)-.00001*S1)320,320,321
  321 TEMP=TEMP*(DEXP((S1-S)*(1.D0/CPP)))
      IDD1=2
      IF(MOF.EQ.10) GO TO 50
      GOTO 500
  320 P2=P2*14.696D0
      T2=TEMP
      HI=H
      H=H1
      P=TP1
      TEMP=TOT1
  325 GOTO 984
  335 IF(IDD1.GT.1)GO TO 338
      TEMP=T2
      P=P1*(TEMP/T1)**ZXC
      ISW1=2
      IDD1=2
      ICI=0
      GO TO 500
  338 IF(DABS(S1-S).LE..00001*S1)GO TO 339
      P=P1*DEXP((S-S1)/RR*DLOG(P/P1))
      ICI=ICI+1
      IF(ICI.LE.45)GO TO 500
      WRITE(6,205)S1,P,P1,T2,IDD,REQ1
      STOP
```

```
  339 T2=TEMP
      H1=H
      P2=P*14.696D0
      P=TP1
      TEMP=TOT1
      H=H1
  984  REQ=REQ1
       RETURN
       END
CTURB
      SUBROUTINE TURBIN
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON WTF(30),TOPRES(30),TOTEMP(30),FAR(30),CORFLO(30),VMACH(30)
      COMMON STATP(30),ERROR(30),DATINP(15,40),DATOUT(9,40)
      COMMON DEPV(15),DTOL(15),PERFF(12),TOL,IOLT,IOLTF
      COMMON JM1,JM2,JP1,JP2,JCX,LOCTBL(9,40)
      COMMON JFIG(5,40),JFLOW(50),IDEDAP(14),JCOMP(50),NIT,IWAY
      COMMON KKINDS(15,25),NCOMP,NOSTAT,NITER,NFINIS,NPASS,JCC,NCTS
      COMMON JCIND(15),JCDEP(15),JCVIND(15),JCVDEP(15),KDTYP(15)
      COMMON RCH
C      *****   MODIFIED BY M.T. ABUJELALA       2/79  *****
C***  REVISED 3/75 M CADDY
      FAR1=FAR(JM1)
      T1=TOTEMP(JM1)
      TP1=TOPRES(JM1)
      CALL THERMO (T1,TP1,H1,S1,5,RCH,FAR1,ZERO,ZERO,ZERO,0,GAM,R1)
      NCOR=LOCTBL(4,JCX)
      NEFF=LOCTBL(6,JCX)
      SQT1=1.0D0/DSQRT(T1)
      CRPM=DATOUT(2,JCX)*22.77432765D0*SQT1
      VGP=DATINP(10,JCX)
      PRT=DATINP(1,JCX)
      IF(IWAY.EQ.0) GO TO 10
      CRPMT=DATINP(12,JCX)
      DATINP(3,JCX)=CRPM/CRPMT
      DHACTL=0.0D0
      HPT=0.0D0
      COREF=CORFLO(JM1)
      PR=2.0D0
      GO TO 20
   10 CRPMT=CRPM/DATINP(3,JCX)
   20 CORF1=DATINP(4,JCX)
      IF(NCOR.GT.0) CALL TABLU(NCOR,PRT,CRPMT,VGP,CORFT)
      CORFT=CORFT*1.549695676D0
      EFFT=DATINP(6,JCX)
      IF(NEFF.GT.0) CALL TABLU(NEFF,PRT,CRPMT,VGP,EFFT)
      IF(IWAY.NE.0) GO TO 30
      COREF=CORFT*DATINP(5,JCX)
      EFF=EFFT*DATINP(7,JCX)
   30 WT1=COREF*TP1*SQT1
      AIR1=WT1/(1.0D0+FAR1)
      FUEL1=FAR1*AIR1
      WTOUT=WT1
      WTIN=WT1
      WB=WTF(JM2)*DATINP(2,JCX)
      IF(WB.GT.0.0D0) GO TO 40
```

```
      AF2=FAR1
      TB2=T1
      H2=H1
      WB2=0.0D0
      S2=0.D0
      GO TO 50
   40 T2=TOTEMP(JM2)
      FAR2=FAR(JM2)
      TP2=TOPRES(JM2)
      CALL THERMO (T2,TP2,HB,S2,5,RCH,FAR2,ZERO,ZERO,ZERO,0,GAM,RI)
      WB1=WB*DATINP(9,JCX)
      WTIN=WTIN+WB1
      C=1.0D0/(1.0D0+FAR2)
      AB1=WB1*C
      WB2=WB-WB1
      AB2=WB2*C
      FUEL1=FUEL1+FAR2*AB1
      AIR1=AIR1+AB1
      AF2=FUEL1/AIR1
      FUEL1=FUEL1+FAR2*AB2
      AIR1=AIR1+AB2
      WTFOUT=WTFOUT+WB
C*** FLOW WEIGHT ENTHALPY TO GET MIXED INLET TEMP   ( WHEN WB1 GT 0)
      H2=(WT1*H1+WB1*HB)/WTIN
   50 S3=(S1*WT1+S2*WB1)/WTIN
      CALL THERMO (T1,TP1,H2,S3,4,RCH,AF2,TB2,H2,P3,4,GAM,R1)
      IF(IWAY)80,60,70
   60 PR=DATINP(8,JCX)*(PRT-1.0D0)+1.0D0
      TP3=P3/PR
      CALL THERMO (TB2,P3,H2,S3,1,RCH,AF2,T3,H3,TP3,4,GAM,R1)
      DHACTL=EFF*(H2-H3)
      HPT=1.415D0*WTIN*DHACTL
      GO TO 80
   70 DATINP(5,JCX)=COREF/CORFT
      EFF=DATINP(11,JCX)
      DATINP(7,JCX)=EFF/EFFT
      HPT=DATOUT(1,JCX)
      H3I=H2-HPT/(1.415D0*WTIN*EFF)
      CALL THERMO (TB2,P3,H2,S3,4,RCH,AF2,T3I,H3I,P3I,4,GAM,R1)
      PR=P3/P3I
      DATINP(8,JCX)=(PR-1.0D0)/(PRT-1.0D0)
      DHACTL=EFF*(H2-H3I)
   80 HOUT=H2-DHACTL
C*** FLOW WEIGHT ENTALPY TO GET EXIT TEMP   (WHEN WB2 GT 0)
      IF(WB2.GT.0.0D0)HOUT=(HOUT*WTIN+HB*WB2)/WTFOUT
      FAR(JP1)=FUEL1/AIR1
      FARZ=FAR(JP1)
      P2=TP1/PR
      CALL THERMO (TOUT,P2,HOUT,S1,6,RCH,FARZ,ZERO,ZERO,ZERO,0,GAM,R1)
      TOTEMP(JP1)=TOUT
      TOPRES(JP1)=TP1/PR
      WTF(JP1)=WTFOUT
      CORFLO(JP1)=WTFOUT*DSQRT(TOUT)/TOPRES(JP1)
      WTF(JM1)=WT1
      CORFLO(JM1)=COREF
      DATOUT(1,JCX)=HPT
```

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      DATOUT(3,JCX)=VGP
      DATOUT(4,JCX)=PRT
      DATOUT(5,JCX)=DATINP(3,JCX)
      DATOUT(6,JCX)=CRPMT
      DATOUT(7,JCX)=DATINP(5,JCX)
      DATOUT(8,JCX)=EFF
      DATOUT(9,JCX)=PR
      RETURN
      END
      BLOCK DATA
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION TDEL(7),XMA(16)
      COMMON/QIN/ TDEL,XMA,ALT,WMAX,PUNCHO,TIT,JCB,JN1,JN2,IDESN,IPRINT,
     1  JCAB2,JCAB1,NP,NM
      COMMON /NEPOPT/ SECAST,DD,NDSET,NPARTS,IOPTP,NPASSO,NVOPT,NJOPT,
     1  TOLOPT,NOPT
      COMMON /TSIZE/ TDATA(3000),NMAX
      COMMON /TABLE/ ITAB(50),NTBL
      DATA TDEL,TIT,PUNCHO / 9*0.D0/
      DATA NDSET,NVOPT,IDESN,NJOPT,IOPTP,IPRINT,NTBL / 7*0/
      DATA DD,TOLOPT,NMAX / 0.0D0,.000200,3000/
      END
```

VITA

Muftah Taher Abujelala was born in Musrata, Libya, in 1950. He grew up in Agedabia, Libya, and graduated from Agedabia High School in 1971. In 1976, he received a Bachelor of Science degree in Mechanical Engineering from the University of Al-Fateh, Tripoli, Libya. In January 1977 he accepted a teaching assistantship at The University of Al-Fateh, and in September 1977 he was awarded a scholarship for advanced study in jet propulsion from the same University.

The author was honored by the Ministry of Education, University of Al-Fateh and the Department of Mechanical Engineering at the same University for achieving the highest grade point average in his B. S. studies.

He is married to Mariam El-Sallabi and has a daughter named Nabila.