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# WALL TEMPERATURE DISTRIBUTION CALCULATION FOR A ROCKET NOZZLE CONTOUR

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16. Abstract

The JANNAF Turbulent Boundary Layer (TBL) computer program, applicable to rocket nozzles, requires a wall temperature distribution among other input parameters to determine boundary layer behavior, heat transfer, and performance degradation. The inclusion of a complete regenerative cooling cycle model with associate geometry, material and fluid property data provides a capability to internally calculate wall temperature profiles on the hot gas and coolant flow-side, as well as the coolant flow bulk temperature variation. Besides the regular heat transfer and performance degradation calculations, the new concept can be used to optimize the cooling cycle, coolant flow requirements, and cooling jacket geometry.

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# DEFINITION OF SYMBOLS

| Symbol | Definition |
|---|---|
| $A_{tube}$ | Cross-sectional area of each cooling tube or channel, $ft^2$ |
| $C_f$ | Skin friction coefficient |
| $C_H$ | Stanton number |
| $D_{tube}$ | Equivalent tube diameter, ft |
| H | Enthalpy, $ft^2/s^2$ |
| J | Conversion factor between thermal and work units (778.2), ft-lbf/Btu |
| $M_\infty$ | Mach number at boundary layer edge |
| $\mathfrak{M}$ | Mean molecular weight at boundary layer edge, lbm/mole |
| $P_\infty$ | Static pressure at boundary layer edge, $lbf/ft^2$ |
| $\dot{Q}_w$ | Total heat transfer rate, Btu/s |
| $P_r$ | Prandtl number |
| $R_e$ | Reynolds number |
| $\mathcal{R}$ | Universal gas constant |
| T | Temperature, °R |
| $U_\infty$ | Velocity at boundary layer edge, ft/s |
| $C_p$ | Specific heat at constant pressure, Btu/lbm °R |
| g | Acceleration of gravity (32.174), ft-lbm/lbf $s^2$ |
| $h_0$ | Total enthalpy, $ft^2/s^2$ |

## DEFINITION OF SYMBOLS (Continued)

| Symbol | Definition |
|---|---|
| $h_g$ | Heat transfer coefficient on the gas side, Btu/ft$^2$ s°R |
| $h_\ell$ | Heat transfer coefficient on the coolant side, Btu/ft$^2$ s°R |
| $m_\ell$ | Coolant mass flow rate, lbm/s |
| $\dot{q}_w$ | Specific heat transfer rate, Btu/ft$^2$ s |
| $\dot{q}_w'$ | Specific heat transfer rate into coolant, Btu/ft$^2$ s |
| r | Nozzle radius, ft |
| t | Chamber wall thickness, ft |
| u | Velocity within boundary layer, ft/s |
| x | Axial coordinate, ft or - |
| y | Distance normal to wall, ft or - |
| $\alpha$ | Angle between wall and nozzle axis |
| $\delta$ | Velocity thickness, ft |
| $\delta_r'$ | Distance from nth streamline to real wall, ft |
| $\delta^*$ | Displacement thickness, ft |
| $\Delta$ | Temperature thickness, ft |
| $\theta$ | Momentum thickness, ft |
| $\phi$ | Energy thickness, ft |
| $\mu$ | Dynamic viscosity, lbm/ft s |

## DEFINITION OF SYMBOLS (Continued)

| Symbol | Definition |
|---|---|
| $\rho$ | Density, lbm/ft$^3$ |
| $\lambda$ | Thermal conductivity, Btu/ft s°R |
| $\tau_w$ | Shear stress, lbm/s$^2$ |
| $\eta$ | Cooling coefficient for geometry effects |
| $\eta_E$ | Efficiency (enhancement) factor for surface roughness and turbulence effects |

**Subscripts**

| | |
|---|---|
| aw | Adiabatic wall |
| c | Calculated value or convection |
| IXTAB | Final section of input tables |
| i | Section |
| j | Overall iteration number |
| $\ell$ | Coolant |
| N | Final section of input tables |
| r | Radiation |
| w | Wall or wall material |
| wg | Gas side wall |
| w$\ell$ | Coolant side wall |
| $\infty$ | Free stream or boundary layer edge |

# DEFINITION OF SYMBOLS (Concluded)

Subscripts

| | |
|---|---|
| 0 | Stagnation or approximated value |
| 1 | Section or iteration number |
| 2 | Section or iteration number |

# WALL TEMPERATURE DISTRIBUTION CALCULATION FOR A ROCKET NOZZLE CONTOUR

## SUMMARY

A concept is presented which allows the calculation of the temperatures along a thrust chamber nozzle contour on the hot gas and on the coolant flow-side. Also considered is a regenerative coolant flowing in the opposite or the same direction to the chamber reaction products. Coupling of the boundary layer equations for the hot gas-side with the regenerative cooling equations provides the results. Since the new analytical model has been integrated into the JANNAF Turbulent Boundary Layer computer program, the thrust degradation, due to the viscous effects close to the wall, is simultaneously obtained. The calculation is started with approximated temperature distributions for the hot gas-side wall and the coolant flow. Iterations within the computer program are executed until the heat transfer rates from the boundary layer to the wall and from the wall to the coolant are equal. Kinetic inviscid flow conditions for the boundary layer edge are considered by means of table inputs representing the variation of appropriate parameters. Since the chamber wall thickness and the coolant flow channel geometry are part of the analysis, optimization studies can be performed for these parameters by consecutive computer runs. A sample calculation, utilizing the new concept for a small area ratio high pressure thrust chamber, is included.

## INTRODUCTION

The calculation of various turbulent boundary layer thicknesses in the thrust chamber and the temperatures of the gas-side wall, the regenerative coolant-side wall, and the coolant fluid along the thrust chamber contour is simultaneously made, by considering the heat exchange between the combustion product flow in the thrust chamber and the coolant flow in the cooling jacket. The Turbulent Boundary Layer Computer Program TBL-I [1] has been modified to carry out the calculation by using a new concept in which the boundary layer equations are coupled with regenerative cooling equations.

The steady-state conditions that are considered require the temperatures of the combustion products, the chamber walls, and also the heat flux through the walls to remain constant at any point in time. It is assumed that heat transfer occurs only by convection and conduction from the hot combustion products to the thrust chamber wall, neglecting the radiation. However, inclusion of radiation is not difficult, if the emissivity of the combustion products and the Stefan-Boltzmann constant can be accurately determined; since the total specific heat flux from the hot gas into the chamber wall is composed of the convective $\dot{q}_c$ and the radiant $\dot{q}_r$ heat flux.

$$\dot{q} = \dot{q}_c + \dot{q}_r \quad .$$

The coolant fluid in this analysis flows through the tubes or channels in the opposite or same direction to the combustion products, receiving the heat by convection and conduction. The heat exchange takes place simultaneously in many small sections which have an arbitrary length along the contour of the thrust chamber, accounting for the gas phase turbulent combustion product flow, the temperature of the thrust chamber wall material, and the temperature of regenerative coolant flow. The temperature distributions obtained from the first iteration are internally used as initial values for the second iteration. Iterations are performed until convergence is obtained. Since the influence of the coolant transport properties on the resulting temperatures is quite significant, it is important to use pertinent values especially in the supercritical region of the coolant fluid. The empirical relationship of the heat transfer coefficient for computing the heat exchange with the coolant flow significantly affects the results as well as the Stanton number of the combustion products [1].

The methods to calculate the various turbulent boundary layer thicknesses in the thrust chamber are explained in detail in the documentations of TBL [2] and TBL-I [1], and only the fundamental equations and concepts of the calculations improving the latter TBL-I computer program are outlined in this report. The concept is demonstrated for a regenerative coolant flowing in opposite direction to the combustion products. The alternate equations for the coolant flowing in the same direction are explained in the section entitled Same Direction Coolant Flow.

## FUNDAMENTAL EQUATIONS FOR THE BOUNDARY LAYER

The integral momentum and energy equations in axisymmetric form [2,3] for compressible turbulent boundary layer flow are:

$$\frac{d\theta}{dx} = \frac{C_f}{2} \left[1 + \left(\frac{dr}{dx}\right)^2\right]^{1/2} - \theta \left[\frac{1 + \frac{\delta^*}{\theta}}{U_\infty} \frac{dU_\infty}{dx} + \frac{1}{\rho_\infty U_\infty} \frac{d(\rho_\infty U_\infty)}{dx} + \frac{1}{r}\frac{dr}{dx}\right] \quad , \qquad (1)$$

and

$$\frac{d\phi}{dx} = C_H \left[\frac{H_{aw} - H_w}{H_0 - H_w}\right] \left[1 + \left(\frac{dr}{dx}\right)^2\right]^{1/2} - \phi \left[\frac{1}{\rho_\infty U_\infty} \frac{d(\rho_\infty U_\infty)}{dx} + \frac{1}{r}\frac{dr}{dx} + \frac{1}{H_0 - H_w} \frac{d\left(H_0 - H_w\right)}{dx}\right] \quad , \qquad (2)$$

where the displacement thickness $\delta^*$ , momentum thickness $\theta$ and energy thickness $\phi$ are identified as follows:

$$\delta^* = \int_0^{\delta'_r} \left(1 - \frac{\rho u}{\rho_\infty U_\infty}\right) dy \quad , \qquad (3)$$

$$\theta = \int_0^{\delta'_r} \frac{\rho u}{\rho_\infty U_\infty} \left(1 - \frac{u}{U_\infty}\right) dy \quad , \qquad (4)$$

$$\phi = \int_0^{\delta} r' \frac{\rho u}{\rho_\infty U_\infty} \left( 1 - \frac{h_0 - H_w}{H_0 - H_w} \right) dy \quad . \tag{5}$$

The skin friction coefficient is defined as

$$C_f = \frac{2\tau_w}{\rho_\infty U_\infty^2} \quad , \tag{6}$$

and has a form of the Blasius relation [1]

$$C_f = \frac{0.025}{R_{e\theta}^{0.25}} \quad , \tag{7}$$

with the following Reynolds number based upon the momentum thickness

$$R_{e\theta} = \frac{\rho_\infty U_\infty \theta}{\mu_\infty} \quad . \tag{8}$$

The Stanton number

$$C_H = \frac{\dot{q}_w}{\rho_\infty U_\infty (H_{aw} - H_w)} \quad , \tag{9}$$

is calculated using the formula [1]

$$C_H = \frac{\frac{C_f\left(R_{e\phi}\right)}{2}\left(\frac{\phi}{\theta}\right)^{\tilde{n}}}{1 - 5\left[\frac{C_f\left(R_{e\phi}\right)}{2}\right]^{1/2}\left[1 - P_r + \ell n\left(\frac{6}{5\,P_r + 1}\right)\right]} \quad . \tag{10}$$

Velocity and enthalpy profiles across the boundary layer are assumed to follow the relationships:

$$\text{for } y \leq \delta \qquad \frac{u}{U_\infty} = \left(\frac{y}{\delta}\right)^{\frac{1}{n}} \quad , \tag{11}$$

$$\text{for } y > \delta \qquad \frac{u}{U_\infty} = 1 \quad , \tag{12}$$

$$\text{for } y \leq \Delta \qquad \frac{h_0 - H_w}{H_0 - H_w} = \left(\frac{y}{\Delta}\right)^{\frac{1}{n}} \quad , \tag{13}$$

$$\text{for } y > \Delta \qquad \frac{h_0 - H_w}{H_0 - H_w} = 1 \quad . \tag{14}$$

The definition of enthalpy is

$$H = \int_0^T C_p \, dT \quad , \tag{15}$$

$$h_0 = H + \frac{u^2}{2} \quad , \tag{16}$$

$$H_w = \int_0^{T_{wg}} C_p \, d\,T \quad . \tag{17}$$

The adiabatic wall enthalpy $H_{aw}$ is defined as

$$\frac{H_{aw}}{H_0} = \frac{H_\infty + \left(P_r\right)^{1/3} \frac{U_\infty^{\,2}}{2}}{H_\infty + \frac{U_\infty^{\,2}}{2}} \quad . \tag{18}$$

The density $\rho$ within the boundary layer is obtained from the perfect gas equation, assuming that the pressure is constant across the boundary layer:

$$\frac{\rho}{\rho_\infty} = \frac{T_\infty}{T} \quad , \tag{19}$$

where the temperature $T$ is calculated via the velocity and enthalpy distributions, equations (11), (12), (13), (14), and (16). The boundary layer calculations use the Runge-Kutta Gill solution method for given parameters at the boundary layer edge such as x, r, $M_\infty$, $P_\infty$, $T_\infty$, $U_\infty$, and $\mathfrak{M}$. The only unknown parameter is the wall temperature $T_{wg}$ in equation (17).

## EQUATIONS FOR THE REGENERATIVE COOLING CYCLE

As shown in Figure 1, the coolant flows in an opposite direction to the combustion products of the thrust chamber. The regenerative fluid enters downstream with a lower temperature and a higher pressure than at the injector head, since heat is continuously transferred from the combustion products to the coolant through the chamber walls. $T_{wg}$ denotes the gas-side wall temperature, $T_{w_\ell}$ the coolant-side wall temperature, and $T_\ell$ the coolant bulk temperature at an arbitrary station x with $x = 0$ at the throat (Figs. 1 and 2). We consider the case in which the heat is transferred only by convection from the hot combustion products to the chamber wall and that the direction of heat flow is normal to it. Since steady-state conditions are treated, the temperatures of the combustion gas and wall and the specific heat flux through the walls remain constant with time at any given point.

The five fundamental equations representing the cooling cycle, including an empirical relation for the heat transfer coefficient of the coolant, are as follows:

1. Specific heat transfer rate on the gas-side,

$$\dot{q}_{w1} = h_g \left(T_{aw} - T_{wg}\right) \quad , \tag{20}$$

where $h_g$ is the heat transfer coefficient in a gas and $T_{aw}$ is the adiabatic wall temperature.

2. Heat transfer coefficient in a gas related to the Stanton number which is calculated in TBL-I,

$$h_g = \rho_\infty U_\infty C_H \frac{H_{aw} - H_w}{T_{aw} - \left[T_{wg}\right]_j} \quad , \tag{21}$$

where

$\rho_\infty$ is the free stream density,

$U_\infty$ is the free stream velocity,

$C_H$ is the Stanton number,

$H_{aw}$ is the adiabatic wall enthalpy,

$H_w$ is the wall enthalpy,

$T_{aw}$ is the adiabatic wall temperature,

and

$\left[T_{wg}\right]_j$ is the input wall temperature or calculated wall temperature.

3. Specific heat transfer rate through the wall by conduction,

$$\dot{q}_{w2} = \lambda_w \frac{T_{wg} - T_{w_\ell}}{t} \quad , \tag{22}$$

where $\lambda_w$ is the thermal conductivity of the wall material and $t$ is the wall thickness.

4. Specific heat transfer rate into the coolant,

$$\dot{q}_{w3} = h_\ell \left(T_{w_\ell} - T_\ell\right) \quad , \tag{23}$$

where $h_\ell$ is the heat transfer coefficient for the coolant.

5. Empirical relation of the heat transfer coefficient for the hydrogen coolant flow [4] is a modified Colburn equation. For any other coolant flow, a similar relationship must be utilized including the effects of curvature, associated turbulence, and surface roughness of the tubes represented by the enhancement factor $\eta_E$. The accuracy of the enhancement factor significantly

affects the heat transfer calculation and the resulting wall temperatures. Since this effect is coupled with the cooling fluid heat transfer coefficient, it is evident that the physical property information must be very precise.

$$h_\ell = 0.025 \frac{\lambda_\ell}{D_{tube}} R_{e_\ell}^{0.8} P_{r_\ell}^{0.4} \left(\frac{T_\ell}{T_{w_\ell}}\right)^{0.55} \eta_E \quad . \tag{24}$$

The above equation is valid for temperature ratios $T_{w_\ell}/T_\ell$ between 1.44 to 9.2, where the Reynolds number and the Prandtl number of the coolant are defined as follows:

$$\text{Reynolds number,} \quad R_{e_\ell} = \frac{\rho_\ell U_\ell D_{tube}}{\mu_\ell} \quad . \tag{25}$$

$$\text{Prandtl number,} \quad P_{r_\ell} = \frac{\mu_\ell C_{p\ell}}{\lambda_\ell} \quad . \tag{26}$$

$$\text{Mass flow density,} \quad \rho_\ell U_\ell = \rho_\ell(x) U_\ell(x) \quad . \tag{27}$$

$$\text{Equivalent tube diameter,} \quad D_{tube} = 2\left(A_{tube}/\pi\right)^{1/2} \quad . \tag{28}$$

$$\text{Coolant bulk viscosity,} \quad \mu_\ell = \mu_\ell\left(T_\ell \;, \; \text{Pressure}\right) \quad . \tag{29}$$

$$\text{Coolant bulk specific heat,} \quad C_{p\ell} = C_{p\ell}\left(T_\ell \ , \ \text{Pressure}\right) \ . \tag{30}$$

$$\text{Coolant bulk thermal conductivity,} \quad \lambda_\ell = \lambda_\ell\left(T_\ell \ , \ \text{Pressure}\right) \ . \tag{31}$$

For steady-state conditions, the heat flux through all three realms must be constant,

$$\dot{q}_{w1} = \dot{q}_{w2} = \dot{q}_{w3} = \dot{q}_w{}' = \text{constant} \ . \tag{32}$$

Unknowns in equations (20) through (24) are $\dot{q}_w{}'$ , $T_{wg}$ , $T_{w_\ell}$ and $T_\ell$ . In equation (21) $h_g$ is independently calculated when $T_{wg}$ is given. Combining equations (20), (22), (23), and (32) results in

$$T_{w_\ell} = \frac{h_\ell\left(1 + \dfrac{\lambda_w}{t\,h_g}\right)T_\ell + \dfrac{\lambda_w}{t}\ T_{aw}}{\dfrac{\lambda_w}{t} + h_\ell\left(1 + \dfrac{\lambda_w}{t\,h_g}\right)} \ , \tag{33}$$

and

$$T_{wg} = \frac{h_g\,T_{aw} + \dfrac{\lambda_w}{t}\ T_{w_\ell}}{h_g + \dfrac{\lambda_w}{t}} \ . \tag{34}$$

Derivations of the above equations are shown in Appendix A. Thus, the solution can be obtained by considering equations (20), (21), (24), (33), and (34), (Table 1). The flow chart to compute $T_{w_\ell}(x)$ , $T_{wgc}(x)$ , $T_{\ell c}(x)$ , and

$\dot{q}_w'(x)$ is shown in Figure 3 where the subscript c denotes the internally calculated temperature.

At the beginning of the calculation, the coolant bulk temperature distribution is approximated. The coolant-side wall temperature $T_{w_\ell}$ at an axial distance x is obtained according to iterations in statement (2) of Figure 3a. The gas-side wall temperature $T_{wg}$ is calculated from equation (34); however, to differentiate between the input table values of $T_{wg}$, the subscript c is added in statement (3) of Figure 3a. The term $\dot{q}_w'$, which differs from the $\dot{q}_w$ output of TBL-I, should coincide with $\dot{q}_w$ after the iteration is complete. In statement (5) of Figure 3a the coolant temperature is calculated by using its previous iteration values. The derivation of the equation in statement (5) is shown in the section entitled Internally Calculated Coolant Bulk Temperature.

After obtaining $T_{wgc}(x)$ and $T_{\ell c}(x)$ at each table point of x, the values of $T_\ell(x)$ and $T_{wg}(x)$ to be input for a successive iteration are determined as follows:

$$\left[T_\ell(x)\right]_2 = \frac{T_{\ell c}(x) + \left[T_\ell(x)\right]_1}{2} , \tag{35}$$

and

$$\left[T_{wg}(x)\right]_2 = \frac{T_{wgc}(x) + \left[T_{wg}(x)\right]_1}{2} \tag{36}$$

In repeating the preceding calculation, we obtain values of $\left[T_\ell(x)\right]_3$ and $\left[T_{wg}(x)\right]_3$. This operation is applied until a desired convergence outlined in a later section is achieved.

# INTERNALLY CALCULATED COOLANT BULK TEMPERATURE

For simplicity, assume that the inner wall of the thrust chamber consists of a single wall and not of tubes. Let us consider an arbitrary section i in Figure 4 and calculate the coolant temperature at $x_i$, which is the distance along the nozzle axis. Section i contains the surface area between B and D, as shown in Figure 4,

$$x_{i-1} = x_i - \Delta x_{i1} \text{, which is } x_A \quad , \tag{37}$$

and

$$x_{i+1} = x_i + \Delta x_{i2} \text{, which is } x_E \quad , \tag{38}$$

where the step sizes $\Delta x_{i1}$ and $\Delta x_{i2}$ are arbitrary.

The inlet temperature of the coolant at section i is $T_\ell\left(x_i + \dfrac{\Delta x_{i2}}{2}\right)$, and the outlet temperature is $T_\ell\left(x_i - \dfrac{\Delta x_{i1}}{2}\right)$. The heat transfer rate through the cylindrical surface area of section i between B and D is

$$\dot{Q}_w(x_i) = \frac{2\pi\, r(x_i)\, \dot{q}_w{}'(x_i)\, \Delta \bar{x}_i}{\cos\alpha\,(x_i)} \quad , \tag{39}$$

where

$$\Delta \bar{x}_i = \frac{\Delta x_{i1} + \Delta x_{i2}}{2} \quad , \tag{40}$$

and $\alpha(x_i)$ is the angle between the chamber wall and the nozzle axis at $x_i$. The wall radius is $r(x_i)$ and $\dot{q}_w'(x_i)$ is the specific heat transfer rate as shown in equation (32). The outlet temperature of the coolant at $x = x_i - \frac{\Delta x_{i1}}{2}$ in section i is calculated by

$$T_\ell\left(x_i - \frac{\Delta x_{i1}}{2}\right) = \frac{\left[T_\ell(x_i)\right]_j + \left[T_\ell(x_i + \Delta x_{i2})\right]_j}{2} + \frac{\dot{Q}_w(x_i)}{\dot{m}_\ell\, C_{p\ell}(x_i)} , \quad (41)$$

where $\left[T_\ell(x_i)\right]_j$ and $\left[T_\ell(x_i + \Delta x_{i2})\right]_j$ are either previously determined coolant bulk temperatures or initial input values. The value $\dot{m}_\ell$ is the coolant flow rate and $C_{p\ell}(x_i)$ the mean specific heat of the coolant between B and D. Then $T_{\ell c}(x_i)$ is approximated as

$$T_{\ell c}(x_i) = \frac{T_\ell\left(x_i - \frac{\Delta x_{i1}}{2}\right) + \frac{\left[T_\ell(x_i)\right]_j + \left[T_\ell(x_i + \Delta x_{i2})\right]_j}{2}}{2} , \quad (42)$$

where the subscript c denotes a calculated value compared with a previously determined value or the initial input number. Combining the above three equations results in

$$T_{\ell c}(x_i) = \frac{\left[T_\ell(x_i)\right]_j + \left[T_\ell(x_i + \Delta x_{i2})\right]_j}{2} + \frac{\pi\, r(x_i)\, \dot{q}_w'(x_i)\, \Delta \bar{x}_i}{\dot{m}_\ell\, C_{p\ell}(x_i) \cos\alpha(x_i)} . \quad (43)$$

This is the internally calculated coolant bulk temperature. For real thrust chambers composed of tubes or channels, a cooling efficiency $\eta$ should be applied to the second term on the right side of equation (43) to account for the real geometry effect. Thus,

$$T_{\ell c}(x_i) = \frac{\left[T_\ell(x_i)\right]_j + \left[T_\ell(x_i + \Delta x_{i2})\right]_j}{2} + \eta \frac{\pi\, r(x_i)\, \dot{q}_w{}'(x_i)\, \Delta \bar{x}_i}{\dot{m}_\ell\, C_{p\ell}(x_i) \cos \alpha(x_i)} \quad . \tag{44}$$

However, the cooling efficiency $\eta$ should be equal to one, if the empirical relationship in equation (24) is based upon real thrust chamber data and not upon a single tube experiment.

To start the calculation, a coolant flow temperature distribution must be given or approximated to obtain $T_{\ell c}(x_i)$ through iteration by equation (44). The initial value $\left[T_\ell(x_i)\right]_2$ for successive iterations can be obtained internally from

$$\left[T_\ell(x_i)\right]_2 = \frac{T_{\ell c}(x_i) + \left[T_\ell(x_i)\right]_1}{2} \quad . \tag{45}$$

Successive iterations are made until the desired convergency is obtained, i.e., the computation is completed when the total heat transfer rate through the chamber wall on the gas side SUMQDA in TBL-I and that on the coolant side [equation (48)] (represented by SUMQWI in the present computer program) become equal. The specific heat transfer rates through the walls on the gas side ($\dot{q}_w$ = QW in TBL-I) and the coolant side ($\dot{q}_w{}'$ = QWI in the present computer program) at each section are simultaneously equal. Now the coupling of the regenerative cooling cycle and TBL-I [1] is completed.

## SEQUENCE OF CALCULATION

The numbers of the items that follow in this topic correspond to those in Figure 3a. The calculation sequence at station $x = x_1$ progresses as follows:

1. As shown in the flow chart of Figure 3a, the coolant bulk temperature $\left[T_\ell(x)\right]_0$ and the gas-side wall temperature distribution $\left[T_{wg}(x)\right]_0$ must be

input to initiate the computation, where the subscript 0 denotes the first approximated value. The gas-side wall temperature $\left[T_{wg}(x)\right]_0$ is used to obtain the heat transfer coefficient on the gas side $h_g(x)$ at each station according to the equation below:

$$h_g(x) = \rho_\infty(x)\, U_\infty(x)\, C_H(x)\, \frac{H_{aw}(x) - H_w(x)}{T_{aw}(x) - \left[T_{wg}(x)\right]_j} \quad , \tag{46}$$

where $j = 0$ denotes the first overall iteration loop. Each parameter except $\left[T_{wg}(x)\right]_j$ , on the right side of the above equation, is calculated by the equations shown in equations (1) through (19), or is input. The velocity $U_\infty(x)$ is the only input parameter in equation (46) which remains constant during all iteration at each local station.

2. The wall temperature on the coolant side $T_{w_\ell}$ and the heat transfer coefficient of the coolant flow $h_\ell$ are calculated by small internal iteration loops, because equation (33) is implicit,

$$T_{w_\ell} = \frac{h_\ell\left(1 + \frac{\lambda_w}{t\, h_g}\right)[T_\ell]_j + \frac{\lambda_w}{t} T_{aw}}{h_\ell\left(1 + \frac{\lambda_w}{t\, h_g}\right) + \frac{\lambda_w}{t}} \qquad \text{(equation 33)}$$

and

$$h_\ell = 0.025\, \frac{\lambda_\ell}{D_{tube}}\, R_{e_\ell}^{0.8}\, P_{r_\ell}^{0.4} \left(\frac{[T_\ell]_j}{T_{w_\ell}}\right)^{0.55} \eta_E \quad . \qquad \text{(equation 24)}$$

Since each parameter in the previous equations is a function of the axial distance x , the argument x is dropped for simplicity purposes. The subscript j identifies the iteration number with $j = 0$ indicating the first iteration.

3. The new gas-side wall temperature $T_{wgc}$ is obtained from equation (34)

$$T_{wgc} = \frac{h_g T_{aw} + \frac{\lambda_w}{t} T_{w_\ell}}{h_g + \frac{\lambda_w}{t}} \quad , \qquad \text{(equation 34)}$$

where the subscript c denotes a calculated value. The $h_g$ in equation (34) is still based upon the input wall temperature on the gas side $\left[T_{wg}\right]_j$. The coolant-side wall temperature $T_{w_\ell}$ in equation (34) has been obtained previously.

4. The specific heat transfer rate is obtained by any one of equations (20), (22), or (23) because of their equivalence represented by equation (32). Equation (20) is selected here,

$$\dot{q}_w' = h_g \left(T_{aw} - T_{wgc}\right) \quad . \qquad \text{(equation 20)}$$

Another specific heat transfer rate based upon the input gas-side wall temperature is obtained from

$$\dot{q}_w = h_g \left(T_{aw} - \left[T_{wg}\right]_j\right) \quad .$$

The $h_g$ term in both equations is based on the temperature $\left[T_{wg}\right]_j$. When the overall iterations are completed, the following condition must be satisfied: $\dot{q}_w = \dot{q}_w'$, because $T_{wgc} = \left[T_{wg}\right]_j$.

5. The coolant bulk temperature has to be corrected at this point by considering the heat transferred at section i with the respective $x = x_i$ and the input coolant bulk temperatures.

$$T_{\ell c} = \frac{\left[T_\ell(x_i)\right]_j + \left[T_\ell(x_i + \Delta x_{i2})\right]_j}{2} + \eta \frac{\pi \, r \, \dot{q}_w{}' \, \Delta \bar{x}_i}{\dot{m}_\ell \, C_{p\ell} \cos \alpha} \; .$$

(equation 44)

Derivation of this equation was shown previously.

6. New temperature approximations for the bulk coolant and the gas-side wall are predicted, for use in the succeeding overall iterations, from

$$\left[T_\ell(x)\right]_{j+1} = \frac{T_{\ell c}(x) + \left[T_\ell(x)\right]_j}{2} \quad ,$$

and

$$\left[T_{wg}(x)\right]_{j+1} = \frac{T_{wgc}(x) + \left[T_{wg}(x)\right]_j}{2} \quad .$$

The above procedure from steps 1 through 6 is repeated at each local station $x = x_i$, and the two total heat transfer rates through the wall are compared at the end of every overall iteration loop station $x = x_{IXTAB}$ (Fig. 3b). A solution is obtained when the two values fall within a small tolerance,

$$\left| \frac{\sum_{i=1}^{N} \tilde{\dot{Q}}_w - \sum_{i=1}^{N} \dot{Q}_w}{\sum_{i=1}^{N} \dot{Q}_w} \right| \lesseqgtr \text{Tolerance} \quad ,$$

The expression $\sum_{i=1}^{N} \dot{Q}_w$ will be described in equations (47) through (51) and is identified as SUMQWI in the computer program, whereas $\sum_{i=1}^{N} \tilde{\dot{Q}}_w$ is based upon $\dot{q}_w$ and denoted as SUMQGA. As long as convergence is not attained, iterations must be continued with new estimates of $\left[T_\ell(x)\right]_{j+1}$ and $\left[T_{wg}(x)\right]_{j+1}$.

## TOTAL HEAT TRANSFER RATE

The heat transfer rate through section i, between B and D in Figure 4 is $\dot{Q}_w(x_i)$ according to equation (39). The surface area of this wall section is

$$\frac{2\pi\, r(x_i)\, \Delta \bar{x}_i}{\cos \alpha(x_i)} \quad . \tag{47}$$

Summation of the heat transferred up to section $i = N$ is equal to

$$\sum_{i=1}^{N} \dot{Q}_w\,(x_i) \quad . \tag{48}$$

This amount is the heat which is transferred through the chamber walls between $x = x_1$ and $x = x_N + \frac{\Delta x_{N2}}{2}$ into the coolant per unit time, and not up to $x = x_N$.

The heat transfer rates through the initial and the final section of the contour are those through the area between C and D, and B and C, respectively, Figure 4. Heat transfer rate through the initial section $i = 1$ between $x = x_1$ and $x = x_1 + \frac{\Delta x_{12}}{2}$ is

$$\dot{Q}_w(x_1) = \frac{\pi\, r(x_1)\, \dot{q}_w{}'(x_1)\, \Delta x_{12}}{\cos \alpha\,(x_1)} \quad , \tag{49}$$

whereas for the final section at $x = x_{IXTAB}$

$$\dot{Q}_w\left(x_{IXTAB}\right) = \frac{\pi\, r\left(x_{IXTAB}\right) \dot{q}_w{}'\left(x_{IXTAB}\right) \Delta x_{IXTAB\;1}}{\cos \alpha \left(x_{IXTAB}\right)} \quad . \tag{50}$$

Integrating the heat transferred from point $x_1$ to $x_{IXTAB}$ per unit time results in

$$\eta \left[ \dot{Q}_w(x_1) + \sum_{i=2}^{IXTAB-1} \dot{Q}_w(x_i) + \dot{Q}_w\left(x_{IXTAB}\right) \right] \quad . \tag{51}$$

The coefficient $\eta$ is used to account for surface area geometry effects; i.e., $\eta = 0.5$ for double pass cooling if only one path is considered. The above amount at $x = x_{IXTAB}$ must coincide with the total heat transfer rate calculated from the gas phase final iteration value. The latter amount has been denoted as "SUMQGA" = "SUMQDA*$\eta$" whereas the former, equation (51), will be designated as "SUMQWI". These two values are not the same at an intermediate section $x = x_i$ because "SUMQGA" in TBL-I is the amount between $x = x_1$ and $x = x_i$, whereas "SUMQWI" is obtained between $x = x_1$ and $x = x_i + \frac{\Delta x_{i2}}{2}$. Iterations are performed until the following convergence is obtained:

$$\left| \frac{SUMQGA - SUMQWI}{SUMQWI} \right| < \text{Tolerance} \quad .$$

## SAME DIRECTION COOLANT FLOW

We have considered the case of the coolant flowing in an opposite direction to the combustion products. Now the coolant bulk temperature calculations are described for the coolant flowing in the same direction as the combustion products. Since rocket nozzles have been built with coolant flow passages in either direction and combinations thereof, the up and downstream coolant flow simulation of this new concept provides a capability for sectional treatment of changing the cooling cycle patterns. Equations in the section entitled Internally Calculated Coolant Bulk Temperature which must be replaced for the downpath simulation, are shown as follows: In changing the arrow of the coolant flow to point in the same direction as the combustion products in Figure 4, the temperature of the coolant leaving section i can be determined by

$$T_\ell\left(x_i + \frac{\Delta x_{i2}}{2}\right) = \frac{\left[T_\ell\left(x_{i-1}\right)\right]_j + \left[T_\ell\left(x_i\right)\right]_j}{2} + \frac{\dot{Q}_w\left(x_i\right)}{\dot{m}_\ell\, C_{p\ell}\left(x_i\right)} \quad , \tag{52}$$

where the argument $x_i + \frac{\Delta x_{i2}}{2}$ represents the coordinate at the coolant outlet location in section i. This equation must replace equation (41).

The coolant bulk temperature to be calculated at $x = x_i$ is obtained in a way similar to equations (42) and (44),

$$T_\ell\left(x_i\right) = \frac{T_\ell\left(x_i + \frac{\Delta x_{i2}}{2}\right) + \frac{\left[T_\ell\left(x_{i-1}\right)\right]_j + \left[T_\ell\left(x_i\right)\right]_j}{2}}{2} \tag{53}$$

$$= \frac{\left[T_\ell\left(x_{i-1}\right)\right]_j + \left[T_\ell\left(x_i\right)\right]_j}{2} + \eta\, \frac{\dot{Q}_w\left(x_i\right)}{2\dot{m}_\ell\, C_{p\ell}\left(x_i\right)} \quad , \tag{54}$$

with $\eta$ as the cooling efficiency due to geometry effects. Since the coolant flow temperature in this case increases toward the nozzle exit, the temperature input tables must be arranged correspondingly.

## DOUBLE PASS COOLING

In carrying out the calculation for a double pass cooling jacket with coolant flowing downstream initially and upstream afterwards, we assume, at first, that the nozzle wall consists only of down-pass tubes engaged in the heat transfer process. A correction is made to the analysis by a cooling coefficient $\eta$ which represents the surface area exposed to the hot gas covered by the downstream cooling tubes, compared to the total surface area. Then, the upstream pass calculation is executed in the same fashion neglecting the downstream coolant flow part. With each heat transfer calculation process, a wall temperature profile is provided. In order to determine the real temperature profile for the nozzle wall on the hot gas side, an average from the two temperature profiles can be determined.

The cooling coefficient $\eta$ is usually less than unity for the double pass cooling jacket. For coolant flowing in one direction, the cooling coefficient may exceed a value of one, since the wall surface area per unit length may be greater than the circumferential area due to the ripples formed between adjacent cooling tubes.

In the computer program an option indicator will identify which type of coolant flow direction should be considered in the analysis:

IDUMP = 0 Coolant flow upstream

IDUMP = 1 Coolant flow downstream

Modifications made to the existing TBL program are shown in Appendix B.

## EXAMPLE

In this section of the paper the previously described new concept is applied to a thrust chamber nozzle similar to the Space Shuttle's main engine. A common chamber down to an area ratio of $\epsilon = 7$ is coupled with different nozzle extensions expanding the combustion products to an area ratio of $\epsilon = 35$ or $\epsilon = 150$ depending on low altitude or vacuum operating conditions, Figure 5. The nozzle contours were optimized according to Rao's method [5,6] to provide maximum performance. Since a common chamber, Figure 6, was considered for both engines, the orbiter contour had to be modified as indicated by the dotted line in Figure 5. In the thrust chamber liquid hydrogen and oxygen react at a mixture ratio of 6.0 at a pressure of 3020 psia (212.33 kgf/cm$^2$), resulting in a stagnation temperature of 6600°R (3667°K). The free stream inviscid flow parameters serving as boundary layer edge conditions such as Mach number $M_\infty$, static pressure $P_\infty$, static temperature $T_\infty$ and mean molecular weight $\mathfrak{M}$, were obtained from the Two-Dimensional Kinetics (TDK) computer program [7].

First, only the combustion chamber expanding the reaction products to an area ratio of $\epsilon = 7$ is considered. In this section the chamber wall is regeneratively cooled with liquid hydrogen which flows in an opposite direction to the combustion products. The input data for the modified computer program are shown in Table 2 and Figure 7. The cross-sectional area variation of an individual cooling tube, assumed values for the gas-side wall temperature, and coolant bulk temperature as functions of the axial nozzle length, are presented in Table 2 and Figures 8 and 9. When a study is performed to optimize the cooling jacket geometry, the cross-sectional area in Table 2 and Figure 8 must be changed in each separate analysis. From such a parametric analysis, the best cooling tube geometry can then be selected. In the present example, however, the jacket geometry is fixed. Table 3 represents the relationship between the specific heat at constant pressure and temperature of the combustion products in the boundary layer. In order to determine the coolant flow heat transfer coefficient, the specific heat, thermal conductivity and viscosity for an expected pressure range between 4500 psia and 6000 psia (316.38 kgf/cm$^2$ and 421.84 kgf/cm$^2$) for the coolant fluid must be established as functions of temperature. The input data based upon References 4 and 8 are specified in Table 4. Additionally required input data can be found in Table 5. The calculated temperature distributions on the hot gas-side, liquid coolant-side and the coolant are plotted in Figure 10. The total heat transferred through the chamber wall without considering an enhancement factor is 10 580 kcal/sec (42 000 Btu/sec), whereas the local specific heat flux is exhibited in Figure 11. The velocity and temperature boundary layer thicknesses are presented in Figure 12 and the momentum and energy thicknesses are plotted in Figure 13.

The most important result from a performance aspect is the boundary layer displacement thickness $\delta^*$, Figure 14. This parameter, significantly affected by the wall temperature, reveals by how much the wall contour, identical to the inviscid flow border streamline, must be displaced to allow the same mass flow condition. A negative sign of $\delta^*$ means a displacement of the inviscid-flow contour towards the thrust chamber centerline.

If the density across the boundary layer is constant, the profile of the mass flow density $\rho u$ is in principle similar to the velocity profile, Figure 15a. However, if the density varies the mass flow density overshoots its free stream value $\rho_\infty U_\infty$, especially when the wall is highly cooled, Figure 15b. The dotted line in either schematic denotes the mass flow density profile for inviscid flow. Results from the present analysis indicate that the displacement thickness $\delta^*$ is negative for the most part of the combustion chamber to compensate for the strong cooling effect, Figure 14. The performance deficiency represented by a thrust loss, Figure 16, down to an expansion ratio of $\epsilon = 7$ is already quite large according to the equation [1, 2, 3]

$$\Delta F_{B.L.} = \left[2\pi r \rho_\infty' U_\infty'^2 \theta \cos \alpha\right]_{exit} \left[1 - \frac{\delta^*}{\theta} \frac{P_\infty'}{\rho_\infty' U_\infty'^2}\right]_{exit} .$$

The corresponding loss in specific impulse is shown in Figure 17.

To investigate the effect of variable and constant properties necessary to calculate the coolant flow heat transfer coefficient, an additional analysis was performed using constant values for the specific heat $C_{p\ell} = 3.75$ Btu/lbm°R, thermal conductivity $\lambda_\ell = 0.0000288$ Btu/ft s °R and the dynamic viscosity $\mu_\ell = 0.0000065$ lbm/ft s which represents mean values between the temperatures of 50°R and 550°R. In comparing the results in Figure 18 with the ones obtained for variable properties in Figure 10, it is evident that the wall temperatures are higher at the throat and lower at an expansion ratio of $\epsilon = 7$. This study clearly outlines that most accurate input data must be used to perform a reliable analysis.

Only the chamber section down to an area ratio of $\epsilon = 7$ has been discussed. Now, the nozzle extension for the booster engine ranging from an area ratio $\epsilon = 7$ to $\epsilon = 35$ is treated. For convenience, this nozzle contour has been selected, although an analysis for the orbiter nozzle contour would be similar. The booster nozzle wall is also cooled by the hydrogen in a double pass cycle. The coolant enters 564 tubes of an area ratio of $\epsilon = 7$, flows toward the nozzle exit area ($\epsilon = 35$) and is then turned upstream. The wall thickness of each tube varies from 0.18 to 0.25 mm toward the nozzle exit. All required input data for the downstream and upstream analysis are shown in Tables 6, 7, and 8. The resulting wall temperature distributions presented in Figure 19 are considerably different for both cooling paths and exhibit a minimum in the down-pass section, where the coolant bulk temperature reaches a value of approximately 140°K (250°R). At this state the hydrogen possesses a maximum specific heat or highest cooling capacity. In the real nozzle the temperature differences between the down and up-pass cooling tube will come to an equilibrium temperature through lateral heat transfer at each local station. Therefore, an arithmetic mean of the different temperatures will represent the real nozzle temperature more realistically, Figure 20. The individual displacement and momentum thicknesses are presented in Table 9, whereas their averaged values are plotted in Figures 21 and 22. The total performance degradation, expressed in thrust and specific impulse loss at the nozzle exit, resulted in $\Delta F_{B.L.} = 4.742$ tons (10 470 lbf) and $\Delta ISP = 7.687$ s (Fig. 23). Heat absorbed by the coolant fluid between the injector face and the nozzle exit ($\epsilon = 35$) amounts to 27 000 kcal/s (107 000 Btu/s). This method was also applied to identify the area of ice formation (wall temperatures less than 460°R) inside the J-2 engine; since deposition of ice crystals along the nozzle exit periphery were observed during altitude simulation test firings.[1]

## CONCLUSION

A new method has been presented by which the hot gas-side and the coolant flow-side wall temperature distributions, as well as the coolant fluid temperature variation of a regeneratively cooled thrust chamber, can be determined. The analytical formulation is based upon a coupling of the boundary layer equations with the heat transfer process through the nozzle wall and the coolant flow heat absorption. The new concept has been incorporated into the existing JANNAF Turbulent Boundary Layer (TBL) computer program. A sample case showing the application of the new calculation process for a thrust chamber similar to the Space Shuttle booster engine, has also been outlined. Since several empirical relationships such as the friction coefficient of the hot gas-side wall, the Stanton number, and Colburn's equation for the

1. Analytical Prediction of Ice Formation Inside the J-2 Engine Nozzle Contour (200 K Thrust Level). Memorandum S&E-ASTN-PP (72M-5) NASA, Marshall Space Flight Center, January 1972.

coolant flow heat transfer coefficient were used and no adjustments for the coolant flow turbulence and channel curvature were made, the results are only approximate. In addition, this new model could serve as a convenient tool for the design of an optimum cooling path and channel geometry concept.

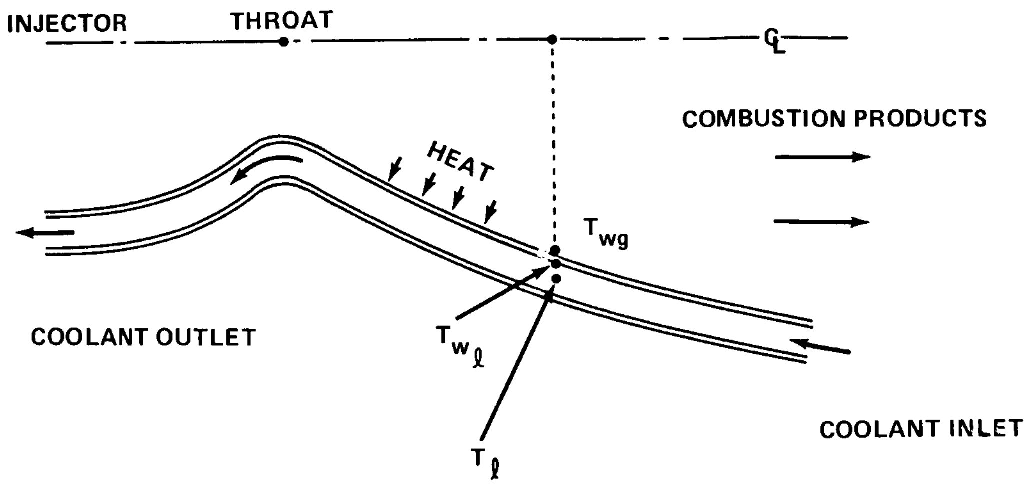



Figure 1. Regeneratively cooled combustor flow model.

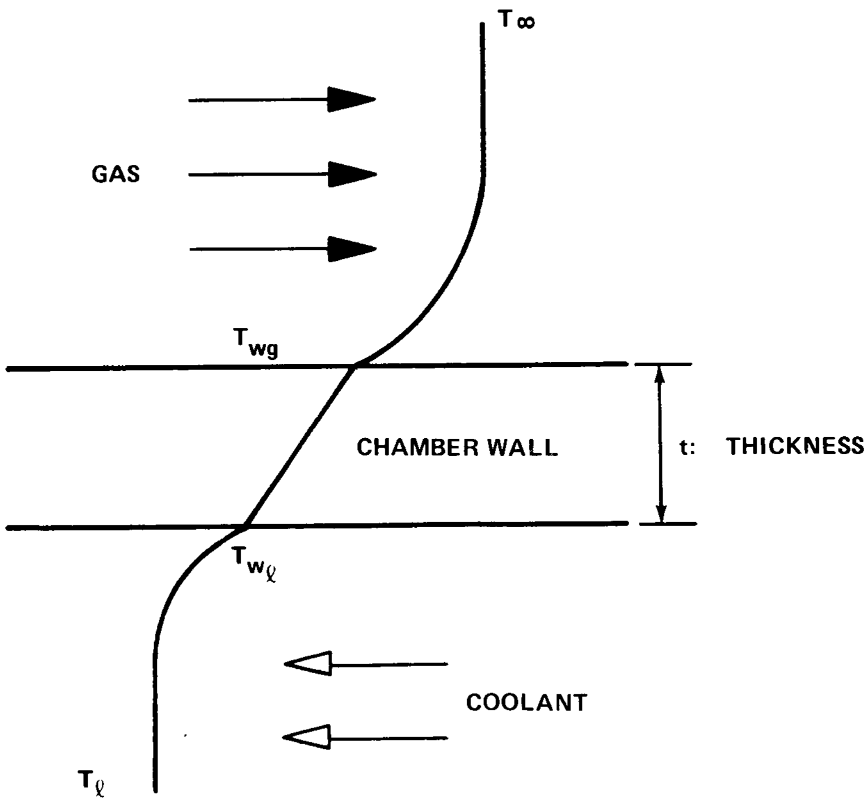



Figure 2. Model of temperature profile.

$$x = x_i$$

(1)

$$[T_\ell]_j$$

$$h_g = \rho_\infty U_\infty C_H \frac{H_{aw} - H_w}{T_{aw} - [T_{wg}]_j}$$

(2)

$$T_{w_\ell} = \frac{h_\ell\left(1 + \frac{\lambda w}{t\, h_g}\right) [T_\ell]_j + \frac{\lambda w}{t} T_{aw}}{h_\ell\left(1 + \frac{\lambda w}{t\, h_g}\right) + \frac{\lambda w}{t}}$$

$$h_\ell = 0.025 \frac{\lambda_\ell}{D_{tube}} R_{e_\ell}^{0.8} P_{r_\ell}^{0.4} \left(\frac{[T_\ell]_j}{T_{w_\ell}}\right)^{0.55} \eta_E$$

(3)

$$T_{wgc} = \frac{h_g T_{aw} + \frac{\lambda_w}{t} T_{w_\ell}}{h_g + \frac{\lambda w}{t}}$$

(4)

$$\dot{q}'_w = h_g (T_{aw} - T_{wgc})$$

(5)

$$T_{\ell c}(x) = \frac{[T_\ell(x)]_j + [T_\ell(x + \Delta x_2)]_j}{2} + \eta \frac{\dot{q}'_w \pi\, r(x) \Delta \bar{x}}{\dot{m}_\ell C_{p\ell}(x) \cos \alpha(x)}$$

(6)

$$[T_\ell(x)]_{j+1} = \frac{T_{\ell c}(x) + [T_\ell(x)]_j}{2}$$

(6)

$$[T_{wg}(x)]_{j+1} = \frac{T_{wgc}(x) + [T_{wg}(x)]_j}{2}$$

Figure 3.a. Flow chart indicating the calculation procedure at each station $x = x_i$.

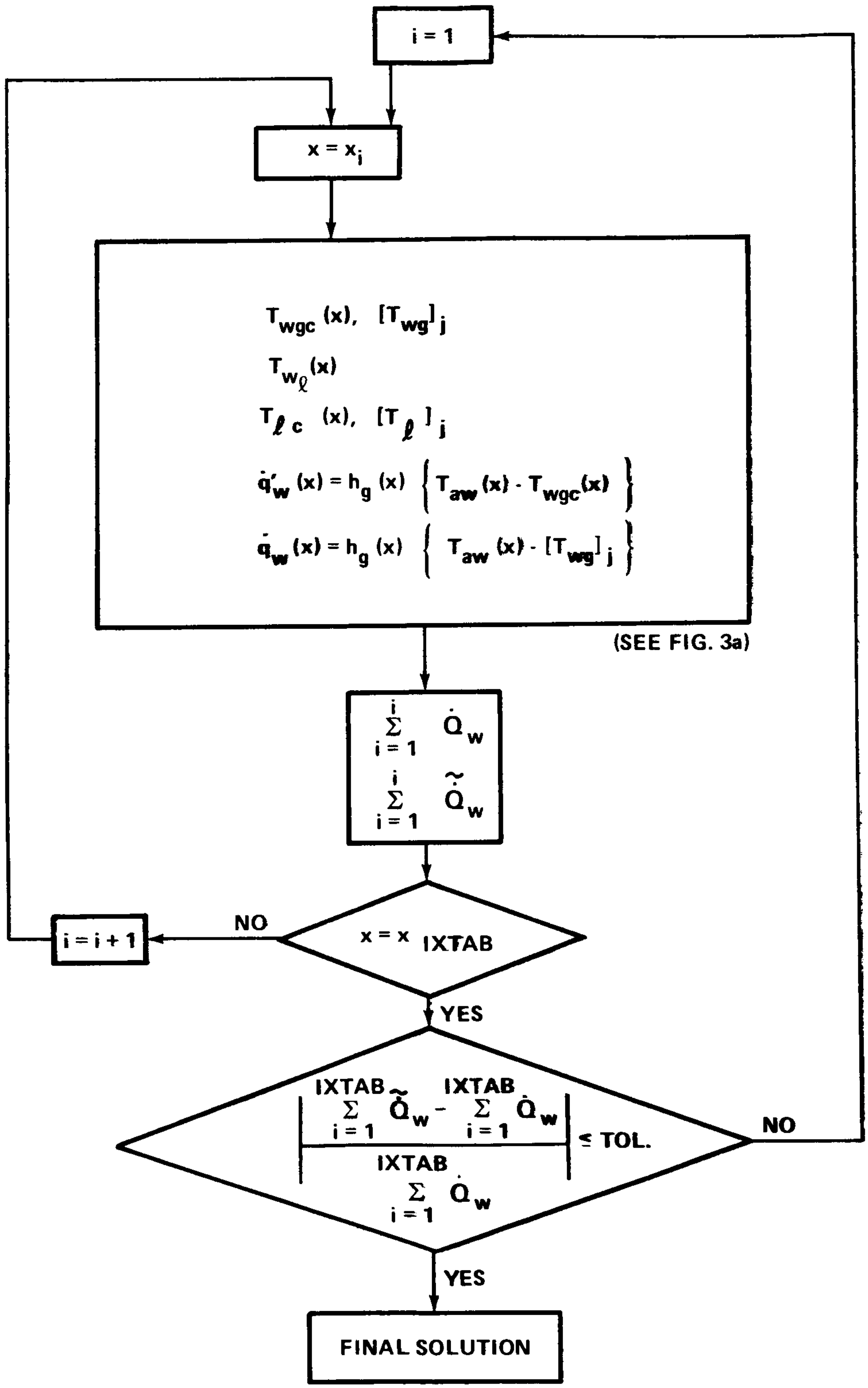



Figure 3. b. Overall flow diagram.

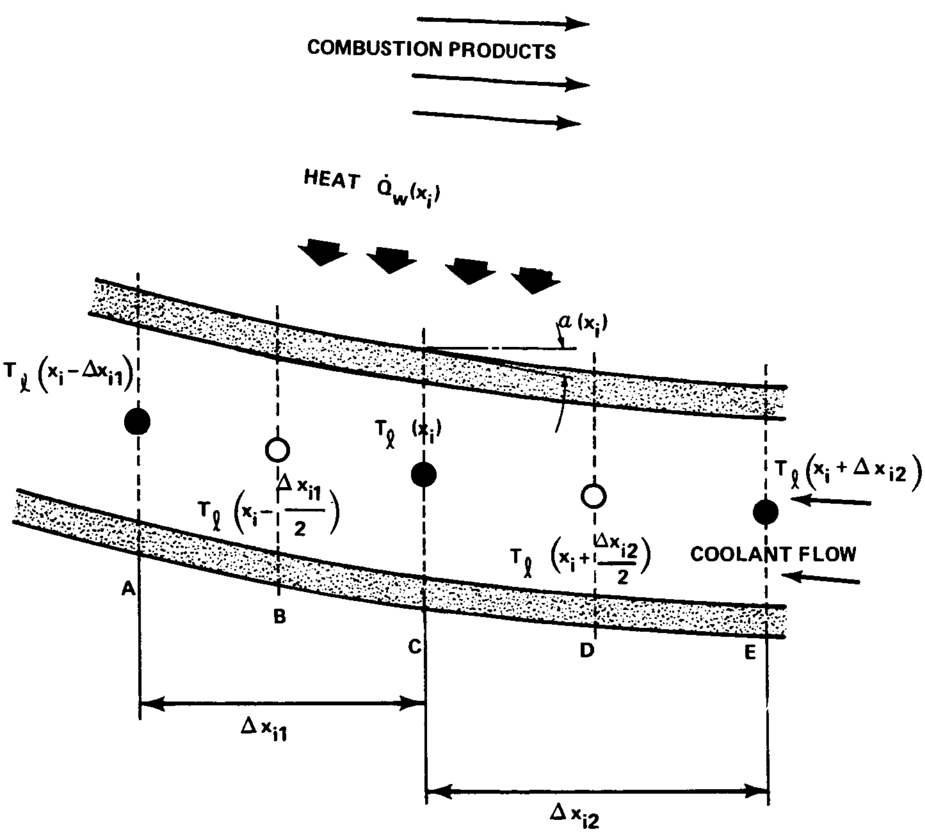



Figure 4. Schematic identifying temperatures used in the coolant flow temperature analysis.

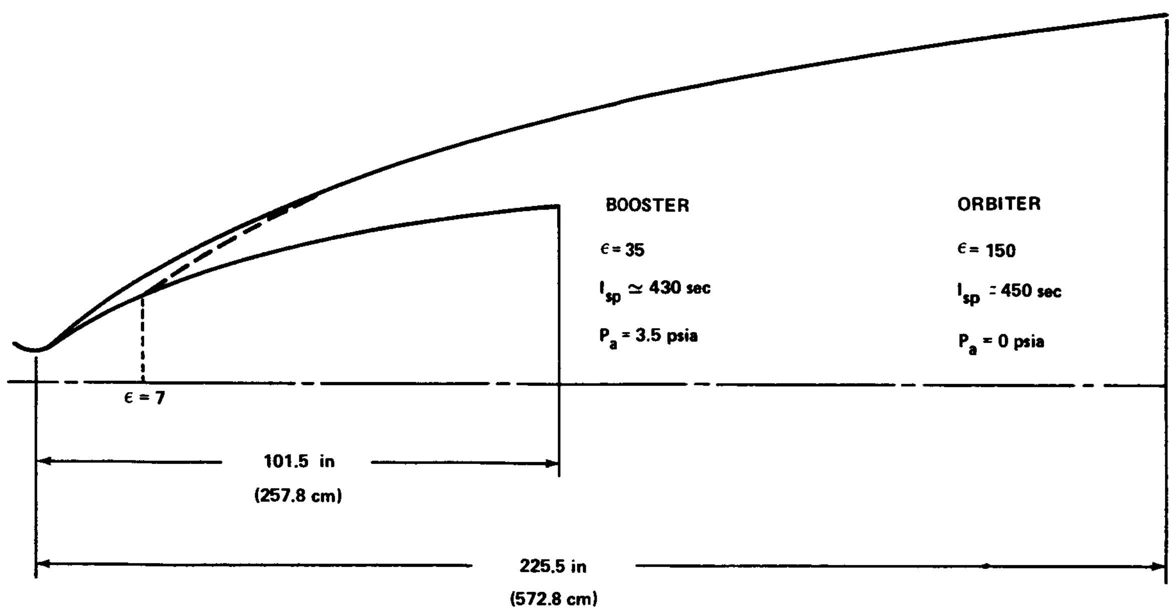



Figure 5. Shuttle engine nozzle contour determined by Rao's method.

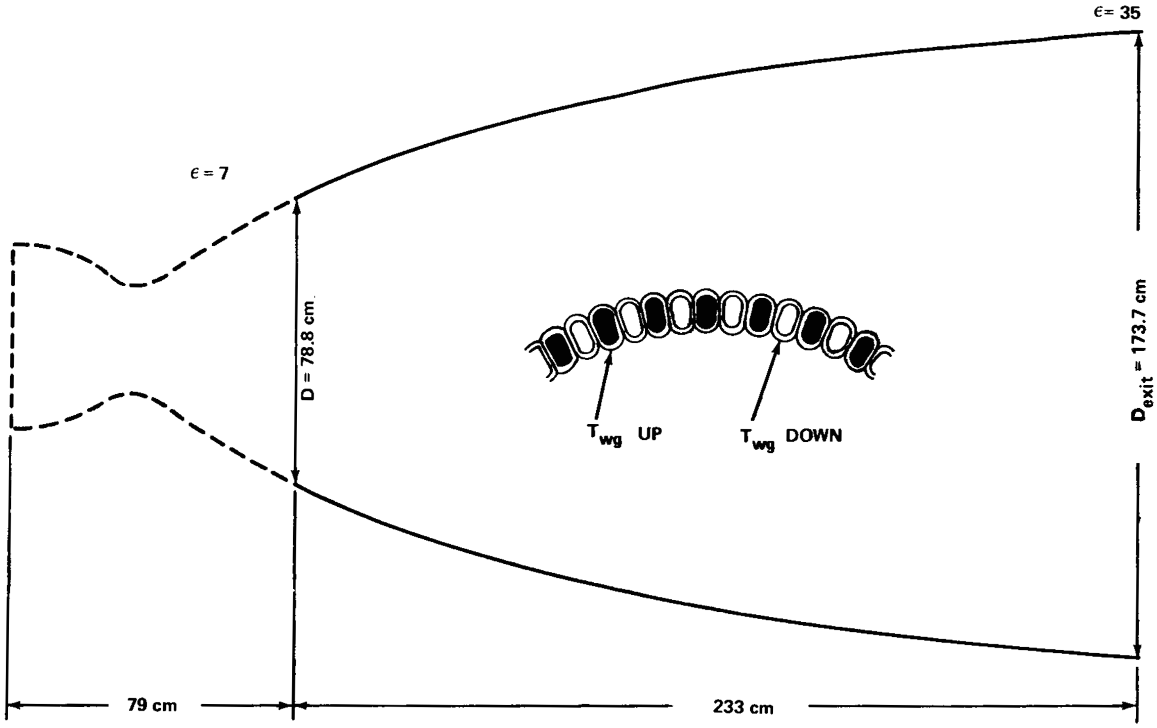



Figure 6. Booster engine contour.

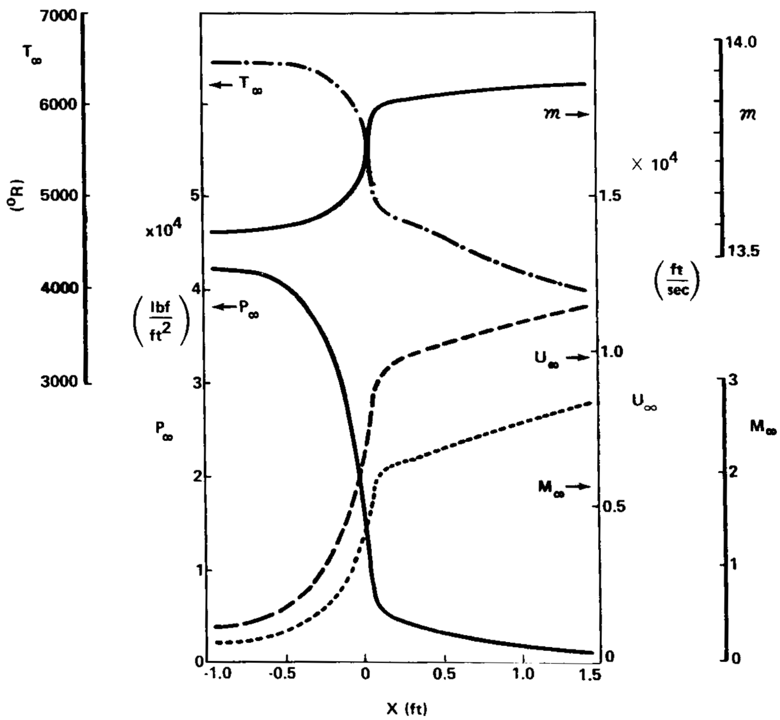



Figure 7. Input freestream parameters (obtained from TDK analysis).

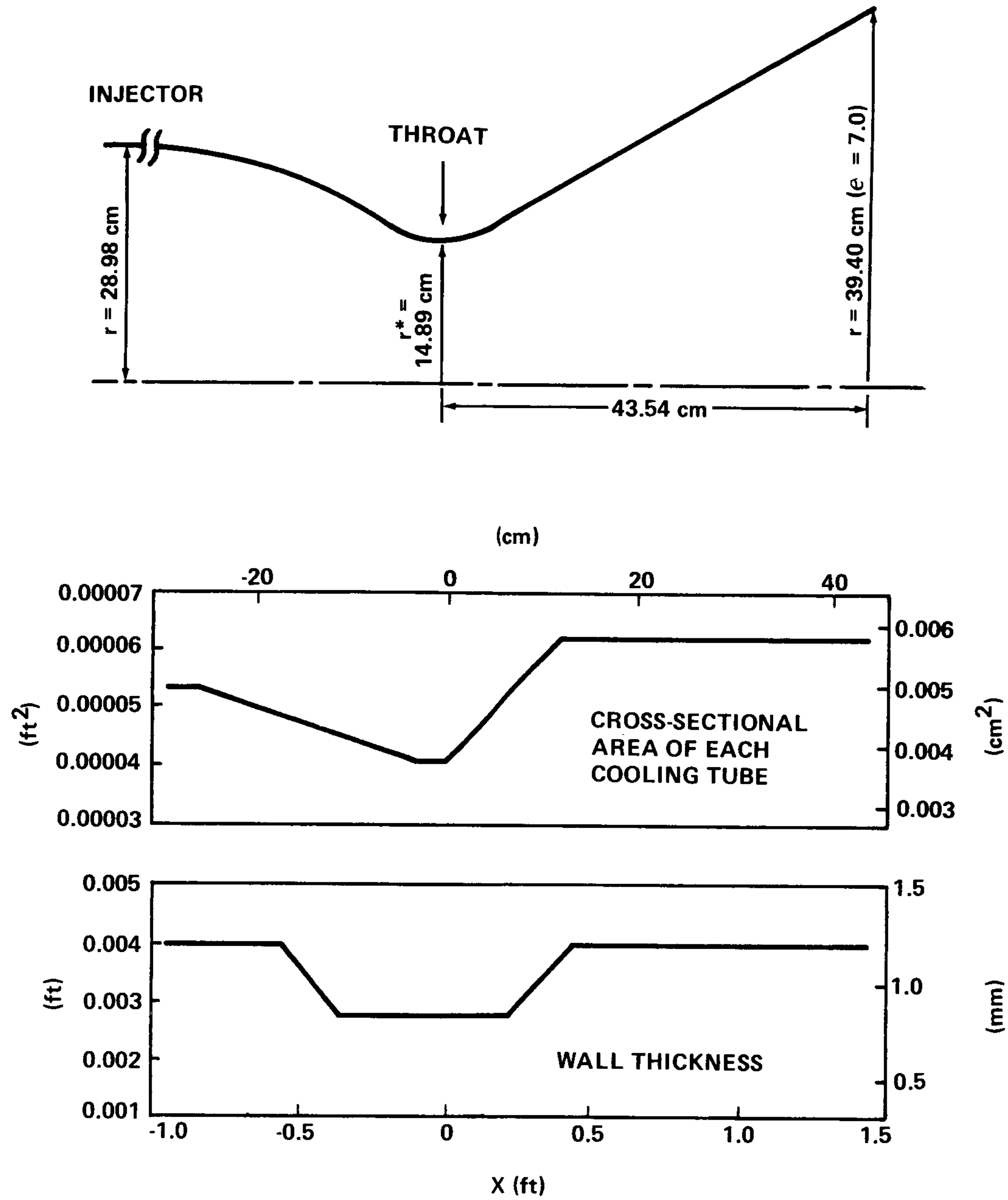



Figure 8. Combustor cooling geometry.

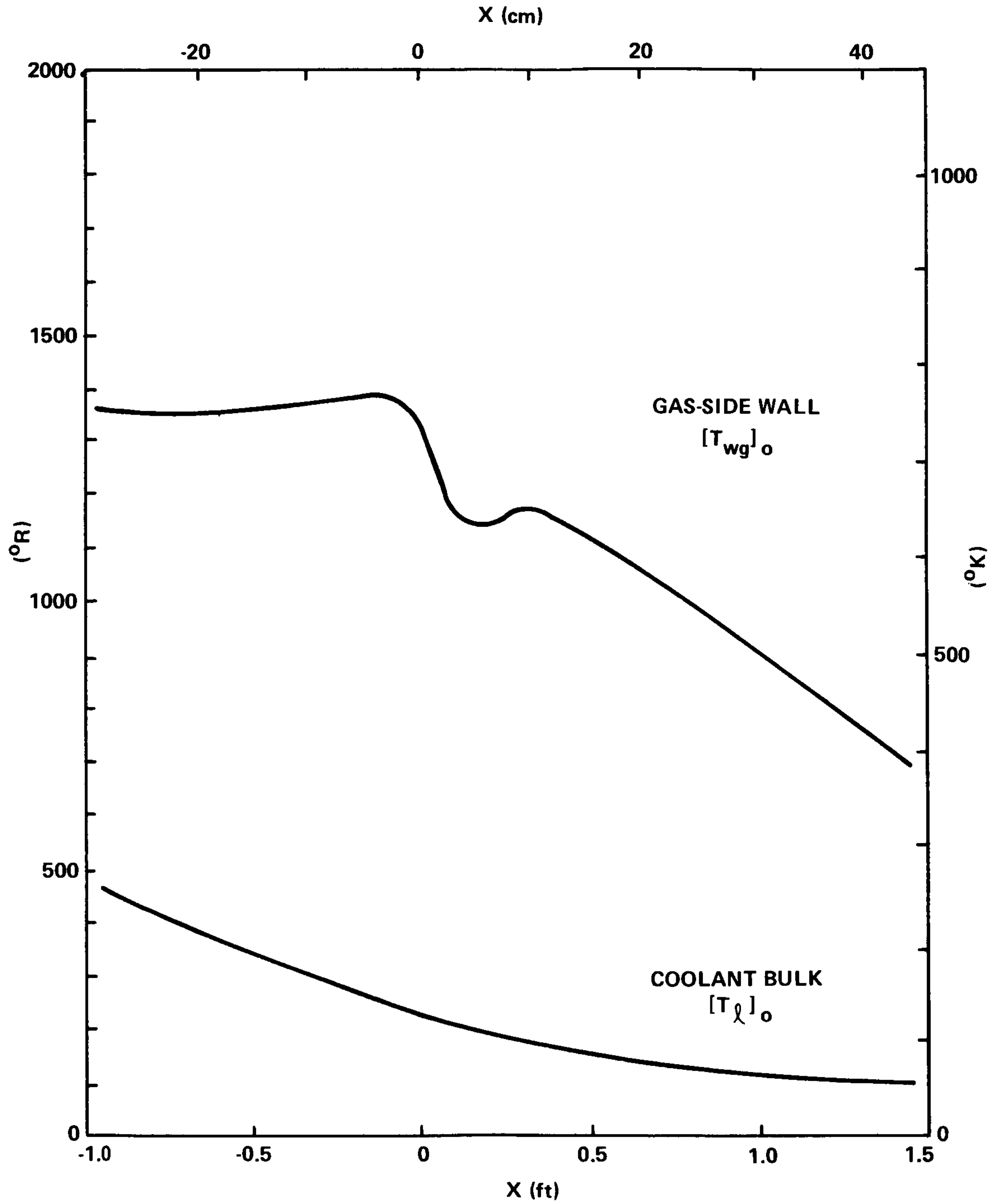



Figure 9. Input temperatures to initiate calculation.

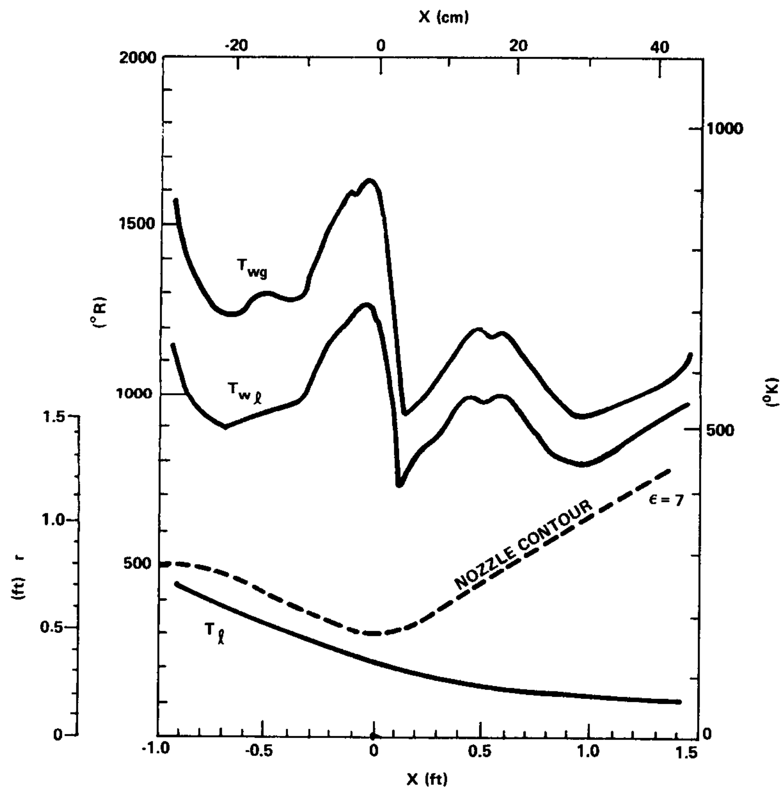



Figure 10. Calculated temperatures.

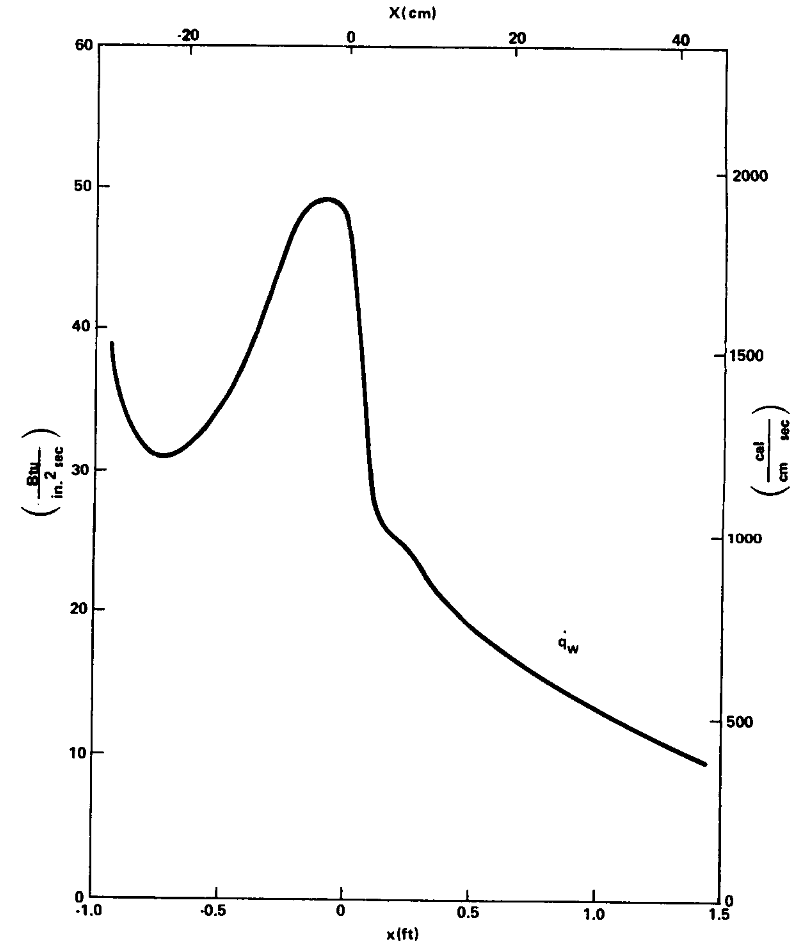



Figure 11. Specific heat transfer rate.

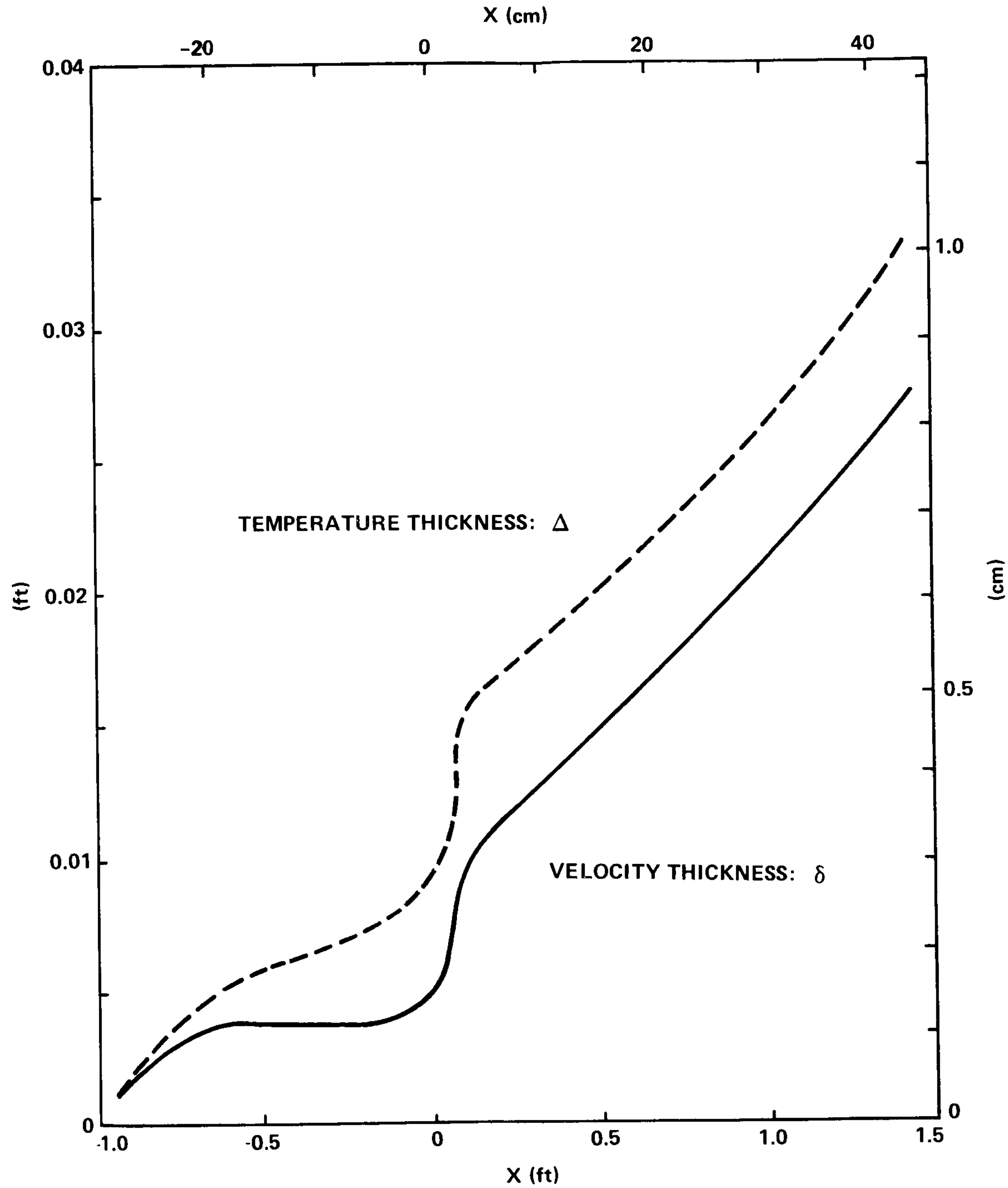



Figure 12. Velocity and temperature thicknesses.

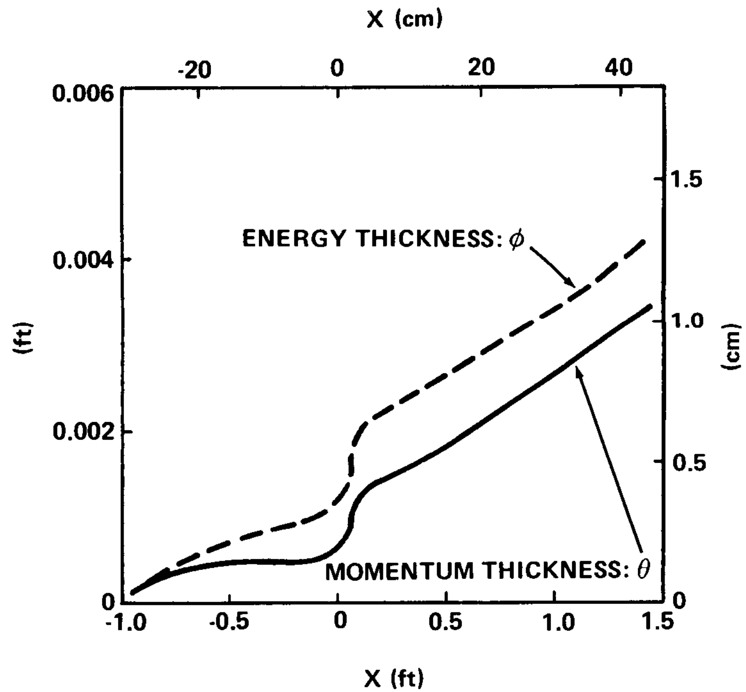



Figure 13. Momentum and energy thicknesses.

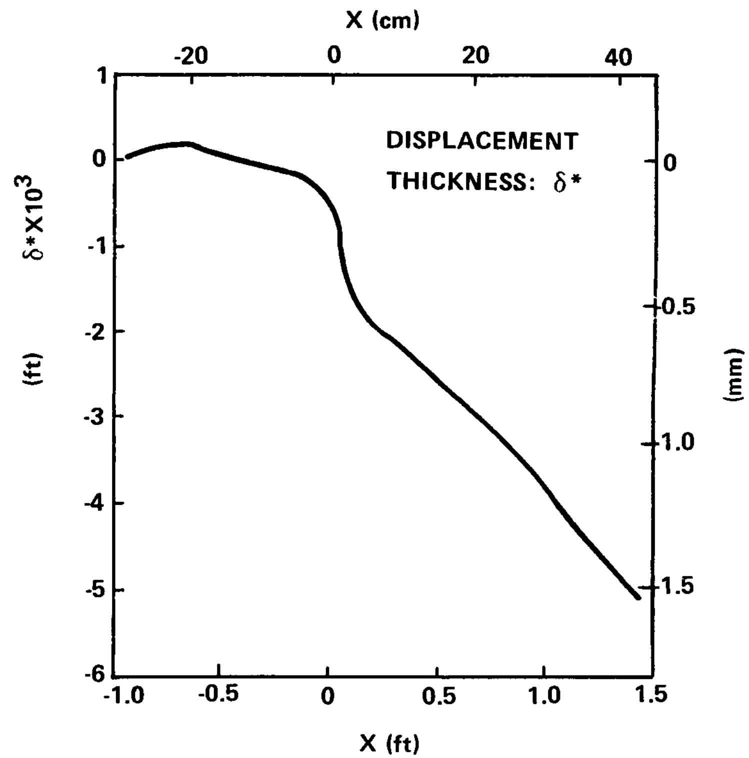



Figure 14. Displacement thickness.

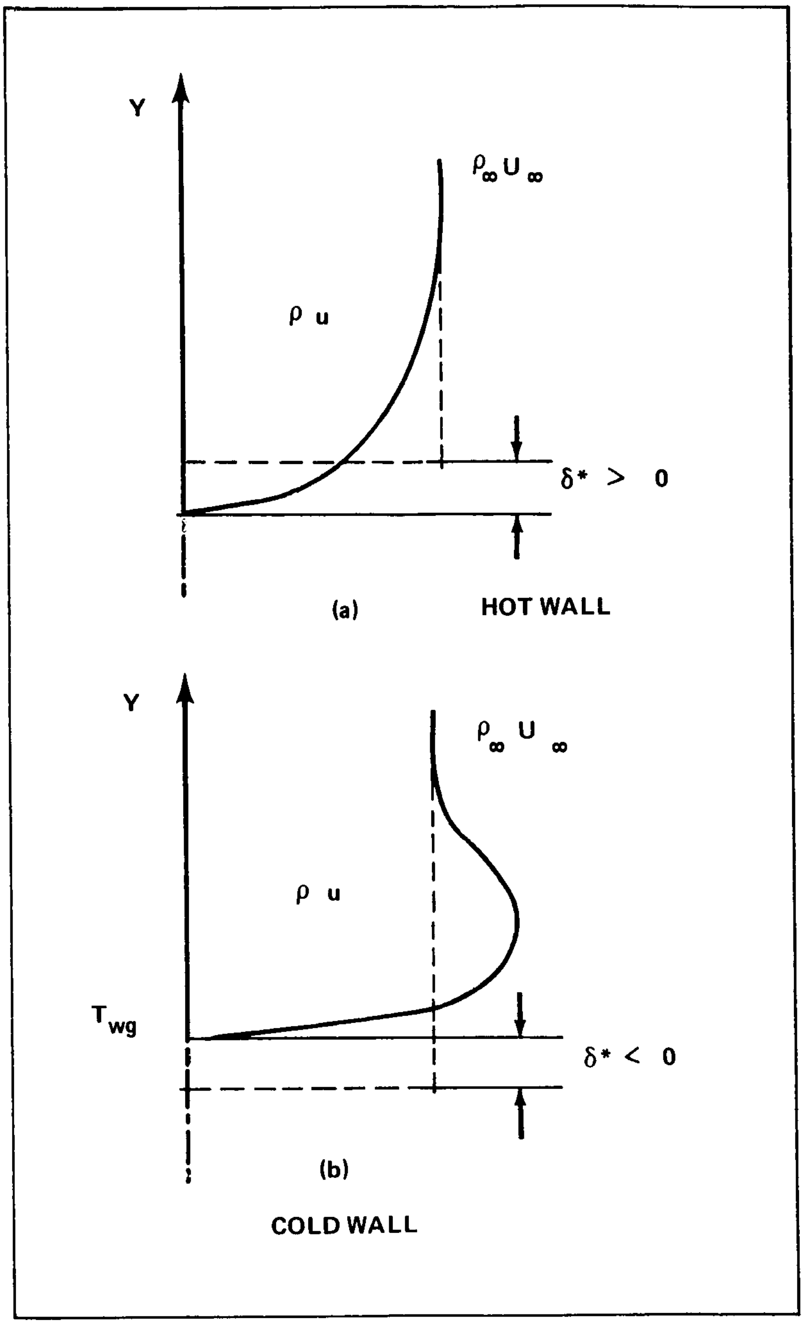



Figure 15. Displacement thickness (hot wall and cold wall).

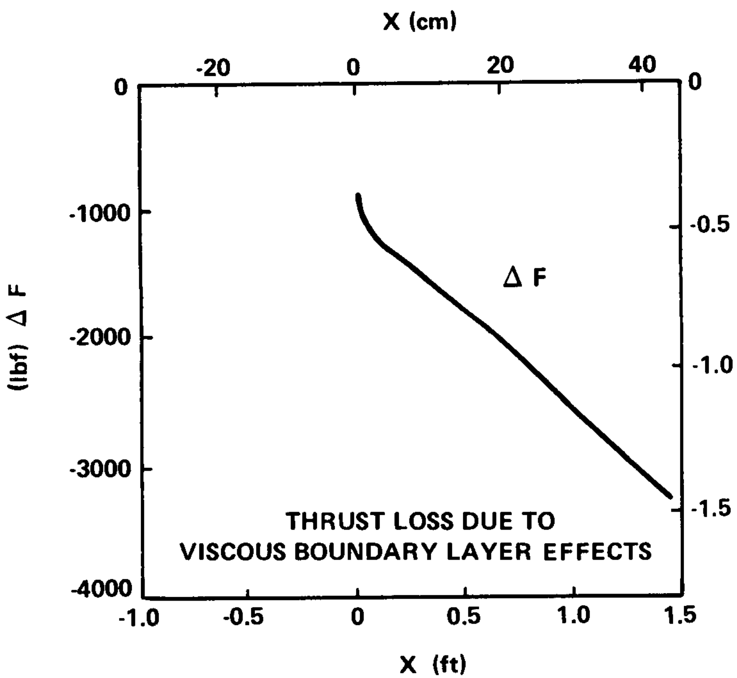



Figure 16. Thrust loss due to viscous boundary layer effects.

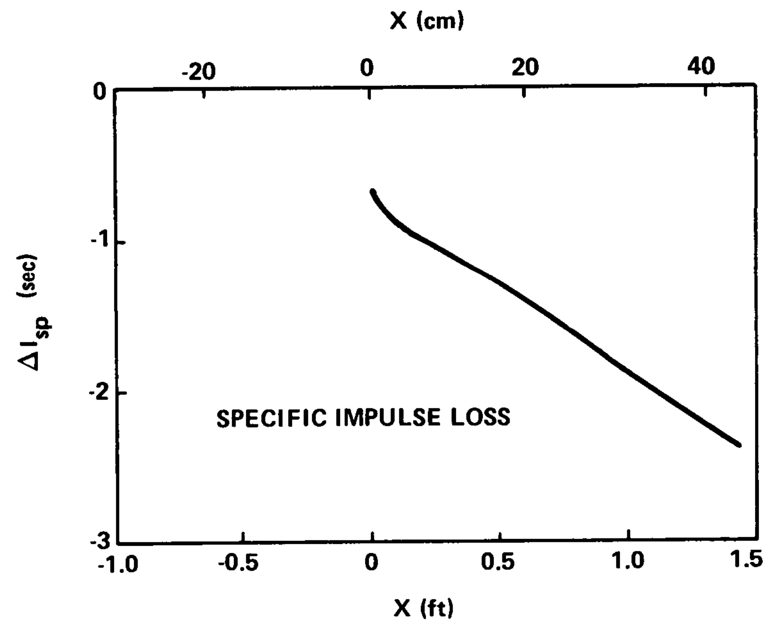



Figure 17. Loss of specific impulse due to boundary layer effects.

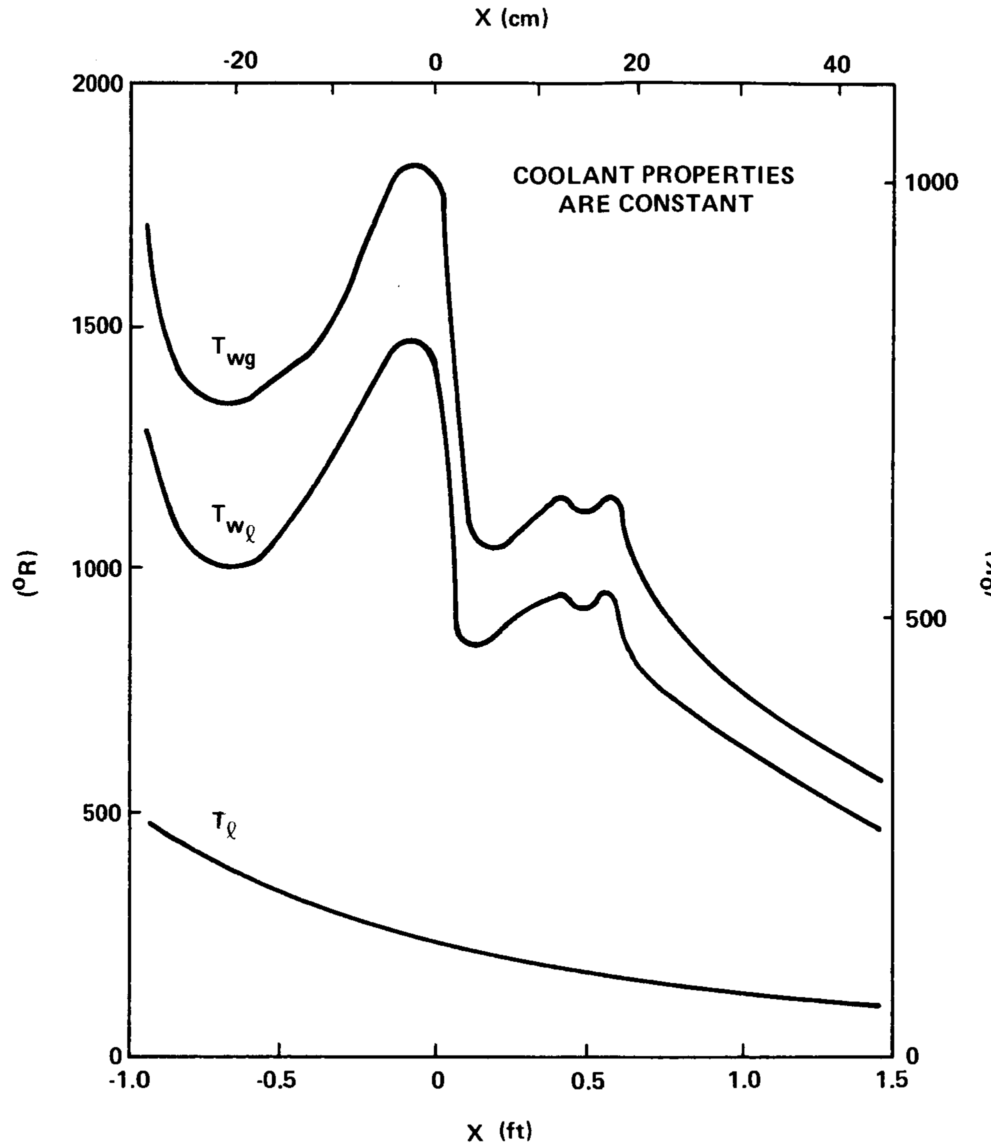



Figure 18. Calculated temperatures.

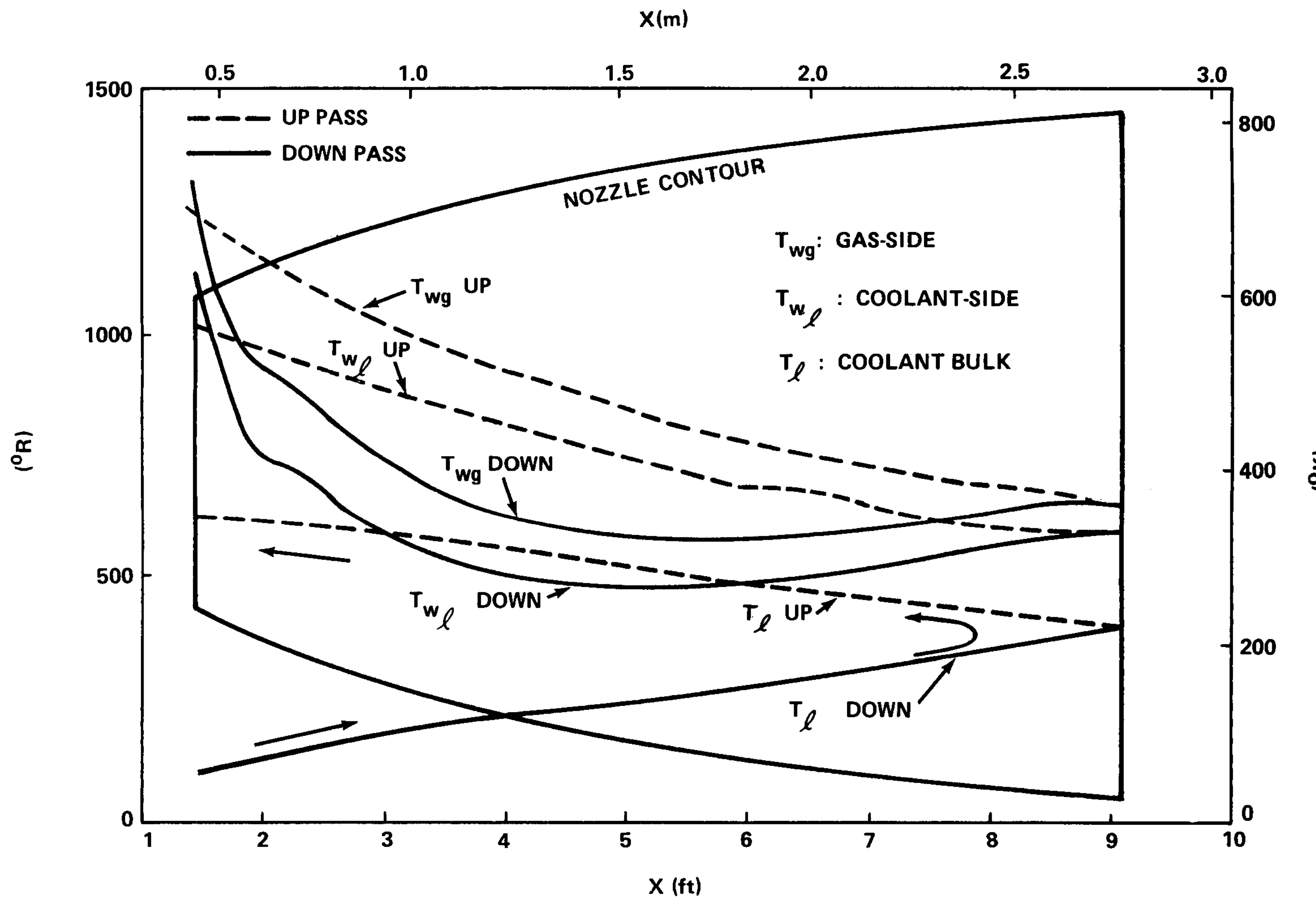



Figure 19. Nozzle temperatures calculated.

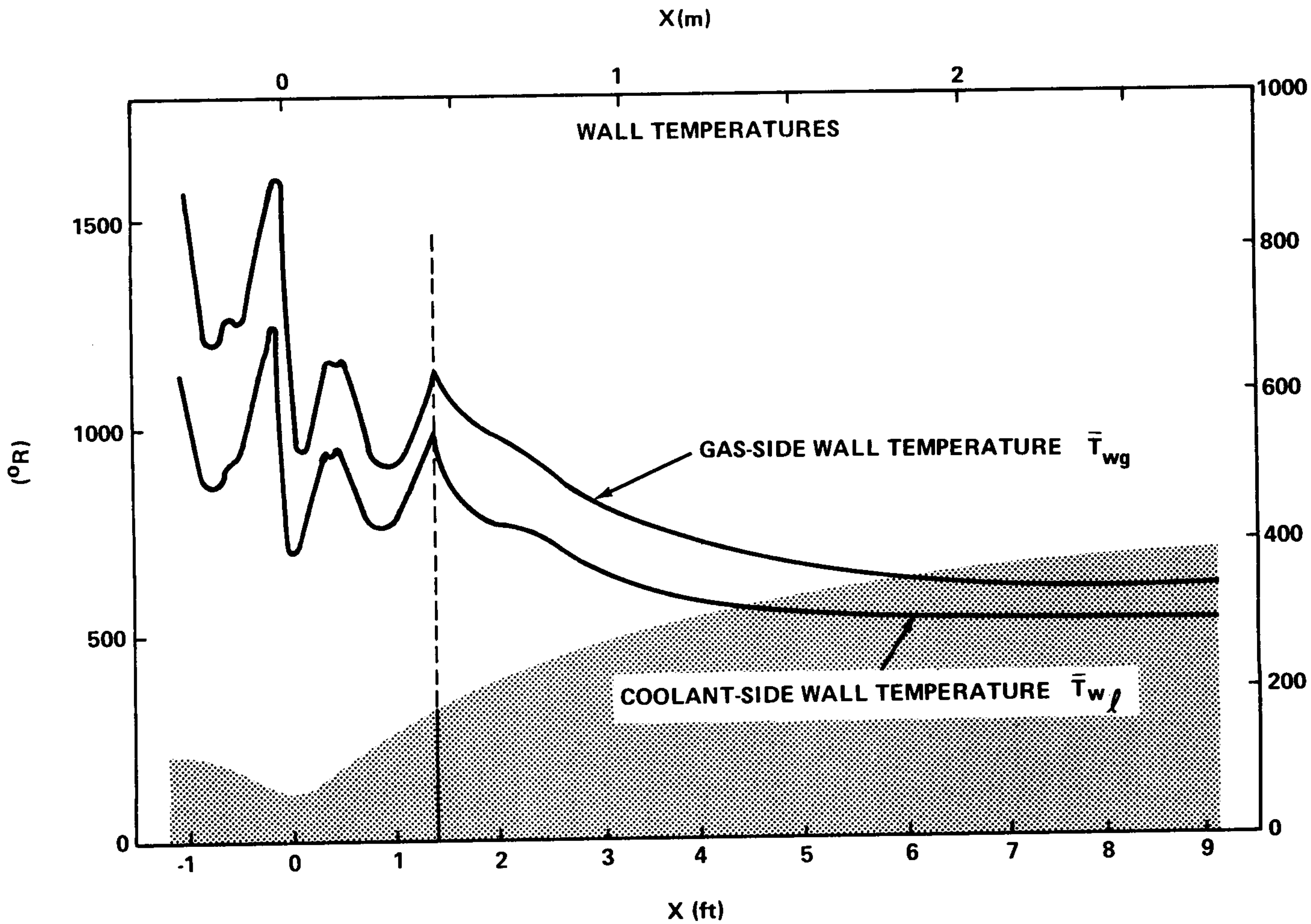



Figure 20. Averaged nozzle wall temperatures.

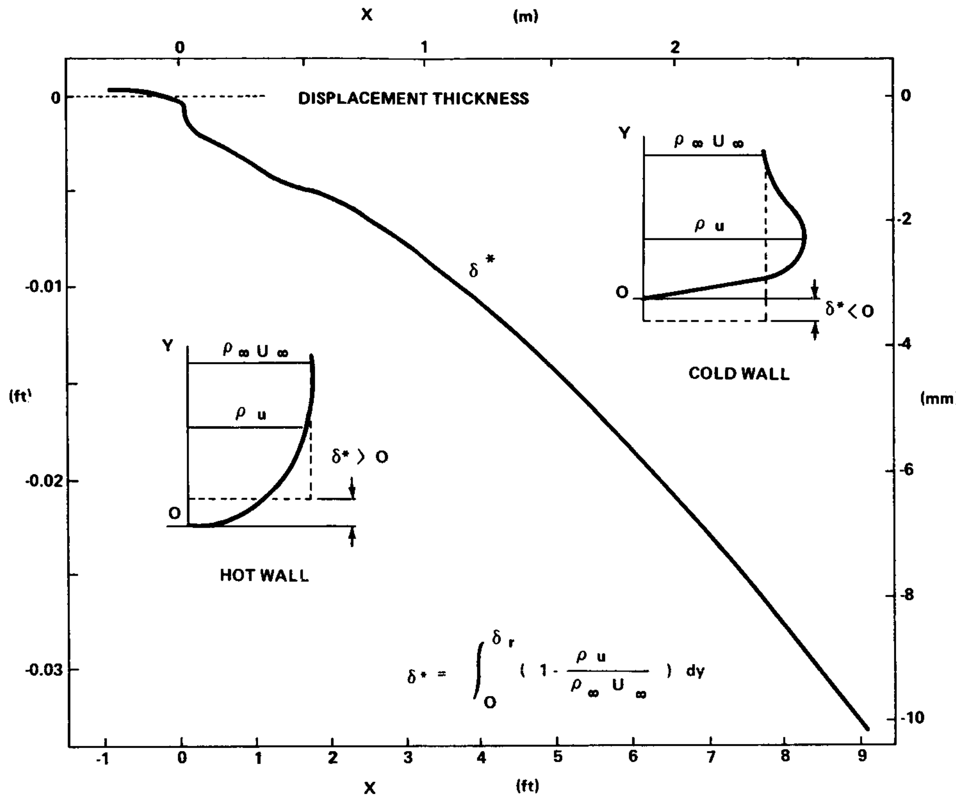
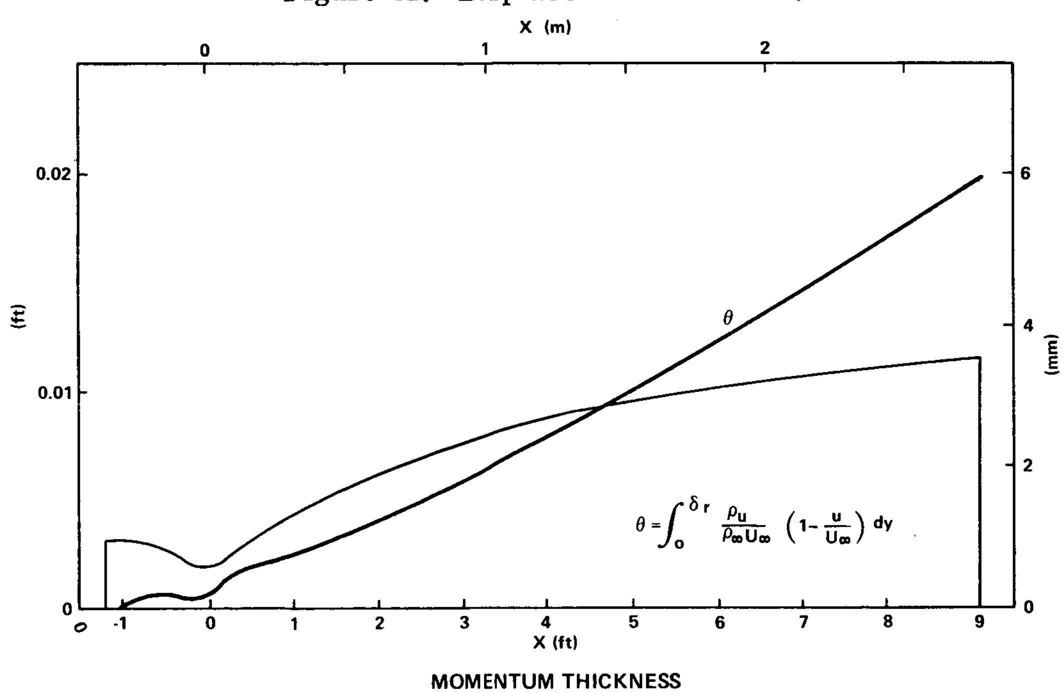
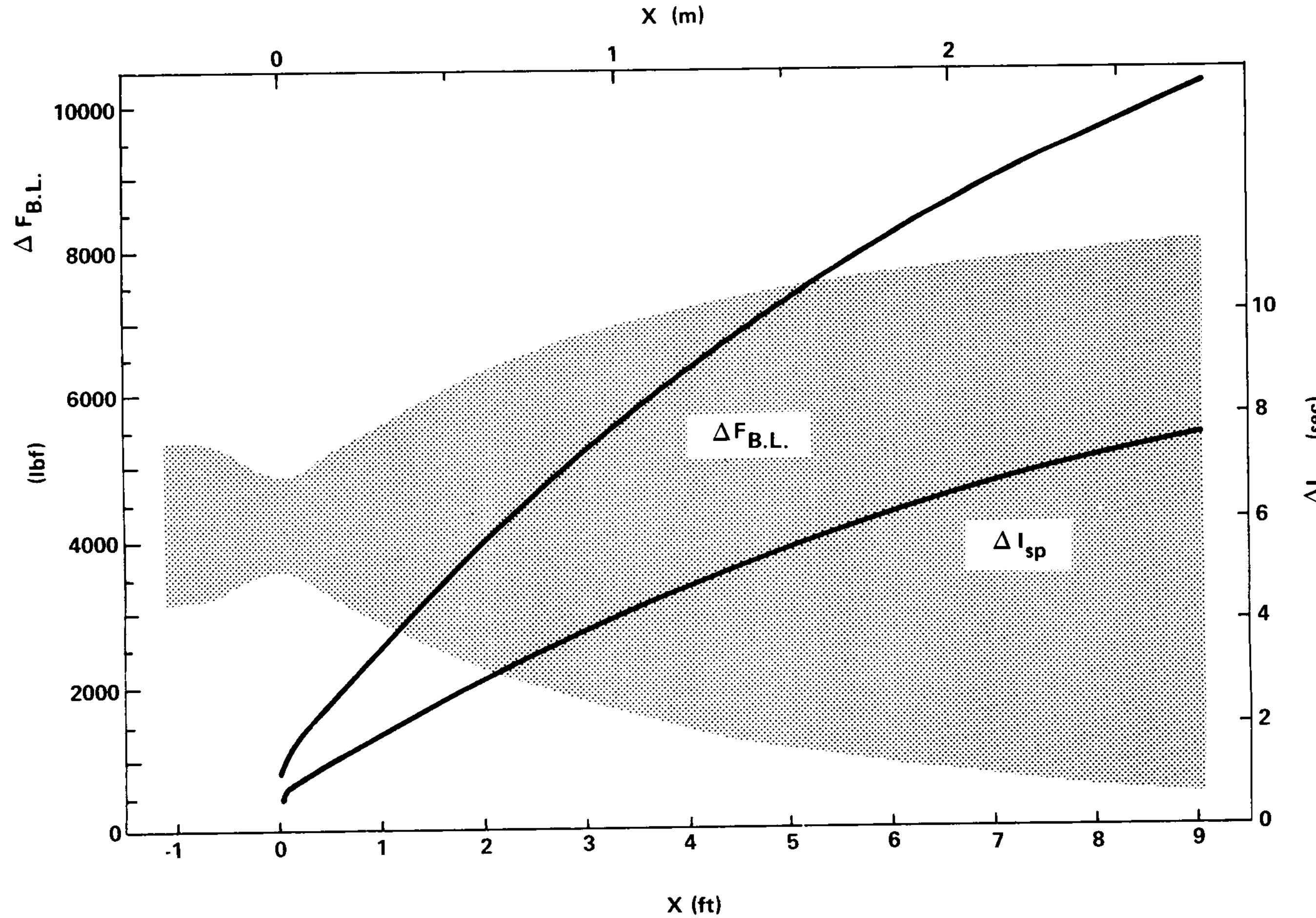



Figure 21. Displacement thickness.




MOMENTUM THICKNESS

Figure 22. Momentum thickness.




$$\Delta F_{B.L.} = \Big[2\pi r\ \rho_\infty U_\infty^2\ \theta\ \cos\alpha\Big]_{exit} \quad \left[1 - \frac{\delta^*}{\theta}\ \frac{\rho_\infty}{\rho_\infty\ U_\infty^2}\right]_{exit}$$

Figure 23. Thrust loss due to viscous boundary layer effects.

TABLE 1. REGENERATIVE COOLING EQUATIONS

| | |
|---|---|
| $\dot{q}_w' = h_g (T_{aw} - T_{wg})$ | (equation 20) |
| $h_g = \rho_\infty U_\infty C_H \dfrac{H_{aw} - H_w}{T_{aw} - \left[T_{wg}\right]_j}$ | (equation 21) |
| $h_\ell = 0.025 \dfrac{\lambda_\ell}{D_{tube}} R_{e_\ell}^{0.8} P_{r_\ell}^{0.4} \left(\dfrac{\left[T_\ell\right]_j}{T_{w_\ell}}\right)^{0.55} \eta_E$ | (equation 24) |
| $T_{w_\ell} = \dfrac{h_\ell \left(1 + \dfrac{\lambda_w}{t\, h_g}\right) \left[T_\ell\right]_j + \dfrac{\lambda_w}{t} T_{aw}}{\dfrac{\lambda_w}{t} + h_\ell \left(1 + \dfrac{\lambda_w}{t\, h_g}\right)}$ | (equation 33) |
| $T_{wg} = \dfrac{h_g T_{aw} + \dfrac{\lambda_w}{t} T_{w_\ell}}{h_g + \dfrac{\lambda_w}{t}}$ | (equation 34) |

## TABLE 2. INPUT DATA FOR COMBUSTOR

| 1 | X | Y | Mach Number | Pressure | Static Temperature |
|---|---|---|---|---|---|
| 1 | -0.950725 | 0.802083 | 0.220976 | 422396.766 | 6476.894 |
| 2 | -0.914726 | 0.801277 | 0.221523 | 422122.793 | 6476.810 |
| 3 | -0.842728 | 0.794779 | 0.225972 | 421622.242 | 6475.952 |
| 4 | -0.770730 | 0.781616 | 0.235435 | 420527.219 | 6474.074 |
| 5 | -0.734732 | 0.772440 | 0.242420 | 419691.812 | 6472.632 |
| 6 | -0.662734 | 0.748573 | 0.262271 | 417197.340 | 6468.317 |
| 7 | -0.590736 | 0.716937 | 0.292080 | 413116.426 | 6461.215 |
| 8 | -0.554738 | 0.699832 | 0.309721 | 410519.758 | 6456.660 |
| 9 | -0.518739 | 0.682727 | 0.329208 | 407496.906 | 6451.318 |
| 10 | -0.446740 | 0.648511 | 0.375117 | 399765.176 | 6437.497 |
| 11 | -0.410741 | 0.631406 | 0.402511 | 394762.754 | 6428.419 |
| 12 | -0.374742 | 0.614301 | 0.433805 | 388714.000 | 6417.295 |
| 13 | -0.302744 | 0.580085 | 0.513023 | 371954.164 | 6385.611 |
| 14 | -0.266745 | 0.562980 | 0.565406 | 359875.809 | 6361.932 |
| 15 | -0.230746 | 0.545875 | 0.628830 | 344318.844 | 6330.417 |
| 16 | -0.194747 | 0.529072 | 0.696138 | 327004.102 | 6293.651 |
| 17 | -0.158749 | 0.515094 | 0.766393 | 308263.379 | 6251.739 |
| 18 | -0.122750 | 0.504252 | 0.839565 | 288302.387 | 6204.368 |
| 19 | -0.086751 | 0.496347 | 0.915600 | 267383.355 | 6151.280 |
| 20 | -0.057200 | 0.491945 | 0.980160 | 249697.223 | 6103.208 |
| 21 | 0.000000 | 0.488583 | 1.193460 | 193860.369 | 5926.078 |
| 22 | 0.003573 | 0.488618 | 1.227370 | 185645.486 | 5888.241 |
| 23 | 0.007256 | 0.488720 | 1.260930 | 177689.357 | 5850.416 |
| 24 | 0.011012 | 0.488901 | 1.293320 | 169966.758 | 5814.319 |
| 25 | 0.014858 | 0.489160 | 1.325760 | 162435.506 | 5777.151 |
| 26 | 0.018786 | 0.489507 | 1.358830 | 155083.424 | 5738.689 |
| 27 | 0.022785 | 0.489942 | 1.392170 | 147900.947 | 5699.396 |
| 28 | 0.030987 | 0.491104 | 1.459980 | 134013.490 | 5617.924 |
| 29 | 0.035185 | 0.491842 | 1.494590 | 127297.204 | 5575.459 |
| 30 | 0.043767 | 0.493650 | 1.565680 | 114299.943 | 5486.489 |
| 31 | 0.048149 | 0.494735 | 1.602360 | 108015.929 | 5439.801 |
| 32 | 0.057091 | 0.497290 | 1.678320 | 95879.731 | 5431.590 |
| 33 | 0.061650 | 0.498775 | 1.717660 | 90029.727 | 5289.898 |
| 34 | 0.070945 | 0.502210 | 1.799740 | 78774.162 | 5180.797 |
| 35 | 0.080477 | 0.506314 | 1.887080 | 68127.430 | 5063.229 |
| 36 | 0.095255 | 0.513926 | 2.005430 | 55677.686 | 4903.150 |
| 37 | 0.110036 | 0.522159 | 2.016620 | 54371.307 | 4891.896 |
| 38 | 0.125698 | 0.531066 | 2.035810 | 52354.768 | 4868.906 |
| 39 | 0.150196 | 0.545269 | 2.056660 | 50226.030 | 4845.773 |
| 40 | 0.186436 | 0.566752 | 2.087750 | 47251.451 | 4810.424 |
| 41 | 0.222098 | 0.588215 | 2.108640 | 45296.231 | 4788.942 |
| 42 | 0.257291 | 0.609630 | 2.133830 | 43109.654 | 4760.864 |
| 43 | 0.292175 | 0.631064 | 2.157400 | 41165.610 | 4734.703 |
| 44 | 0.326872 | 0.652552 | 2.183230 | 39155.333 | 4704.890 |
| 45 | 0.361499 | 0.674113 | 2.206210 | 37436.992 | 4678.748 |
| 46 | 0.396154 | 0.695748 | 2.228720 | 35824.066 | 4652.945 |
| 47 | 0.430941 | 0.717480 | 2.251510 | 34260.629 | 4626.427 |
| 48 | 0.465973 | 0.739363 | 2.274500 | 32744.594 | 4599.258 |
| 49 | 0.501365 | 0.761452 | 2.297430 | 31295.269 | 4571.973 |
| 50 | 0.537202 | 0.783776 | 2.321400 | 29851.381 | 4543.057 |

TABLE 2. (Continued)

| 1 | X | Y | Velocity | Molecular Weight | Coolant Area | Coolant Temperature | Wall Temperature |
|---|---|---|---|---|---|---|---|
| 1 | -0.950725 | 0.802083 | 1175.830 | 13.590460 | 0.000053330 | 460.000 | 1360.000 |
| 2 | -0.914726 | 0.801277 | 1178.720 | 13.597353 | 0.000053330 | 450.000 | 1360.000 |
| 3 | -0.842728 | 0.794779 | 1202.300 | 13.597646 | 0.000053330 | 430.000 | 1360.000 |
| 4 | -0.770730 | 0.781616 | 1252.440 | 13.598282 | 0.000053000 | 410.000 | 1360.000 |
| 5 | -0.734732 | 0.772440 | 1289.430 | 13.598768 | 0.000052500 | 398.000 | 1360.000 |
| 6 | -0.662734 | 0.748573 | 1394.480 | 13.600157 | 0.000051100 | 380.000 | 1360.000 |
| 7 | -0.590736 | 0.716937 | 1551.980 | 13.602585 | 0.000049800 | 366.000 | 1360.000 |
| 8 | -0.554738 | 0.699832 | 1645.040 | 13.604074 | 0.000049100 | 350.000 | 1360.000 |
| 9 | -0.518739 | 0.682727 | 1747.700 | 13.605855 | 0.000048500 | 340.000 | 1360.000 |
| 10 | -0.446740 | 0.648511 | 1988.940 | 13.610415 | 0.000047100 | 320.000 | 1360.000 |
| 11 | -0.410741 | 0.631406 | 2132.440 | 13.613397 | 0.000046500 | 312.000 | 1360.000 |
| 12 | -0.374742 | 0.614301 | 2295.920 | 13.617002 | 0.000045800 | 303.000 | 1360.000 |
| 13 | -0.302744 | 0.580085 | 2707.390 | 13.627159 | 0.000044400 | 287.000 | 1364.000 |
| 14 | -0.266745 | 0.562980 | 2977.420 | 13.634497 | 0.000043700 | 280.000 | 1368.000 |
| 15 | -0.230746 | 0.545875 | 3301.920 | 13.646259 | 0.000043000 | 270.000 | 1370.000 |
| 16 | -0.194747 | 0.529072 | 3643.090 | 13.658344 | 0.000042400 | 262.000 | 1372.000 |
| 17 | -0.158749 | 0.515094 | 3995.360 | 13.672035 | 0.000041700 | 255.000 | 1374.000 |
| 18 | -0.122750 | 0.504252 | 4357.770 | 13.687345 | 0.000041000 | 247.000 | 1380.000 |
| 19 | -0.086751 | 0.496347 | 4729.150 | 13.704345 | 0.000040868 | 240.000 | 1380.000 |
| 20 | -0.057200 | 0.491945 | 5040.040 | 13.719516 | 0.000040868 | 232.000 | 1375.000 |
| 21 | 0.000000 | 0.488583 | 6035.780 | 13.765060 | 0.000040868 | 222.000 | 1320.000 |
| 22 | 0.003573 | 0.488618 | 6186.780 | 13.768245 | 0.000040868 | 221.000 | 1310.000 |
| 23 | 0.007256 | 0.488720 | 6334.890 | 13.771604 | 0.000040868 | 220.000 | 1300.000 |
| 24 | 0.011012 | 0.488901 | 6473.390 | 13.790009 | 0.000040868 | 219.500 | 1295.000 |
| 25 | 0.014858 | 0.489160 | 6612.360 | 13.799884 | 0.000040868 | 219.000 | 1285.000 |
| 26 | 0.018786 | 0.489507 | 6752.420 | 13.809909 | 0.000040868 | 218.000 | 1280.000 |
| 27 | 0.022785 | 0.489942 | 6891.970 | 13.820396 | 0.000040868 | 217.000 | 1272.000 |
| 28 | 0.030987 | 0.491104 | 7170.700 | 13.842066 | 0.000040868 | 216.000 | 1255.000 |
| 29 | 0.035185 | 0.491842 | 7310.530 | 13.852492 | 0.000040868 | 215.000 | 1250.000 |
| 30 | 0.043767 | 0.493650 | 7592.250 | 13.872702 | 0.000041000 | 214.000 | 1235.000 |
| 31 | 0.048149 | 0.494735 | 7734.490 | 13.883344 | 0.000041100 | 213.000 | 1225.000 |
| 32 | 0.057091 | 0.497290 | 8022.470 | 13.905751 | 0.000041400 | 211.000 | 1220.000 |
| 33 | 0.061650 | 0.498775 | 8168.540 | 13.915809 | 0.000042000 | 210.000 | 1210.000 |
| 34 | 0.070945 | 0.502210 | 8456.700 | 13.936370 | 0.000042400 | 209.000 | 1200.000 |
| 35 | 0.080477 | 0.506314 | 8770.780 | 13.958197 | 0.000043200 | 207.000 | 1188.000 |
| 36 | 0.095255 | 0.513926 | 9166.640 | 13.987167 | 0.000044000 | 205.000 | 1180.000 |
| 37 | 0.110036 | 0.522159 | 9205.220 | 13.993980 | 0.000045200 | 202.000 | 1170.000 |
| 38 | 0.125698 | 0.531066 | 9270.930 | 13.996067 | 0.000046000 | 199.000 | 1155.000 |
| 39 | 0.150196 | 0.545269 | 9342.800 | 14.000566 | 0.000047700 | 194.000 | 1145.000 |
| 40 | 0.186436 | 0.566752 | 9449.400 | 14.003944 | 0.000050000 | 188.000 | 1145.000 |
| 41 | 0.222098 | 0.588215 | 9522.320 | 14.006823 | 0.000052500 | 182.000 | 1160.000 |
| 42 | 0.257291 | 0.609630 | 9607.770 | 14.009449 | 0.000055000 | 178.000 | 1180.000 |
| 43 | 0.292175 | 0.631064 | 9686.870 | 14.012815 | 0.000057200 | 172.000 | 1180.000 |
| 44 | 0.326872 | 0.652552 | 9771.880 | 14.015822 | 0.000059400 | 167.000 | 1170.000 |
| 45 | 0.361499 | 0.674113 | 9847.080 | 14.018885 | 0.000061800 | 163.000 | 1164.000 |
| 46 | 0.396154 | 0.695748 | 9919.870 | 14.021893 | 0.000064000 | 160.000 | 1150.000 |
| 47 | 0.430941 | 0.717480 | 9992.570 | 14.024915 | 0.000064000 | 155.000 | 1140.000 |
| 48 | 0.465973 | 0.739363 | 10065.200 | 14.027241 | 0.000064000 | 152.000 | 1125.000 |
| 49 | 0.501365 | 0.761452 | 10136.800 | 14.029441 | 0.000064000 | 150.000 | 1113.000 |
| 50 | 0.537202 | 0.783776 | 10210.600 | 14.031649 | 0.000064000 | 144.000 | 1100.000 |

TABLE 2. (Continued)

| 1 | X | Y | Mach Number | Pressure | Static Temperature | Velocity |
|---|---|---|---|---|---|---|
| 51 | 0.573587 | 0.806348 | 2.343910 | 28549.828 | 4516.006 | 10279.200 |
| 52 | 0.610587 | 0.829199 | 2.366190 | 27316.291 | 4489.143 | 10346.400 |
| 53 | 0.648296 | 0.852358 | 2.388870 | 26120.937 | 4461.624 | 10413.800 |
| 54 | 0.686772 | 0.875849 | 2.414570 | 24838.084 | 4429.732 | 10488.700 |
| 55 | 0.726084 | 0.899687 | 2.437690 | 23733.271 | 4401.310 | 10555.500 |
| 56 | 0.766270 | 0.923882 | 2.460560 | 22689.907 | 4373.128 | 10620.700 |
| 57 | 0.807399 | 0.948448 | 2.482860 | 21710.558 | 4345.459 | 10683.900 |
| 58 | 0.849451 | 0.973326 | 2.509180 | 20618.095 | 4312.209 | 10757.000 |
| 59 | 0.892476 | 0.998528 | 2.531090 | 19741.943 | 4284.989 | 10817.600 |
| 60 | 0.936517 | 1.024076 | 2.553870 | 18875.053 | 4256.567 | 10879.600 |
| 61 | 0.981554 | 1.049966 | 2.581530 | 17880.656 | 4221.445 | 10953.300 |
| 62 | 1.027623 | 1.076202 | 2.605860 | 17046.165 | 4190.827 | 11017.500 |
| 63 | 1.074732 | 1.102816 | 2.630650 | 16238.506 | 4159.610 | 11081.800 |
| 64 | 1.122882 | 1.129785 | 2.653380 | 15529.652 | 4131.084 | 11140.100 |
| 65 | 1.171950 | 1.156931 | 2.679960 | 14741.519 | 4097.262 | 11207.300 |
| 66 | 1.388564 | 1.272066 | 2.766310 | 12451.571 | 3989.778 | 11420.100 |
| 67 | 1.428417 | 1.292666 | 2.775000 | 12100.000 | 3970.000 | 11457.000 |

(The enhancement factor $\eta_E$ is assumed 1.0).

TABLE 2. (Concluded)

| 1 | X | Y | Molecular Weight | Coolant Area | Coolant Temperature | Wall Temperature |
|---|---|---|---|---|---|---|
| 51 | 0.573587 | 0.806348 | 14.033758 | 0.000064000 | 140.000 | 1090.000 |
| 52 | 0.610587 | 0.829199 | 14.035868 | 0.000064000 | 137.000 | 1075.000 |
| 53 | 0.648296 | 0.852358 | 14.038372 | 0.000064000 | 133.000 | 1060.000 |
| 54 | 0.686772 | 0.875849 | 14.040570 | 0.000064000 | 130.000 | 1048.000 |
| 55 | 0.726084 | 0.899687 | 14.042853 | 0.000064000 | 127.000 | 1030.000 |
| 56 | 0.766270 | 0.923882 | 14.045460 | 0.000064000 | 125.000 | 1010.000 |
| 57 | 0.807399 | 0.948448 | 14.046940 | 0.000064000 | 121.000 | 990.000 |
| 58 | 0.849451 | 0.973326 | 14.048340 | 0.000064000 | 120.000 | 980.000 |
| 59 | 0.892476 | 0.998528 | 14.049712 | 0.000064000 | 117.000 | 954.000 |
| 60 | 0.936517 | 1.024076 | 14.051524 | 0.000064000 | 115.000 | 935.000 |
| 61 | 0.981554 | 1.049966 | 14.052984 | 0.000064000 | 113.000 | 920.000 |
| 62 | 1.027623 | 1.076202 | 14.054569 | 0.000064000 | 110.000 | 900.000 |
| 63 | 1.074732 | 1.102816 | 14.056434 | 0.000064000 | 108.000 | 880.000 |
| 64 | 1.122882 | 1.129785 | 14.057979 | 0.000064000 | 106.000 | 850.000 |
| 65 | 1.171950 | 1.156931 | 14.058947 | 0.000064000 | 103.000 | 830.000 |
| 66 | 1.388564 | 1.272066 | 14.065845 | 0.000064000 | 95.000 | 720.000 |
| 67 | 1.428417 | 1.292666 | 14.066350 | 0.000064000 | 92.000 | 700.000 |

(The enhancement factor $\eta_E$ is assumed 1.0).

TABLE 3. $C_p$-T RELATIONSHIP OF COMBUSTION PRODUCTS

| I | Specific Heat (Btu/lbm s) | Temperature (°R) |
|---|---|---|
| 1 | 0.6199999973 | 400.000 |
| 2 | 0.6550000012 | 800.000 |
| 3 | 0.6799999997 | 1200.000 |
| 4 | 0.6950000003 | 1400.000 |
| 5 | 0.7049999982 | 1600.000 |
| 6 | 0.7199999988 | 2000.000 |
| 7 | 0.7282169983 | 2500.000 |
| 8 | 0.7282169983 | 3000.000 |
| 9 | 0.7282169983 | 4000.000 |
| 10 | 0.7282169983 | 5000.000 |
| 11 | 0.7282169983 | 5850.000 |
| 12 | 0.7282169983 | 5926.078 |
| 13 | 0.8833189979 | 6103.208 |
| 14 | 0.8843249977 | 6151.280 |
| 15 | 0.8854160011 | 6204.368 |
| 16 | 0.8893399984 | 6403.409 |
| 17 | 0.8902480006 | 6451.318 |
| 18 | 0.8906119987 | 6470.760 |
| 19 | 0.8907269984 | 6476.894 |
| 20 | 0.8920999989 | 8000.000 |

TABLE 4. PHYSICAL PROPERTIES OF LIQUID HYDROGEN

| Coolant Temperature (°R) | Coolant Specific Heat (Btu/lbm·°R) | Conductivity (Btu/ft s °R) | Viscosity (lbm/ft s) |
|---|---|---|---|
| 50.000 | 1.950000 | 0.0000234000 | 0.0000648000 |
| 100.000 | 2.850000 | 0.0000235200 | 0.0000120000 |
| 150.000 | 3.550000 | 0.0000249000 | 0.0000062400 |
| 200.000 | 3.950000 | 0.0000276000 | 0.0000054000 |
| 250.000 | 4.200000 | 0.0000288000 | 0.0000051600 |
| 300.000 | 4.200000 | 0.0000300000 | 0.0000051600 |
| 350.000 | 4.050000 | 0.0000306000 | 0.0000062400 |
| 400.000 | 3.900000 | 0.0000318000 | 0.0000057600 |
| 450.000 | 3.800000 | 0.0000327600 | 0.0000061200 |
| 500.000 | 3.700000 | 0.0000342000 | 0.0000064800 |
| 550.000 | 3.600000 | 0.0000357600 | 0.0000067200 |
| 600.000 | 3.550000 | 0.0000375600 | 0.0000069600 |
| 650.000 | 3.530000 | 0.0000390000 | 0.0000073200 |
| 700.000 | 3.510000 | 0.0000410400 | 0.0000076800 |
| 750.000 | 3.500000 | 0.0000428400 | 0.0000079200 |
| 800.000 | 3.500000 | 0.0000444000 | 0.0000081600 |
| 850.000 | 3.480000 | 0.0000464400 | 0.0000084000 |
| 900.000 | 3.470000 | 0.0000482400 | 0.0000087600 |
| 950.000 | 3.460000 | 0.0000504000 | 0.0000090000 |
| 1000.000 | 3.460000 | 0.0000528000 | 0.0000093600 |

TABLE 5. INPUT DATA OF THRUST CHAMBER

| | | | | |
|---|---|---|---|---|
| MZETA | = | VELOCITY PROFILE POWER LAW EXPONENT | = | 7 |
| IPRINT | = | PRINT AT EVERY CALCULATED POINT (=1) OR AT INPUT INTERVALS (=0) | = | 0 |
| ITWTAB | = | NUMBER OF POINTS IN X . VS. Y . VS. M TABLES | = | 67 |
| ICTAB | = | NUMBER OF POINTS IN CP . VS. T TABLE | = | 20 |
| ITWTAB | = | WALL TEMP. OPTION - - ADIABATIC (=-1), CONSTANT (=0), TABLE (=1) | = | 1 |
| T0 | = | FREE STREAM STAGNATION TEMPERATURE | = | 6.6000000+03 |
| P0 | = | FREE STREAM STAGNATION PRESSURE | = | 4.3488000+05 |
| GAM0 | = | STAGNATION RATIO OF SPECIFIC HEATS | = | 1.1130000+00 |
| ZMU0 | = | STAGNATION VISCOSITY | = | 5.9330000-05 |
| ZMVIS | = | EXPONENT OF VISCOSITY - TEMPERATURE LAW | = | 7.5000000-01 |
| ZNSTAN | = | BOUNDARY LAYER INTERACTION EXPONENT | = | 1.0000000-01 |
| DXMAX | = | MAXIMUM STEP SIZE | = | 2.0000000-02 |
| THETAI | = | INITIAL VALUE OF MOMENTUM THICKNESS | = | 1.0000000-04 |
| PHII | = | INITIAL VALUE OF ENERGY THICKNESS | = | 1.0000000-04 |
| EPSZ | = | GEOMETRY . . . AXISYMMETRIC (=1.), PLANE (=0.) | = | 1.0000000+00 |
| RBAR | = | GAS CONSTANT AT STAGNATION | = | 1.1370900+02 |
| FJ | = | CONVERSION BETWEEN THERMAL AND WORK UNITS | = | 7.7820000+02 |
| G | = | PROPORTIONALITY CONSTANT IN EQUATION - - F=M/G*A | = | 3.2174000+01 |
| SCALE | = | CONTOUR SCALE FACTOR | = | 4.8858333-01 |
| ITZTAB | = | NUMBER OF POINTS IN T . VS. CPL . VS. RAMDL . VS. ZMYUL TABLES | = | 20 |
| IDUMP | = | COOLANT FLOW OPTION - - SAME DIRECTION (=1), REVERSE (=0) | = | 0 |
| FLOWRT | = | COMBUSTION CHAMBER MASS FLOW RATE (LBM/SEC) | = | 1.3620300+03 |
| MASSL | = | COOLANT MASS FLOW RATE (LBM/SEC) | = | 3.8310000+01 |
| RAMDW | = | HEAT CONDUCTIVITY OF THE CHAMBER WALL | = | 5.2800000-02 |
| COEFCL | = | COEFFICIENT OF COOLING | = | 9.5000000-01 |
| TUBEN | = | TUBE NUMBER | = | 3.2000000+02 |

(Regenerative cooling in the opposite direction; Injector to $\epsilon = 7$)

TABLE 6. INPUT DATA OF SSME BOOSTER NOZZLE (DOWN PASS)

| | | | | |
|---|---|---|---|---|
| MZETA | = | VELOCITY PROGILE POWER LAW EXPONENT | = | 7 |
| IPRINT | = | PRINT AT EVERY CALCULATED POINT (=1) OR AT INPUT INTERVALS (=0) | = | 0 |
| IXTAB | = | NUMBER OF POINTS IN ~ X .VS. Y .VS. M TABLES | = | 19 |
| ICTAB | = | NUMBER OF POINTS IN CP .VS. T TABLE | = | 20 |
| ITWTAB | = | WALL TEMP. OPTION - - ADIABATIC (=-1), CONSTANT (=0), TABLE (=1) | = | 1 |
| T0 | = | FREE STREAM STAGNATION TEMPERATURE | = | 6.6000000+03 |
| P0 | = | FREE STREAM STAGNATION PRESSURE | = | 4.3488000+05 |
| GAM0 | = | STAGNATION RATIO OF SPECIFIC HEATS | = | 1.1130000+00 |
| ZMU0 | = | STAGNATION VISCOSITY | = | 5.9330000-05 |
| ZMVIS | = | EXPONENT OF VISCOSITY -TEMPERATURE LAW | = | 7.5000000-01 |
| ZNSTAN | = | BOUNDARY LAYER INTERACTION EXPONENT | = | 1.0000000-01 |
| DXMAX | = | MAXIMUM STEP SIZE | = | 2.0000000-02 |
| THETAI | = | INITIAL VALUE OF MOMENTUM THICKNESS | = | 3.3948700-03 |
| PHII | = | INITIAL VALUE OF ENERGY THICKNESS | = | 4.2186860-03 |
| EPSZ | = | GEOMETRY . . . AXISYMMETRIC (=1.), PLANE (=0.) | = | 1.0000000+00 |
| RBAR | = | GAS CONSTANT AT STAGNATION | = | 1.1370900+02 |
| FJ | = | CONVERSION BETWEEN THERMAL AND WORK UNITS | = | 7.7820000+02 |
| G | = | PROPORTIONALITY CONSTANT IN EQUATION - - F=M/G*A | = | 3.2174000+01 |
| SCALE | = | CONTOUR SCALE FACTOR | = | 4.8858333-01 |
| ITZTAB | = | NUMBER OF POINTS IN T .VS. CPL .VS. RAMDL .VS. ZMYUL TABLES | = | 20 |
| IDUMP | = | COOLANT FLOW OPTION - - SAME DIRECTION (=1), REVERSE (=0) | = | 1 |
| FLOWRT | = | COMBUSTION CHAMBER MASS FLOW RATE (LBM/SEC) | = | 1.3620300+03 |
| MASSL | = | COOLANT MASS FLOW RATE (LBM/SEC) | = | 3.6000000+01 |
| RAMDW | = | HEAT CONDUCTIVITY OF THE CHAMBER WALL | = | 3.6800000-03 |
| COEFCL | = | COEFFICIENT OF COOLING | = | 5.0000000-01 |
| TUBEN | = | TUBE NUMBER | = | 5.6400000+02 |

(SSME Booster Engine Double Pass Cooling from $\epsilon = 7.0$ to $35.0$)

TABLE 6. (Continued)

| I | X | Y | Mach Number | Pressure | Static Temperature | Velocity | Molecular Weight |
|---|---|---|---|---|---|---|---|
| 1 | 1.428417 | 1.292666 | 2.775000 | 12100.000 | 3970.000 | 11457.000 | 14.066350 |
| 2 | 1.619703 | 1.386746 | 2.834430 | 10888.482 | 3905.792 | 11582.400 | 14.068051 |
| 3 | 1.889127 | 1.507026 | 2.890390 | 9749.662 | 3837.881 | 11712.300 | 14.069824 |
| 4 | 2.238669 | 1.645798 | 2.969260 | 8353.958 | 3741.841 | 11887.500 | 14.071408 |
| 5 | 2.685791 | 1.800835 | 3.069210 | 6877.540 | 3621.335 | 12097.900 | 14.072373 |
| 6 | 3.230000 | 1.963167 | 3.173570 | 5618.780 | 3497.795 | 12305.600 | 14.073443 |
| 7 | 3.565095 | 2.051659 | 3.233430 | 5005.382 | 3428.143 | 12419.400 | 14.072809 |
| 8 | 3.943175 | 2.142785 | 3.300140 | 4406.465 | 3351.785 | 12541.400 | 14.073171 |
| 9 | 4.377819 | 2.237555 | 3.369150 | 3863.639 | 3274.160 | 12663.200 | 14.073800 |
| 10 | 4.876321 | 2.335077 | 3.442460 | 3361.705 | 3193.403 | 12787.500 | 14.074077 |
| 11 | 5.453665 | 2.435373 | 3.524560 | 2880.836 | 3105.011 | 12920.700 | 14.074358 |
| 12 | 6.125760 | 2.537448 | 3.605940 | 2474.389 | 3019.491 | 13047.200 | 14.074749 |
| 13 | 6.499184 | 2.588275 | 3.652070 | 2270.413 | 2972.016 | 13116.300 | 14.074811 |
| 14 | 6.899334 | 2.638599 | 3.694760 | 2098.009 | 2928.753 | 13178.800 | 14.074976 |
| 15 | 7.332024 | 2.688542 | 3.739500 | 1932.268 | 2884.092 | 13242.500 | 14.075116 |
| 16 | 7.799891 | 2.737806 | 3.786160 | 1773.636 | 2838.125 | 13307.600 | 14.075269 |
| 17 | 8.306454 | 2.786073 | 3.830220 | 1636.414 | 2795.375 | 13367.500 | 14.075416 |
| 18 | 8.855280 | 2.832933 | 3.875800 | 1506.255 | 2751.858 | 13427.900 | 14.075552 |
| 19 | 9.071527 | 2.849970 | 3.895190 | 1454.047 | 2733.559 | 13453.100 | 14.075584 |

(The enhancement factor $\eta_E$ is assumed 1.0)

TABLE 6. (Concluded)

| I | X | Y | Coolant Area | Coolant Temperature | Wall Temperature |
|---|---|---|---|---|---|
| 1 | 1.428417 | 1.292666 | 0.000050000 | 95.000 | 1460.000 |
| 2 | 1.619703 | 1.386746 | 0.000054000 | 103.000 | 1445.000 |
| 3 | 1.889127 | 1.507026 | 0.000060000 | 115.000 | 1425.000 |
| 4 | 2.238669 | 1.645798 | 0.000068000 | 130.000 | 1400.000 |
| 5 | 2.685791 | 1.800835 | 0.000078000 | 145.000 | 1370.000 |
| 6 | 3.230000 | 1.963167 | 0.000091000 | 167.000 | 1325.000 |
| 7 | 3.565095 | 2.051659 | 0.000098000 | 180.000 | 1295.000 |
| 8 | 3.943175 | 2.142785 | 0.000108000 | 195.000 | 1260.000 |
| 9 | 4.377819 | 2.237555 | 0.000118000 | 213.000 | 1210.000 |
| 10 | 4.876321 | 2.335077 | 0.000131000 | 232.000 | 1145.000 |
| 11 | 5.453665 | 2.435373 | 0.000147000 | 255.000 | 1072.000 |
| 12 | 6.125760 | 2.537448 | 0.000166000 | 282.000 | 985.000 |
| 13 | 6.499184 | 2.588275 | 0.000178000 | 295.000 | 940.000 |
| 14 | 6.899334 | 2.638599 | 0.000190000 | 312.000 | 895.000 |
| 15 | 7.332024 | 2.688542 | 0.000205000 | 330.000 | 846.000 |
| 16 | 7.799891 | 2.737806 | 0.000220000 | 350.000 | 800.000 |
| 17 | 8.306454 | 2.786073 | 0.000238000 | 367.000 | 750.000 |
| 18 | 8.855280 | 2.832933 | 0.000258000 | 389.000 | 700.000 |
| 19 | 9.071527 | 2.849970 | 0.000266000 | 400.000 | 680.000 |

TABLE 7. INPUT DATA OF SSME BOOSTER NOZZLE (UP PASS)

| | | | | |
|---|---|---|---|---|
| MZETA | = | VE LOCITY PROFILE POWER LAW EXPONENT | = | 7 |
| IPRINT | = | PRINT AT EVERY CALCULATED POINT (=1) OR AT INPUT INTERVALS (=0) | = | 0 |
| IXTAB | = | NUMBER OF POINTS IN X . VS. Y . VS. M TABLES | = | 19 |
| ICTAB | = | NUMBER OF POINTS IN CP . VS. T TABLE | = | 20 |
| ITWTAB | = | WALL TEMP. OPTION - - ADIABATIC (=-1), CONSTANT (=0), TALBE (=1) | = | 1 |
| T0 | = | FREE STREAM STAGNATION TEMPERATURE | = | 6.6000000+03 |
| P0 | = | FREE STREAM PRESSURE | = | 4.3488000+05 |
| GAM0 | = | STAGNATION RATIO OF SPECIFIC HEATS | = | 1.1130000+00 |
| ZMU0 | = | STAGNATION VISCOSITY | = | 5.9330000-05 |
| ZMVIS | = | EXPONENT OF VISCOSITY - TEMPERATURE LAW | = | 7.5000000-01 |
| ZNSTAN | = | BOUNDARY LAYER INTERACTION EXPONENT | = | 1.0000000-01 |
| DXMAX | = | MAXIMUM STEP SIZE | = | 2.0000000-02 |
| THETAI | = | INITIAL VALUE OF MOMENTUM THICKNESS | = | 3.3948700-03 |
| PHII | = | INITIAL VALUE OF ENERGY THICKNESS | = | 4.2186860-03 |
| EPSZ | = | GEOMETRY . . . AXISYMMETRIC (=1.), PLANE (=0.) | = | 1.0000000+00 |
| RBAR | = | GAS CONSTANT AT STAGNATION | = | 1.1370900+02 |
| FJ | = | CONVERSION BETWEEN THERMAL AND WORK UNITS | = | 7.7820000+02 |
| G | = | PROPORTIONALITY CONSTANT IN EQUATION - - F=M/G*A | = | 3.2174000+01 |
| SCALE | = | CONTOUR SCALE FACTOR | = | 4.8858333-01 |
| ITZTAB | = | NUMBER OF POINTS IN T . VS. CPL . VS. RAMDL . VS. ZMYUL TALBES | = | 20 |
| IDUMP | = | COOLANT FLOW OPTION - - SAME DIRECTION (=1), REVERSE (=0) | = | 0 |
| FLOWRT | = | COMBUSTION CHAMBER MASS FLOW RATE (LBM/SEC) | = | 1.3620300+03 |
| MASSL | = | COOLANT MASS FLOW RATE (LBS/SEC) | = | 3.6000000+01 |
| RAMDW | = | HEAT CONDUCTIVITY OF THE CHAMBER WALL | = | 3.6800000-03 |
| COEFCL | = | COEFFICIENT OF COOLING | = | 5.0000000-01 |
| TUBEN | = | TUBE NUMBER | = | 5.6400000+02 |

(SSME Booster Engine Double Pass Cooling from $\epsilon = 7.0$ to $35.0$)

TABLE 7. (Continued)

| I | X | Y | Mach Number | Pressure | Static Temperature | Velocity | Molecular Weight |
|---|---|---|---|---|---|---|---|
| 1 | 1.428417 | 1.292666 | 2.775000 | 12100.000 | 3970.000 | 11457.000 | 14.066350 |
| 2 | 1.619703 | 1.386746 | 2.834430 | 10888.482 | 3905.792 | 11582.400 | 14.068051 |
| 3 | 1.889127 | 1.507026 | 2.890390 | 9749.662 | 3837.881 | 11712.300 | 14.069824 |
| 4 | 2.238669 | 1.645798 | 2.969260 | 8353.958 | 3741.841 | 11887.500 | 14.071408 |
| 5 | 2.685791 | 1.800835 | 3.069210 | 6877.540 | 3621.335 | 12097.900 | 14.072373 |
| 6 | 3.230000 | 1.963167 | 3.173570 | 5618.780 | 3497.795 | 12305.600 | 14.073443 |
| 7 | 3.565095 | 2.051659 | 3.233430 | 5005.382 | 3428.143 | 12419.400 | 14.072809 |
| 8 | 3.943175 | 2.142785 | 3.300140 | 4406.465 | 3351.785 | 12541.400 | 14.073171 |
| 9 | 4.377819 | 2.237555 | 3.369150 | 3863.639 | 3274.160 | 12663.200 | 14.073800 |
| 10 | 4.876321 | 2.335077 | 3.442460 | 3361.705 | 3193.403 | 12787.500 | 14.074077 |
| 11 | 5.453665 | 2.435373 | 3.524560 | 2880.836 | 3105.011 | 12920.700 | 14.074358 |
| 12 | 6.125760 | 2.537448 | 3.605940 | 2474.389 | 3019.491 | 13047.200 | 14.074749 |
| 13 | 6.499184 | 2.588275 | 3.652070 | 2270.413 | 2972.016 | 13116.300 | 14.074811 |
| 14 | 6.899334 | 2.638599 | 3.694760 | 2098.009 | 2928.753 | 13178.800 | 14.074976 |
| 15 | 7.332024 | 2.688542 | 3.739500 | 1932.268 | 2884.092 | 13242.500 | 14.075116 |
| 16 | 7.799891 | 2.737806 | 3.786160 | 1773.636 | 2838.125 | 13307.600 | 14.075269 |
| 17 | 8.306454 | 2.786073 | 3.830220 | 1636.414 | 2795.375 | 13367.500 | 14.075416 |
| 18 | 8.855280 | 2.832933 | 3.875800 | 1506.255 | 2751.858 | 13427.900 | 14.075552 |
| 19 | 9.071527 | 2.849970 | 3.895190 | 1454.047 | 2733.559 | 13453.100 | 14.075584 |

TABLE 7. (Concluded)

| I | X | Y | Coolant Area | Coolant Temperature | Wall Temperature |
|---|---|---|---|---|---|
| 1 | 1.428417 | 1.292666 | 0.000093750 | 610.000 | 1460.000 |
| 2 | 1.619703 | 1.386746 | 0.000096000 | 600.000 | 1445.000 |
| 3 | 1.889127 | 1.507026 | 0.000101000 | 592.000 | 1425.000 |
| 4 | 2.238669 | 1.645798 | 0.000107800 | 580.000 | 1400.000 |
| 5 | 2.685791 | 1.800835 | 0.000116000 | 570.000 | 1370.000 |
| 6 | 3.230000 | 1.963167 | 0.000126000 | 550.000 | 1325.000 |
| 7 | 3.565095 | 2.051659 | 0.000132500 | 540.000 | 1295.000 |
| 8 | 3.943175 | 2.142785 | 0.000140000 | 530.000 | 1260.000 |
| 9 | 4.377819 | 2.237555 | 0.000149200 | 515.000 | 1210.000 |
| 10 | 4.876321 | 2.335077 | 0.000160000 | 500.000 | 1145.000 |
| 11 | 5.453665 | 2.435373 | 0.000162000 | 483.000 | 1072.000 |
| 12 | 6.125760 | 2.537448 | 0.000187800 | 460.000 | 985.000 |
| 13 | 6.499184 | 2.588275 | 0.000196000 | 450.000 | 940.000 |
| 14 | 6.899334 | 2.638599 | 0.000206100 | 437.000 | 895.000 |
| 15 | 7.332024 | 2.688542 | 0.000217000 | 425.000 | 846.000 |
| 16 | 7.799891 | 2.737806 | 0.000230000 | 410.000 | 783.000 |
| 17 | 8.306454 | 2.786073 | 0.000245000 | 393.000 | 722.000 |
| 18 | 8.855280 | 2.832933 | 0.000260000 | 377.000 | 660.000 |
| 19 | 9.071527 | 2.849970 | 0.000266000 | 370.000 | 630.000 |

(The enhancement factor is assumed 1.0)

TABLE 8. INPUT DATA OF SSME BOOSTER NOZZLE (UP AND DOWN PASSES)

| I | Specific Heat | Temperature | Coolant Temperature | Coolant Specific Heat | Conductivity | Viscosity |
|---|---|---|---|---|---|---|
| 1 | 0.6199999973 | 400.000 | 50.000 | 1.950000 | 0.0000234000 | 0.0000648000 |
| 2 | 0.6550000012 | 800.000 | 100.000 | 2.850000 | 0.0000235200 | 0.0000120000 |
| 3 | 0.6799999997 | 1200.000 | 150.000 | 3.550000 | 0.0000249000 | 0.0000062400 |
| 4 | 0.6950000003 | 1400.000 | 200.000 | 3.950000 | 0.0000276000 | 0.0000054000 |
| 5 | 0.7049999982 | 1600.000 | 250.000 | 4.200000 | 0.0000288000 | 0.0000051600 |
| 6 | 0.7199999988 | 2000.000 | 300.000 | 4.200000 | 0.0000300000 | 0.0000051600 |
| 7 | 0.7282169983 | 2500.000 | 350.000 | 4.050000 | 0.0000306000 | 0.0000062400 |
| 8 | 0.7282169983 | 3000.000 | 400.000 | 3.900000 | 0.0000318000 | 0.0000057600 |
| 9 | 0.7282169983 | 4000.000 | 450.000 | 3.800000 | 0.0000327600 | 0.0000061200 |
| 10 | 0.7282169983 | 5000.000 | 500.000 | 3.700000 | 0.0000342000 | 0.0000064800 |
| 11 | 0.7282169983 | 5850.000 | 550.000 | 3.600000 | 0.0000357600 | 0.0000067200 |
| 12 | 0.7282169983 | 5926.078 | 600.000 | 3.550000 | 0.0000375600 | 0.0000069600 |
| 13 | 0.8833189979 | 6103.208 | 650.000 | 3.530000 | 0.0000390000 | 0.0000073200 |
| 14 | 0.8843249977 | 6151.280 | 700.000 | 3.510000 | 0.0000410400 | 0.0000076800 |
| 15 | 0.8854160011 | 6204.368 | 750.000 | 3.500000 | 0.0000428400 | 0.0000079200 |
| 16 | 0.8893399984 | 6403.409 | 800.000 | 3.500000 | 0.0000444000 | 0.0000081600 |
| 17 | 0.8902480006 | 6451.318 | 850.000 | 3.480000 | 0.0000464400 | 0.0000084000 |
| 18 | 0.8906119987 | 6470.760 | 900.000 | 3.470000 | 0.0000482400 | 0.0000087600 |
| 19 | 0.8907269984 | 6476.894 | 950.000 | 3.460000 | 0.0000504000 | 0.0000090000 |
| 20 | 0.8920999989 | 8000.000 | 1000.000 | 3.460000 | 0.0000528000 | 0.0000093600 |

TABLE 9. CALCULATED DISPLACEMENT AND MOMENTUM THICKNESSES ALONG NOZZLE WALL

| x (ft) | $\delta^*_{down}$ | $\delta^*_{up}$ | $\bar{\delta}^*$ | $\theta_{down}$ | $\theta_{up}$ | $\bar{\theta}$ |
|---|---|---|---|---|---|---|
| 1.428417 | -0.004536 | -0.004805 | -0.004671 | 0.003395 | 0.003395 | 0.003395 |
| 1.619903 | -0.004488 | -0.005164 | -0.004826 | 0.003642 | 0.003647 | 0.003645 |
| 1.889127 | -0.004672 | -0.005606 | -0.005139 | 0.003933 | 0.003947 | 0.003940 |
| 2.238669 | -0.005425 | -0.006357 | -0.005891 | 0.004421 | 0.004449 | 0.004435 |
| 2.686791 | -0.006477 | -0.007505 | -0.006991 | 0.005158 | 0.005204 | 0.005181 |
| 3.230000 | -0.007881 | -0.008983 | -0.008432 | 0.006087 | 0.006152 | 0.006120 |
| 3.565095 | -0.008844 | -0.009975 | -0.009410 | 0.006704 | 0.006781 | 0.006743 |
| 3.943175 | -0.010083 | -0.011208 | -0.010646 | 0.007460 | 0.007550 | 0.007505 |
| 4.377819 | -0.011551 | -0.012660 | -0.012106 | 0.008338 | 0.008443 | 0.008391 |
| 4.876321 | -0.013393 | -0.014426 | -0.013909 | 0.009392 | 0.009511 | 0.009452 |
| 5.453665 | -0.015773 | -0.016597 | -0.016185 | 0.010720 | 0.010854 | 0.010787 |
| 6.125760 | -0.018604 | -0.019305 | -0.018955 | 0.012235 | 0.012385 | 0.012310 |
| 6.499184 | -0.020425 | -0.020933 | -0.020679 | 0.013184 | 0.013342 | 0.013263 |
| 6.899334 | -0.022331 | -0.022607 | -0.022469 | 0.014133 | 0.014298 | 0.014216 |
| 7.332023 | -0.024556 | -0.024488 | -0.024522 | 0.015201 | 0.015371 | 0.015286 |
| 7.799891 | -0.027096 | -0.026620 | -0.026858 | 0.016403 | 0.016579 | 0.016491 |
| 8.306454 | -0.029727 | -0.028881 | -0.029304 | 0.017642 | 0.017820 | 0.017731 |
| 8.855280 | -0.032634 | -0.031474 | -0.032055 | 0.019027 | 0.019207 | 0.019118 |
| 9.071527 | -0.033966 | -0.032616 | -0.033291 | 0.019645 | 0.019824 | 0.019735 |

# DESCRIPTION OF PROGRAM INPUT

## Input Data

| | |
|---|---|
| MZETA = n | Exponent in velocity profile power law |
| IPRINT | Print option at every calculated point (= 1) or at input intervals (= 0) |
| IXTAB | Number of points in $x = f(y)$ and $x = g(M_\infty)$ tables |
| ICTAB | Number of points in $C_p = f(T)$ table |
| ITWTAB | Wall temperature option = 1 (must be input) |
| T0 = $T_0$ | Stagnation temperature, °R |
| P0 = $P_0$ | Stagnation pressure, lbf/ft$^2$ |
| GAM0 = $\gamma_0$ | Stagnation specific heat ratio |
| ZMU0 = $\mu_0$ | Stagnation viscosity, lbm/ft-s |
| ZMVIS | Exponent of viscosity temperature law |
| ZNSTAN | Boundary layer interaction exponent |
| DXMAX | Maximum step size |
| THETAI = $\theta_i$ | Initial value of momentum thickness, ft |
| PHII = $\phi_i$ | Initial value of energy thickness, ft |
| EPSZ | Geometry option - Axisymmetric = 1.<br>Plane = 0. |
| RBAR | Gas constant at stagnation, ft-lbf/°R-lbm |
| FJ = J | Conversion factor between thermal and work units = 778.2, ft-lbf/Btu |
| G = g | Acceleration of gravity = 32.174, ft-lbm/lbf-s$^2$ |

| | |
|---|---|
| SCALE | Contour scale factor |
| ITZTAB | Number of points in temperature versus $C_{p\ell}$, $\lambda_\ell$ and $\mu_\ell$ table |
| IDUMP | Coolant flow option<br>Same direction = 1<br>Reverse flow = 0 |
| FLOWRT | Combustion chamber mass flow rate, lbm/s |
| MASSL = $\dot{m}_\ell$ | Coolant mass flow rate, lbm/s |
| RAMDW = $\lambda_w$ | Thermal conductivity of the chamber wall, Btu/ft–s°R |
| COEFCL = $\eta$ | Cooling coefficient (surface area effect) |
| TUBEN | Number of cooling tubes |

## Input Tables

(i) Specific $C_p$ (CPTAB) versus temperature T (TITAB)

(ii)

| | |
|---|---|
| XITAB | Axial distance, ft |
| YITAB | Radius, ft |
| ZMTAB | Mach number $M_\infty$ at boundary layer edge |
| PETAB | Static pressure $P_\infty$ at boundary layer edge, lbf/ft$^2$ |
| TETAB | Static temperature $T_\infty$ at boundary layer edge, °R |
| UETAB | Velocity $U_\infty$ at boundary layer edge, ft/s |
| SMTAB | Mean molecular weight $\mathfrak{M}$ at boundary layer edge |
| ALTAB | Cross-sectional area of each cooling tube, ft$^2$ |
| TLTAB | Assumed coolant temperature $\left[T_\ell\right]_0$, °R |

| | | |
|---|---|---|
| | TWTAB | Assumed wall temperature on the gas-side $\left[T_{wg}\right]_0$, °R |
| | THITAB | Wall thickness of the cooling jacket, ft |
| (iii) | TZTAB | Coolant temperature table used to obtain $C_{p\ell}$, $\lambda_\ell$ and $\mu_\ell$, °R |
| | CPLTAB | Coolant specific heat $C_{p\ell}$, Btu/lbm-°R |
| | RAMTAB | Thermal conductivity of coolant $\lambda_\ell$, Btu/ft-s°R |
| | ZMYTAB | Viscosity of coolant $\mu_\ell$, lbm/ft-s |

# DESCRIPTION OF PROGRAM OUTPUT

The following parameters are printed out in addition to the original TBL computer program results [3]:

| | |
|---|---|
| RBAR $=\mathcal{R}/\mathfrak{M}$ | Specific gas constant, ft-lbf/lbm°R |
| PRANDT = Pr | Prandtl number of the free stream |
| GAME $= \gamma_\infty$ | Specific heat ratio at the boundary layer edge |
| SMOL $= \mathfrak{M}$ | Mean molecular weight, lbm |
| COSAL = $\cos \alpha(x)$ | Cosine of the wall angle |
| DELFA $= \Delta F_{B.L.}$ | Thrust degradation due to turbulent boundary layer effects downstream of the throat only, lbf |
| THRUST = F | Vacuum thrust, lbf |
| DEFTHR $= \Delta F/F \times 100$ | Percent of thrust degradation |
| TBLISP $= -\Delta I_{sp}$ | Specific impulse loss due to turbulent boundary layer effects, s |
| THRUSA | Thrust at sea level, lbf |
| VISP $= I_{sp_{vacuum}}$ | Vacuum specific impulse downstream of the throat only, s |

$AISP = I_{sp_{sea\ level}}$ — Specific impulse at sea level of the throat only, s

$DMASSL = \rho_\ell U_\ell$ — Mass flow density of the coolant fluid, $lbm/ft^2$-s

$HL = h_\ell$ — Heat transfer coefficient of the coolant fluid, $Btu/ft^2$-s°R

$QWI = \dot{q}_w{}'$ — Specific heat transfer rate based upon calculations for the coolant flow side, $Btu/ft^2$-s

$REYL = R_{e_\ell}$ — Reynolds number of the coolant fluid based upon tube diameters

SUMQGA — Total heat transfer rate, Btu/s

SUMQWI — Total heat transfer rate (includes cooling flow calculation), Btu/s

$TEMPRL = T_{w_\ell}/T_\ell$ — Temperature ratio

$TLCA = T_{\ell c}$ — Calculated coolant temperature, °R

$TWGCA = T_{wgc}$ — Calculated wall temperature on the gas side, °R

$TWL = T_{w_\ell}$ — Calculated wall temperature on the coolant side, °R

$DIATUB = 2\sqrt{A_{tube}/\pi}$ — Equivalent diameter of the cooling jacket, ft

$THICK = t$ — Chamber wall thickness (input value), ft

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama, February 11, 1972

# APPENDIX A

## DERIVATION OF EQUATIONS (33) AND (34)

Using equations (20) and (22) with equation (32), we obtain

$$h_g(T_{aw} - T_{wg}) = \frac{\lambda_w}{t}(T_{wg} - T_{w_\ell}) \quad .$$

Rewrite the above equation, as

$$T_{wg} = \frac{h_g T_{aw} + \frac{\lambda_w}{t} T_{w_\ell}}{h_g + \frac{\lambda_w}{t}} \quad . \qquad \text{(equation 34)}$$

Equations (20) and (23) reduce to

$$h_g(T_{aw} - T_{wg}) = h_\ell\left(T_{w_\ell} - T_\ell\right) \quad ,$$

so that

$$T_{wg} = T_{aw} - \frac{h_\ell}{h_g}\left(T_{w_\ell} - T_\ell\right) \quad .$$

Substitute equation (34) into the above equation, then

$$h_g T_{aw} + \frac{\lambda_w}{t} T_{w_\ell} = \left(h_g + \frac{\lambda_w}{t}\right)\left[T_{aw} - \frac{h_\ell}{h_g}\left(T_{w_\ell} - T_\ell\right)\right] \quad .$$

$$\left[\frac{\lambda_w}{t} + \left(h_g + \frac{\lambda_w}{t}\right)\frac{h_\ell}{h_g}\right] T_{w_\ell} = \frac{\lambda_w}{t} T_{aw} + \left(h_g + \frac{\lambda_w}{t}\right)\frac{h_\ell}{h_g} T_\ell \quad .$$

Therefore,

$$T_{w_\ell} = \frac{h_\ell \left(1 + \frac{\lambda_w}{t\,h_g}\right) T_\ell + \frac{\lambda_w}{t} T_{aw}}{\frac{\lambda_w}{t} + h_\ell \left(1 + \frac{\lambda_w}{t\,h_g}\right)} \quad . \qquad \text{(equation 33)}$$

# APPENDIX B

# TBL MODIFIED COMPUTER PROGRAM LISTING (TBLREG)

```
      SUBROUTINE BARCON                                                 BARC0001
C
C -- BARCON -- CONTROLLING SUBROUTINE                                   BARC0002
C
      COMMON /COOL/  ICOOL,IDUMP,ITZTAB,AL,COEFCL,CPL,DELXBA,DIATUB,    /COOL/
     1               FLOWRT,MASSL,PRANDL,RAMDL,RAMDW,REYL,SUMQGA,SUMQWI, /COOL/
     2               THICK,TLO,TL1,TL2,TLCA,TOLITE,TUBEN,TWGCA,ZMYUL,   /COOL/
     3               CPLTAB(20),RAMTAB(20),TZTAB(20),ZMYTAB(20),        /COOL/
     4               ALTAB(100),THITAB(100),TLCTAB(100),TLTAB(100),     /COOL/
     5               TWGTAB(100)                                        /COOL/
      REAL MASSL                                                        /COOL/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,      /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,   /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN      /INPUT/
C
      COMMON /INTER/ CFAGT,CFAGP,CHPAR1,DX,DXRHO,HE,HW,IBEG,MZETAM,     /INTER/
     A               OOMZET,PHIP,PRE103,RHOE,RHOUE,RMZETA,THETAP,       /INTER/
     K               XIBASE,XIEND,ZETATM,ZMZETA,ZMZETM,ZMZETP           /INTER/
C
      COMMON /LOOKUP/ ICX,IMX,IPX,IRX,ISX,ITPOS,ITWX,ITX,IUX,IXPOS,IYX, /LOOKUP/
     1               IZX,CCX(6),CMX(6),CPX(6),CRX(6),CSX(6),CTWX(6),    /LOOKUP/
     2               CTX(6),CUX(6),CYX(6),CZX(6)                        /LOOKUP/
C
      COMMON /NHANCE/ IEX,CEX(6),ENHTAB(100)                            /NHANCE/
C
      COMMON /OUTPUT/ BDELTA,CF,CH,DELTA,DELSOT,DELSTR,FLAT,FORCE,HG,   /OUTPUT/
     A               PE,PHI,QW,SUMQDA,TE,THETA,TW,UE,X,XLARC,YR,Z1,     /OUTPUT/
     K               Z2,Z3,Z4,Z5,ZETA,ZME                               /OUTPUT/
C
      COMMON /TABLES/ PETAB(100),SMTAB(100),TETAB(100),TWTAB(100),      /TABLES/
     1               UETAB(100),XITAB(100),YITAB(100),ZMTAB(100)        /TABLES/
C
      DIMENSION DPHIRK(4),DTHERK(4),XCCP(100),YCCP(100)
C
      IF (ICOOL .EQ. 0)  GO TO 11
      ITER = 0
   10 ITER = ITER + 1
      WRITE (6,1) ITER
    1 FORMAT (1H1,35X,54HREGENERATIVE COOLING WALL TEMPERATURE ITERATION
     1 NUMBER,I3///////////)
   11 MZETAM = MZETA - 1
      ZMZETA=MZETA                                                      BARC0031
      ZMZETP=ZMZETA+1.                                                  BARC0032
      ZMZETM=ZMZETA-1.                                                  BARC0033
      RMZETA=1./ZMZETP                                                  BARC0034
      OOMZET=1./ZMZETA                                                  BARC0035
      X=XITAB(1)                                                        BARC0036
      DX=0.                                                             BARC0037
      XLARC=0.                                                          BARC0038
      SUMQDA=0.                                                         BARC0039
      SUMQGA = 0.0
      SUMQWI = 0.0
      FORCE=0.                                                          BARC0040
      FLAT=0.                                                           BARC0041
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      QW              = 0.0                                                    BARC0042
      HG              = 0.0                                                    BARC0043
      IXPOS=1                                                                  BARC0044
      ITPOS = 1
      ICX = 0
      IEX = 0
      IRX = 0
      ISX = 0
      IUX = 0
      IZX = 0
      IMX=0                                                                    BARC0045
      ITX=0                                                                    BARC0046
      IPX=0                                                                    BARC0047
      IYX=0                                                                    BARC0048
      ITWX=0                                                                   BARC0049
      DXRHO=0.                                                                 BARC0050
      IBEG            = 2                                                      BARC0051
      CFAGT           = .002                                                   BARC0052
      ISTART          = 0                                                      BARC0053
      IF (THETAI .LE. 0.0)  GO TO 2
      ZETA = (PHII/THETAI)**RMZETA
      GO TO 3                                                                  BARC0056
    2 CALL START                                                               BARC0057
      ISTART          = 1                                                      BARC0058
    3 CFAGP           = CFAGT                                                  BARC0059
      IF (ICOOL .EQ. 0)  GO TO 4
      DELXOL = 0.0
      DELXNE = ABS(XITAB(2) - XITAB(1))
      DELXBA = (DELXOL + DELXNE)/2.0
      AL = ALTAB(1)
      TL1 = TLTAB(1)
      THICK = THITAB(1)
      TL2 = TLTAB(2)
      TLO = TL1
      CALL XNTERP (TL1,ZMYUL,ZP,IZX,TZTAB,ZMYTAB,ITZTAB,CZX,ITPOS)
      ITPOS = IZX
      DIATUB = 2.0*SQRT(AL/PIE)
      REYL = MASSL*DIATUB/(AL*TUBEN*ZMYUL)
    4 PHI = PHII
      THETA = THETAI
      XIBASE          = XITAB(1)                                               BARC0062
      XIEND           = XITAB(IXTAB)                                           BARC0063
      IF (IXTAB .LE. 1)  GO TO 15
      DXRHO = (XITAB(2) - XIBASE)/10.0
   15 CALL BARPRO(1)                                                           BARC0066
      CALL BARPRO(5)                                                           BARC0067
      TWGTAB(1) = TWGCA
      TLCTAB(1) = TLCA
      CALL XNTERP ( X, YR, YRP, IYX, XITAB, YITAB, IXTAB, CYX, IMX )           BARC0068
C                                                                              BARC0069
C     SAVE INITIAL Y AND DELSTR.                                               BARC0070
C                                                                              BARC0071
      DEL = DELSTR                                                             BARC0072
      YMIN = YR                                                                BARC0073
C                                                                              BARC0074
      ONOC            = SQRT( 1. + YRP * YRP )                                 BARC0075
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      XCCP(1)        = X + DELSTR * YRP / ONOC                              BARC0076
      YCCP(1)        = YR - DELSTR / ONOC                                   BARC0077
      IF (IXTAB .LE. 1)  RETURN
      DO 20 I = IBEG,IXTAB
      XNEW=XITAB(I)                                                         BARC0080
      IF (ICOOL .EQ. 0)  GO TO 16
      AL = ALTAB(I)
      THICK = THITAB(I)
      DELXOL = ABS(XITAB(I) - XITAB(I-1))
      IF (I .GE. IXTAB)  GO TO 3000
      DELXNE = ABS(XITAB(I+1) - XITAB(I))
      TL0 = TLTAB(I-1)
      TL1 = TLTAB(I)
      TL2 = TLTAB(I+1)
      GO TO 3001
 3000 DELXNE = 0.0
      TL0 = TLTAB(I-1)
      TL1 = TLTAB(I)
      TL2 = TL1
 3001 DELXBA = (DELXOL + DELXNE)/2.0
   16 XMAG = (ABS(XNEW) + ABS(X))/2.0
      DXINT=XNEW-X                                                          BARC0082
      NX             = DXINT / DXMAX + 0.99                                 BARC0083
      IF (NX .GT. 0)   GO TO 18
      NX = 1
   18 ZNX=NX                                                                BARC0086
      DX=DXINT/ZNX                                                          BARC0087
      DX02=DX/2.                                                            BARC0088
      DXRHO=DX/10.                                                          BARC0089
      DO 30 INX=1,NX                                                        BARC0090
      PHIOLD=PHI                                                            BARC0091
      THEOLD=THETA                                                          BARC0092
      XOLD=X                                                                BARC0093
      DPHIRK(1)=DX*PHIP                                                     BARC0094
      DTHERK(1)=DX*THETAP                                                   BARC0095
      X=XOLD+DX02                                                           BARC0096
      DO 40 IRK=2,4                                                         BARC0097
      IF (IRK .NE. 4)   GO TO 44
      X = XOLD + DX
      IF (ABS((X - XNEW)/XMAG) .GT. 1.0E-6)   GO TO 43
      X = XNEW
   43 PHI = PHIOLD + DPHIRK(IRK - 1)
      THETA=THEOLD+DTHERK(IRK-1)                                            BARC0104
      GO TO 45                                                              BARC0105
   44 PHI = PHIOLD + DPHIRK(IRK - 1)*0.50
      THETA=THEOLD+DTHERK(IRK-1)*.5                                         BARC0108
   45 IF (PHI .LE. 0.0)   GO TO 62
      IF (THETA .LE. 0.0)   GO TO 62
      CALL BARPRO(IRK)                                                      BARC0113
      DPHIRK(IRK)=DX*PHIP                                                   BARC0114
   40 DTHERK(IRK) = DX*THETAP
      PHI=PHIOLD+(DPHIRK(1)+2.*DPHIRK(2)+2.*DPHIRK(3)+DPHIRK(4))/6.        BARC0117
      THETA=THEOLD+(DTHERK(1)+2.*DTHERK(2)+2.*DTHERK(3)+DTHERK(4))/6.      BARC0118
      IF (PHI .LE. 0.0)    GO TO 62
      IF (THETA .GT. 0.0)   GO TO 72
   62 WRITE(6,63) X, ZME, THETA, PHI                                        BARC0121
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   63 FORMAT ( 41H **BARCON FAILURE... AXIAL DISTANCE  X = , 1PE14.7,    BARC0122
     1          5X,  11HMACH NO. = , E14.7, 2X, 8HTHETAI =, E14.7, 2X,   BARC0123
     2          6HPHII =, E14.7 / 44H THETAI OR PHII COMPUTED AS NEGATIVEBARC0124
     3 OR ZERO / 64H  *CHECK CONTOUR AND MACH NUMBER DISTRIBUTION TABLESBARC0125
     4 FOR ERRORS./ 110H  *MORE INPUT POINTS MAY BE REQUIRED TO ADEQUATEBARC0126
     5LY DESCRIBE DERIVATIVE VALUES ALONG THE CONTOUR AT THIS POINT. /  BARC0127
     6  96H  *A SMALLER RUNGE-KUTTA STEP SIZE MAY BE REQUIRED TO ADEQUATBARC0128
     7ELY APPROXIMATE INTEGRATION VALUES                                BARC0129
      CALL BARPRO(5)                                                    BARC0130
      CALL QUITS                                                        BARC0131
   72 CALL BARPRO(1)
C                                                                       BARC0134
C                                                                       BARC0135
C     SELECT MINIMUM Y AND ITS CORRESPONDING DELSTR.                    BARC0136
C                                                                       BARC0137
      IF(YR.GT.YMIN) GO TO 29                                           BARC0138
      DEL = DELSTR                                                      BARC0139
      YMIN = YR                                                         BARC0140
C                                                                       BARC0142
   29 IF (IPRINT .LE. 0)  GO TO 30
      CALL BARPRO(5)
   30 CONTINUE                                                          BARC0145
      CALL XNTERP ( X, YR, YRP, IYX, XITAB, YITAB, IXTAB, CYX, IMX )    BARC0146
      ONOC           = SQRT( 1. + YRP * YRP )                           BARC0147
      XCCP(I)        = X + DELSTR * YRP / ONOC                          BARC0148
      YCCP(I)        = YR - DELSTR / ONOC                               BARC0149
      IF (IPRINT .GT. 0)  GO TO 20
      CALL BARPRO(5)
      TWGTAB(I) = TWGCA
      TLCTAB(I) = TLCA
   20 CONTINUE                                                          BARC0153
C                                                                       BARC0154
C     YMIN  = MINIMUM Y VALUE FOR NOZZLE.                               BARC0155
C     DEL   = DELSTR CORRESPONDING TO MINIMUM Y (THROAT).               BARC0157
C     RPOT  = THE POTENTIAL THROAT RADIUS.                              BARC0158
C                                                                       BARC0159
      RPOT = YMIN          - DEL                                        BARC0160
C                                                                       BARC0161
      WRITE(6,1000) RPOT                                                BARC0162
C                                                                       BARC0163
C     NORMALIZE TABLE OF CORRECTED CONTOUR POINTS USING THE POTENTIAL   BARC0164
C     THROAT RADIUS.                                                    BARC0165
C                                                                       BARC0166
      XCCP(1) = XCCP(1) / RPOT                                          BARC0167
      YCCP(1) = YCCP(1) / RPOT                                          BARC0168
      DO 79 I = IBEG,IXTAB                                              BARC0169
      XCCP(I) = XCCP(I) / RPOT                                          BARC0170
   79 YCCP(I) = YCCP(I)/RPOT
C                                                                       BARC0173
      WRITE(6,1001)                                                     BARC0174
      IF (ISTART .LE. 0)  GO TO 85
      WRITE (6,1010) XCCP(1),YCCP(1),(I,XCCP(I),YCCP(I),I=IBEG,IXTAB)
      GO TO 86
   85 WRITE(6,1020) ( I, XCCP(I), YCCP(I), I = 1, IXTAB )               BARC0179
   86 IF (ICOOL .EQ. 0)  RETURN
      IF (ABS((SUMQDA*COEFCL - SUMQWI)/SUMQWI) .LT. TOLITE)  RETURN
```

```
      DO 87 I = 1,IXTAB
      TWTAB(I) = (TWTAB(I) + TWGTAB(I))/2.0
   87 TLTAB(I) = (TLTAB(I) + TLCTAB(I))/2.0
      GO TO 10
 1000 FORMAT(1H1,29X,41HTHROAT RADIUS CORRECTED FOR DISPLACEMENT ,      BARC0181
     1 11HTHICKNESS =,1PE15.8//)                                        BARC0182
 1001 FORMAT(1H0,29X,48HTABLE OF NORMALIZED CONTOUR POINTS CORRECTED FORBARC0183
     1 23H DISPLACEMENT THICKNESS // 37X,10HDATA POINT,10X,1HX,24X,1HY/)BARC0184
 1010 FORMAT ( 40X, 6HM = 1., 4X, 1PE15.8, 10X, E15.8 / ( 40X, I5,     BARC0185
     1          5X, E15.8, 10X, E15.8 ) )                               BARC0186
 1020 FORMAT ( 40X, I5, 5X, 1PE15.8, 10X, E15.8 )                       BARC0187
      END                                                               BARC0188
```

```
      SUBROUTINE BARPRO (IND)
C
      COMMON /COFIIF/ IFINT,AFINT,BFINT,CFINT,MMINT,TFINT               /COFIIF/
C
      COMMON /COOL/ ICOOL,IDUMP,ITZTAB,AL,COEFCL,CPL,DELXBA,DIATUB,     /COOL/
     1              FLOWRT,MASSL,PRANDL,RAMDL,RAMDW,REYL,SUMQGA,SUMQWI, /COOL/
     2              THICK,TLO,TL1,TL2,TLCA,TOLITE,IUBEN,TWGCA,ZMYUL,    /COOL/
     3              CPLTAB(20),RAMTAB(20),TZTAB(20),ZMYTAB(20),         /COOL/
     4              ALTAB(100),THITAB(100),TLCTAB(100),TLTAB(100),      /COOL/
     5              TWGTAB(100)                                         /COOL/
      REAL MASSL                                                        /COOL/
C
      COMMON /CSEVAL/ NOCTAB,IS,ROJ,FJG,CJG,GMIO2,GOGMI,POMAX,CPO,HO,   /CSEVAL/
     A                SO,TCTAB(20),CPTAB(20),BCP(20),CCP(20),DCP(20),   /CSEVAL/
     K                GTAB(20),HTAB(20),BARB1(20),BARB2(20),BARB3(20)   /CSEVAL/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,      /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,   /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN      /INPUT/
C
      COMMON /INTER/ CFAGT,CFAGP,CHPART,DX,DXRHO,HE,HW,IBEG,MZETAM,     /INTER/
     A               OOMZET,PHIP,PREI03,RHOE,RHOUE,RMZETA,THETAP,       /INTER/
     K               XIBASE,XIEND,ZETATM,ZMZETA,ZMZETM,ZMZETP           /INTER/
C
      COMMON /LOOKUP/ ICX,IMX,IPX,IRX,ISX,ITPOS,ITWX,ITX,IUX,IXPOS,IYX, /LOOKUP/
     1                IZX,CCX(6),CMX(6),CPX(6),CRX(6),CSX(6),CTWX(6),   /LOOKUP/
     2                CTX(6),CUX(6),CYX(6),CZX(6)                       /LOOKUP/
C
      COMMON /NHANCE/ IEX,CEX(6),ENHTAB(100)                            /NHANCE/
C
      COMMON /OUTPUT/ BDELTA,CF,CH,DELTA,DELSOT,DELSTR,FLAT,FORCE,HG,   /OUTPUT/
     A                PE,PHI,QW,SUMQDA,TE,THETA,TW,UE,X,XLARC,YR,Z1,    /OUTPUT/
     K                Z2,Z3,Z4,Z5,ZETA,ZME                              /OUTPUT/
C
      COMMON /SAVED/ A,B,C,Z11,Z11P,Z12,Z12P,Z13,Z13P,Z14,Z15,Z16,Z17   /SAVED/
C
      COMMON /TABLES/ PETAB(100),SMTAB(100),TETAB(100),TWTAB(100),      /TABLES/
     1                UETAB(100),XITAB(100),YITAB(100),ZMTAB(100)       /TABLES/
C
      DIMENSION ZINTPR(10)
      DATA (ZINTPR(I), I = 1,10) /6HZI4  =,6HZI5  =,6HZI6  =,6HZI7  =,
     A     6HZI1P =,6HZI1  =,6HZI2  =,6HZI3  =,6HZI2P =,6HZI3P =/
C
      GO TO (4,4,3,4,5), IND
    4 CALL XNTERP(X, ZME, ZMEP, IMX, XITAB, ZMTAB, IXTAB, CMX, IXPOS)
      IXPOS=IMX
      CALL XNTERP (X,TE,TEP,ITX,XITAB,TETAB,IXTAB,CTX,IXPOS)
      CALL XNTERP (X,PE,PEP,IPX,XITAB,PETAB,IXTAB,CPX,IXPOS)
      CALL XNTERP (X,UE,UEP,IUX,XITAB,UETAB,IXTAB,CUX,IXPOS)
      CALL XNTERP (X,SMOL,SMOLP,ISX,XITAB,SMTAB,IXTAB,CSX,IXPOS)
      CALL SEVAL(1,TE,CPE,HE)
      RBAR = 1545.0/SMOL
      ROJ = RBAR/FJ
      GAME = CPE/(CPE - ROJ)
      PRANDT = 4.0*GAME/(9.0*GAME - 5.0)
      UE202 = UE*UE/2.0
      HEP=FJG*CPE*TEP
      RHOE=PE/TE/RBAR
*DIAGNOSTIC*  THE TEST FOR EQUALITY BETWEEN NON-INTEGERS MAY NOT BE MEANINGFUL.
      IF (DXRHO .NE. 0.0)  GO TO 201
      RHOEP = 0.0
      GO TO 210
  201 IF (X .GT. XIBASE)  GO TO 203
```

```
      Z1 = RHOE
      Z3=1.
      GO TO 204
203   CALL XNTERP (X-DXRHO,Z4,Z4P,IPX,XITAB,PETAB,IXTAB,CPX,IXPOS)
      CALL XNTERP (X-DXRHO,Z5,Z5P,ITX,XITAB,TETAB,IXTAB,CTX,IXPOS)
      CALL XNTERP (X-DXRHO,SM1,SM1P,ISX,XITAB,SMTAB,IXTAB,CSX,IXPOS)
      R1 = 1545.0/SM1
      Z1 = Z4/Z5/R1
      Z3=.5
204   IF (X .LT. XIEND)  GO TO 206
      Z2 = RHOE
      Z3=1.
      GO TO 207
206   CALL XNTERP (X+DXRHO,Z4,Z4P,IPX,XITAB,PETAB,IXTAB,CPX,IXPOS)
      CALL XNTERP (X+DXRHO,Z5,Z5P,ITX,XITAB,TETAB,IXTAB,CTX,IXPOS)
      CALL XNTERP (X+DXRHO,SM1,SM1P,ISX,XITAB,SMTAB,IXTAB,CSX,IXPOS)
      R1 = 1545.0/SM1
      Z2 = Z4/Z5/R1
207   RHOEP=(Z2-Z1)/DXRHO*Z3
210   RHOUE = RHOE*UE
      RHOUEP=RHOE*UEP+UE*RHOEP
      ZMU=ZMUO*(TE/TO)**ZMVIS
      HO = HE + UE2O2
      HOP = HEP + UE*UEP
      PRE1O3 = PRANDT**(1.0/3.0)
      HAW=HE+PRE1O3*UE2O2
      CALL SEVAL(2,TAW,ERASE3,HAW)
      IF(ITWTAB) 11,12,13
   11 TW=TAW
      HW=HAW
      HWP=HEP+PRE1O3*UE*UEP
      GO TO 14
   12 TW=TWTAB(1)
      HW=TWTAB(2)
      HWP=0.
      GO TO 14
   13 CALL XNTERP ( X, TW, TWP, ITWX, XITAB, TWTAB, IXTAB, CTWX, IXPOS )
      CALL SEVAL(1,TW,CPW,HW)
      HWP=FJG*CPW*TWP
   14 IF (TW .LE. TAW)  GO TO 170
      WRITE(6,155) TW,TAW
  155 FORMAT ( 45HO**BARPRO FAILURE... WALL TEMPERATURE ( TW = , F8.2,
     1 62H ) CALCULATED GREATER THAN ADIABATIC WALL TEMPERATURE ( TAW =
     2,F8.2, 3H ). )
      WRITE(6,106) X, ZME, THETA, PHI
  106 FORMAT ( 23H   AXIAL DISTANCE  X = , 1PE14.7, 5X, 11HMACH NO. = ,
     1 E14.7, 5X, 8HTHETAI =, E14.7, 5X, 6HPHII =, E14.7 )
      WRITE(6,250)
  250 FORMAT ( 64H  *CHECK CONTOUR AND MACH NUMBER DISTRIBUTION TABLES F
     1OR ERRORS. / 110H  *MORE INPUT POINTS MAY BE REQUIRED TO ADEQUATEL
     2Y DESCRIBE DERIVATIVE VALUES ALONG THE CONTOUR AT THIS POINT. /
     396H  *A SMALLER RUNGE-KUTTA STEP SIZE MAY BE REQUIRED TO ADEQUATEL
     4Y APPROXIMATE INTEGRATION VALUES. // )
      CALL QUITS
  170 A              = HW
      B=HO-HW
```

```
      C=-UE2O2
      TFINT=TE
    3 CALL ZETAIT
      CREY=RHOUE/ZMU
      RTHE=CREY*THETA
      RPHI=CREY*PHI
      CF = 0.0250/(RTHE**0.250)
      CFAG = 0.0250/(RPHI**0.250)
      CHPAR1 = 1.0 - PRANDT + ALOG(6.0/(5.0*PRANDT + 1.0))
      CH=(PHI/THETA)**ZNSTAN*(CFAG/2.)/(1.-5.*SQRT(CFAG/2.)*CHPAR1)
      IF (ITWTAB .LT. 0)  CH = 0.0
      ERASE1 = RHOUEP/RHOUE
      ERASE2=(1.+DELSOT)/UE*UEP
      CALL XNTERP ( X, YR, YRP, IYX, XITAB, YITAB, IXTAB, CYX, IXPOS )
      DARC=SQRT(1.+YRP*YRP)
      CDFORC=RHOUE/G*UE/DARC*CF/2.
      IF (EPSZ .LE. 0.0)  GO TO 40
      ERASE1 = ERASE1 + EPSZ/YR*YRP
   40 THETAP = CF/2.0*DARC - THETA*(ERASE2 + ERASE1)
      ERASE2=HO-HW
      PHIP = CH*DARC/ERASE2*(HAW-HW) - PHI*(ERASE1 - (HOP-HWP)/ERASE2)
      IF (IND .NE. 1)  RETURN
      IF (ITWTAB .LT. 0)  GO TO 66
      QW = RHOUE/FJ*CH/G*(HAW - HW)
      HG=QW/(TAW-TW)
   66 QDAO         = QDA
      DFORCO=DFORCE
      DFLATO=DFLAT
      IF (EPSZ .LE. 0.0)  GO TO 44
      ERASE1 = PIE*YR
      QDA            = ERASE1 * QW
      DFORCE=ERASE1*CDFORC
      DFLAT=0.
      GO TO 45
   44 QDA = QW
      DFORCE=CDFORC/2.
      DFLAT=DFORCE*YRP
   45 YOARC = Y2ARC
      Y2ARC=DARC
      IF (DX .LE. 0.0)  RETURN
      CALL XNTERP(X - DX/2.0, ERASE1, ERASE2, IYX, XITAB, YITAB,
     A                IXTAB, CYX, IXPOS)
      Y1ARC=SQRT(1.+ERASE2*ERASE2)
      DXLARC=(YOARC+4.*Y1ARC+Y2ARC)/6.*DX
      XLARC=XLARC+DXLARC
      SUMQDA=SUMQDA+DXLARC*(QDA+QDAO)
      IF (ICOOL .EQ. 0)  GO TO 2
      SUMQGA = COEFCL*SUMQDA
      CALL XNTERP (TL1,ZMYUL,ZP,IZX,TZTAB,ZMYTAB,ITZTAB,CZX,ITPOS)
      ITPOS = IZX
      DIATUB = 2.0*SQRT(AL/PIE)
      REYL = MASSL*DIATUB/(AL*TUBEN*ZMYUL)
    2 FORCE = FORCE + DXLARC*(DFORCE + DFORCO)
      FLAT=FLAT+DXLARC*(DFLAT+DFLATO)
      RETURN
    5 RXLN = CREY*XLARC
```

```
      RDLS=CREY*DELSTR
      IF (ZETA .GE. 1.0)  GO TO 62
      I = 1
      Z1=Z14
      Z2=Z15
      Z3=Z16
      Z4=Z17
      Z5=Z11P
      GO TO 63
   62 I=6
      Z1=Z11
      Z2=Z12
      Z3=Z13
      Z4=Z12P
      Z5=Z13P
   63 WRITE(6,51)
   51 FORMAT (1H0/1X,16HCONTOUR PROPERTIES,5X,15HFLOW PROPERTIES,8X,
     A          14HBOUNDARY LAYER,9X,13HHEAT TRANSFER,7X,
     K          18HINTERNAL INTEGRALS,7X,12HCOEFFICIENTS/)
      WRITE(6,52) X,ZME,DELTA,HG,ZETA,CF
   52 FORMAT (1X,7HX      =,F11.6,3X,7HZME    =,F12.6,3X,7HDELTA =,
     A          1PE13.6,3X,7HHG     =,0PF12.6,3X,6HZETA =,1PE14.6,3X,
     K          6HCF   =,1PE13.6)
      WRITE(6,53) XLARC,TE,BDELTA,QW,ZINTPR(I),Z1,CH
   53 FORMAT (1X,7HXLARC =,F11.6,3X,7HTE     =,F12.6,3X,7HBDELTA=,
     A          1PE13.6,3X,7HQW     =,1PE12.6,3X,A6,1PE14.6,3X,6HCH    =,
     K          1PE13.6)
      WRITE(6,54) YR,TW,DELSTR,SUMQDA,ZINTPR(I+1),Z2,RTHE
   54 FORMAT (1X,7HYR     =,F11.6,3X,7HTW     =,F12.6,3X,7HDELSTR=,
     A          1PE13.6,3X,7HSUMQDA=,1PE12.6,3X,A6,1PE14.6,3X,6HRTHE =,
     K          1PE13.6)
      WRITE(6,55) YRP,TAW,THETA,FORCE,ZINTPR(I+2),Z3,RXLN
   55 FORMAT (1X,7HYRP    =,F11.7,3X,7HTAW    =,F12.6,3X,7HTHETA =,
     A          1PE13.6,3X,7HFORCE =,0PF12.6,3X,A6,1PE14.6,3X,6HRXLN =,
     K          1PE13.6)
      YRDELS = YR - DELSTR
      WRITE (6,56) YRDELS,ZMEP,PHI,FLAT,ZINTPR(I+3),Z4,RPHI
   56 FORMAT (1X,7HYRDELS=,F11.8,3X,7HZMEP   =,F12.8,3X,7HPHI    =,
     1 1PE13.6,3X,7HFLAT   =,0PF12.6,3X,A6,1PE14.6,3X,6HRPHI =,1PE13.6)
      WRITE (6,57) UE,DELSOT,RBAR,ZINTPR(I+4),Z5,RDLS
   57 FORMAT (22X,7HUE     =,F12.6,3X,7HDELSOT=,F13.6,3X,7HRBAR   =,F12.6,
     A          3X,A6,1PE14.6,3X,6HRDLS =,1PE13.6)
      WRITE (6,58) PE,RHOE,PRANDT,GAME,SMOL
   58 FORMAT (22X,7HPE     =,1PE12.6,3X,7HRHOE   =,0PF13.6,3X,7HPRANDT=,
     A          F12.10,3X,6HGAME =,F14.8,3X,6HSMOL =,F13.6)
      COSAL = 1.0/DARC
      IF (EPSZ .LE. 0.0)  GO TO 500
      DELF1 = 2.0*PIE*YR*RHOUE*THETA*UE*COSAL/G
      DELF2 = 1.0 - DELSOT*PE/(RHOUE*UE/G)
      DELFA = DELF1*DELF2
      THRUST = PIE*YR**2*(RHOUE*UE/G + PE)
      DEFTHR = 100.0*DELFA/THRUST
      THRUSA = PIE*YR**2*(RHOUE*UE/G + PE - 2116.2240)
      ZMASSR = PIE*(YR + DELSTR*COSAL)**2*RHOUE
      XMASSR = PIE*YR**2*RHOUE
      GO TO 510
```

```
C
C     THE TWO DIMENSIONAL CASE ASSUMES A WIDTH OF ONE FOOT
C
  500 DELF1 = 2.0*RHOUE*THETA*UE*COSAL/G
      DELF2 = 1.0 - DELSOT*PE/(RHOUE*UE/G)
      DELFA = DELF1*DELF2
      THRUST = 2.0*YR*(RHOUE*UE/G + PE)
      DEFTHR = 100.0*DELFA/THRUST
      THRUSA = 2.0*YR*(RHOUE*UE/G + PE - 2116.2240)
      ZMASSR = 2.0*(YR + DELSTR*COSAL)*RHOUE
      XMASSR = 2.0*YR*RHOUE
  510 VISP = THRUST/ZMASSR
      AISP = THRUSA/ZMASSR
      TBLISP = -DELFA/FLOWRT
      WRITE (6,1) AISP,XMASSR,THRUSA,DELFA,TBLISP,VISP,ZMASSR,THRUST,
     1            DEFTHR,COSAL
    1 FORMAT (//25X,81HTHRUST DEFICIENCY AND SPECIFIC IMPULSE DECREMENT
     1DUE TO THE BOUNDARY LAYER EFFECT//5X,6HAISP =,F10.4,5X,8HXMASSR =,
     2 F13.4,5X,8HTHRUSA =,F14.4,5X,7HDELFA =,F12.4,5X,8HTBLISP =,F11.6/
     3 5X,6HVISP =,F10.4,5X,8HZMASSR =,F13.4,5X,8HTHRUST =,F14.4,5X,
     4 8HDEFTHR =,F11.8,5X,7HCOSAL =,F12.8//)
      IF (ICOOL .EQ. 0)  RETURN
      TWL = TL1
      CALL XNTERP (TL1,CPL,CPP,ICX,TZTAB,CPLTAB,ITZTAB,CCX,ITPOS)
      CALL XNTERP (TL1,RAMDL,RP,IRX,TZTAB,RAMTAB,IIZTAB,CRX,ITPOS)
      CALL XNTERP (TL1,ZMYUL,ZP,IZX,TZTAB,ZMYTAB,IIZTAB,CZX,ITPOS)
      CALL XNTERP (X,ENHA,ENHAP,IEX,XITAB,ENHTAB,IXTAB,CEX,IXPOS)
      PRANDL = CPL*ZMYUL/RAMDL
   70 TWLG = TWL
      HL = 0.0250*RAMDL/DIATUB*REYL**0.80*PRANDL**0.40*(TL1/TWL)**0.550
      HL = HL*ENHA
      SA1 = HL*(1.0 + RAMDW/(THICK*HG))
      SA2 = RAMDW/THICK
      TWL = (SA1*TL1 + SA2*TAW)/(SA1 + SA2)
      IF (ABS(TWLG - TWL) .GT. 0.010)  GO TO 70
      TEMPRL = TWL/TL1
      TWGCA = (HG*TAW + RAMDW/THICK*TWL)/(HG + RAMDW/THICK)
      QWI = HG*(TAW - TWGCA)
      IF (EPSZ .LE. 0.0)  GO TO 600
      SST = PIE*YR*QWI*DELXBA*DARC*COEFCL
      GO TO 610
  600 SST = QWI*DELXBA*DARC*COEFCL
  610 TLCA = (TL1 + TL2)/2.0 + SST/(CPL*MASSL)
      IF (IDUMP .GT. 0)  TLCA = (TL0 + TL1)/2.0 + SST/(CPL*MASSL)
      DMASSL = MASSL/(AL*TUBEN)
      SUMQWI = SUMQWI + SST*2.0
      WRITE (6,71) DMASSL,HL,QWI,REYL,SUMQWI,TEMPRL,TLCA,TWGCA,TWL,
     1             DIATUB,THICK,SUMQGA
   71 FORMAT (/50X,31HREGENERATIVE CALCULATION OUTPUT//5X,8HDMASSL =,
     1 F12.4,5X,4HHL =,F10.6,7X,5HQWI =,F12.4,5X,6HREYL =,F19.4,5X,
     2 8HSUMQWI =,F15.6/5X,8HTEMPRL =,F10.4,7X,6HTLCA =,F10.4,5X,
     3 7HTWGCA =,F10.4,5X,5HTWL =,F10.4,15X,8HDIATUB =,F15.10/
     4 5X,7HTHICK =,F10.6,81X,8HSUMQGA =,F15.6////////)
      RETURN
      END
```

```
      SUBROUTINE BARSET                                                 BARS   1
C
      COMMON /CSEVAL/ NOCTAB,IS,ROJ,FJG,CJG,GM1O2,GOGM1,PUMAX,CPO,HO,  /CSEVAL/
     A                SO,TCTAB(20),CPTAB(20),BCP(20),CCP(20),DCP(20),  /CSEVAL/
     K                GTAB(20),HTAB(20),BARB1(20),BARB2(20),BARB3(20)  /CSEVAL/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,     /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHI1,PIE,PRANDT,RBAR,SCALE,TO,  /INPUT/
     K               THETA1,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN     /INPUT/
C
      COMMON /TABLES/ PETAB(100),SMTAB(100),TETAB(100),TWTAB(100),     /TABLES/
     1                UETAB(100),XITAB(100),YITAB(100),ZMTAB(100)      /TABLES/
C
      PIE=3.14159265                                                    BARS  24
      FJG=FJ*G                                                          BARS  25
      ROJ=RBAR/FJ                                                       BARS  26
      TMAX=TC                                                           BARS  27
      I1=1                                                              BARS  28
      IF(ITWTAB) 15,12,11                                               BARS  29
   11 I1=IXTAB                                                          BARS  30
   12 DO 14 I=1,I1                                                      BARS  31
      IF (TWTAB(I) .LE. TMAX)  GO TO 14
      TMAX = TWTAB(I)
   14 CONTINUE                                                          BARS  34
  15  IF (ICTAB .EQ. 0)  GO TO 20
      IF (TMAX .LT. TCTAB(ICTAB))  GO TO 16
      WRITE(6,52) TMAX,TCTAB(ICTAB)
   52 FORMAT ( // 44H **BARSET ERROR**  TEMPERATURE INPUT VALUE (,      BARS  39
     1       1PE14.7, 29H) EXCEEDS TABLE UPPER LIMIT (, E14.7, 1H) )    BARS  40
      GO TO 57                                                          BARS  41
   16 NOCTAB=ICTAB                                                      BARS  42
      CALL BMFITS (TCTAB,CPTAB,ICTAB,BCP,CCP,DCP)
      TIE1=TCTAB(1)                                                     BARS  51
      TIE2=TIE1*TIE1                                                    BARS  52
      TIE3=TIE2*TIE1                                                    BARS  53
      HTAB(1) = CPTAB(1)*TIE1 - BCP(1)*TIE2/2.0
      BARB1(1) = CPTAB(1) - BCP(1)*TIE1 + CCP(1)*TIE2 - DCP(1)*TIE3
      BARB2(1) = BCP(1) - 2.0*CCP(1)*TIE1 + 3.0*DCP(1)*TIE2
      BARB3(1)=(CCP(1)-3.*DCP(1)*TIE1)/2.                               BARS  57
      GTAB(1)=-BARB1(1)*ALOG(TIE1)-BARB2(1)*TIE1-BARB3(1)*TIE2          BARS  58
     X        -DCP(1)/3.*TIE3                                           BARS  59
      G1=0.                                                             BARS  60
      DO 19 I=2,ICTAB                                                   BARS  61
      TME1=TIE1                                                         BARS  62
      TME2=TIE2                                                         BARS  63
      TME3=TIE3                                                         BARS  64
      TIE1=TCTAB(I)                                                     BARS  65
      TIE2=TIE1*TIE1                                                    BARS  66
      TIE3=TIE2*TIE1                                                    BARS  67
      DELT=TIE1-TME1                                                    BARS  68
      HTAB(I) = HTAB(I-1) + CPTAB(I-1)*DELT + BCP(I-1)*DELT**2/2.0 +
     A          CCP(I-1)*DELT**3/3.0 + DCP(I-1)*DELT**4/4.0
      IF (I .GE. ICTAB)  GO TO 19
      BARB1(I) = CPTAB(I) - BCP(I)*TIE1 + CCP(I)*TIE2 - DCP(I)*TIE3
      BARB2(I)=BCP(I)-CCP(I)/.5*TIE1+3.*DCP(I)*TIE2                     BARS  73
```

```
      BARB3(I)=(CCP(I)-3.*DCP(I)*TIE1)/2.                                 BARS  74
      G1=G1+BARB1(I-1)*ALOG(TIE1/TME1)+BARB2(I-1)*DELT                    BARS  75
     X     +BARB3(I-1)*(TIE2-TME2)+DCP(I-1)/3.*(TIE3-TME3)                BARS  76
      G2=BARB1(I)*ALOG(TIE1)+BARB2(I)*TIE1+BARB3(I)*TIE2+DCP(I)/3.*TIE3   BARS  77
      GTAB(I)=G1-G2                                                       BARS  78
   19 CONTINUE                                                            BARS  79
      IS=ICTAB-1                                                          BARS  80
      CALL SEVAL(1,TO,CPO,HO)                                             BARS  81
      GAMO=CPO/(CPO-RO)                                                   BARS  82
20    IF (GAMO .GT. 1.0)  GO TO 56
      WRITE (6,54) GAMO
   54 FORMAT (    81H **BARSET ERROR**  RATIO OF SPECIFIC HEATS MUST BE BARS  86
     1GREATER THAN ONE (1).  GAMO = , E14.7 / 46H CHECK FOR INCONSISTENTBARS  87
     2 UNITS.... CP, RBAR, FJ  // )                                       BARS  88
   57 CALL QUITS                                                          BARS  89
56    GM102 = (GAMO - 1.0)/2.0
      GOGM1=GAMO/(GAMO-1.)                                                BARS  92
      POMAX=PO                                                            BARS  93
      IF (ICTAB .GT. 0)  GO TO 30
      NOCTAB = 6
      NOCTM1=NOCTAB-1                                                     BARS  99
      IS=NOCTM1                                                           BARS 100
      CPO=GOGM1/FJ*RBAR                                                   BARS 101
      CJG=CPO*FJG                                                         BARS 102
      HO=CJG*TO                                                           BARS 103
      DO 23 I=1,IXTAB                                                     BARS 104
      TE = TETAB(I)
      IF (TE .LE. TMAX)  GO TO 23
      TMAX = TE
   23 CONTINUE                                                            BARS 108
      TCTAB(NOCTAB)=TMAX+100.                                             BARS 109
      TCTAB(1)=1.E-10                                                     BARS 110
      Z1=NOCTM1                                                           BARS 111
      DELT=(TCTAB(NOCTAB)-TCTAB(1))/Z1                                    BARS 112
      ERASE1=-CPO*ALOG(TCTAB(1))                                          BARS 113
      DO 25 I=1,NOCTAB                                                    BARS 114
      GTAB(I)=ERASE1                                                      BARS 115
      CPTAB(I) = CPO
      BCP(I)=0.                                                           BARS 117
      CCP(I)=0.                                                           BARS 118
      DCP(I)=0.                                                           BARS 119
      BARB1(I)=CPO                                                        BARS 120
      BARB2(I)=0.                                                         BARS 121
      BARB3(I)=0.                                                         BARS 122
      HTAB(I)=CPO*(TCTAB(I)-TCTAB(1))                                     BARS 123
      IF (I .GE. NOCTM1)  GO TO 25
      TCTAB(I+1) = TCTAB(I) + DELT
   25 CONTINUE                                                            BARS 126
30    IF (ITWTAB .NE. 0)  GO TO 38
      CALL SEVAL(1, TWTAB(1), ERASE1, TWTAB(2))
38    CALL SEVAL(0,TO,PO,SO)                                              BARS 132
      RETURN                                                              BARS 133
      END
```

```
BMFITS
      SUBROUTINE BMFITS (X,Y,N,BL,CL,DL)
C
      DIMENSION A(20),B(20),C(20),F(20),G(20),X(20),Y(20),
     A          BL(20),CL(20),DL(20),FL(20),YPP(20)
C
      I = 1
   11 FL(I) = X(I+1) - X(I)
      I = I + 1
      IF (I .LT. N)  GO TO 11
      I = 2
   15 B(I) = -FL(I-1)/FL(I)
      A(I) = -2.0*(FL(I) + FL(I-1))/FL(I)
      C(I) = 6.0/FL(I)*((Y(I+1) - Y(I))/FL(I) - (Y(I) - Y(I-1))/FL(I-1))
      I = I + 1
      IF (I .LT. N)  GO TO 15
      G(2) = 1.0
      F(2) = 0.0
      I = 3
   32 G(I) = A(I-1) + B(I-1)/G(I-1)
      F(I) = -(B(I-1)*F(I-1)/G(I-1) + C(I-1))
      I = I + 1
      IF (I .LE. N)  GO TO 32
      YPP(N) = F(N)/(G(N) - 1.0)
      YPP(N-1) = YPP(N)
      I = N - 2
   47 YPP(I) = (YPP(I+1) + F(I+1))/G(I+1)
      I = I - 1
      IF (I .GT. 0)  GO TO 47
      I = 1
   51 BL(I) = (Y(I+1)-Y(I))/FL(I) - (FL(I)*(YPP(I+1) + 2.0*YPP(I)))/6.0
      CL(I) = YPP(I)/2.0
      DL(I) = (YPP(I+1) - YPP(I))/(6.0*FL(I))
      I = I + 1
      IF (I .LT. N)  GO TO 51
      RETURN
      END
```

```
CFEVAL
      FUNCTION CFEVAL(CFRT)                                             CFEV   1
C
      DIMENSION X(8),A(7),B(7),C(7),D(7),IX(8)                          CFEV   2
      EQUIVALENCE (X,IX),(Z,IZ)                                         CFEV   3
      DATA A/-2.0791773E-2,-4.9715425E-3,1.2614392E-3,-1.0088617E-3,
     1      1.7521422E-4,-2.883630E-4,5.9985794E-6/, B/0.20915862,
     2      7.3896560E-2,-1.6794227E-2,2.9519911E-2,-1.5620821E-3,
     3      1.3318747E-2,2.1035707E-3/, C/-0.92142043,-0.53592107,
     4      -9.607530E-2,-0.41101115,-0.13904416,-0.29826897,
     5      -0.15583627/, D/-4.4457710,-4.8119952,-5.5230787,-4.8092254,
     6      -5.6024598,-5.0345585,-5.6375232/, J/1/, X/2.5099998,
     7      17.287782,127.74039,897.84729,6310.6880,44355.857,
     8      327747.91,1982759.2/, ZERO/0.0/
C
      Z=CFRT                                                            CFEV  15
      IF (Z .LE. 0.0)  GO TO 3
    1 IF(IZ-IX(J)) 2,7,9                                                CFEV  17
    2 J=J-1                                                             CFEV  18
      IF ( J ) 3, 5, 1                                                  CFEV  19
    3 J=1                                                               CFEV  20
      WRITE(6,4) Z,ZERO,X(8)                                            CFEV  21
    4 FORMAT (/10X,14HCFEVAL FAILURE,5X,3HZ =,1PE15.8,5X,15HLIMITS ARE F
     1ROM,5X,E18.8,2X,2HTO,E18.8)
      CALL QUITS                                                        CFEV  23
 5    IF (Z .LE. 0.0)  GO TO 3
      J = 1
      Y=.009896/Z**.562                                                 CFEV  26
      GO TO 8                                                           CFEV  27
    7 ZL=ALOG(Z)                                                        CFEV  28
      YL=D(J)+ZL*(C(J)+ZL*(B(J)+ZL*A(J)))                               CFEV  29
      Y=EXP(YL)                                                         CFEV  30
    8 CFEVAL=Y                                                          CFEV  31
      RETURN                                                            CFEV  32
 9    IF (IZ .LE. IX(J+1))  GO TO 7
      J = J + 1
      IF(J-8) 9,3,3                                                     CFEV  35
      END                                                               CFEV  36
```

```
DIRECT
      SUBROUTINE DIRECT                                                 DIRE   1
C
   10 CALL READIN                                                       DIRE   2
      CALL BARSET                                                       DIRE   3
      CALL BARCON                                                       DIRE   4
      GO TO 10
      END                                                               DIRE   7
```

FIIF

```
      FUNCTION FIIF (S)
C
      COMMON /COFIIF/ IFINT,AFINT,BFINT,CFINT,MMINT,TFINT               /COFIIF/
C
      STOM=1.                                                           FIIF   4
      IF (MMINT .LE. 0)  GO TO 12
      DO 4 I=1,MMINT                                                    FIIF   7
    4 STOM = STOM* S                                                    FIIF   8
   12 FDEN = AFINT + S*(BFINT + S*CFINT)
      IF (IFINT .GE. 2)  GO TO 2
      FNUM = STOM*(1.0 - S)
      GO TO 3                                                           FIIF  13
    2 FNUM=STOM                                                         FIIF  14
    3 CALL SEVAL(2,T,0,FDEN)                                            FIIF  15
      FIIF=FNUM/T*TFINT                                                 FIIF  16
      RETURN                                                            FIIF  17
      END                                                               FIIF  18
```

```
GETPT
      SUBROUTINE GETPT (ZME,PI,TI)
C
      COMMON /CSEVAL/ NOCTAB,IS,ROJ,FJG,CJG,GM102,GOGM1,POMAX,CPO,HO,   /CSEVAL/
     A                SO,TCTAB(20),CPTAB(20),BCP(20),CCP(20),DCP(20),   /CSEVAL/
     K                GTAB(20),HTAB(20),BARB1(20),BARB2(20),BARB3(20)   /CSEVAL/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,      /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,   /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN      /INPUT/
C
      ZME2=ZME*ZME                                                      GETP   9
      PRODI=2./RBAR/ZME2/G                                              GETP  10
      DENM2=1.+GM102*ZME2                                               GETP  11
      TE=TO/DENM2                                                       GETP  12
      IF (ICTAB .GT. 0)  GO TO 20
      PE=PO/DENM2**GOGM1                                                GETP  15
   15 PI = PE
      TI=TE                                                             GETP  18
      RETURN                                                            GETP  19
   20 ITER = 0
      TOL = TOLZME/ZME
   21 TEO=TEG                                                           GETP  23
      TCO=TC                                                            GETP  24
      TEG=TE                                                            GETP  25
      CALL SEVAL(1,TE,CPE,HE)                                           GETP  26
      GAME=CPE/(CPE-ROJ)                                                GETP  27
      TC=(HO-HE)/GAME*PRODI                                             GETP  28
      IF (ABS((TC - TE)/TE) .LE. TOL)  GO TO 30
      IF (ITER .GT. 0)  GO TO 24
      TE = (2.0*TE + TC)/3.0
      GO TO 28                                                          GETP  32
   24 IF (ITER .LE. 50)  GO TO 27
      WRITE (6,26) ZME,TC,TCO,TE,TEO
   26 FORMAT ( 31HO**GETPT FAILURE... MACH NO. = , 1PE14.7 / 14X,      GETP  35
     1          17HT (CALCULATED) = , 2E16.7 / 14X, 17HT (GUESSED)    = ,GETP  36
     2          2E16.7 // )                                             GETP  37
      GO TO 30                                                          GETP  38
   27 ZK=(TC-TCO)/(TE-TEO)                                              GETP  39
      TE=(TC-ZK*TE)/(1.-ZK)                                             GETP  40
      IF (ABS((TE - TEG)/TE) .LT. TOL)  GO TO 29
      IF (ITER .LT. 10)  GO TO 28
      IF (ABS((TE - TEO)/TE) .LT. TOL)  GO TO 29
   28 ITER=ITER+1                                                       GETP  44
      GO TO 21                                                          GETP  45
   29 TE=(TE+TEG)/2.                                                    GETP  46
   30 CALL SEVAL(-1,TE,PE,SO)
      GO TO 15                                                          GETP  49
      END                                                               GETP  50
```

```
INTZET
      SUBROUTINE INTZET (X1,X2,ZINT)
C
C  -   INTZET  -  QUADRATIC FOUR POINT INTEGRATION SCHEME  -  ZETA(BARTZ)INTZ   2
C
      DIMENSION XC(21),YC(21),YM(4)                                     INTZ   3
C
      DX21=X2-X1                                                        INTZ   7
      SUMINT=0.                                                         INTZ   8
      IF (DX21 .EQ. 0.0)  GO TO 15
      DXC=DX21/20.                                                      INTZ  11
      IMAX=-9999                                                        INTZ  12
      FMAX=-1.E30                                                       INTZ  13
      DO 10 I=1,21                                                      INTZ  14
      XC(I)=X1+FLOAT(I-1)*DXC                                           INTZ  15
      YC(I)=FIIF(XC(I))                                                 INTZ  16
      IF (YC(I) .LE. FMAX)  GO TO 10
      IMAX = I
      XMAX=XC(I)                                                        INTZ  19
      FMAX=YC(I)                                                        INTZ  20
   10 CONTINUE                                                          INTZ  22
      IF (DX21 .GT. 0.10)  GO TO 17
      SUMINT=10.*YC(1)+16.*YC(2)-2.*YC(3)                               INTZ  25
      DO 14 I=2,19                                                      INTZ  26
      PARINT=13.*(YC(I)+YC(I+1))-YC(I-1)-YC(I+2)                        INTZ  27
  14  SUMINT = SUMINT + PARINT
      SUMINT=SUMINT+10.*YC(21)+16.*YC(20)-2.*YC(19)                     INTZ  30
      SUMINT=SUMINT/24.*DXC                                             INTZ  31
   15 ZINT=SUMINT                                                       INTZ  32
      RETURN                                                            INTZ  33
  17  FBRK = FMAX*0.20
      SUAINT=0.                                                         INTZ  35
      SUBINT=0.                                                         INTZ  36
      IF (IMAX .LE. 2)  GO TO 21
      DO 19 I=2,IMAX                                                    INTZ  39
      IF (YC(I) .LE. FBRK)  GO TO 19
      IBRK = I - 1
      GO TO 20                                                          INTZ  42
   19 CONTINUE                                                          INTZ  43
      IBRK=IMAX-1                                                       INTZ  44
  20  IF (IBRK .GT. 1)  GO TO 22
   21 IBRK=1                                                            INTZ  46
      IBRKM1=0                                                          INTZ  47
      GO TO 25                                                          INTZ  48
   22 IBRKM1=IBRK-1                                                     INTZ  49
      SUAINT=10.*YC(1)+16.*YC(2)-2.*YC(3)                               INTZ  50
      IF (IBRK .LE. 2)  GO TO 204
      DO 23 I=2,IBRKM1                                                  INTZ  53
      PARINT=13.*(YC(I)+YC(I+1))-YC(I-1)-YC(I+2)                        INTZ  54
  23  SUAINT = SUAINT + PARINT
 204  SUAINT = SUAINT/24.0*DXC
  25  DXM = DXC/3.0
      IF (IBRKM1 .GT. 0)  GO TO 206
      K = 2
      JS = 2                                                            INTZ  63
      GO TO 207                                                         INTZ  64
```

```
 206 K = 3                                                INTZ  65
     JS = 1                                               INTZ  66
 207 DO 26 I = 2,4
     XM=XC(IBRK)+FLOAT(I-K)*DXM                           INTZ  69
  26 YM(I) = FIIF(XM)
     IF (IBRKM1 .GT. 0)  GO TO 209
     SUBINT = 10.0*YM(2) + 16.0*YM(3) - 2.0*YM(4)
 209 DO 27 I = IBRK,19
     DO 28 J=JS,3                                         INTZ  76
     YM(1)=YM(2)                                          INTZ  77
     YM(2)=YM(3)                                          INTZ  78
     YM(3)=YM(4)                                          INTZ  79
     XM=XM+DXM                                            INTZ  80
     YM(4)=FIIF(XM)                                       INTZ  81
     PARINT=13.*(YM(2)+YM(3))-YM(1)-YM(4)                 INTZ  82
  28 SUBINT = SUBINT + PARINT
     JS = 1                                               INTZ  85
  27 XM = XC(I+1) + DXM
     DO 29 J=1,2                                          INTZ  88
     YM(1)=YM(2)                                          INTZ  89
     YM(2)=YM(3)                                          INTZ  90
     YM(3)=YM(4)                                          INTZ  91
     XM=XM+DXM                                            INTZ  92
     YM(4)=FIIF(XM)                                       INTZ  93
     PARINT=13.*(YM(2)+YM(3))-YM(1)-YM(4)                 INTZ  94
  29 SUBINT = SUBINT + PARINT
     SUBINT=SUBINT+10.*YM(4)+16.*YM(3)-2.*YM(2)           INTZ  97
     SUBINT=SUBINT/24.*DXM                                INTZ  98
     SUMINT=SUMINT+SUBINT                                 INTZ  99
     GO TO 15                                             INTZ 100
     END                                                  INTZ 101
```

```
MAINTB
C     I C R P G REFERENCE PROGRAM  TBL
C     DECK SEQUENCED BY SUBROUTINE
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,        /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,     /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN        /INPUT/
C
      IDXMAX = 0
      CALL DIRECT                                                          TBL      1
      END                                                                  TBL      3
```

```
QUITS
      SUBROUTINE QUITS                                                  QUIT    1
C
      COMMON /COFIIF/ IFINT,AFINT,BFINT,CFINT,MMINT,TFINT               /COFIIF/
C
      COMMON /COOL/ ICOOL,IDUMP,ITZTAB,AL,COEFCL,CPL,DELXBA,DIATUB,     /COOL/
     1              FLOWRT,MASSL,PRANDL,RAMDL,RAMDW,REYL,SUMQGA,SUMQWI, /COOL/
     2              THICK,TLO,TL1,TL2,TLCA,TOLITE,TUBEN,TWGCA,ZMYUL,    /COOL/
     3              CPLTAB(20),RAMTAB(20),TZTAB(20),ZMYTAB(20),         /COOL/
     4              ALTAB(100),THITAB(100),TLCTAB(100),TLTAB(100),      /COOL/
     5              TWGTAB(100)                                         /COOL/
      REAL MASSL                                                        /COOL/
C
      COMMON /CSEVAL/ NOCTAB,IS,ROJ,FJG,CJG,GM102,GOGM1,POMAX,CPO,HO,   /CSEVAL/
     A                SO,TCTAB(20),CPTAB(20),BCP(20),CCP(20),DCP(20),   /CSEVAL/
     K                GTAB(20),HTAB(20),BARB1(20),BARB2(20),BARB3(20)   /CSEVAL/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,      /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,   /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN      /INPUT/
C
      COMMON /INTER/ CFAGT,CFAGP,CHPAR1,DX,DXRHO,HE,HW,IBEG,MZETAM,     /INTER/
     A               OOMZET,PHIP,PRE103,RHOE,RHOUE,RMZETA,THETAP,       /INTER/
     K               XIBASE,XIEND,ZETATM,ZMZETA,ZMZETM,ZMZETP           /INTER/
C
      COMMON /LOOKUP/ ICX,IMX,IPX,IRX,ISX,ITPOS,ITWX,ITX,IUX,IXPOS,IYX, /LOOKUP/
     1                IZX,CCX(6),CMX(6),CPX(6),CRX(6),CSX(6),CTWX(6),   /LOOKUP/
     2                CTX(6),CUX(6),CYX(6),CZX(6)                       /LOOKUP/
C
      COMMON /NHANCE/ IEX,CEX(6),ENHTAB(100)                            /NHANCE/
C
      COMMON /OUTPUT/ BDELTA,CF,CH,DELTA,DELSOT,DELSTR,FLAT,FORCE,HG,   /OUTPUT/
     A                PE,PHI,QW,SUMQDA,TE,THETA,TW,UE,X,XLARC,YR,Z1,    /OUTPUT/
     K                Z2,Z3,Z4,Z5,ZETA,ZME                              /OUTPUT/
C
      COMMON /SAVED/ A,B,C,ZI1,ZI1P,ZI2,ZI2P,ZI3,ZI3P,ZI4,ZI5,ZI6,ZI7   /SAVED/
C
      COMMON /TABLES/ PETAB(100),SMTAB(100),TETAB(100),TWTAB(100),      /TABLES/
     1                UETAB(100),XITAB(100),YITAB(100),ZMTAB(100)       /TABLES/
C
      WRITE(6,1)                                                        QUIT    7
    1 FORMAT(34H1QUITS COMMON DIAGNOSTIC OUTPUT...)                     QUIT    8
      WRITE(6,5) IFINT,AFINT,BFINT,CFINT,MMINT,TFINT                    QUIT    9
    5 FORMAT (//50X,21HCOMMON BLOCK /COFIIF//25X,I10,1P3E20.8,I10,E20.8)
      WRITE (6,2) IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,EPSZ,FJ,
     A            G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,THETAI,
     K            TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN
    2 FORMAT (//50X,20HCOMMON BLOCK /INPUT///3X,6I6,5(4X,1PE13.6)/5X,
     A       7(4X,1PE13.6)/5X,7(4X,1PE13.6)/)
      WRITE (6,10) BDELTA,CF,CH,DELTA,DELSOT,DELSTR,FLAT,FORCE,HG,PE,
     A             PHI,QW,SUMQDA,TE,THETA,TW,UE,X,XLARC,YR,Z1,Z2,Z3,
     K             Z4,Z5,ZETA,ZME
   10 FORMAT (//50X,21HCOMMON BLOCK /OUTPUT///4(5X,7(4X,1PE13.6)/)/)
      WRITE (6,3) NOCTAB,IS,ROJ,FJG,CJG,GM102,GOGM1,POMAX,CPO,HO,SO,
     A            TCTAB,CPTAB,BCP,CCP,DCP,GTAB,HTAB,BARB1,BARB2,BARB3
    3 FORMAT (//50X,21HCOMMON BLOCK /CSEVAL///3X,2I5,1P9E13.6/
```

```
     A          (10(1X,1PE12.6)))
      WRITE (6,4) CFAGT,CFAGP,CHPAR1,DX,DXRHO,HE,HW,IBEG,MZETAM,OOMZET,
     A                PHIP,PRE103,RHOE,RHOUE,RMZETA,THETAP,XIBASE,
     K                XIEND,ZETATM,ZMZETA,ZMZETM,ZMZETP
    4 FORMAT (//50X,20HCOMMON BLOCK /INTER///5X,7(5X,1PE13.6)/5X,2I9,
     A          6(5X,1PE13.6)/5X,7(5X,1PE13.6)/)
      WRITE (6,9) A,B,C,Z11,Z11P,Z12,Z12P,Z13,Z13P,Z14,Z15,Z16,Z17
    9 FORMAT (//50X,20HCOMMON BLOCK /SAVED///5X,7(5X,1PE13.6)/5X,
     A          6(5X,1PE13.6)/)
      WRITE (6,6) ICX,IMX,IPX,IRX,ISX,ITPOS,ITWX,ITX,IUX,IXPOS,IYX,IZX,
     1                CCX,CMX,CPX,CRX,CSX,CTWX,CTX,CUX,CYX,CZX
    6 FORMAT (//50X,21HCOMMON BLOCK /LOOKUP///10X,12(I5,5X)/
     1          (5X,6(5X,1PE15.8)))
      IF (IXTAB .LE. 0)  GO TO 100
      IF (IXTAB .LT. 100)  GO TO 22
      I3 = 95
      GO TO 23
   22 I3 = IXTAB
   23 I3 = 10*(I3/10 + 1)
      WRITE  (6,7)
    7 FORMAT (//24X,77HCOMMON BLOCK /TABLES/  PETAB, SMTAB, TETAB, TWTAB
     1, UETAB, XITAB, YITAB, ZMTAB/)
    8 FORMAT (5X,I3,1P10E12.5)
      DO 24 I = 1,I3,10
      K = I + 9
   24 WRITE (6,8) I,(PETAB(J), J = I,K)
      DO 26 I = 1,I3,10
      K = I + 9
   26 WRITE (6,8) I,(SMTAB(J), J = I,K)
      DO 27 I = 1,I3,10
      K = I + 9
   27 WRITE (6,8) I,(TETAB(J), J = I,K)
      DO 28 I = 1,I3,10
      K = I + 9
   28 WRITE (6,8) I,(TWTAB(J), J = I,K)
      DO 29 I = 1,I3,10
      K = I + 9
   29 WRITE (6,8) I,(UETAB(J), J = I,K)
      DO 30 I = 1,I3,10
      K = I + 9
   30 WRITE (6,8) I,(XITAB(J), J = I,K)
      DO 31 I = 1,I3,10
      K = I + 9
   31 WRITE (6,8) I,(YITAB(J), J = I,K)
      DO 32 I = 1,I3,10
      K = I + 9
   32 WRITE (6,8) I,(ZMTAB(J), J = I,K)
      WRITE (6,11) ICOOL,IDUMP,ITZTAB,AL,COEFCL,CPL,DELXBA,DIATUB,
     1                 FLOWRT,MASSL,PRANDL,RAMDL,RAMDW,REYL,SUMQGA,SUMQWI,
     2                 THICK,TLO,TL1,TL2,TLCA,TOLITE,TUBEN,TWGCA,ZMYUL,
     3                 CPLTAB,RAMTAB,TZTAB,ZMYTAB
   11 FORMAT (//51X,19HCOMMON BLOCK /COOL///55X,I1,3X,I1,3X,I2/
     1           11(2X,1PE10.4)/11(2X,E10.4)/(10(2X,E11.5)))
      DO 33 I = 1,I3,10
      K = I + 9
   33 WRITE (6,8) I,(ALTAB(J), J = I,K)
```

```
      DO 34 I = 1,13,10
      K = I + 9
   34 WRITE (6,8) I,(TLTAB(J), J = I,K)
      DO 35 I = 1,13,10
      K = I + 9
   35 WRITE (6,8) I,(THITAB(J), J = I,K)
      DO 36 I = 1,13,10
      K = I + 9
   36 WRITE (6,8) I,(TWGTAB(J), J = I,K)
      DO 37 I = 1,13,10
      K = I + 9
   37 WRITE (6,8) I,(TLCTAB(J), J = I,K)
      WRITE (6,12) IEX,CEX
   12 FORMAT (//50X,21HCOMMON BLOCK /NHANCE///3X,I3,6(5X,1PE15.8))
      DO 38 I = 1,13,10
      K = I + 9
   38 WRITE (6,8) I, (ENHTAB(J), J = I,K)
  100 CALL DIRECT
      END                                                          QUIT  41
```

READIN

```
      SUBROUTINE READIN                                                 READ0001
C
      COMMON /COOL/ ICOOL,IDUMP,ITZTAB,AL,COEFCL,CPL,DELXBA,DIATUB,     /COOL/
     1              FLOWRT,MASSL,PRANDL,RAMDL,RAMDW,REYL,SUMQGA,SUMQWI, /COOL/
     2              THICK,TLO,TLI,TL2,TLCA,TOLITE,TUBEN,TWGCA,ZMYUL,    /COOL/
     3              CPLTAB(20),RAMTAB(20),TZTAB(20),ZMYTAB(20),         /COOL/
     4              ALTAB(100),THITAB(100),TLCTAB(100),TLTAB(100),      /COOL/
     5              TWGTAB(100)                                         /COOL/
      REAL MASSL                                                        /COOL/
C
      COMMON /CSEVAL/ NOCTAB,IS,ROJ,FJG,CJG,GM102,GOGM1,POMAX,CPO,HO,   /CSEVAL/
     A                SO,TCTAB(20),CPTAB(20),BCP(20),CCP(20),DCP(20),   /CSEVAL/
     K                GTAB(20),HTAB(20),BARB1(20),BARB2(20),BARB3(20)   /CSEVAL/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,      /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,   /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN      /INPUT/
C
      COMMON /NHANCE/ IEX,CEX(6),ENHTAB(100)                            /NHANCE/
C
      COMMON /TABLES/ PETAB(100),SMTAB(100),TETAB(100),TWTAB(100),      /TABLES/
     1                UETAB(100),XITAB(100),YITAB(100),ZMTAB(100)       /TABLES/
C
      DIMENSION PITAB(100),TITAB(100),TITLE(13),VITAB(100)
      EQUIVALENCE (PETAB,PITAB),(TETAB,TITAB),(UETAB,VITAB)
C
      NAMELIST /NAM1/ ALTAB,COEFCL,CPLTAB,CPTAB,DXMAX,ENHTAB,EPSZ,FJ,    /NAM1/
     1                FLOWRT,G,GAMO,ICOOL,ICTAB,IDUMP,IPRINT,ITWTAB,     /NAM1/
     2                ITZTAB,IXTAB,MASSL,MZETA,PO,PETAB,PHII,PITAB,      /NAM1/
     3                RAMDW,RAMTAB,RBAR,SCALE,SMTAB,TO,TCTAB,TETAB,      /NAM1/
     4                THETAI,THITAB,TITAB,TLTAB,TOLCFA,TOLITE,TOLZET,    /NAM1/
     5                TOLZME,TUBEN,TWTAB,TZTAB,UETAB,VITAB,XITAB,YITAB,  /NAM1/
     6                ZMTAB,ZMUO,ZMVIS,ZMYTAB,ZNSTAN                     /NAM1/
C
      SCALE = 1.0                                                       READ0026
      MZETA        = 7                                                  READ0027
      ZNSTAN       = 0.1                                                READ0028
      FJ           = 778.2                                              READ0029
      G            = 32.174                                             READ0030
      TOLCFA       = 1.0E-04                                            READ0031
      TOLITE = 0.0020
      TOLZME       = 1.0E-07                                            READ0032
      TOLZET       = 0.0003                                             READ0033
      DXMAXO       = DXMAX                                              READ0034
      DXMAX        = -28982.0                                           READ0035
      READ(5,2) TITLE                                                   READ0036
    2 FORMAT (13A6)
      READ(5,NAM1)                                                      READ0038
      IF (DXMAX .NE. -28982.0)  GO TO 411
      IF (IDXMAX .EQ. 0)  GO TO 415
      DXMAX = DXMAXO
      GO TO 416                                                         READ0043
  411 IF (DXMAX .LE. 0.0)  GO TO 414
      IDXMAX = 1
      GO TO 416                                                         READ0045
```

```
 414 IDXMAX       = 0                                                READ0046
 415 DXMAX        =( ( XITAB(IXTAB) - XITAB(1) ) / 100.0 ) * SCALE   READ0047
416   IF (EPSZ .LE. 0.0)  WRITE (6,7)
 7    FORMAT (//////////56X,19H*** INFORMATION ***//30X,44H1.  THIS CASE
     1 CONSIDERS TWO-DIMENSIONAL FLOW//30X,32H2.  THE NOZZLE WIDTH IS ON
     2E FOOT//30X,59H3.  THE SIDE WALLS ARE ASSUMED TO BE ADIABATIC AND
     3INVISCID//30X,68H4.  HEAT TRANSFER OCCURS ONLY THROUGH THE ONE FOO
     4T WIDE CURVED WALLS//30X,59H5.  THE CALCULATED THRUST LOSS IS BASE
     5D ON TWO CURVED WALLS//30X,65H6.  THE CALCULATED THRUST IS BASED O
     6N AN AREA OF ONE BY 2*YR FEET//30X,55H7.  CHECK THE INPUT VALUES F
     7OR FLOWRT, MASSL, AND TUBEN/)
      WRITE (6,3) TITLE
 3    FORMAT (1H1,27X,13A6//)
      IERROR      = 0                                                READ0050
      WRITE(6,102) MZETA                                             READ0051
 102 FORMAT(45H MZETA  = VELOCITY PROFILE POWER LAW EXPONENT27X1H=I4)  READ0052
      IF (MZETA .GE. 0)  GO TO 25
      WRITE (6,300)
 300 FORMAT ( 47H **ERROR** VALUE MUST BE GREATER THAN ZERO (0). // )  READ0055
      IERROR      = 1                                                READ0056
  25 WRITE(6,103) IPRINT                                             READ0057
 103 FORMAT(73H IPRINT = PRINT AT EVERY CALCULATED POINT(=1) OR AT INPUREAD0058
     1T INTERVALS(=0) =I4)                                           READ0059
      IF (IPRINT .EQ. 1 .OR. IPRINT .EQ. 0)  GO TO 513
      WRITE (6,502)
 502 FORMAT ( 45H **ERROR** VALUE MUST BE ZERO (0) OR ONE (1).  // )   READ0063
      IERROR      = 1                                                READ0064
513   WRITE(6,104) IXTAB
 104 FORMAT(52H IXTAB  = NUMBER OF POINTS IN X .VS. Y .VS. M TABLES20X1READ0067
     1H=I4)                                                          READ0068
      IF (IXTAB .GE. 4 .AND. IXTAB .LE. 100)  GO TO 30
      WRITE (6,304)
304   FORMAT (/2X,104H** ERROR ** VALUE MUST BE GREATER THAN OR EQUAL TO
     1 FOUR (4) OR LESS THAN OR EQUAL TO ONE HUNDRED (100). //)
      IERROR      = 1                                                READ0076
  30 WRITE(6,105) ICTAB                                              READ0077
 105 FORMAT(45H ICTAB  = NUMBER OF POINTS IN CP .VS. T TABLE27X1H=I4)  READ0078
      IF (ICTAB .EQ. 0)  GO TO 37
      IF (ICTAB .GE. 3 .AND. ICTAB .LE. 20)  GO TO 37
      WRITE (6,306)
306   FORMAT (/2X,98H** ERROR ** VALUE MUST BE GREATER THAN OR EQUAL TO
     1THREE (3) OR LESS THAN OR EQUAL TO TWENTY (20).///)
      IERROR      = 1                                                READ0089
  37 WRITE(6,106) ITWTAB                                             READ0090
 106 FORMAT(73H ITWTAB = WALL TEMP. OPTION -- ADIABATIC(=-1), CONSTANT(READ0091
     1=0), TABLE(=1)  =I4)                                           READ0092
      IF (IABS(ITWTAB) .EQ. 1 .OR. ITWTAB .EQ. 0)  GO TO 523
      WRITE (6,512)
 512 FORMAT ( 67H **ERROR** VALUE MUST BE ZERO (0), PLUS ONE (1), OR MIREAD0096
     1NUS ONE (-1).   // )                                           READ0097
      IERROR      = 1                                                READ0098
523   WRITE(6,111) TO
 111 FORMAT(48H TO     = FREE STREAM STAGNATION TEMPERATURE    24X1H=1PREAD0101
     1E15.7)                                                         READ0102
      IF (TO .GT. 0.0)  GO TO 41
      WRITE (6,300)
```

```
      IERROR      = 1                                                   READ0105
   41 WRITE(6,112) PO                                                   READ0106
  112 FORMAT(50H PO      = FREE STREAM STAGNATION PRESSURE        22X1H=READ0107
     11PE15.7)                                                          READ0108
      IF (PO .GT. 0.0)  GO TO 43
      WRITE (6,300)
      IERROR      = 1                                                   READ0111
   43 WRITE(6,113) GAMO                                                 READ0112
  113 FORMAT(44H GAMO    = STAGNATION RATIO OF SPECIFIC HEATS28X1H=1PE15.READ0113
     17)                                                                READ0114
      IF (ICTAB .NE. 0)  GO TO 47
      IF (GAMO .GT. 1.0)  GO TO 47
      WRITE (6,541)
  541 FORMAT ( 48H **ERROR** VALUE MUST BE GREATER THAN ONE (1.0).  // )READ0118
      IERROR      = 1                                                   READ0119
   47 WRITE (6,115) ZMUO
  115 FORMAT(38H ZMUO    = STAGNATION VISCOSITY        34X1H=1PE15.7)    READ0126
      IF (ZMUO .GT. 0.0)  GO TO 51
      WRITE (6,300)
      IERROR      = 1                                                   READ0129
   51 WRITE(6,116) ZMVIS                                                READ0130
  116 FORMAT(47H ZMVIS   = EXPONENT OF VISCOSITY-TEMPERATURE LAW25X1H=1PEREAD0131
     115.7)                                                             READ0132
      WRITE(6,117) ZNSTAN                                               READ0133
  117 FORMAT(45H ZNSTAN = BOUNDARY LAYER INTERACTION EXPONENT27X1H=1PE15READ0134
     1.7)                                                               READ0135
      WRITE(6,118) DXMAX                                                READ0136
  118 FORMAT(31H DXMAX   = MAXIMUM STEP SIZE    41X1H=1PE15.7)          READ0137
      IF (THETAI .LT. 0.0)  GO TO 44
      WRITE (6,119) THETAI
  119 FORMAT(49H THETAI = INITIAL VALUE OF MOMENTUM THICKNESS    23X1H=1READ0140
     1PE15.7)                                                           READ0141
      WRITE (6,120) PHII
  120 FORMAT(47H PHII    = INITIAL VALUE OF ENERGY THICKNESS    25X1H=1PEREAD0143
     115.7)                                                             READ0144
   44 WRITE(6,121) EPSZ
  121 FORMAT(51H EPSZ    = GEOMETRY... AXISYMMETRIC(=1.), PLANE(=0.)21X1HREAD0147
     1=1PE15.7)                                                         READ0148
      IF (EPSZ .EQ. 0.0 .OR. EPSZ .EQ. 1.0)  GO TO 533
      WRITE (6,502)
      IERROR      = 1                                                   READ0152
  533 WRITE(6,122) RBAR
  122 FORMAT (1X,35HRBAR   = GAS CONSTANT AT STAGNATION,36X,1H=,1PE15.7)
      IF (RBAR .GT. 0.0)  GO TO 53
      WRITE (6,300)
      IERROR      = 1                                                   READ0158
   53 WRITE(6,123) FJ                                                   READ0159
  123 FORMAT(51H FJ      = CONVERSION BETWEEN THERMAL AND WORK UNITS21X1HREAD0160
     1=1PE15.7)                                                         READ0161
      IF (FJ .GT. 0.0)  GO TO 55
      WRITE (6,300)
      IERROR      = 1                                                   READ0164
   55 WRITE(6,124) G                                                    READ0165
  124 FORMAT(57H G       = PROPORTIONALITY CONSTANT IN EQUATION -- F=M/G*READ0166
     1A15X1H=1PE15.7)                                                   READ0167
      IF (G .GT. 0.0)  GO TO 420
```

```
      WRITE (6,300)
      IERROR        = 1                                                 READ0170
  420 WRITE(6,421) SCALE                                                READ0171
  421 FORMAT ( 30H SCALE  = CONTOUR SCALE FACTOR, 42X, 1H=, 1PE15.7 )   READ0172
      IF (TOLCFA .EQ. 1.0E-4)  GO TO 402
      WRITE (6,401) TOLCFA
  401 FORMAT ( 47H TOLCFA = TOLERANCE FOR SKIN FRICTION ITERATION, 25X, READ0175
     1          1H=, 1PE15.7 )                                          READ0176
 402  IF (TOLZET .EQ. 0.0003)  GO TO 405
      WRITE (6,404) TOLZET
  404 FORMAT ( 49H TOLZET = TOLERANCE FOR SHAPE PARAMETER ITERATION,    READ0179
     1          23X, 1H=, 1PE15.7 )                                     READ0180
 405  IF (TOLZME .EQ. 1.0E-7)  GO TO 205
      WRITE (6,407) TOLZME
  407 FORMAT ( 65H TOLZME = TOLERANCE FOR MACH NO. - TEMPERATURE RELATIOREAD0183
     1N ITERATION, 7X, 1H=, 1PE15.7 )                                   READ0184
 205  WRITE (6,900) ITZTAB,IDUMP,FLOWRT,MASSL,RAMDW,COEFCL,TUBEN,
     1              TOLITE,ICOOL
 900  FORMAT (1X,68HITZTAB = NUMBER OF POINTS IN T .VS. CPL .VS. RAMDL .
     1VS. ZMYUL TABLES,3X,1H=,I4/1X,63HIDUMP  = COOLANT FLOW OPTION -- S
     2AME DIRECTION(=1), REVERSE(=0),8X,1H=,I4/1X,52HFLOWRT = COMBUSTION
     3 CHAMBER MASS FLOW RATE (LBM/SEC),19X,1H=,1PE15.7/1X,41HMASSL  = C
     4OOLANT MASS FLOW RATE (LBM/SEC),30X,1H=,E15.7/1X,46HRAMDW  = HEAT
     5CONDUCTIVITY OF THE CHAMBER WALL,25X,1H=,E15.7/1X,31HCOEFCL = COEF
     6FICIENT OF COOLING,40X,1H=,E15.7/1X,20HTUBEN  = TUBE NUMBER,51X,
     7 1H=,E15.7/1X,52HTOLITE = TOLERANCE FOR TOTAL HEAT TRANSFER ITERAT
     8ION,19X,1H=,E15.7/1X,64HICOOL  = COOLING OPTION -- WITH COOLING(=1
     9), WITHOUT COOLING(=0),7X,1H=,I4)
      IF (ICTAB .LE. 0 .AND. ITZTAB .LE. 0)  GO TO 11
      WRITE (6,131)
 131  FORMAT (//2X,1HI,5X,13HSPECIFIC HEAT,5X,11HTEMPERATURE,5X,
     1 12HCOOLANT TEMP,5X,10HCOOLANT CP,5X,12HCONDUCTIVITY,5X,
     2 9HVISCOSITY)
      IMAX = AMAX1(ICTAB,ITZTAB)
      DO 133 I = 1,IMAX
      IF (I .LE. ICTAB .AND. I .LE. ITZTAB)  GO TO 130
      IF (ICTAB .GT. ITZTAB)  GO TO 132
      WRITE (6,1) I,TZTAB(I),CPLTAB(I),RAMTAB(I),ZMYTAB(I)
 1    FORMAT (I3,41X,F9.3,6X,F10.6,5X,F12.10,3X,F12.10)
      GO TO 133
 130  WRITE (6,4) I,CPTAB(I),TCTAB(I),TZTAB(I),CPLTAB(I),RAMTAB(I),
     1            ZMYTAB(I)
 4    FORMAT (I3,5X,F13.10,6X,F9.3,8X,F9.3,6X,F10.6,5X,F12.10,3X,F12.10)
      GO TO 133
 132  WRITE (6,5) I,CPTAB(I),TCTAB(I)
 5    FORMAT (I3,5X,F13.10,6X,F9.3)
 133  CONTINUE
      IF (ICTAB .LE. 0)  GO TO 11
      II            = ICTAB - 1                                         READ0193
      DO 59  I = 1, II                                                  READ0194
      IF (TCTAB(I+1) .GT. TCTAB(I))  GO TO 59
      WRITE (6,310)
 310  FORMAT (/2X,99H** ERROR ** TABLE OF SPECIFIC HEATS - TEMPERATURE V
     1ALUES MUST BE IN MONATONICALLY INCREASING ORDER.//)
      IERROR        = 1                                                 READ0201
   59 CONTINUE                                                          READ0202
```

```
      IF (TCTAB(1) .GT. 0.0)  GO TO 61
      WRITE(6,312)                                                      READ0205
312   FORMAT (/2X,87H** ERROR ** TABLE OF SPECIFIC HEATS - TEMPERATURE V
     1ALUES MUST BE GREATER THAN ZERO (0).//)
      IERROR = 1
 61   DO 63 I = 1,ICTAB
      IF (CPTAB(I) .GT. 0.0)  GO TO 63
      WRITE(6,313)                                                      READ0211
313   FORMAT (/2X,89H** ERROR ** TABLE OF SPECIFIC HEATS - SPECIFIC HEAT
     1 VALUES MUST BE GREATER THAN ZERO (0).//)
      IERROR        = 1                                                 READ0214
  63 CONTINUE                                                           READ0215
 11   DO 65 I = 1,IXTAB
      IF (ZMTAB(I) .GT. 0.0)  GO TO 65
      WRITE (6,314)
314   FORMAT (/2X,97H** ERROR ** TABLE OF MACH NUMBER DISTRIBUTION - MAC
     1H NUMBER VALUES MUST BE GREATER THAN ZERO (0).//)
      IERROR        = 1                                                 READ0223
  65 CONTINUE                                                           READ0224
      II            = IXTAB - 1                                         READ0225
      DO 67 I = 1, II                                                   READ0226
      IF (XITAB(I+1) .GE. XITAB(I))  GO TO 67
      WRITE (6,316)
 316 FORMAT ( 40H **ERROR** TABLE OF CONTOUR DESCRIPTION. / 69H AXIAL DREAD0229
     1ISTANCE VALUES (X) MUST BE IN MONOTONICALLY INCREASING ORDER. // )READ0230
      IERROR        = 1                                                 READ0231
  67 CONTINUE                                                           READ0232
      IF(ITWTAB) 14,13,12                                               READ0233
 12 DO 69  I = 1, IXTAB                                                 READ0234
      IF (TWTAB(I) .GT. 0.0)  GO TO 69
      WRITE (6,317)
317   FORMAT (/2X,102H** ERROR ** TABLE OF WALL TEMPERATURE DISTRIBUTION
     1 - TEMPERATURE VALUES MUST BE GREATER THAN ZERO (0).//)
      IERROR        = 1                                                 READ0239
  69 CONTINUE                                                           READ0240
      GO TO 14                                                          READ0241
 13   IF (TWTAB(1) .GT. 0.0)  GO TO 14
      WRITE (6,317)
      IERROR        = 1                                                 READ0245
 14   IF (SCALE .EQ. 1.0)  GO TO 424
      DO 423 I = 1,IXTAB
      XITAB(I)      = XITAB(I) * SCALE                                  READ0250
 423 YITAB(I)      = YITAB(I) * SCALE                                   READ0251
424   IF (ITWTAB) 137,135,140
135   WRITE (6,136) TWTAB(1)
136   FORMAT (//2X,18HWALL TEMPERATURE =,F20.8)
137   WRITE (6,6)
 6    FORMAT (1H1)
      WRITE (6,138)
138   FORMAT (3X,1HI,12X,5HAXIAL,11X,6HRADIAL,10X,4HMACH,9X,8HPRESSURE,
     1 4X,11HSTATIC TEMP,7X,8HVELOCITY,6X,9HMOLECULAR/15X,6H(FEET),11X,
     2 6H(FEET),9X,6HNUMBER,8X,8H(LB/FT2),4X,11H(DEGREES R),7X,
     3 8H(FT/SEC),8X,6HWEIGHT)
      WRITE (6,139) (I,XITAB(I),YITAB(I),ZMTAB(I),PETAB(I),TETAB(I),
     1                  UETAB(I),SMTAB(I), I = 1,IXTAB)
139   FORMAT (I4,6X,F11.6,6X,F11.6,6X,F9.6,6X,F10.3,6X,F9.3,6X,F9.3,6X,
```

```
1          F9.6)
      GO TO 145                                                      READ0260
140   WRITE (6,6)
      WRITE (6,142)
142   FORMAT (3X,1HI,12X,5HAXIAL,11X,6HRADIAL,10X,4HMACH,9X,8HPRESSURE,
     1 4X,11HSTATIC TEMP,7X,8HVELOCITY,6X,9HMOLECULAR,6X,9HWALL TEMP/
     2 15X,6H(FEET),11X,6H(FEET),9X,6HNUMBER,8X,8H(LB/FT2),4X,
     3 11H(DEGREES R),7X,8H(FT/SEC),8X,6HWEIGHT,5X,11H(DEGREES R))
      WRITE (6,141) (I,XITAB(I),YITAB(I),ZMTAB(I),PETAB(I),TETAB(I),
     1                UETAB(I),SMTAB(I),TWTAB(I), I = 1,IXTAB)
141   FORMAT (I4,6X,F11.6,6X,F11.6,6X,F9.6,6X,F10.3,6X,F9.3,6X,F9.3,6X,
     1          F9.6,6X,F9.3)
145   IF (ICOOL .GT. 0)  WRITE (6,33) (I,ALTAB(I),TLTAB(I),THITAB(I),
     1                                  ENHTAB(I), I = 1,IXTAB)
 33   FORMAT (1H1,5X,1HI,5X,17HCOOLANT TUBE AREA,5X,19HCOOLANT TEMPERATU
     1RE,5X,14HWALL THICKNESS,5X,11HENHANCEMENT/16X,13H(SQUARE FEET),7X,
     2 17H(DEGREES RANKINE),13X,6H(FEET),7X,7HFACTORS/(4X,I3,11X,F11.8,
     2 14X,F10.3,8X,F11.8,5X,F11.8))
      IF (IXTAB .LE. 1)  GO TO 260
      DO 257 I = 2,IXTAB
      IF (XITAB(I) .GT. XITAB(I-1))  GO TO 257
      WRITE (6,212)
 212  FORMAT ( 33H **ERROR** TABLE OF XITAB VALUES. // )             READ0269
      IERROR      = 1                                                READ0270
 257  CONTINUE                                                       READ0271
260   IF (ITWTAB .LT. 0)  GO TO 77
      IF (THETAI .GE. 0.0)  GO TO 77
      WRITE(6,76)
  76  FORMAT ( // 99H **ERROR** MACH ONE START DOES NOT PRODUCE REASONABREAD0276
     1LE VALUES FOR OTHER THAN AN ADIABATIC WALL CASE.  // )         READ0277
      IERROR      = 1                                                READ0278
77    IF (IERROR .LE. 0)  RETURN
      CALL QUITS
      END                                                            READ0284
```

```
SEVAL
      SUBROUTINE SEVAL (IND1,AA,BB,CC)
C
      COMMON /CSEVAL/ NOCTAB,IS,ROJ,FJG,CJG,GM1O2,GOGM1,POMAX,CPO,HO,   /CSEVAL/
     A                SO,TCTAB(20),CPTAB(20),BCP(20),CCP(20),DCP(20),   /CSEVAL/
     K                GTAB(20),HTAB(20),BARB1(20),BARB2(20),BARB3(20)   /CSEVAL/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,      /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHI1,PIE,PRANDT,RBAR,SCALE,TO,   /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN      /INPUT/
C
C         DEFINE THE FUNCTION ROUTINE TO BE USED BY SEVAL
C
      GAPF(T,G,A1,B1,C1,D1) = G+A1*ALOG(T)+(B1+(C1+D1/3.*T)*T)*T-PR     SEVA  16
             T = AA                                                     SEVA  19
             A = BB                                                     SEVA  20
             B = CC                                                     SEVA  21
      IF(IND1-2)3,1,155                                                 SEVA  22
    1 B = B/FJG
      IF (ICTAB .GT. 0)  GO TO 35
      T = B/CPO
      A = CPO
      GO TO 600                                                         SEVA  27
    3 IF (IND1 .LT. 1)  GO TO 10
      IF (ICTAB .GT. 0)  GO TO 10
      A = CPO
      B = CJG*T
      GO TO 600                                                         SEVA  32
  155 PR = ROJ*ALOG(A/POMAX)
  160 STAB = GAPF(TCTAB(IS),GTAB(IS),BARB1(IS),BARB2(IS),BARB3(IS),
     A               DCP(IS))
      IF (B .GE. STAB)  GO TO 175
      IS = IS - 1
      IF (IS .LE. 0)  GO TO 17
      GO TO 160                                                         SEVA  38
  175 STAB = GAPF(TCTAB(IS+1),GTAB(IS),BARB1(IS),BARB2(IS),BARB3(IS),
     A               DCP(IS))
      IF (B .LT. STAB)  GO TO 190
      IS = IS + 1
      IF (IS .GE. 20)  GO TO 17
      GO TO 175                                                         SEVA  43
  190 IF (IS .GE. NOCTAB .OR. IS .LE. 0)  GO TO 17
      TTP = TCTAB(IS)
      FP = GAPF(TCTAB(IS),GTAB(IS),BARB1(IS),BARB2(IS),BARB3(IS),
     D               DCP(IS))
      TTPP = TCTAB(IS+1)
          FPP = STAB                                                    SEVA  50
      GO TO 75                                                          SEVA  51
   10 IF (T .GE. TCTAB(IS))  GO TO 15
      IS = IS - 1
      IF (IS .LE. 0)  GO TO 17
      GO  TO 10                                                         SEVA  54
   15 IF (T .LT. TCTAB(IS+1))  GO TO 16
      IS = IS + 1
      IF (IS .GE. 20)  GO TO 17
       GO  TO  15                                                       SEVA  57
```

```
16   IF (IS .GT. 0)  GO TO 19
 17  WRITE(6,18) IS,INDI,T,A,B
18   FORMAT (17HOSEVAL FAILURE...,5X,4HIS =,I4,5X,6HINDI =,I2,5X,
   A         3HT =,1PE15.7,5X,3HA =,1PE15.7,5X,3HB =,1PE15.7)
     CALL QUITS
19   IF (IS .GE. NOCTAB)  GO TO 17
     IF (INDI) 70,65,60
60   DELT = T - TCTAB(IS)
     B = HTAB(IS) + CPTAB(IS)*DELT + 0.5*BCP(IS)*DELT**2 +
   A    CCP(IS)/3.0*DELT**3 + 0.25*DCP(IS)*DELT**4
     B = B*FJG
     GO TO 141
65   PR = ROJ*ALOG(A/POMAX)
     B = GAPF(T,GTAB(IS),BARB1(IS),BARB2(IS),BARB3(IS),DCP(IS))
     GO TO 600
70   A = POMAX*EXP((GTAB(IS) + BARB1(IS)*ALOG(T) + (BARB2(IS) +
   A              (BARB3(IS) + DCP(IS)/3.0*T)*T)*T - B)/ROJ)
     GO TO 600
35   IF (B .GE. HTAB(IS))  GO TO 50
     IS = IS - 1
     IF (IS .LE. 0)  GO TO 17
     GO TO 35
50   IF (B .LT. HTAB(IS+1))  GO TO 51
     IS = IS + 1
     IF (IS .GE. 20)  GO TO 17
     GO TO 50
51   IF (IS .GE. NOCTAB .OR. IS .LE. 0)  GO TO 17
     TTP = TCTAB(IS)
     FP = HTAB(IS)
     TTPP = TCTAB(IS+1)
     FPP = HTAB(IS+1)
 75  TTO  = (TTP * (FPP - B ) -  TTPP * (FP - B )) /( FPP - FP)
     IF (INDI .GT. 2)  GO TO 215
     DELT = TTO - TCTAB(IS)
     FO = HTAB(IS) + CPTAB(IS)*DELT + 0.5*BCP(IS)*DELT**2 +
   A     CCP(IS)/3.0*DELT**3 + 0.25*DCP(IS)*DELT**4
     GO TO 220
215  FO = GAPF(TTO,GTAB(IS),BARB1(IS),BARB2(IS),BARB3(IS),DCP(IS))
220  TT1P = (TTO * (FPP - B )  - TTPP *(FO - B)) /( FPP - FO)
     TT1PP  =   (TTO  * ( FP - B ) - TTP * ( FO - B))/( FP  - FO)
     N = -1
     TAU  =   TTO
     SF   =   FO
104  IF (ABS((SF - B)/B) .LE. 1.0E-7)  GO TO 100
     IF (SF .LE. B)  GO TO 135
     TTPP = TAU
     FPP = SF
     GO TO 130
100  T  =  TAU
     GO TO 225
135  TTP   =  TAU
      FP   =  SF
130   IF ( N )115 , 120 , 125
115   N  =  0
      TAU  =  TT1P
      GO  TO 85
```

```
120   N     =   1
       TAU  =   TT1PP
 85   IF (TAU .LE. TTP .OR. TAU .GE. TTPP)  GO TO 130
      IF (IND1 .LE. 2)  GO TO 95
      SF = GAPF(TAU,GTAB(IS),BARB1(IS),BARB2(IS),BARB3(IS),DCP(IS))
      GO TO 104
 95   DELT = TAU - TCTAB(IS)
      SF = HTAB(IS) + CPTAB(IS)*DELT + 0.5*BCP(IS)*DELT**2 +
     A     CCP(IS)/3.0*DELT**3 + 0.25*DCP(IS)*DELT**4
      GO TO 104
125   IF (((FPP - FP)/(FP + FPP)) .GT. 0.0010)  GO TO 75
      T = (TTP*(FPP - B) - TTPP*(FP - B))/(FPP - FP)
225   IF (IND1 .GT. 2)  GO TO 600
      DELT = T - TCTAB(IS)
141   A = CPTAB(IS) + BCP(IS)*DELT + CCP(IS)*DELT**2 + DCP(IS)*DELT**3
600   AA = T
           BB = A
      IF (IND1 .EQ. 2)  RETURN
      CC = B
      RETURN
      END
```

```
START
      SUBROUTINE START                                                  STAR    1
C
      COMMON /COFIIF/ IFINT,AFINT,BFINT,CFINT,MMINT,TFINT               /COFIIF/
C
      COMMON /CSEVAL/ NOCTAB,IS,ROJ,FJG,CJG,GM102,GOGM1,POMAX,CPO,HO,   /CSEVAL/
     A                SO,TCTAB(20),CPTAB(20),BCP(20),CCP(20),DCP(20),   /CSEVAL/
     K                GTAB(20),HTAB(20),BARB1(20),BARB2(20),BARB3(20)   /CSEVAL/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,      /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,   /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN      /INPUT/
C
      COMMON /INTER/ CFAGT,CFAGP,CHPAR1,DX,DXRHO,HE,HW,IBEG,MZETAM,     /INTER/
     A               OOMZET,PHIP,PREI03,RHOE,RHOUE,RMZETA,THETAP,       /INTER/
     K               XIBASE,XIEND,ZETATM,ZMZETA,ZMZETM,ZMZETP           /INTER/
C
      COMMON /LOOKUP/ ICX,IMX,IPX,IRX,ISX,ITPOS,ITWX,ITX,IUX,IXPOS,IYX, /LOOKUP/
     1                IZX,CCX(6),CMX(6),CPX(6),CRX(6),CSX(6),CTWX(6),   /LOOKUP/
     2                CTX(6),CUX(6),CYX(6),CZX(6)                       /LOOKUP/
C
      COMMON /OUTPUT/ BDELTA,CF,CH,DELTA,DELSOT,DELSTR,FLAT,FORCE,HG,   /OUTPUT/
     A                PE,PHI,QW,SUMQDA,TE,THETA,TW,UE,X,XLARC,YR,Z1,    /OUTPUT/
     K                Z2,Z3,Z4,Z5,ZETA,ZME                              /OUTPUT/
C
      COMMON /SAVED/ A,B,C,ZI1,ZI1P,ZI2,ZI2P,ZI3,ZI3P,ZI4,ZI5,ZI6,ZI7   /SAVED/
C
      COMMON /TABLES/ PETAB(100),SHTAB(100),TETAB(100),TWTAB(100),      /TABLES/
     1                UETAB(100),XITAB(100),YITAB(100),ZMTAB(100)       /TABLES/
C
      IMX          = -1                                                 STAR   35
      IYS = -1
      ITWX         = -1                                                 STAR   37
      I            = 0                                                  STAR   38
    5 I            = I + 1                                              STAR   39
      IF ( ZMTAB(I) - 1. ) 10, 20, 15                                   STAR   40
   10 IF (I .LT. IXTAB)  GO TO 5
   25 WRITE (6,1000)
 1000 FORMAT (/35X,62H** START FAILURE ** MACH NUMBER TABLE DOES NOT INC
     1LUDE M = 1.0//)
      CALL QUITS
   20 X            = XITAB(I)                                           STAR   43
      IBEG         = I + 1                                              STAR   44
      GO TO 50                                                          STAR   45
   15 IF (I .LE. 1)  GO TO 25
      XG = XITAB(I)
      ZME          = ZMTAB(I)                                           STAR   49
      X            = XITAB(I-1) + ( XITAB(I) - XITAB(I-1) ) / ( ZMTAB(I)STAR   50
     1             - ZMTAB(I-1) ) * ( 1. - ZMTAB(I-1) )                 STAR   51
      J            = 0                                                  STAR   52
      IBEG         = I                                                  STAR   53
   35 J            = J + 1                                              STAR   54
      XO           = XG                                                 STAR   55
      ZMO          = ZME                                                STAR   56
      XG           = X                                                  STAR   57
      CALL XNTERP ( X, ZME, ZMEP, IMX, XITAB, ZMTAB, IXTAB, CMX, IMX )  STAR   58
```

```
      IF (ABS(ZME - 1.0) .LE. TOLCFA)  GO TO 50
      ZMX = (XG - XO)/(ZME - ZMO)
      X              = XO + ( 1. - ZMO ) * ZMX                           STAR  61
      IF (J .LE. 50)  GO TO 35
      WRITE (6,1010)
 1010 FORMAT ( 64H **START FAILURE... MACH NO. CALCULATION EXCEEDED 50 ISTAR  25
     1TERATIONS. // )                                                    STAR  26
   50 CALL XNTERP ( X, ZME, ZMEP, IMX, XITAB, ZMTAB, IXTAB, CMX, IMX )   STAR  64
      CALL XNTERP (X,YR,YRP,IYS,XITAB,YITAB,IXTAB,CYX,IMX)
      CALL GETPT (ZME,PSE,TE)
      CALL SEVAL ( 1, TE, CPE, HE )                                      STAR  67
      GAME           = CPE / ( CPE - RBAR / FJ )                         STAR  68
      HB             = HO - HE                                           STAR  69
      UE             = SQRT( 2.* HB )                                    STAR  70
      RHSE = PSE/TE/RBAR
      ZMU            = ZMUO * ( TE / TO ) ** ZMVIS                       STAR  72
      HAW            = HE +(PRANDT ** ( 1./ 3. )) * HB                   STAR  73
      CALL SEVAL ( 2, TAW, CPAW, HAW )                                   STAR  74
      IF ( ITWTAB ) 55, 60, 65                                           STAR  75
   55 HW             = HAW                                               STAR  76
      TW             = TAW                                               STAR  77
      GO TO 70                                                           STAR  78
   60 HW = TWTAB(2)
      TW             = TWTAB(1)                                          STAR  80
      GO TO 70                                                           STAR  81
   65 CALL XNTERP ( X, TW, TWP, ITWX, XITAB, TWTAB, IXTAB, CTWX, IMX )   STAR  82
      CALL SEVAL ( 1, TW, CPW, HW )                                      STAR  83
   70 AFINT          = HW                                                STAR  84
      BFINT          = HO - HW                                           STAR  85
      CFINT          = - HB                                              STAR  86
      TFINT          = TE                                                STAR  87
      MMINT          = MZETA                                             STAR  88
      IFINT          = 1                                                 STAR  89
      CALL INTZET ( 0., 1., ZI1 )                                        STAR  90
      IFINT          = 2                                                 STAR  91
      CALL INTZET ( 0., 1., ZI2 )                                        STAR  92
      DELSOT         = ( 1. / ZMZETA - ZI2 ) / ZI1                       STAR  93
      IF (EPSZ .EQ. 0.0)  GO TO 72
      ERASE5 = YRP/YR
      GO TO 73                                                           STAR  96
   72 ERASE5         = 1.0                                               STAR  97
   73 ERASE4         = ( 1. + DELSOT ) / ( 1. + ( GAME - 1. ) / 2. ) *   STAR  98
     1                   ZMEP + ERASE5                                   STAR  99
      IF (ERASE4 .NE. 0.0)  GO TO 80
      WRITE (6,1020)
 1020 FORMAT (/2X,74H** START FAILURE ** INITIAL VALUES FOR PHII AND THE
     1TAI CANNOT BE COMPUTED./3X,55H* CHECK SLOPES OF MACH NUMBER AND CO
     2NTOUR INPUT TABLES.//)
   80 ERASE1         = 17.2 * ( TO - TAW ) / TAW                         STAR 103
      ERASE2         = 305. * ( TE - TO ) / TAW                          STAR 104
      CTHET = 0.50*SQRT(1.0 + YRP**2)/ERASE4
      CRT2 = (TAW/TE)**(1.0 - ZMVIS)*RHSE*UE/(ZMU*CTHET)
      ERASE3         = TAW / TE                                          STAR 108
      CFA            = .001                                              STAR 109
      JE             = 0                                                 STAR 110
   85 JE             = JE + 1                                            STAR 111
```

```
      CFG           = CFA                                                 STAR 112
      THETA         = CFG * CTHET                                         STAR 113
      CR            = CRT2 * THETA * THETA                                STAR 114
      CFB = CFEVAL(CR)                                                    STAR 115
      TTAW = 1.0 + ERASE1*SQRT(CFB/2.0) + ERASE2*CFB/2.0
      IF (TTAW .GT. 0.0)  GO TO 120
      CFA = 3.0*CFG
  105 Z4            = CFA                                                 STAR 119
      Z2            = CFG                                                 STAR 120
  110 IF (JE .LE. 50)  GO TO 85
      WRITE(6,1030)                                                       STAR 123
 1030 FORMAT (/2X,74H** START FAILURE ** INITIAL VALUES FOR PHII AND THE
     1TAI CANNOT BE COMPUTED./3X,27H* CHECK SKIN FRICTION DATA.//)
      GO TO 140                                                           STAR 124
  120 CFA           = CFB / ( ERASE3 * TTAW ** ZMVIS )                    STAR 125
      IF (ABS((CFA - CFG)/(CFA + CFG)) .LE. TOLCFA)  GO TO 140
      IF (JE .LT. 2)  GO TO 105
      Z3 = Z4
      Z1            = Z2                                                  STAR 129
      Z4            = CFA                                                 STAR 130
      Z2            = CFG                                                 STAR 131
      ZS5 = (Z4 - Z3)/(Z2 - Z1)
      CFA = (Z4 - ZS5*Z2)/(1.0 - ZS5)
      GO TO 110                                                           STAR 134
  140 THETAI = CFA*CTHET
      PHII = THETAI
      CFAGT         = CFA                                                 STAR 138
      ZETA          = 1.                                                  STAR 139
      WRITE (6,1040) X,YR,THETAI,PHII
 1040 FORMAT ( 94H0INITIAL VALUES FOR ENERGY ( PHII) AND MOMENTUM ( THETSTAR  30
     1AI) THICKNESSES CALCULATED AT THROAT...  / 5H X = , 1PE14.7, 5X,   STAR  31
     2 4HY = , E14.7, 5X, 8HTHETAI =, E14.7, 5X, 6HPHII =, E14.7 // )    STAR  32
      RETURN                                                              STAR 141
      END                                                                 STAR 142
```

```
XNTERP
      SUBROUTINE XNTERP (X,Y,YP,IXIN,XAR,YAR,IAR,CAR,IPOS)
C
      DIMENSION C(6),CAR(6),XAR(IAR),XI(4),YAR(IAR),YI(4)
C
      IXO=IXIN                                                          XNTE   4
      IXMAX=IAR-1                                                       XNTE   5
      IX=IPOS                                                           XNTE   6
      DO 11 I = 1,6
   11 C(I)=CAR(I)                                                       XNTE  21
      IF (IXO .GT. 0)  GO TO 13
   12 IFIRST=1                                                          XNTE  23
      IXO=IXMAX+2                                                       XNTE  24
      IX=1                                                              XNTE  25
   13 IF (IX .LE. 0)  GO TO 12
   20 IF (X .GE. XAR(IX))  GO TO 25
      IX = IX - 1
      IF (IX .GT. 0)  GO TO 20
   22 WRITE(6,23) X, XAR(1), XAR(IXMAX+1), YAR(1), YAR(IXMAX+1)         XNTE  30
   23 FORMAT ( 28HOXNTERP OUT OF RANGE...,  X =, 1PE15.7, 8H, X(1) =,   XNTE  31
     1         E15.7, 8H, X(N) =, E15.7 / 43X, 8H, Y(1) =, E15.7,       XNTE  32
     2         8H  Y(N) =, E15.7 // )                                    XNTE  33
      CALL QUITS                                                        XNTE  34
   25 IF (X .LE. XAR(IX+1))  GO TO 27
      IX = IX + 1
      IF(IX-IXMAX) 25,25,22                                             XNTE  37
   27 DO 28 I=1,4                                                       XNTE  38
      I1=IX-2+I                                                         XNTE  39
      XI(I)=XAR(I1)                                                     XNTE  40
   28 YI(I)=YAR(I1)                                                     XNTE  41
      DX2 = X - XI(2)
      DX32=XI(3)-XI(2)                                                  XNTE  49
      IF (IX - IXO) 40,31,60
   31 IXOGO=0                                                           XNTE  51
      IF (IX .GT. 1)  GO TO 33
   32 IGO=-1                                                            XNTE  53
      GO TO 101                                                         XNTE  54
   33 IF (IX .LT. IXMAX)  GO TO 35
      IF (IFIRST .EQ. 0)  GO TO 34
      IFIRST = 0
      IGO=1                                                             XNTE  58
      GO TO 45                                                          XNTE  59
   34 IGO=1                                                             XNTE  60
      GO TO 100                                                         XNTE  61
   35 IGO=0                                                             XNTE  62
      GO TO 100                                                         XNTE  63
   40 IXOGO=-1                                                          XNTE  64
      IF (IX .LT. IXO - 1)  GO TO 42
      C(4) = C(1)
      C(5)=C(2)                                                         XNTE  67
      C(6)=C(3)                                                         XNTE  68
      GO TO 43                                                          XNTE  69
   42 C(4)=YI(2)                                                        XNTE  70
      DX42=XI(4)-XI(2)                                                  XNTE  71
      DY32=YI(3)-YI(2)                                                  XNTE  72
      DYOX32=DY32/DX32                                                  XNTE  73
```

```
      C(6)=(DYOX32-(YI(4)-YI(2))/DX42)/(XI(3)-XI(4))
      C(5)=DYOX32-C(6)*DX32
      IF (IXOGO .GT. 0)  GO TO 100
 43   IF (IX .LE. 1)  GO TO 32
      IGO = 0
 45   C(1)=YI(1)
      DX21=XI(2)-XI(1)
      DX31=XI(3)-XI(1)
      DY21=YI(2)-YI(1)
      DYOX21=DY21/DX21
      C(3)=(DYOX21-(YI(3)-YI(1))/DX31)/(XI(2)-XI(3))
      C(2)=DYOX21-C(3)*DX21
      IF(IXOGO) 100,100,62
 60   IXOGO=1
      IF (IX .GT. IXO + 1)  GO TO 45
      C(1) = C(4)
      C(2)=C(5)
      C(3)=C(6)
 62   IF (IX .GE. IXMAX)  GO TO 34
      IGO = 0
      GO TO 42
100   DX1 = X - XI(1)
      YB1=(C(3)*DX1+C(2))*DX1+C(1)
      YPB1=C(3)/.5*DX1+C(2)
      IF (IGO .GT. 0)  GO TO 110
101   YB2 = (C(6)*DX2 + C(5))*DX2 + C(4)
      YPB2=C(6)/.5*DX2+C(5)
      IF (IGO .LT. 0)  GO TO 120
      U1 = DX2/DX32
      U2=U1*U1
      U3=U2*U1
      A1=3.*U2-2.*U3
      A1P=6.*(U1-U2)/DX32
      Y=(1.-A1)*YB1+A1*YB2
      YP=(1.-A1)*YPB1-A1P*(YB1-YB2)+A1*YPB2
105   IXIN=IX
      IF (IXOGO .EQ. 0)  RETURN
      DO 107 I = 1,6
107   CAR(I)=C(I)
      RETURN
110   Y=YB1
      YP=YPB1
      GO TO 105
120   Y=YB2
      YP=YPB2
      GO TO 105
      END
```

ZETAIT

```
      SUBROUTINE ZETAIT                                                 ZETA   1
C
      COMMON /COFIIF/ IFINT,AFINT,BFINT,CFINT,MMINT,TFINT               /COFIIF/
C
      COMMON /INPUT/ IDXMAX,ICTAB,IPRINT,ITWTAB,IXTAB,MZETA,DXMAX,      /INPUT/
     A               EPSZ,FJ,G,GAMO,PO,PHII,PIE,PRANDT,RBAR,SCALE,TO,   /INPUT/
     K               THETAI,TOLCFA,TOLZET,TOLZME,ZMUO,ZMVIS,ZNSTAN      /INPUT/
C
      COMMON /INTER/ CFAGT,CFAGP,CHPAR1,DX,DXRHO,HE,HW,IBEG,MZETAM,     /INTER/
     A               OOMZET,PHIP,PREI03,RHOE,RHOUE,RMZETA,THETAP,       /INTER/
     K               XIBASE,XIEND,ZETATM,ZMZETA,ZMZETM,ZMZETP           /INTER/
C
      COMMON /OUTPUT/ BDELTA,CF,CH,DELTA,DELSOT,DELSTR,FLAT,FORCE,HG,   /OUTPUT/
     A                PE,PHI,QW,SUMQDA,TE,THETA,TW,UE,X,XLARC,YR,Z1,    /OUTPUT/
     K                Z2,Z3,Z4,Z5,ZETA,ZME                              /OUTPUT/
C
      COMMON /SAVED/ A,B,C,ZI1,ZI1P,ZI2,ZI2P,ZI3,ZI3P,ZI4,ZI5,ZI6,ZI7   /SAVED/
C
      ERASE1=PHI/THETA                                                  ZETA  16
      IFINT=1                                                           ZETA  17
      DO  30  I = 1, 50                                                 ZETA  18
      MMINT=MZETA                                                       ZETA  19
      AFINT=A                                                           ZETA  20
      ZETAG=ZETA                                                        ZETA  21
      IF (ZETA .GE. 1.0)  GO TO 32
      BFINT = B
      CFINT=C*ZETA*ZETA                                                 ZETA  24
      CALL INTZET(0.,1.,ZI1P)                                           ZETA  25
      BFINT=B/ZETA                                                      ZETA  26
      CFINT=C                                                           ZETA  27
      CALL INTZET(0.,ZETA,ZI4)                                          ZETA  28
      AFINT=A+B                                                         ZETA  29
      BFINT=0.                                                          ZETA  30
      CALL INTZET(ZETA,1.,ZI5)                                          ZETA  31
      ZETA=(ERASE1/ZI1P*(ZI4+ZI5))**RMZETA                              ZETA  32
      GO TO 33                                                          ZETA  33
   32 BFINT=B/ZETA                                                      ZETA  34
      CFINT=C                                                           ZETA  35
      CALL INTZET(0.,1.,ZI1)                                            ZETA  36
      BFINT=B                                                           ZETA  37
      CFINT=C*ZETA*ZETA                                                 ZETA  38
      ERASE2=1./ZETA                                                    ZETA  39
      CALL INTZET(0.,ERASE2,ZI2P)                                       ZETA  40
      MMINT=MZETAM                                                      ZETA  41
      AFINT=A+C                                                         ZETA  42
      CFINT=0.                                                          ZETA  43
      CALL INTZET(ERASE2,1.,ZI3P)                                       ZETA  44
      ZETA=(ERASE1/(ZI2P+ZI3P/ZETA)*ZI1)**RMZETA                        ZETA  45
   33 DZETA = (ZETA - ZETAG)/ZETAG
      IF (ABS(DZETA) .LT. TOLZET)  GO TO 35
      IF (I .GE. 2)  GO TO 76
      Z4=ZETA
      Z2=ZETAG                                                          ZETA  50
      GO TO 30                                                          ZETA  51
   76 Z3=Z4                                                             ZETA  52
```

```
      Z1=Z2                                                             ZETA  53
      Z4=ZETA                                                           ZETA  54
      Z2=ZETAG                                                          ZETA  55
      Z5=(Z4-Z3)/(Z2-Z1)                                                ZETA  56
      ZETA=(Z4-Z5*Z2)/(1.-Z5)                                           ZETA  57
   30 CONTINUE                                                          ZETA  58
      WRITE(6,34) X, ZME, THETA, PHI                                    ZETA  59
   34 FORMAT ( 57H0**ZETAIT FAILURE... SHAPE PARAMETER ITERATION FAILUREZETA  60
     1... / 22H0  AXIAL DISTANCE  X =, 1PE14.7, 5X, 11HMACH NO. = ,     ZETA  61
     2 E14.7, 5X, 8HTHETAI =, E14.7, 5X, 6HPHII =, E14.7 )              ZETA  62
      WRITE(6,50) Z1, Z2, ZETA, Z3, Z4                                  ZETA  63
   50 FORMAT (  20H ZETA (GUESSED)    =,1P3E16.7 / 20H ZETA (CALCULATED)ZETA  64
     1 =, 2E16.7 // )                                                   ZETA  65
   35  IFINT = 2
      MMINT=MZETA                                                       ZETA  68
      AFINT=A                                                           ZETA  69
      BFINT=B/ZETA                                                      ZETA  70
      CFINT=C                                                           ZETA  71
      ZETATM=ZETA**ZMZETA                                               ZETA  72
      IF (ZETA .GE. 1.0)  GO TO 37
      CALL INTZET(0.,ZETA,Z16)
      AFINT=A+B                                                         ZETA  75
      BFINT=0.                                                          ZETA  76
      CALL INTZET(ZETA,1.,Z17)                                          ZETA  77
      ERASE2=Z14+Z15                                                    ZETA  78
      DELSOT=(OOMZET-Z16-Z17)/ERASE2                                    ZETA  79
      DELTA=THETA/ZMZETA/ERASE2                                         ZETA  80
      GO TO 38                                                          ZETA  81
   37 CALL INTZET(0.,1.,Z12)                                            ZETA  82
      MMINT=MZETAM                                                      ZETA  83
      AFINT=A+C                                                         ZETA  84
      CFINT=0.                                                          ZETA  85
      CALL INTZET(1.,ZETA,Z13)                                          ZETA  86
      DELTA=THETA/ZMZETA/Z11                                            ZETA  87
      DELSOT=(ZETATM/ZMZETA-Z13-Z12)/Z11                                ZETA  88
   38  BDELTA = ZETATM*DELTA
      DELSTR=THETA*DELSOT                                               ZETA  91
      RETURN                                                            ZETA  92
      END                                                               ZETA  93
```

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