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Computer Program To Solve Two-Dimensional Shock-Wave Interference Problems With an Equilibrium Chemically Reacting Air Model

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Summary

The computer program EASI, Equilibrium Air Shock Interference, has been developed to calculate the inviscid flow field, the maximum surface pressure, and the maximum heat flux produced by six shock-wave interference patterns on a two-dimensional cylindrical configuration. Thermodynamic properties of the inviscid flow field are determined with either an 11-specie, 7-reaction equilibrium chemically reacting air model or a calorically perfect air model. The inviscid flow field is solved by the integral form of the conservation equations. Surface heating calculations at the impingement point for the equilibrium chemically reacting air model use variable transport properties and specific heat. However, for the calorically perfect air model, heating rate calculations use a constant Prandtl number. Sample calculations of the six shock-wave interference patterns, a listing of the computer program, and flowcharts of the programming logic are included.

Introduction

Recent concerns with the effects from shock-wave interference on various structural components of hypersonic vehicles such as the NASP (National Aero-Space Plane) have led to a renewed interest in some older techniques to calculate the maximum surface heating. Present state-of-the-art discretizing computer programs are computationally expensive and grid refinement in regions of extremely high heat transfer, such as the surface impingement of a supersonic jet, are inadequate to predict the local flow field and resolve the heat flux to the wall. However, some older techniques provide reasonably accurate predictions of maximum heating with little computational effort. One such method, which was exploited in a computer program written by Morris and Keyes (ref. 1), first calculates the inviscid flow field of the shock-wave interference pattern and then calculates the maximum heating by applying empirical and stagnation-point heating relationships. The Morris and Keyes computer program was developed with compressible flow relationships for a calorically perfect gas and is limited to flow fields in which the ratio of specific heats γ can be considered constant. In addition, the Morris and Keyes program calculates maximum heating for an interaction with a two-dimensional leading edge, except for supersonic jet impingement. For supersonic jet impingement, the program calculates heating to a spherical leading edge.

The Equilibrium Air Shock Interference (EASI) computer program was developed to extend the methods used by Morris and Keyes (ref. 1) for the calculation of the shock-wave interference phenomena to an equilibrium chemically reacting gas mixture and to a two-dimensional cylindrical leading edge for supersonic jet impingement. The inclusion of the gas chemistry is important for calculations of maximum pressure and heating loads on the scramjet cowl leading edge of the NASP which will be subjected to a flow field with high temperatures in the shock layer and in various regions of the shock-wave interference. For some cases, the high temperatures will excite the vibrational modes of the gas molecules and cause dissociation. The equilibrium chemically reacting air model in the EASI program will account for these effects.

The EASI program was modeled after the earlier Morris and Keyes program; key portions of the logic from the earlier program were included. However, the EASI program does not have the calorically perfect gas limitations because, unlike the Morris and Keyes program, the integral form of the conservation equations for compressible flow are solved in an iterative manner to determine the downstream conditions of a normal shock wave or Prandtl-Meyer expansion fan (ref. 2) with the equilibrium chemically reacting air model of reference 3. The present code also includes pressure- and temperature-dependent thermodynamic and transport properties (refs. 4 and 5) for the solution of the heating problem. Although some geometric aspects of the shock-wave interference and model geometry configuration are needed for the solution of maximum heat flux for a specific problem, the EASI computer program offers the advantage of providing an equilibrium air solution for a two-dimensional shock-wave interference with gas temperatures up to 15 000 K.

The present computer program solves the flow field and the associated maximum surface pressure and heat flux for the six types of shock-wave interference that were originally categorized by Edney. (See ref. 6.) Edney's classification scheme is followed in the present paper. The effects of the interactions on the surface which are solved by the computer program are the shock-wave–boundary-layer interaction (Types I, II, and V), expansion-fan–boundary-layer interaction (Type VI), attaching shear layer (Type III), and supersonic jet impingement (Type IV). For the prediction of supersonic jet impingement heating, the stagnation-point heat transfer is calculated by the method of Fay and Riddell (ref. 7) on an equivalent radius jet body. Heat flux calculations for the other surface interactions include a laminar and turbulent prediction.

The EASI computer program was written in FORTRAN-77 programming language for a DEC VAX 8500 series computer which uses the VAX/VMS operating system. (See ref. 8.) A user's guide for the EASI program is provided in appendix A. The upper- and mid-level subroutines of the code are discussed with the aid of flowcharts that show the programming logic. In addition, a listing of the EASI program is given in appendix B.

The input information to the EASI program is provided through a standard FORTRAN namelist called "$NAMES" in the file "inname.dat", and the output information is written to a file called "sjout.dat" after the program execution is complete. The output file contains flow-field information for the various shock-wave interference patterns and their associated maximum surface pressure and heat flux predictions. Documentation of the EASI computer program also includes sample calculations for each of the six interference patterns.

Symbols

c_p	specific heat at constant pressure, Btu/lbm-°R or J/kg-K
h	enthalpy, Btu/lbm
k	frozen thermal conductivity, Btu/hr-ft-°R or W/m-K
L	reference length, ft
M	Mach number
Pr	frozen Prandtl number
p	pressure, psia or atm
q	heat flux, Btu/ft^2-sec
Re	unit Reynolds number, per foot
r	radius, in.
T	temperature, °R or K
t	shear-layer thickness, in.
V	velocity, ft/sec
w	supersonic jet width, ft
β	shock-wave angle, deg
γ	ratio of specific heats
Θ	circumferential position on blunt leading edge, positive above undisturbed stagnation point, deg
θ	flow deflection angle, deg
μ	viscosity, lbm/ft-sec or N-sec/m^2
ρ	density, slugs/ft^3
ϕ	shear-layer angle, deg

Subscripts:

o	stagnation-point value
$1, 2, 3, \ldots, n$	region of shock-wave interference pattern
abs	with respect to free-stream flow direction (region 1)
aw	adiabatic wall
b	blunt leading edge
i	incident shock wave
j	supersonic jet
jb	equivalent blunt leading edge for supersonic jet
max	maximum
min	minimum
rel	with respect to preceding region
s	bow-shock-wave standoff
sl	shear layer
t	total flow conditions
ts	transmitted shock wave
w	wall

Description of Shock-Wave Interference

Edney (ref. 6) categorized six interference patterns and the resulting maximum surface pressure and heat transfer that occur when a weak oblique shock wave intersects a bow shock wave at various locations. Features of the inviscid flow field show the physical mechanisms that cause these interference patterns. Although each interference pattern is discussed in detail in reference 6, a brief description of the inviscid features of each pattern is given in the following section to show the basic flow features and define the conditions which have been observed experimentally in reference 9. Because several of these patterns result in similar surface interactions (such as shock-wave–boundary-layer), the effect of the interference pattern on the local surface heat transfer is presented after the discussion on the inviscid flow features.

The discussion that follows shows the theory behind the programming methodology used in the EASI program to solve the flow field and maximum local surface pressure and heating for the various shock-wave interference patterns. It is important that the user of the EASI program be aware of the limitations implied in the following discussion, especially the empiricism in the heat-transfer calculations.

Shock-Wave Interference Patterns

The shock-wave interference pattern is determined by the location where the incident and bow shock waves intersect and by the angle of the leading-edge surface with respect to the free-stream flow at the impingement point as shown in figure 1. (See ref. 6.) Type I, II, and V shock-wave interference patterns result in a shock-wave–boundary-layer interaction at the blunt leading-edge surface. Shock-wave–boundary-layer interactions increase the pressure and heat transfer at the surface. The Type VI interference pattern results in an expansion-fan–boundary-layer interaction that reduces the surface pressure and heat transfer. The Type III interference pattern produces a shear layer that attaches to the boundary layer and increases surface pressure and heat transfer. If the shear layer is turbulent when it attaches to the boundary layer, heating can increase to levels above those caused by shock-wave–boundary-layer interaction. The greatest increase in pressure and heat transfer is caused by the Type IV supersonic jet impingement on the leading edge.

In general, all two-dimensional interference patterns can be grouped as either the intersection of shocks of opposite families or the intersection of shocks of the same family. (See ref. 2.) Intersection of shocks of opposite families occurs when a left-running and a right-running shock wave intersect. This causes either Type I, Type II, Type III, or Type IV interference depending on the relative shock strengths of the two shock waves. (See ref. 6.) Intersection of shocks of the same family occurs when either two left- or right-running waves intersect and result in either Type IV, Type V, or Type VI interference patterns. Notice that the Type IV interference pattern can occur from the intersection of shocks of opposite families or of the same family. This depends on whether the incident shock intersects above or below the normal-shock portion of the bow shock. (See ref. 6 for a complete discussion of the difference.) The common convention used to describe a left-running wave is that it turns a supersonic flow to the left from an observer positioned on the flow streamline. A left-running wave turns the flow through a positive deflection angle. The opposite is true for the right-running wave. This convention is used in the present paper.

Inviscid flow features of each interference pattern are presented in the following sections. Schematic and pressure-deflection diagrams of six flow-field examples are used in the discussion. The pressure-deflection diagram is the locus of points describing all possible flow deflection angles and static pressures behind both weak and strong oblique shock waves for a given Mach number. The diagram is commonly called a "Mach number heart curve" because its shape resembles a heart. Five of the six shock-wave interference examples discussed were taken from reference 1. The exception is the Type IV interference example which is a calculation of an interference experiment reported in reference 9.

Type I interference pattern. The Type I interference pattern occurs when two weak oblique shock waves of opposite families intersect as shown schematically in figure 2(a). The weak shocks are generated by either two sharp leading edges or by a sharp leading edge and a bow shock where the intersection point is sufficiently downstream of the sonic point on the bow shock wave. The free-stream flow field (region 1) is turned by the two weak shock waves and results in the flow in regions 2 and 3. The two shock waves intersect and continue as refracted shock waves downstream of the intersection point. (See ref. 2.) The flow fields for regions 4 and 5 are behind the two refracted shock waves. The flow direction and pressure in regions 4 and 5 are the same and are separated by a shear layer because the velocities in regions 4 and 5 differ. The refracted shock wave separating regions 2 and 4 impinges on the surface resulting in a shock-wave–boundary-layer interaction. Then, the flow field in region 4 is turned through an oblique shock wave to match the angle of the upper wall boundary in region 6. Pressure and heating-rate amplification at the shock-wave–boundary-layer interaction is dependent on the impinging shock strength and whether the boundary layer is laminar or turbulent. (For example, see refs. 1 and 10 to 24.)

This shock interference can be shown graphically on the pressure-deflection diagram shown in figure 2(b). The free-stream flow, region 1, is turned downward through a right-running wave to region 2 and upward through a left-running wave to region 3. The intersection of the pressure-deflection curve of region 2 with the curve of region 3 defines the equal pressure and flow direction requirement of the resulting flow in regions 4 and 5. The flow in region 6 is described by the point that lies on the pressure-deflection curve of region 4 at the upper wall turning angle as shown in the figure. Note that the curves of regions 2 and 3 also intersect the strong shock portion of the free-stream flow curve at a pressure above the intersection with each other. When this situation exists, the resulting interference flow field will occur at the lower pressure, that is, at the intersection of the pressure-deflection curves of regions 2 and 3.

Type II interference pattern. The Type II interference pattern, shown schematically in figure 3(a), is similar to the Type I pattern because both result from the intersection of shocks of opposite families and result in a shock-wave–boundary-layer interaction. However, with the Type II interference, the right-running wave (bow shock) is stronger than the one for Type I but still results in supersonic flow in region 2. For an incident shock intersection with a bow shock, the intersection point on the bow shock is just downstream of the sonic point. The pressure-deflection diagram for the Type II interference is shown in figure 3(b). The free-stream flow (region 1) is turned through two weak shocks to regions 2 and 3. Unlike the Type I interference, the intersection of the pressure-deflection curves for regions 2 and 3 is above their intersection with the strong shock solution of the free-stream flow (region 1). The transition point between the Type I and Type II interference is characterized by the movement of the region 2 and region 3 intersection point to a pressure above the strong shock solution of the region 1 curve. (Compare fig. 3(b) with fig. 2(b).) Because all three regions must be linked, the only valid solution is one in which regions 2 and 3 are linked to region 1 through the subsonic patch as shown in the figure.

The pressure and flow angle in regions 4 and 5 are determined by the intersection point of the pressure-deflection curve of region 2 with the curve of region 1. Flow in region 4 is supersonic because it results from a weak compression of flow from region 2. However, the flow of region 5 is subsonic because it results from compression of the free-stream flow through a strong shock wave. Likewise, the pressure and flow angle in regions 7 and 8 are determined by the intersection of the region 3 and region 1 curves. Region 7 flow is supersonic, and region 8 flow is subsonic. The two supersonic flow regions (regions 4 and 7) are separated by shear layers from the subsonic flow. Note that the extent of the subsonic region is not given. In addition, the subsonic flow between the shear layers separating regions 4 and 7 has a variation in pressure, velocity, and turning angle between the limits of regions 5 and 8. However, this subsonic zone merges into a single region as the flow moves downstream.

The surface effects from the Type II interference are similar to those of Type I. The flow field in region 4 is turned to match the angle of the upper wall boundary and results in the flow field in region 6. The shock wave upstream of region 4 impinges on the wall boundary layer and results in a shock-wave–boundary-layer interaction at the wall, similar to the Type I interference.

Type III interference pattern. The Type III interference is caused by the intersection of shocks of opposite families when a weak incident shock intersects a bow shock inside the subsonic region near the sonic point. This occurs in the lower subsonic region for the Type III interference pattern shown in figure 4(a). The left-running incident shock wave turns the free-stream flow upward to region 3 and intersects the bow shock. Behind the intersection point, the flow in regions 2 and 4 are at the same pressure and are turned to the same flow angle. The flow is subsonic in region 2 and supersonic in region 4, and these two regions are separated by a shear layer.

The pressure-deflection diagram for the Type III interference is shown in figure 4(b). Pressure in region 3 is located on the pressure-deflection curve of region 1 at the appropriate turning angle. The turning angle and pressure of the flow in regions 2 and 4 are determined by the intersection of the pressure-deflection curves of regions 1 and 3. The shear layer that separates region 2 from region 4 will attach to the wall boundary layer and cause a shear-layer–boundary-layer interaction. The interaction maximum heating depends on the impingement angle θ_5 between the shear layer and the wall boundary layer, pressure rise between regions 4 and 5, and whether the shear layer is laminar or turbulent.

The transition from Type II to Type III interference occurs when the flow turning angle to region 2 is greater than the maximum turning angle, shown in figure 4(b), for a supersonic flow solution to exist in region 2. The transition is determined by the intersection point of the incident shock with the bow shock sonic point. An intersection below the sonic point in the supersonic region behind the bow shock produces a Type II interference pattern. Above the sonic point, a Type III interference pattern is produced. This transition is also seen by comparing the Type II and Type III pressure-deflection diagrams shown in figures 3(b) and 4(b), respectively. The pressure and turning angle of region 2 flow are uniquely defined by the wall (or shock-wave) turning angle for a Type II interference. (See fig. 3(a).) However, for the Type III interference, the pressure and turning angle in region 2 are defined by the intersection of the region 3 curve with the strong shock portion of the region 1 curve as shown in figure 4(b). Note that the shear-layer length L_{sl} and the transmitted shock length L_{ts} are dependent on body shape and intersection conditions, and hence they are undefined.

Type IV interference pattern. The Type IV interference pattern is caused by the intersection of either shocks of opposite families or shocks of the same family. The intersection point of the incident shock with the bow shock can be above or below the normal-shock portion of the bow shock as shown in figure 1. However, both result in a Type IV interference pattern as shown schematically in figure 5(a).

When the wall turning angle is greater than the maximum turning angle given by the pressure-deflection curve for region 4 (fig. 4(b)), the Type III interference will transition to Type IV. The transition occurs as the incident shock intersects closer to the normal-shock portion of the bow shock. The region 4 curve, shown in figure 4(b), defines the pressure increase to region 5 for various wall turning angles. The onset of the Type IV interference becomes apparent with the formation of a well-defined supersonic jet embedded within the subsonic regions between the bow shock wave and the surface. The supersonic jet is separated by shear layers from the subsonic flow in regions 2 and 5 as shown in figure 5(a) and may impinge on the blunt leading edge.

A pressure-deflection diagram for Type IV interference is shown in figure 5(b). Up to region 4, the flow process is identical to the Type III interference. Supersonic flow in region 4 is turned through a weak left-running wave to region 6. Flow in region 6 matches flow direction and pressure with the subsonic flow in region 5. Supersonic flow from region 6 to region 7 is expanded through a Prandtl-Meyer expansion fan to match the pressure in region 2 shown as a long-dash–short-dash line in figure 5(b). Supersonic jet flow is recompressed from region 7 to region 8 through a series of left-running waves to match again the pressure in region 5. The jet is terminated at the surface by a jet bow shock because the wall turning angle is greater than the maximum turning angle of the supersonic flow in the jet. The supersonic jet is assumed to terminate in either region 7 or 8 for a free-stream Mach number between 6 and 20 when the jet impinges on the surface. (See ref. 14.) Weak compression of the flow in the jet and then compression through the jet bow shock results in high localized pressure and heating at the wall stagnation point.

Note that the supersonic jet is turned upward for the example shown schematically in figure 5(a) because the pressure in region 5 is greater than in region 2. The supersonic jet is turned by the higher pressure in region 5 to the lower pressure in region 2. Impingement of the jet above $\Theta = 0^\circ$ gives a Type IV interference which grazes the surface or dissipates prior to impinging on the surface.

Type V interference pattern. The Type V interference pattern occurs when the incident shock wave intersects the bow shock just above the upper sonic point for the orientation shown in figure 6(a). Both shock waves are of the same family. A supersonic jet is present for the Type V interference; however, the jet is much thinner than the Type IV supersonic jet. The Type V jet turns away from the surface, dissipates, and does not impinge on the surface.

A pressure-deflection diagram for Type V interference is shown in figure 6(b). The flow that affects the surface is initially compressed to region 2 through the weak, left-running incident shock wave. Then, flow in region 2 is compressed to region 3 by flow deflection to match the leading-edge wall turning angle. A requirement of the flow in regions 4 and 5 is that the pressure and flow turning angles must match at the shear layer which separates them. The intersection of the pressure-deflection curves of regions 2 and 3 shown in figure 6(b) satisfies this set of conditions. Therefore, region 3 flow is compressed to region 5 through a right-running wave to match the pressure and flow direction in region 4. The right-running shock wave that impinges on the wall boundary layer results in the shock-wave–boundary-layer interaction at the wall. This causes increased pressure and heat transfer at the surface similar to the Type I and Type II interference.

Type VI interference pattern. The Type VI interference results from the intersection of shocks of the same family similar to the Type V interference. However, for a Type VI interference, the incident shock must intersect the bow shock sufficiently downstream of the upper sonic point so that supersonic flow exists in all regions.

A schematic and a pressure-deflection diagram of Type VI interference are shown in figures 7(a) and (b), respectively. The free-stream flow (region 1) is initially compressed through the weak left-running incident shock wave to region 3. Then flow is compressed from region 3 to region 4 by another left-running wave to the local turning angle at the wall. These two left-running shock waves coalesce, and the resulting shock wave compresses the flow from region 1 to region 2. Pressure and flow direction are matched in regions 2 and 5, and the match point will be located on the pressure-deflection curve of region 1. The match is found by expanding isentropically from the flow conditions in region 4 to its intersection with the pressure-deflection curve of region 1 as shown in the inset of figure 7(b). Therefore, the flow in region 4 must expand through a Prandtl-Meyer expansion fan to match the pressure in region 2. The expansion fan impinges on the wall boundary layer resulting in an expansion-fan–boundary-layer interaction. Region 5 flow expands to region 6 because the expansion fan reflects from a solid boundary in a like manner. (See ref. 2.) This interaction decreases the local pressure and heat transfer at the surface.

Surface Heating From Shock-Wave Interference

The previous discussion is useful to determine the inviscid shock-wave pattern and inviscid flowfield features of the various types of shock-wave interferences. Maximum surface pressure can be determined from the pressure-deflection diagram for the given type of interference pattern. However, the viscous effects that cause heating have not been addressed. In this section, a brief discussion of some empirical correlations used to determine the maximum surface heat flux resulting from shock-wave interference is given.

Shock-wave–boundary-layer interactions increase pressure and heat transfer and result from Type I, Type II, and Type V interferences. Pressure and heat transfer are reduced from the expansion-fan–boundary-layer interaction of the Type VI interference. The Type III interference affects the heat transfer at the surface by a shear-layer attachment to the boundary layer. Shear-layer–boundary-layer attachment can increase heat transfer above the level for a shock-wave–boundary-layer interaction if the shear layer is turbulent. The greatest increase in heat transfer is caused by the Type IV supersonic jet impingement on the blunt leading edge. Details of the various surface interactions and how they affect heating are given in the following sections.

Shock-wave–boundary-layer interaction. Surface pressure and heat-transfer augmentation caused by the Type I, Type II, and Type V interference patterns is a result of shock-wave–boundary-layer interaction. The flow physics of the shock-wave–boundary-layer interaction are covered in great detail in many of the classic compressible flow textbooks. (For example, see refs. 21 to 24.) The information on shock-wave–boundary-layer interaction is extensive (e.g., refs. 1 and 10 to 20).

The condition of the boundary layer prior to the shock-wave interaction is important in the determination of heat-transfer augmentation. A shock-wave–laminar-boundary-layer interaction may cause boundary-layer separation just upstream of the interaction point. Pressure waves are propagated upstream through the subsonic region of the boundary layer and cause the boundary layer to adjust before the shock interaction region. However, the turbulent boundary layer has a much thinner subsonic region and, therefore, results in less flow adjustment and less separation prior to the shock-wave interaction region.

A simple empirical relationship has been used to estimate the shock-wave–boundary-layer interaction heating (ref. 15):

$$\frac{q_2}{q_1} = \left(\frac{p_2}{p_1}\right)^n \tag{1}$$

where subscript 1 refers to the pressure and heat flux upstream of the refracted shock and subscript 2 refers to the maximum pressure and heat flux downstream of the reflected shock wave. The upstream laminar and turbulent boundary-layer heating q_1 is determined by the reference enthalpy methods of references 25 and 26. Boundary-layer growth is assumed over the reference length L from a sharp leading edge as shown in figures 2(a), 3(a), 6(a), and 7(a). The experimentally determined value of the exponent n in equation (1) for the shock-wave–laminar-boundary-layer interaction varies from 1.29 (refs. 1, 10, 12 to 15, and 18) to 0.5 (refs. 10, 18, and 24). Reference 19 suggests that the shock-wave interaction with the incoming laminar boundary layer causes boundary-layer transition which strongly affects the local heating. The laminar data of reference 19 do not support the simple correlation of maximum pressure to maximum heat flux given by equation (1). However, for a shock-wave–turbulent-boundary-layer interaction, $n = 0.85$ appears to give the best empirical curve fit for most turbulent experimental data. (See refs. 1, 10, 13 to 18, and 24.)

Expansion-fan–boundary-layer interaction. An expansion-fan–boundary-layer interaction at the leading-edge surface results from a Type VI interference. The empirical relationship given as equation (1) has been shown to apply to the reduction of heating from the expansion-fan–boundary-layer interaction. (See refs. 1, 14, and 16.) Reference 1 suggests using $n = 1.29$ for a laminar-boundary-layer interaction and $n = 0.85$ for a turbulent-boundary-layer interaction. The experimental data presented in references 14 and 16 support this approach. The subscripts of equation (1) are defined as 1 for the upstream undisturbed value and 2 for the reduced value downstream of the expansion-fan–boundary-layer interaction.

Shear-layer–boundary-layer interaction. Shear-layer attachment to the boundary layer increases heating for the Type III interference.

Maximum heating at the shear-layer attachment point is analogous to the attachment of a separated boundary layer. (See refs. 1 and 12 to 14.) References 12 and 13 suggest using a relationship similar to that given in reference 27 to calculate the increased heat transfer. This relationship is given as

$$q_{\max} = A\rho_w V_5 c_{p,w} \left(T_{aw} - T_w\right) \left(\frac{\mu_w \sin\theta_5}{\rho_w V_5 t}\right)^n \tag{2}$$

where the constants A and n for a laminar-shear-layer attachment are 0.19 and 0.5, respectively. For a turbulent-shear-layer attachment, the constants are 0.021 and 0.2, respectively. These values for the constants A and n are taken from reference 27. In equation (2), the subscript 5 refers to region 5. (See fig. 4(a).) The wall values, indicated by the subscript w, are evaluated at the wall temperature T_w and the local pressure in region 5.

The local flow conditions on either side of the shear layer will determine if it is laminar or turbulent. (See ref. 28.) The shear-layer thickness t is calculated by the following laminar and turbulent relationships taken from reference 27:

$$t = 5.0\left(\frac{L_{sl}\mu_4}{\rho_4 V_4}\right)^{0.5} \qquad \text{(Laminar)} \tag{3}$$

$$t = 0.123 L_{sl} \qquad \text{(Turbulent)} \tag{4}$$

The shear-layer length L_{sl} and the wall turning angle θ_5 are determined from the geometry of the interference pattern shown in figure 4(a). Calculation of the increased heating by this method is limited because an experimentally or numerically determined shear-layer length L_{sl} is required.

Supersonic jet surface impingement. A Type IV interference pattern terminates at the blunt leading edge by supersonic jet impingement. Supersonic jet impingement on the surface causes a narrow, localized stagnation region of high pressure and heat transfer. The supersonic jet terminates through a strong shock in either region 7 or 8, as shown in figure 8, for free-stream Mach numbers between 6 and 20. (See ref. 1.) It is assumed that the terminating shock is a normal shock and will have little effect on the jet stagnation pressure because it is strong. However, the jet stagnation heating will vary with the sine of the impingement angle θ_j (ref. 6) shown in figure 8. Maximum heat transfer occurs when the supersonic jet impinges normal to the surface. For the present maximum heating calculations, normal jet impingement is assumed.

The surface pressure at the jet impingement is calculated by assuming stagnation flow downstream of the jet bow shock starting with regions 7 and 8 upstream flow conditions. The stagnation heat transfer is calculated on an equivalent "jet body" radius r_{jb} shown in figure 8 for the calculated jet width and normal-shock density ratio. (See ref. 7.) The jet width w_j is determined by solving the inviscid compressible flow relationships (ref. 2) to obtain the jet geometry shown in figure 5(a). The jet width is dependent on the free-stream flow conditions, incident shock strength, and an experimentally or numerically obtained transmitted shock length L_{ts}. Next, the jet-bow-shock standoff distance L_s is calculated from an empirical formula given in references 1 and 14 as $L_s/w_j = 0.45$, which is applicable for jet Mach numbers ranging from 1.2 to 2.5 and $\gamma = 1.4$. Having found the jet-bow-shock standoff distance, the jet body radius is determined by the relationships given in references 29 and 30. Then, the two-dimensional jet stagnation heat transfer is calculated by the following relationships given by Fay and Riddell (ref. 7):

$$q_{\max} = 0.567\,\mathrm{Pr}_1^{-0.6} \left(\mu_w \rho_w\right)^{0.1} \left(\mu_o \rho_o\right)^{0.4} \times \left(h_o - h_w\right) \left(\frac{\partial V}{\partial x}\right)_o^{0.5} \tag{5}$$

where

$$\left(\frac{\partial V}{\partial x}\right)_o = \frac{1}{r_{jb}} \left[\frac{2\left(p_o - p_1\right)}{\rho_o}\right]^{0.5} \tag{6}$$

In equations (5) and (6), subscript 1 refers to the flow conditions upstream of the jet normal shock wave and subscript o refers to the jet stagnation conditions.

A calculation of the maximum heat transfer for supersonic jet impingement with the procedure outlined above is cumbersome, includes many assumptions, and requires knowledge of the transmitted shock length to determine the jet width. However, agreement with experimental data is quite good for both axisymmetric configurations (refs. 1, 13, and 14) and two-dimensional bodies (ref. 31) with supersonic jet impingement.

A sketch of the Type IV supersonic jet impingement region and resulting pressure and heat-transfer distributions are shown in figure 9. These details were first postulated by Edney (ref. 6) and are included to describe the surface pressure and heat transfer resulting from supersonic jet impingement. The supersonic jet is terminated just before the blunt leading edge by a normal shock wave that causes pressure and heating to increase in a narrow stagnation region between points c and d as shown in figure 9. The maximum pressure and heat transfer will occur at stagnation point o and are a function of the impingement angle that the jet makes with the blunt leading edge. The jet splits to flow in both directions and passes through a series of expansion and compression waves from point c to point a and from point d to point f to match the pressure in regions 5 and 2, respectively. These trends are evident for the data presented in a latter section for the Type IV shock-wave interference.

Relevance of the EASI Program

Both the EASI program and the earlier Morris and Keyes program use the approaches that were discussed in the previous section to predict the maximum surface pressure and heat transfer caused by shock-wave interference. However, the EASI program extends the predictions to interference flow fields with gas pressures and temperatures where air is composed of a mixture of chemically reacting gases in thermodynamic equilibrium. Shock-wave-interference heating predictions can be affected by the thermodynamic properties of the high-temperature air. An example given in the following section shows that air chemistry should be included to give a more accurate pressure and heating prediction for high-temperature flow fields.

To calculate gas properties of the interference flow field, the Morris and Keyes program uses shock-wave relationships for a gas with a constant γ. However, the EASI program avoids the use of γ by solving the integral conservation equations for steady, compressible flow in an iterative manner to find the gas properties behind shock waves and expansion fans for the various shock-wave interference flow fields. (See ref. 2.) The air thermodynamic properties are determined from either an 11-specie chemically reacting equilibrium air subroutine or a calorically perfect air subroutine. Caloric imperfections and specie dissociation of high-temperature air cause shock-wave angles, flow deflection angles, and thermodynamic properties to differ from those calculated with the constant γ relationships. These high-temperature effects are included in a shock-wave interference prediction by using the equilibrium air subroutine of the EASI program.

Sample Problems and Comparisons for Code Validation

In this section, maximum pressure and heating predictions from the EASI program are compared with other predictions and experimental data for the various interference patterns. These comparisons are used to validate predictions of maximum pressure and heating made by the EASI program. In the first example, predictions from the Morris and Keyes perfect gas program of some sample problems given in reference 1 are compared with predictions from the EASI program. The calorically perfect air option in the EASI program was used in this comparison. For the next example, results from two-dimensional shock-wave interference experiments that were performed in the Calspan 48-inch and 96-inch legs of the Hypersonic Shock Tunnel (refs. 9, 31, and 32) are compared with EASI program predictions. The equilibrium air option of the EASI program was used for these calculations because the stagnation temperature of the free-stream flow was in the temperature range where air exhibits caloric imperfections. For the final example, a Type IV interference problem with equilibrium air temperatures up to 12 500°R is presented to show the difference between the equilibrium chemically reacting air prediction and the calorically perfect gas prediction from the EASI program.

Maximum pressure and heating-rate predictions for the Type I, II, V, and VI interference problems given in reference 1 were made with both the EASI and Morris and Keyes programs. The Type III and IV interference examples were taken from reference 9 because the input conditions for a two-dimensional configuration were available. In addition, the Morris and Keyes program was modified to calculate heating for the two-dimensional Type IV interference because the original program, obtained from COSMIC (Computer Software Management and Information Center), calculated maximum heating for supersonic jet impingement on a spherical leading edge. For these six comparisons, the EASI program used the calorically perfect air model to match the gas model in the Morris and Keyes program. Maximum pressure and heating rate predictions are shown in table 1 for the six interference patterns that are compared. The input conditions are shown in table 2. The input and output files for these six examples from the EASI program are given in appendix C. The predictions from the two programs shown in table 1 are in good agreement with less than 1 percent difference in the calculated values except for the turbulent heating predictions for a shock-wave–boundary-layer interaction (Types I, II, and V) and the stagnation pressure calculation in region 8 for the Type IV interference example.

The difference in the turbulent-shock-wave–boundary-layer prediction may be due to the method used to obtain the undisturbed-boundary-layer heating prior to the interaction. The Morris and Keyes program uses a laminar relationship between the Stanton number and skin friction coefficient to determine the turbulent-boundary-layer heat-transfer coefficient. The undisturbed turbulent-boundary-layer heating prediction from the EASI program uses a turbulent relationship at a constant surface temperature between the Stanton number and the skin friction coefficient. (See ref. 26.) Because the two programs use different relationships to calculate the undisturbed turbulent boundary-layer heating, the maximum heating predictions differ by about 10 percent.

A discrepancy of about 9 percent between the two predictions for the Type IV, region 8 stagnation pressure is shown in table 1. The difference in this case is because the Morris and Keyes program sets the Mach number in region 8 equal to the Mach number in region 6 (fig. 5(a)), whereas the Mach number in region 8 calculated by the EASI program is obtained by compressing the flow in region 7 to the local pressure of the lower subsonic region (region 5 in fig. 5(a)) through a weak shock. By doing so, the EASI program includes the weak-shock-wave losses from region 7 to region 8 and this results in a lower region 8 stagnation pressure.

The EASI program was then used to predict the maximum pressure and heating rate from Type III and Type IV shock-wave interference experiments presented in references 9, 31, and 32. The interference experiments are distinguished by a run number which refers to an individual test of an experimental study performed in the Calspan 48-inch and 96-inch legs of the Hypersonic Shock Tunnel. The experimental data are shown in figures 10 to 12 as schlieren photographs of the interference patterns and surface pressure and heat-transfer distributions on a 3-inch-diameter cylindrical leading edge. Experimental heat-transfer data shown in the figures were extrapolated to an isothermal, cold wall temperature of 530°R by assuming a constant heat-transfer coefficient. The maximum pressure and heating rate predictions shown in the figures were calculated with the equilibrium chemically reacting air gas model. The transmitted shock length L_{ts} was measured from the schlieren photographs for each of these interference patterns. The EASI predictions are also presented in table 3, and the experimental test conditions are given in table 4.

For the Type III interference prediction, the predicted pressure for region 5 (fig. 4(a)) is in good agreement with the maximum experimental pressure as shown in figure 10(b). The shear layer that attached to the cylindrical leading-edge boundary layer was turbulent for the flow conditions of the interference pattern (ref. 32), and the predicted turbulent value agrees with the maximum experimental heating-rate level as shown in figure 10(c).

Results from the Type IV shock-wave-interference experiments are presented along with the EASI program predictions in figures 11 and 12. The experimental data are for free-stream Mach numbers of approximately 8 and 16, respectively. Note that the experimental pressure and heating-rate distributions have a sharp, well-defined spike where the supersonic jet impingement occurred on the cylindrical leading edge. The experimental maximum pressure is best predicted by the calculated stagnation pressure in region 7, as shown in figures 11(b) and 12(b). This is probably because the pressure sensor diameter (0.0625 in.) was of the same order as the region 8 jet width, and the sensor effectively took an integrated pressure reading rather than the jet stagnation point pressure. However, the maximum experimental heat flux data agree best with the predicted stagnation-point heat flux in region 8 shown in figures 11(c) and 12(c). This is because the heat-transfer gauges were smaller (0.010 in. wide) and spaced closer than the pressure sensors. Closer heat-transfer-gauge spacing allowed better resolution of the maximum heating rate on the leading edge.

The final example in this section is a heating prediction for the cowl leading edge of the NASP scramjet subjected to Type IV supersonic jet impingement heating. Type IV heating will occur when the vehicle bow-shock wave or inlet-ramp shock waves interact with the cowl leading-edge bow shock and form an impinging supersonic jet indicative of the Type IV shock-wave interference. For this example, the local air temperature in the supersonic jet stagnation region is above the temperature where air behaves as a calorically perfect gas. Therefore, the heating predictions from the EASI program were made with both the calorically perfect and equilibrium chemically reacting air options to show the difference between the two heating-rate predictions.

The vehicle bow shock of the NASP is expected to cross the cowl leading edge of the scramjet engine at approximately Mach number 16 (ref. 31) and at a dynamic pressure between 1000 and 3000 psf. (See ref. 33.) The free-stream flow conditions used as an input to the EASI program for this example correspond to flight altitudes which match the dynamic-pressure range for Mach numbers between 14 and 17. (See ref. 34.) Other input parameters to the EASI program are a cowl leading-edge diameter of 0.25 in. with an assumed transmitted shock length L_{ts} of 0.093 in. and a constant cowl leading-edge temperature of 2000°R. In addition, two incident flow deflection angles θ_i of 5° and 10° were chosen as the limiting values of the expected NASP underbody turning angle. The variation of predicted region 8 maximum heating for the parameters given is shown in figure 13.

The calculated gas temperatures in the jet stagnation region with the calorically perfect air option range from about 17 000°R to 27 000°R. With the equilibrium air option, the temperatures range from approximately 10 000°R to 12 500°R and pressures range from 20 to 135 atm in the jet stagnation region. For the air at these equilibrium conditions, the O_2 is almost completely dissociated to O, a significant amount of NO is present in the mixture, and the N_2 has begun dissociation. (See ref. 3.) The change in the thermodynamic and transport properties from the high-temperature effects results in the variation in stagnation-point heating rate as shown in figure 13. The greatest difference in heating for this example occurs for the 3000-psf-dynamic-pressure condition at Mach number 14.4 and $\theta_i = 10°$. The difference in predicted heating between the two gas models is about 13 percent and is attributed to the caloric imperfections and dissociation of air.

The use of these three comparisons, that is, against the earlier Morris and Keyes interference program, with experimental data of the Type III and Type IV interference, and for air with the high-temperature effects ranging from caloric imperfections to dissociation, shows the capability of the EASI program to predict maximum pressure and heating for the various interference patterns. Although the EASI program requires some knowledge of the inviscid flow field, the predicted results are accurate and easily obtained.

Concluding Remarks

A computer program which solves the inviscid flow field and maximum surface pressure and heating for six shock-wave interference patterns has been developed. The program is called EASI, Equilibrium Air Shock Interference. The inviscid flow field is treated as either 11-specie equilibrium chemically reacting air or as calorically perfect air. The computer code predicts maximum surface pressure and heat flux caused by two-dimensional shock-wave interference. Heat-flux predictions require a knowledge of the shock impingement point on the leading edge for the Type I, II, V, and VI interference patterns and the transmitted shock length for the Type III and IV interference patterns. These lengths can be obtained from experimental data or from inviscid calculations. A comparison of results for the shock-wave interference examples showed good agreement between the prediction from the EASI computer program and predictions from the Morris and Keyes program. In addition, predictions from the EASI computer program were in good agreement with experimental data from two-dimensional Type III and Type IV tests performed in the Calspan 48-inch and 96-inch legs of the Hypersonic Shock Tunnel. The EASI program was also applied to a scramjet cowl leading-edge heating example, and the results showed up to a 13-percent difference in heating between the calorically perfect and the equilibrium chemistry predictions.

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Appendix A

User's Guide for EASI Computer Program and Programming Logic Flowcharts

A description of the main program and the higher level subroutines which calculate the inviscid flow field and maximum pressure and heating for the six interference patterns is given in this appendix. Flowcharts containing the general programming logic for these subroutines are presented as figures 14 to 24. A listing of the EASI computer program is given in appendix B. A discussion of all the subroutines contained in the EASI program is not included; however, the user of the EASI program will find liberal comment cards in the program listing that describe the logic flow for the subroutines not described below.

Program EASI

The EASI program is executed with data read from a standard FORTRAN programming language namelist input, in this case called "$NAMES," that is contained on the input file "inname.dat" as shown in figure 14. The namelist input specifies the free-stream flow-field thermodynamic state properties, gas model to be used, and geometric information about the specific interference pattern. A detailed description of the namelist variables common to all interference pattern predictions are discussed in this section. The namelist variables that have multiple definitions, depending on the chosen interference pattern, are discussed in the appropriate sections. A complete list of the namelist variables with a brief description of each is as follows:

`$NAMES`

`ISHOCK`	interference pattern to be calculated
`INCON`	specifies which thermodynamic state properties are input
`IGAS`	specifies the gas model used in the calculations
`RUNNO`	run number identification
`TOBU`	total temperature, °R
`POBU`	total pressure, psia
`RHOOBU`	total density, slugs/ft^3
`T1BU`	free-stream temperature, °R
`P1BU`	free-stream pressure, psia
`RHO1BU`	free-stream density, slugs/ft^3
`V1BU`	free-stream velocity, ft/sec
`PRNUM`	Prandtl number, default set at 0.72
`THEIDEG`	flow deflection angle of the incident shock wave, deg
`TWBU`	leading-edge wall temperature, °R
`RBODY`	leading-edge body radius, in.
`ITYPE`	not used, default set at 1
`THEBDEG`	flow deflection angle on the leading edge, deg
`SL12`	length, ft

`$`

The flow field is considered to be air which is modeled as either an equilibrium chemically reacting gas mixture or a calorically perfect ideal gas, depending on the value assigned to the input variable `IGAS`. For the equilibrium gas model, `IGAS = 1`; and for the ideal gas model, `IGAS = 2`. The equilibrium chemically reacting gas model was taken from reference 3 and is named subroutine SUBR1 in the EASI program. The ideal gas model is named subroutine SUBR2; and the gas constant and specific heats for the ideal gas model were taken from reference 35. The equilibrium and ideal gas subroutines, SUBR1 and SUBR2, respectively, require input of the temperature and density and output specific heat at a constant pressure, pressure, internal energy, enthalpy, and entropy of air at the given input conditions.

To describe the free-stream flow field, the program requires input of the free-stream velocity V_1 and two of the following thermodynamic state properties: T, p, or ρ. An option is provided to use either the free-stream or total flow conditions by specifying the input variable `INCON` as follows:

`INCON` = 1: input p_1 and ρ_1

`INCON` = 2: input T_1 and ρ_1

`INCON` = 3: input p_1 and T_1

`INCON` = 10: input p_t and ρ_t

`INCON` = 20: input T_t and ρ_t

`INCON` = 30: input p_t and T_t

The type of shock-wave interference pattern is calculated based on the value assigned to the namelist input variable `ISHOCK`. Program execution is transferred to the appropriate subroutine for the specified value of `ISHOCK` as shown on the flowchart. For example, if `ISHOCK = 1`, subroutine TYP1 is called to calculate a Type I interference;

if `ISHOCK = 2`, subroutine TYP2 is called to calculate a Type II interference; ...; and if `ISHOCK = 6`, subroutine TYP6 is called to calculate a Type VI interference. In addition, logic has been provided in subroutines TYP1, TYP2, ..., TYP6 to determine if the specified interference pattern exists for the namelist input variables. The subroutine will identify the proper interference pattern on the output file if the interference pattern does not exist. Subroutines TYP1, TYP2, ..., and TYP6 solve the inviscid flow field and return execution to program EASI where the maximum heating is calculated by calling the appropriate subroutine for the interference pattern.

After the shock-wave interference calculations are completed, output is written to the file called "sjout.dat." The namelist variables are written on the file first. Next, the pressure, temperature, density, internal energy, unit Reynolds number, velocity, Mach number, enthalpy, entropy, and Prandtl number are written to the file for each region shown in figures 2(a) to 7(a). Then, the flow deflection and shock-wave angles for each region are written, followed by the undisturbed and maximum heat flux at the interference impingement point on the leading edge. Finally, the undisturbed stagnation heat transfer (ref. 7) for a two-dimensional body of radius `RBODY` is written to the output file as a reference heating value.

Subroutine TYP1

Subroutine TYP1 calculates the inviscid flow field for a Type I interference pattern and transfers program execution to determine the maximum heating that results from a shock-wave–boundary-layer interaction. In addition to the general flow-field information discussed in the previous section, the subroutine requires input of the body flow deflection angle θ_b and the incident shock-wave flow deflection angle θ_i (fig. 2(a)) as the namelist variables `THEBDEG` and `THEIDEG`, respectively. The length L shown in figure 2(a) is also required to determine the undisturbed heating for a laminar and turbulent boundary layer at the shock-wave–boundary-layer interaction. The value of L is input as the variable SL12 in the namelist.

As shown in figure 15, the subroutine starts the flow-field calculations by determining local flow conditions in regions 2 and 3 using a weak oblique shock solution. Limits are set on the shear-layer angle ϕ between the flow fields in regions 4 and 5 (fig. 2) to ensure that the resulting flows behind the refracted shock waves are supersonic and parallel. Then, the correct turning angle is obtained by changing ϕ within the set limits until the pressure in regions 4 and 5 is matched. The refracted shock wave between regions 2 and 4 reflects from the solid wall of the leading edge, and the resultant flow properties downstream of the shock-wave reflection (region 6) are determined. After the inviscid flow-field thermodynamic properties in each of the regions are determined, program execution is returned to program EASI.

Subroutine TYP2

To calculate the Type II interference, the EASI program requires the namelist input of the body flow deflection angle θ_b and the incident shock-wave flow deflection angle θ_i (fig. 3(a)) using the namelist variables `THEBDEG` and `THEIDEG`, respectively. Also, the undisturbed laminar and turbulent heating calculations require the value of L shown in figure 3(a), which is input as the variable `SL12` in the namelist.

The calculation for a Type II interference pattern proceeds in much the same manner as that for the Type I interference, and the procedure is shown in figure 16. However, because the body shock wave for the Type II interference is stronger than for the Type I interference, a region of subsonic flow is produced. The subsonic region is separated from the two supersonic flow regions by shear layers behind the refracted shock waves. This results in two triple-shock configurations, one at the intersection of regions 1, 2, 4, and 5 and the other at the intersection of regions 1, 3, 7, and 8. (See fig. 3(a).) The conditions imposed by the triple-shock configuration on the flow after the intersection point are (1) parallel flow separated by a shear layer, (2) matched pressure, and (3) subsonic and supersonic flow on either side of the shear layer. After the flows behind the two triple-shock configurations have been calculated, the flow in region 6 is determined from the shock-wave reflection at the wall. Program execution returns to program EASI after the inviscid flow-field properties have been determined.

Subroutine TYP3

Subroutine TYP3 requires the incident shock-wave flow deflection angle θ_i, the shear-layer impingement angle on the body $\theta_{5,\text{abs}}$, and the transmitted shock length L_{ts} (fig. 4(a)) to calculate the inviscid flow field for a Type III interference pattern. The values for θ_i, $\theta_{5,\text{abs}}$, and L_{ts} are input in the namelist as `THEIDEG`, `THEBDEG`, and `SL12`, respectively.

The inviscid flow field is calculated as shown by the flowchart in figure 17. The weak shock solution between regions 1 and 3 is first determined. Then, the flow at the triple-shock configuration between regions 1, 2, 3, and 4 is calculated. Finally, the flow-field solution for region 5 is determined by turning the flow in region 4 at the wall deflection angle. After the inviscid flow-field thermodynamic properties have been calculated, program execution is returned to program EASI.

Subroutine TYP4

Subroutine TYP4 calculates the inviscid flow for the Type IV interference. The subroutine requires input of the incident shock flow deflection angle θ_i and transmitted shock length L_{ts} (fig. 5(a)) as namelist variables `THEIDEG` and `SL12`, respectively.

The inviscid flow-field calculation scheme is shown in figure 18. The flow-field calculation starts with the weak shock solution for region 3. The triple-shock configuration at point J1, as shown in figure 5(a), is determined and results in the flow in regions 2 and 4. The flow in region 4 is supersonic, and the flow in region 2 is subsonic. Another triple-shock configuration is present at point J2 (fig. 5(a)), and the resulting supersonic flow in region 6 is turned to match the pressure in region 5. Because the pressure in region 6 is higher than the pressure in the upper subsonic zone (region 2), the flow in region 6 is expanded through a Prandtl-Meyer expansion fan to region 7. Then, the supersonic jet is recompressed to region 8 which is at the pressure of the lower subsonic zone (region 5). The inviscid flow-field thermodynamic properties are then determined, and program execution returns to program EASI.

Subroutine TYP5

Subroutine TYP5 calculates the inviscid flow field for a Type V interference as shown in figure 6(a). The subroutine requires input of the body flow deflection angle θ_b and the incident shock-wave flow deflection angle θ_i using the namelist variables `THEBDEG` and `THEIDEG`, respectively. Also, the undisturbed laminar and turbulent heating calculations require the value of length L shown in figure 6(a) input as the variable `SL12` in the namelist.

Flow-field calculations begin with the weak shock solution for the flow in regions 2 and 3 as shown in figure 19. A triple-shock configuration exists between the intersection of regions 2, 3, 4, and 5 and determines the flow deflection angle for the flow in region 5. Region 5 flow is turned by a reflected shock wave to match the wall angle and results in region 6 flow downstream of the reflected shock wave. After the flow deflection angles in the interference pattern have been determined, the subroutine calculates the thermodynamic properties in each of the regions and returns program execution to program EASI.

Subroutine TYP6

To calculate the inviscid flow field for a Type VI interference, subroutine TYP6 requires input of the body flow deflection angle θ_b and the incident shock-wave flow deflection angle θ_i using the namelist variables `THEBDEG` and `THEIDEG`, respectively. Also, the undisturbed heating calculations require the input value of length L (fig. 7(a)) as the variable `SL12` in the namelist.

The inviscid solution for a Type VI interference starts with the calculation of the weak shock solutions from regions 1 to 3 and from regions 3 to 4 as shown in figure 20. Next, a solution for the flow in regions 2 and 5 requires that the flows are parallel and the pressure is matched. Because the pressure in region 4 is higher than any weak shock solution for the free stream at the same turning angle, region 4 flow must expand through a Prandtl-Meyer expansion fan to region 5 to meet the parallel flow and matched pressure requirements imposed by the separating shear layer. These requirements cause an expansion fan reflection from the leading-edge wall boundary. Region 5 flow expands through the reflected expansion fan to the wall turning angle and results in region 6 flow. Thermodynamic properties from each of the regions are then calculated and the program execution is transferred to program EASI.

Mid-Level Subroutines

The mid-level subroutines of the EASI program that calculate the surface heating rates produced by shock-wave–boundary-layer interaction, shear-layer attachment, and supersonic jet impingement are described in this section. A general programming logic flowchart is included with the discussion of each of these subroutines, similar to the flowcharts presented in the previous section.

***Subroutine* SBLLOC.** Shock-wave–boundary-layer interaction occurs for the Type I, II, and V interference patterns. Subroutine SBLLOC calculates the maximum heat transfer for these interference patterns. This subroutine is also used to calculate the reduced heat transfer for the Type VI interference which results in an expansion-fan–boundary-layer interaction on the leading edge.

Program EASI controls the calling sequence for the various subroutines. For the Type I, II, V, and VI interference calculations, the program execution is transferred to subroutine SBLLOC to calculate the surface heating at the interaction point after the inviscid flow field has been determined.

The first task of subroutine SBLLOC is to calculate the various flow turning angles θ's and shock-wave angles β's with respect to the free-stream flow direction (region 1), and with respect to the flow direction of the preceding region. (See fig. 21.) Next, the undisturbed heating rates for both a laminar and a fully developed turbulent boundary layer are determined at the shock-wave–boundary-layer impingement point by the reference enthalpy methods given in references 25 and 26. Boundary-layer growth is assumed over the length L (input as the namelist variable `SL12`) from a sharp leading edge as shown in figures 2(a), 3(a), 6(a), and 7(a). After the undisturbed flat-plate heating has been determined, the maximum heating at the shock-wave–boundary-layer interaction point is calculated from equation (1) with the undisturbed heating values and the upstream and downstream impingement point pressures from the inviscid analysis. The maximum pressure used in equation (1) is assumed to be the inviscid pressure downstream of the reflected shock wave. The program execution is then returned to program EASI.

***Subroutine* SHERLOC.** A Type III interference results in a shear-layer attachment to the wall boundary layer. Subroutine SHERLOC calculates the maximum heating for both a laminar and turbulent shear-layer attachment, as shown in figure 22. The subroutine is called by program EASI after the inviscid Type III flow field has been determined by subroutine TYP3. The shear-layer attachment heating calculation requires input of the transmitted shock length L_{ts} and the wall attachment angle $\theta_{5,\mathrm{abs}}$ as namelist variables `SL12` and `THEBDEG`, respectively.

Flow turning angles θ's and shock-wave angles β's for each region are first determined in the subroutine. The transmitted shock length and flow-field geometry at the wall attachment point fix the shear-layer length L_{sl} as shown in figure 4(a). The shear-layer thickness t is then calculated from the shear-layer length by the relationships given as equations (3) and (4). The shear-layer thickness, the flow deflection angle at the wall, and flow properties from the inviscid analysis determine the maximum heating from shear-layer attachment with the relationship given as equation (2). Program execution is returned to program EASI after the maximum heating from shear-layer attachment has been calculated.

***Subroutine* JETLOC.** Subroutine JETLOC calculates the geometric shape and maximum heating from the Type IV interference supersonic jet impingement. The subroutine is called after the inviscid flow field has been determined from subroutine TYP4. Subroutine JETLOC requires input of the transmitted shock length L_{ts} to determine the supersonic jet geometry.

Like the other subroutines that calculate heat transfer (SBLLOC and SHERLOC), subroutine JETLOC determines the flow deflection angles and shock-wave angles in each region as shown in figure 23 to determine the geometry of the supersonic jet. The subroutine calculates points J1, J2, J3, J4, and J5, as shown in figure 5(a), from the various shock-wave angles and the input value of the transmitted shock length L_{ts}. The subroutine then calculates the jet width for regions 7 and 8 and calls an auxiliary subroutine (JETHEAT) to calculate the stagnation-point heating for an assumed jet impingement normal to the surface. Subroutine JETLOC then returns program execution to EASI.

***Subroutine* JETHEAT.** Subroutine JETHEAT is called by subroutine JETLOC and calculates the two-dimensional maximum heating for supersonic jet impingement by equations (5) and (6). The subroutine calculates flow properties for a normal shock with the flow conditions in regions 7 and 8. Then, an equivalent two-dimensional jet body radius is determined, and the stagnation heat transfer (ref. 7) is calculated for the equivalent body radius and flow conditions of regions 7 and 8 as shown in figure 24. The program then returns execution to subroutine JETLOC.

***Subroutine* MUANDK.** Transport properties, μ and k, used to determine the unit Reynolds number, frozen Prandtl number, and maximum heating, are calculated in subroutine MUANDK. The subroutine is called internally in the EASI program and uses the local gas temperature, constant-pressure specific heat, and the gas molecular weight to calculate the viscosity and thermal conductivity.

The transport properties for low-temperature air ($T \leq 1500$ K) are calculated with Sutherland's law as given in reference 36. For high gas temperatures ($T \geq 2000$ K), the viscosity is calculated by a relationship which uses a Chapman-Enskog treatment of the intermolecular forces for air. (See ref. 4.) Thermal conductivity is calculated from the Eucken semiempirical formula using the air viscosity and constant-pressure specific heat. (See ref. 5.) The calculated thermal conductivity only includes the convective portion of the energy flux and not the energy flux contribution from specie diffusion or radiation; therefore, it is termed as the frozen thermal conductivity.

For gas temperatures in the range $1500 \text{ K} < T < 2000$ K, the viscosity and thermal conductivity are calculated by both methods and the two values are linearly weighted at the given temperature to produce a continuous variation of the two transport properties. The variation of viscosity and thermal conductivity with temperature and pressure are shown in figures 25 and 26, respectively, for air temperatures up to 10 000 K and for pressure from 10^{-3} to 100 atm with the molecular weight and specific heat at a constant pressure from the equilibrium air model.

Prandtl number Pr for the chemically reacting equilibrium gas model is calculated from the viscosity and thermal conductivity as given by subroutine MUANDK and the constant-pressure specific heat as determined by the equilibrium air model (subroutine SUBR1). The variation of constant-pressure specific heat for gas temperatures up to 10 000 K and for pressure from 10^{-3} to 100 atm is shown in figure 27. Because the Prandtl number uses the frozen thermal conductivity in its determination, it is the so-called frozen Prandtl number. The frozen Prandtl number variation with temperature and pressure is shown in figure 28.

Appendix B

Listing of EASI Computer Program

```
     PROGRAM EASI
      IMPLICIT REAL*16 ( A-H, O-Z )
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /START/ PRES1,DENS1,VEL1,THEINC
      COMMON /TOTPROP/BUTO,BURHOO,BUPO,BUEO,BUHO,BUSO,BUPRO
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /WALL/ TW,ITYPE
      COMMON /E/ CPP
      COMMON /GAS/ IGAS,PRNUM
      OPEN(UNIT=2,FILE='SJOUT.DAT',STATUS='NEW')
      OPEN(UNIT=3,FILE='INNAME.DAT',STATUS='OLD')
      NAMELIST /NAMES/ISHOCK,INCON,IGAS,RUNNO,TOBU,POBU,RHOOBU,
     1                T1BU,P1BU,RHO1BU,V1BU,PRNUM,THEIDEG,TWBU,
     2                RBODY,ITYPE,THEBDEG,SL12
      ISHOCK=1
      INCON=1
      IGAS=1
      RUNNO=1.
      TOBU=0.0
      POBU=0.0
      RHOOBU=0.0
      T1BU=0.0
      P1BU=0.0
      RHO1BU=0.0
      V1BU=0.0
      PRNUM=.72
      THEIDEG=1.
      TWBU=1.
      RBODY=1.
      ITYPE=1
      THEBDEG=1.
      SL12=1.
      READ(3,NAMES)
      API=-1.000000
      PI=QACOS(API)
C
C     CONVERT FROM DEGREES TO RADIANS
C
      THEBODY=THEBDEG*PI/180.000
      THEINC=THEIDEG*PI/180.000
C
C     DEFINE CONVERSION FACTORS :
C
C     VERTT - CONVERT FROM KELVIN TO RANKINE
C     VERTP - CONVERT FROM PASCALS TO PSIA
```

```
C     VERTD - CONVERT FROM KG/M**3 TO SLUGS/FT**3
C     VERTE - CONVERT FROM J/KG TO BTU/LBM
C     VERTQ - CONVERT FROM J/(M**2-SEC) TO BTU/(FT**2-SEC)
C     VERTS - CONVERT FROM J/(KG-K) TO BTU/(LBM-R)
C     VERTV - CONVERT FROM M/SEC TO FT/SEC OR M TO FT
C
      VERTT=1.80000
      VERTP=1.0000/6894.757
      VERTD=1.0000/515.379
      VERTE=1.0000/2326.1
      VERTQ=.31721/3600.0000
      VERTS=1.0000/4186.8
      VERTV=1.0000/0.3048
C
C     CONVERT FROM BRITISH UNITS TO SI
C
     VEL1=V1BU/VERTV
     TW=TWBU/VERTT
     RBOD=(RBODY/12.000)/VERTV
       IF(INCON.LT.10) THEN
       TEMP1=T1BU/VERTT
       PRES1=P1BU/VERTP

        DENS1=RHO1BU/VERTD
        ELSE
        TO=TOBU/VERTT
        PO=POBU/VERTP
        RHOO=RHOOBU/VERTD
        ENDIF
C
C     DETERMINE THE APPROPRIATE INPUT STATE PROPERTIES FROM
C     THE VALUE OF INCON GIVEN BELOW :
C
C       INCON =  1 : INPUT FREESTREAM PRESSURE AND DENSITY
C       INCON =  2 : INPUT FREESTREAM TEMPERATURE AND DENSITY
C       INCON =  3 : INPUT FREESTREAM TEMPERATURE AND PRESSURE
C       INCON = 10 : INPUT TOTAL PRESSURE AND DENSITY
C       INCON = 20 : INPUT TOTAL TEMPERATURE AND DENSITY
C       INCON = 30 : INPUT TOTAL TEMPERATURE AND PRESSURE
C
        IF (INCON.EQ.1) THEN
        CALL PRPROP(TEMP1,DENS1,PRES1,EDUM,HDUM,SDUM,SIGDUM)
        CALL TOTAL (TO,RHOO,PO,TEMP1,DENS1,PRES1,VEL1,INCON)
        GOTO 10
        ENDIF
        IF (INCON.EQ.2) THEN
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(TEMP1,DENS1,PRES1,EDUM,HDUM,SDUM,SIGDUM)
          ELSE
          CALL SUBR2(TEMP1,DENS1,PRES1,EDUM,HDUM,SDUM,SIGDUM)
          ENDIF
        CALL TOTAL (TO,RHOO,PO,TEMP1,DENS1,PRES1,VEL1,INCON)
        GOTO 10
        ENDIF
        IF (INCON.EQ.3) THEN
```

```
        CALL TOTAL (T0,RHO0,P0,TEMP1,DENS1,PRES1,VEL1,INCON)
        GOTO 10
        ENDIF
        IF (INCON.EQ.10) THEN
        CALL PRPROP(T0,RHO0,P0,E0,H0,S0,SIG0)
        CALL TOTAL (T0,RHO0,P0,TEMP1,DENS1,PRES1,VEL1,INCON)
        GOTO 10
        ENDIF
        IF (INCON.EQ.20) THEN
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(T0,RHO0,P0,E0,H0,S0,SIG0)
          ELSE
          CALL SUBR2(T0,RHO0,P0,E0,H0,S0,SIG0)
          ENDIF
        CALL TOTAL (T0,RHO0,P0,TEMP1,DENS1,PRES1,VEL1,INCON)
        GOTO 10
        ENDIF
        IF (INCON.EQ.30) THEN
        CALL TOTAL (T0,RHO0,P0,TEMP1,DENS1,PRES1,VEL1,INCON)
        GOTO 10
        ENDIF
   10 CONTINUE
C
C     SOLVE FOR THE TOTAL PROPERTIES AND CONVERT TO BRITISH UNITS
C
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(T0,RHO0,P0,E0,H0,S0,SIG0)
          ELSE
          CALL SUBR2(T0,RHO0,P0,E0,H0,S0,SIG0)
          ENDIF
      CPP0=CPP
      BUT0=T0*VERTT
      BURHO0=RHO0*VERTD
      BUP0=P0*VERTP
      BUE0=E0*VERTE
      BUH0=H0*VERTE
      BUS0=S0*VERTS
      CALL MUANDK (T0,AIRMU0,AIRK0,CPP0,SIG0)
         IF (IGAS.EQ.1) THEN
         BUPR0=AIRMU0*CPP0/AIRK0
         ELSE
         BUPR0=PRNUM
         ENDIF
          IF (IGAS.EQ.1) THEN
          WRITE(2,50)RUNNO
          ELSE
          WRITE(2,55)RUNNO
          ENDIF
      WRITE(2,60)
      WRITE(2,NAMES)
   50 FORMAT(1X,'************************************************',
     1   /,/,1X,' THIS SOLUTION FOR RUN NUMBER ',F4.0,' IS BASED ON',
     2     /,1X,'  AN 11-SPECIE CHEMICALLY REACTING EQUILIBRIUM',
     3     /,1X,'             GAS MODEL FOR AIR',
     4   /,/,1X,'***********************************************',/)
```

```
   55 FORMAT(1X,'***********************************************',
     1   /,/,1X,' THIS SOLUTION FOR RUN NUMBER ',F4.0,' IS BASED ON',
     2     /,1X,' A CALORICALLY PERFECT IDEAL GAS MODEL FOR AIR',
     3   /,/,1X,'***********************************************',/)
   60 FORMAT(/,/,1X,'INPUT  DATA  FROM  NAMELIST  :',/,/)
C
C     TYPE I INTERFERENCE PATTERN
C
        IF(ISHOCK.EQ.1) THEN
        XL=SL12/VERTV
        CALL TYP1(THEBODY)
        CALL SBLLOC (XL,ISHOCK)
        WRITE(2,155)
        CALL QSTAG(PRES1,DENS1,VEL1,RBOD,TW,QW,ITYPE)
        ENDIF
C
C     TYPE II INTERFERENCE PATTERN
C
        IF(ISHOCK.EQ.2) THEN
        XL=SL12/VERTV
        CALL TYP2(THEBODY)
        CALL SBLLOC (XL,ISHOCK)
        WRITE(2,155)
        CALL QSTAG(PRES1,DENS1,VEL1,RBOD,TW,QW,ITYPE)
        ENDIF
C
C     TYPE III INTERFERENCE PATTERN
C
        IF(ISHOCK.EQ.3) THEN
        CALL TYP3(THEBODY)
        XL=SL12/VERTV
        CALL SHERLOC(XL)
        WRITE(2,155)
        CALL QSTAG(PRES1,DENS1,VEL1,RBOD,TW,QW,ITYPE)
        ENDIF
C
C     TYPE IV INTERFERENCE PATTERN
C
        IF(ISHOCK.EQ.4) THEN
        CALL TYP4
        CALL JETLOC(SL12)
        WRITE(2,155)
        CALL QSTAG(PRES1,DENS1,VEL1,RBOD,TW,QW,ITYPE)
        ENDIF
C
C     TYPE V INTERFERENCE PATTERN
C
        IF(ISHOCK.EQ.5) THEN
        XL=SL12/VERTV
        CALL TYP5(THEBODY)
        CALL SBLLOC (XL,ISHOCK)
        WRITE(2,155)
        CALL QSTAG(PRES1,DENS1,VEL1,RBOD,TW,QW,ITYPE)
        ENDIF
C
```

```
C     TYPE VI INTERFERENCE PATTERN
C
         IF(ISHOCK.EQ.6) THEN
         XL=SL12/VERTV
         CALL TYP6(THEBODY)
         CALL SBLLOC (XL,ISHOCK)
         WRITE(2,155)
         CALL QSTAG(PRES1,DENS1,VEL1,RBOD,TW,QW,ITYPE)
         ENDIF
  155 FORMAT(/,/,1X'*****  STAGNATION CONDITIONS WITHOUT INTERFERENCE',
     1'  *****',/)
      STOP
      END
C************************************************************C
C
C               TYPE I INTERFERENCE
C
C************************************************************C
      SUBROUTINE TYP1(THE2)
      IMPLICIT REAL*16 ( A-H, O-Z )
C
C
C     SUBROUTINE TYP1 USES AN 11-SPECIE EQUILIBRIUM CHEMISTRY MODEL TO
C     CALCULATE GAS PROPERTIES FOR A TYPE I INTERFERENCE PATTERN
C
      REAL*16 M1,M2,M3,M4,M5,M6,M7,M8,M9,MU6,MU7,MU8,MU9
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10),MW(10)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1                MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
      COMMON /BAMAX/ BTM
      COMMON /START/ PRES1,DENS1,VEL1,THEINC
      COMMON /TOTPROP/BUTO,BURHOO,BUPO,BUEO,BUHO,BUSO,BUPRO
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
      EQUIVALENCE (M1,MACHNO(1)),(M2,MACHNO(2)),(M3,MACHNO(3)),
     1            (M4,MACHNO(4)),(M5,MACHNO(5)),(M6,MACHNO(6)),
     2            (M7,MACHNO(7)),(M8,MACHNO(8))
      EQUIVALENCE (T1,TEMP(1)),(T2,TEMP(2)),(T3,TEMP(3)),(T4,TEMP(4)),
     1            (T5,TEMP(5)),(T6,TEMP(6)),(T7,TEMP(7)),(T8,TEMP(8))
      EQUIVALENCE (V1,VEL(1)),(V2,VEL(2)),(V3,VEL(3)),(V4,VEL(4)),
     1            (V5,VEL(5)),(V6,VEL(6)),(V7,VEL(7)),(V8,VEL(8))
      EQUIVALENCE (P1,PRES(1)),(P2,PRES(2)),(P3,PRES(3)),(P4,PRES(4)),
     1            (P5,PRES(5)),(P6,PRES(6)),(P7,PRES(7)),(P8,PRES(8))
      EQUIVALENCE (RHO1,DENS(1)),(RHO2,DENS(2)),(RHO3,DENS(3)),
     1            (RHO4,DENS(4)),(RHO5,DENS(5)),(RHO6,DENS(6)),
     2            (RHO7,DENS(7)),(RHO8,DENS(8))
      EQUIVALENCE (E1,INTER(1)),(E2,INTER(2)),(E3,INTER(3)),
```

```
     1              (E4,INTER(4)),(E5,INTER(5)),(E6,INTER(6)),
     2              (E7,INTER(7)),(E8,INTER(8))
      EQUIVALENCE (H1,ENTHA(1)),(H2,ENTHA(2)),(H3,ENTHA(3)),
     1              (H4,ENTHA(4)),(H5,ENTHA(5)),(H6,ENTHA(6)),
     2              (H7,ENTHA(7)),(H8,ENTHA(8))
      EQUIVALENCE (S1,ENTROP(1)),(S2,ENTROP(2)),(S3,ENTROP(3)),
     1              (S4,ENTROP(4)),(S5,ENTROP(5)),(S6,ENTROP(6)),
     2              (S7,ENTROP(7)),(S8,ENTROP(8))
      EQUIVALENCE (SIG1,MW(1)),(SIG2,MW(2)),(SIG3,MW(3)),(SIG4,MW(4)),
     1              (SIG5,MW(5)),(SIG6,MW(6)),(SIG7,MW(7)),(SIG8,MW(8))
      TWO=2.000000000
      THETA2=THE2
      THETA3=THEINC
      TOLER=1.E-4
      API=-1.0
      PI=QACOS(API)

      P1=PRES1
      RHO1=DENS1
      V1=VEL1
      WRITE(2,150)
C
C     SOLVE FOR REGIONS 2 AND 3 (WEAK SHOCK SOLUTION)
C     AND WRITE A WARNING IF THETA > THETA-MAX
C
      CALL FINDB(P1,RHO1,V1,PM,RHOM,VM,THETAM,BETAM,1)
        IF(QABS(THETA2).GT.THETAM) THEN
        WRITE(2,100) 2
        STOP
        ENDIF
        IF(THETA3.GT.THETAM) THEN
        WRITE(2,100) 3
        STOP
        ENDIF
      BTM=BETAM
      CALL FINDB(P1,RHO1,V1,P2,RHO2,V2,THETA2,BETA2,3)
      CALL FINDB(P1,RHO1,V1,P3,RHO3,V3,THETA3,BETA3,3)
C
C     FIND THETA-MAX FOR REGIONS 4 AND 5
C
      CALL FINDB(P2,RHO2,V2,P4M,RHO4M,V4M,THETA4M,BETA4M,1)
      CALL FINDB(P3,RHO3,V3,P5M,RHO5M,V5M,THETA5M,BETA5M,1)
C
C     SET LIMITS ON THE SHEAR LAYER TURNING ANGLE ( PHI )
C
      CALL NORMAL (P1,RHO1,V1,P1NOR,RHO1NOR,V1NOR)
      CALL FINDB(P2,RHO2,V2,P1NOR,RHODUM4,VDUM4,THE4,BET4,6)
      CALL FINDB(P3,RHO3,V3,P1NOR,RHODUM5,VDUM5,THE5,BET4,7)
      PHIMAX=THETA2+THE4
      PHIMIN=THETA3+THE5
C     PHIMAX=THETA2+THETA4M
C     PHIMIN=THETA3-THETA5M
C
C     CHECK FOR A TYPE II INTERFERENCE
C
```

```
        IF(PHIMIN.GT.PHIMAX) THEN
        WRITE(2,200)
        STOP
        ENDIF
C
C     SOLVE FOR REGIONS 4 AND 5 WITH THE CONDITIONS THAT :
C          1 - ABSOLUTE THETA (4) EQUALS ABSOLUTE THETA (5)
C          2 - P (4)  EQUALS  P (5)
C          3 - SOLUTION FOR REGIONS 4 AND 5 ARE SUPERSONIC
C
      I=1
   10 PHI=(PHIMAX+PHIMIN)/TWO
      THETA4=PHI-THETA2
      BTM=BETA4M
      CALL FINDB(P2,RHO2,V2,P4,RHO4,V4,THETA4,BETA4,3)
      THETA5=PHI-THETA3
      BTM=BETA5M
      CALL FINDB(P3,RHO3,V3,P5,RHO5,V5,THETA5,BETA5,3)
C     WRITE(2,*)PHI,P4,P5
      PCHECK=QABS((P4-P5)/P4)
      IF(PCHECK.LT.TOLER) GOTO 20
        IF(I.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      I=I+1
        IF(P5.GT.P4) THEN
        PHIMIN=PHI
        ELSE
        PHIMAX=PHI
        ENDIF
      GOTO 10
   20 CONTINUE
C
C     SOLVE FOR REGION 6
C
      CALL FINDB(P4,RHO4,V4,P6M,RHO6M,V6M,THETA6M,BETA6M,1)
        IF(THETA6M.LE.QABS(THETA4)) THEN
        CALL NORMAL (P4,RHO4,V4,P6,RHO6,V6)
        THETA6=-THETA4
        BETA6=-PI/TWO+THETA6
        ELSE
        THETA6=-THETA4
        BTM=BETA6M
        CALL FINDB(P4,RHO4,V4,P6,RHO6,V6,THETA6,BETA6,3)
        ENDIF
C
C     DEFINE PROPERTIES IN EACH REGION
C
   30 CALL PRPROP (T1,RHO1,P1,E1,H1,S1,SIG1)
      SPHEAT(1)=CPP
      CALL PRPROP (T2,RHO2,P2,E2,H2,S2,SIG2)
      SPHEAT(2)=CPP
      CALL PRPROP (T3,RHO3,P3,E3,H3,S3,SIG3)
      SPHEAT(3)=CPP
```

```
      CALL PRPROP (T4,RHO4,P4,E4,H4,S4,SIG4)
      SPHEAT(4)=CPP
      CALL PRPROP (T5,RHO5,P5,E5,H5,S5,SIG5)
      SPHEAT(5)=CPP
      CALL PRPROP (T6,RHO6,P6,E6,H6,S6,SIG6)
      SPHEAT(6)=CPP
      CALL SOUND (P1,RHO1,A1)
      CALL SOUND (P2,RHO2,A2)
      CALL SOUND (P3,RHO3,A3)
      CALL SOUND (P4,RHO4,A4)
      CALL SOUND (P5,RHO5,A5)
      CALL SOUND (P6,RHO6,A6)
      M1=V1/A1
      M2=V2/A2
      M3=V3/A3
      M4=V4/A4
      M5=V5/A5
      M6=V6/A6
C
C     CALCULATE UNIT REYNOLDS NUMBER PER FOOT
C     AND PRANDLT NUMBER FOR EACH REGION
C
      DO 45 I=1,6
      CALL MUANDK (TEMP(I),VISC(I),TCON(I),SPHEAT(I),MW(I))
         IF (IGAS.EQ.1) THEN
         PRNO(I)=VISC(I)*SPHEAT(I)/TCON(I)
         ELSE
         PRNO(I)=PRNUM
         ENDIF
      REX(I)=(VEL(I)*DENS(I)/VISC(I))/VERTV
   45 CONTINUE
      CALL PRNTOUT(6)
C
C     FORMAT STATEMENTS
C
  100 FORMAT(/,1X,'******** WARNING ********',/,1X,'THETA(',I1,
     1       ') IS GREATER THAN THETA-MAX')
  150 FORMAT(//,1X,'CALCULATION FOR TYPE I INTERFERENCE'/)
  200 FORMAT(/,1X,'FOR THESE CONDITIONS, TRY A TYPE II INTERFERENCE')
  500 FORMAT(/,1X,'NO CONVERGENCE IN TYP1 AFTER 50 ITERATIONS')
      RETURN
      END
C*********************************************************C
C
C                TYPE II INTERFERENCE
C
C*********************************************************C
      SUBROUTINE TYP2(THE2)
      IMPLICIT REAL*16 ( A-H, O-Z )
C
C
C     SUBROUTINE TYP2 USES AN 11-SPECIE EQUILIBRIUM CHEMISTRY MODEL TO
C     CALCULATE GAS PROPERTIES FOR A TYPE II INTERFERENCE PATTERN
C
      REAL*16 M1,M2,M3,M4,M5,M6,M7,M8,M9,MU6,MU7,MU8,MU9
```

```
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10),MW(10)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1                MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
      COMMON /BAMAX/ BTM
      COMMON /START/ PRES1,DENS1,VEL1,THEINC
      COMMON /TOTPROP/BUTO,BURHOO,BUPO,BUEO,BUHO,BUSO,BUPRO
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
      EQUIVALENCE (M1,MACHNO(1)),(M2,MACHNO(2)),(M3,MACHNO(3)),
     1            (M4,MACHNO(4)),(M5,MACHNO(5)),(M6,MACHNO(6)),
     2            (M7,MACHNO(7)),(M8,MACHNO(8))
      EQUIVALENCE (T1,TEMP(1)),(T2,TEMP(2)),(T3,TEMP(3)),(T4,TEMP(4)),
     1            (T5,TEMP(5)),(T6,TEMP(6)),(T7,TEMP(7)),(T8,TEMP(8))
      EQUIVALENCE (V1,VEL(1)),(V2,VEL(2)),(V3,VEL(3)),(V4,VEL(4)),
     1            (V5,VEL(5)),(V6,VEL(6)),(V7,VEL(7)),(V8,VEL(8))
      EQUIVALENCE (P1,PRES(1)),(P2,PRES(2)),(P3,PRES(3)),(P4,PRES(4)),
     1            (P5,PRES(5)),(P6,PRES(6)),(P7,PRES(7)),(P8,PRES(8))
      EQUIVALENCE (RHO1,DENS(1)),(RHO2,DENS(2)),(RHO3,DENS(3)),
     1            (RHO4,DENS(4)),(RHO5,DENS(5)),(RHO6,DENS(6)),
     2            (RHO7,DENS(7)),(RHO8,DENS(8))
      EQUIVALENCE (E1,INTER(1)),(E2,INTER(2)),(E3,INTER(3)),
     1            (E4,INTER(4)),(E5,INTER(5)),(E6,INTER(6)),
     2            (E7,INTER(7)),(E8,INTER(8))
      EQUIVALENCE (H1,ENTHA(1)),(H2,ENTHA(2)),(H3,ENTHA(3)),
     1            (H4,ENTHA(4)),(H5,ENTHA(5)),(H6,ENTHA(6)),
     2            (H7,ENTHA(7)),(H8,ENTHA(8))
      EQUIVALENCE (S1,ENTROP(1)),(S2,ENTROP(2)),(S3,ENTROP(3)),
     1            (S4,ENTROP(4)),(S5,ENTROP(5)),(S6,ENTROP(6)),
     2            (S7,ENTROP(7)),(S8,ENTROP(8))
      EQUIVALENCE (SIG1,MW(1)),(SIG2,MW(2)),(SIG3,MW(3)),(SIG4,MW(4)),
     1            (SIG5,MW(5)),(SIG6,MW(6)),(SIG7,MW(7)),(SIG8,MW(8))
      TWO=2.000000000
      THETA2=THE2
      THETA3=THEINC
      TOLER=1.E-4
      API=-1.0
      PI=QACOS(API)
      P1=PRES1
      RHO1=DENS1
      V1=VEL1
      WRITE(2,150)
C
C     SOLVE FOR REGIONS 2 AND 3 (WEAK SHOCK SOLUTION)
C     AND WRITE A WARNING IF THETA > THETA-MAX
C
C     CHECK FOR A TYPE III INTERFERENCE
C
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      CALL FINDB(P1,RHO1,V1,PM,RHOM,VM,THETAM,BETAM,1)
        IF(QABS(THETA2).GT.THETAM) THEN
        WRITE(2,100) 2
        WRITE(2,200)
        STOP
        ENDIF
        IF(THETA3.GT.THETAM) THEN
        WRITE(2,100) 3
        STOP
        ENDIF
      BTM=BETAM
      CALL FINDB(P1,RHO1,V1,P2,RHO2,V2,THETA2,BETA2,3)
      CALL FINDB(P1,RHO1,V1,P3,RHO3,V3,THETA3,BETA3,3)
C
C     SOLVE FOR REGIONS 4 AND 5 WITH THE CONDITIONS THAT :
C          1 - ABSOLUTE THETA (4) EQUALS ABSOLUTE THETA (5)
C          2 - P (4)  EQUALS  P (5)
C          3 - SOLUTION FOR REGION 4 IS SUPERSONIC
C          4 - SOLUTION FOR REGION 5 IS SUBSONIC
C
      CALL FINDB(P2,RHO2,V2,P4M,RHO4M,V4M,THETA4M,BETA4M,1)
      THETA4=THETA4M
      THETA5=THETA2+THETA4
      BTM=BETAM
      CALL FINDB(P1,RHO1,V1,P5,RHO5,V5,THETA5,BETA5,5)
      P4=P5
C
C     CONVERGE TO THE CONDITIONS GIVEN ABOVE
C
      LOOP1=0
   10 LOOP1=LOOP1+1
      CALL FINDB(P2,RHO2,V2,P4,RHO4,V4,THETA4,BETA4,6)
      THETA5=THETA2+THETA4
      THEDIF=QABS(THETA5-THE50)
      IF(THEDIF.LT.TOLER) GOTO 20
C     WRITE(2,*)THE50,THETA5
        IF(LOOP1.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      BTM=BETAM
      CALL FINDB(P1,RHO1,V1,P5,RHO5,V5,THETA5,BETA5,5)
      THE50=THETA5
      P4=P5
      GOTO 10
   20 CONTINUE
C
C     SOLVE FOR REGIONS 7 AND 8 WITH THE CONDITIONS THAT :
C          1 - ABSOLUTE THETA (7) EQUALS ABSOLUTE THETA (8)
C          2 - P (7)  EQUALS  P (8)
C          3 - SOLUTION FOR REGION 7 IS SUPERSONIC
C          4 - SOLUTION FOR REGION 8 IS SUBSONIC
C
      CALL NORMAL (P1,RHO1,V1,P8N,RHO8N,V8N)
      THE80=0.000000
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      P7=P8N
      LOOP2=0
   30 LOOP2=LOOP2+1
      CALL FINDB(P3,RHO3,V3,P7,RHO7,V7,THETA7,BETA7,7)
      THETA8=THETA3+THETA7
      THEDIF=QABS(THETA8-THE8O)
      IF(THEDIF.LT.TOLER) GOTO 40
C     WRITE(2,*)THE8O,THETA8
        IF(LOOP2.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      BTM=BETAM
      CALL FINDB(P1,RHO1,V1,P8,RHO8,V8,THETA8,BETA8,5)
      THE8O=THETA8
      P7=P8
      GOTO 30
   40 CONTINUE
C
C     CHECK FOR A TYPE I INTERFERENCE
C
        ABST7=THETA3+THETA7
        ABST4=THETA2+THETA4
        IF(ABST7.LT.ABST4) THEN
        WRITE(2,250)
        STOP
        ENDIF
C
C     SOLVE FOR REGION 6
C
      CALL FINDB(P4,RHO4,V4,P6M,RHO6M,V6M,THETA6M,BETA6M,1)
        IF(THETA6M.LE.QABS(THETA4)) THEN
        CALL NORMAL (P4,RHO4,V4,P6,RHO6,V6)
        THETA6=-THETA4
        BETA6=-PI/TWO+THETA6
        ELSE
        THETA6=-THETA4
        BTM=BETA6M
        CALL FINDB(P4,RHO4,V4,P6,RHO6,V6,THETA6,BETA6,3)
        ENDIF
C
C     DEFINE PROPERTIES IN EACH REGION
C
      CALL PRPROP (T1,RHO1,P1,E1,H1,S1,SIG1)
      SPHEAT(1)=CPP
      CALL PRPROP (T2,RHO2,P2,E2,H2,S2,SIG2)
      SPHEAT(2)=CPP
      CALL PRPROP (T3,RHO3,P3,E3,H3,S3,SIG3)
      SPHEAT(3)=CPP
      CALL PRPROP (T4,RHO4,P4,E4,H4,S4,SIG4)
      SPHEAT(4)=CPP
      CALL PRPROP (T5,RHO5,P5,E5,H5,S5,SIG5)
      SPHEAT(5)=CPP
      CALL PRPROP (T6,RHO6,P6,E6,H6,S6,SIG6)
      SPHEAT(6)=CPP
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      CALL PRPROP (T7,RHO7,P7,E7,H7,S7,SIG7)
      SPHEAT(7)=CPP
      CALL PRPROP (T8,RHO8,P8,E8,H8,S8,SIG8)
      SPHEAT(8)=CPP
      CALL SOUND (P1,RHO1,A1)
      CALL SOUND (P2,RHO2,A2)
      CALL SOUND (P3,RHO3,A3)
      CALL SOUND (P4,RHO4,A4)
      CALL SOUND (P5,RHO5,A5)
      CALL SOUND (P6,RHO6,A6)
      CALL SOUND (P7,RHO7,A7)
      CALL SOUND (P8,RHO8,A8)
      M1=V1/A1
      M2=V2/A2
      M3=V3/A3
      M4=V4/A4
      M5=V5/A5
      M6=V6/A6
      M7=V7/A7
      M8=V8/A8
C
C     CALCULATE UNIT REYNOLDS NUMBER PER FOOT
C     AND PRANDLT NUMBER FOR EACH REGION
C
      DO 45 I=1,8
      CALL MUANDK (TEMP(I),VISC(I),TCON(I),SPHEAT(I),MW(I))
         IF (IGAS.EQ.1) THEN
         PRNO(I)=VISC(I)*SPHEAT(I)/TCON(I)
         ELSE
         PRNO(I)=PRNUM
         ENDIF
      REX(I)=(VEL(I)*DENS(I)/VISC(I))/VERTV
   45 CONTINUE
      CALL PRNTOUT(8)
C
C     FORMAT STATEMENTS
C
  100 FORMAT(/,1X,'******** WARNING ********',/,1X,'THETA(',I1,
     1       ') IS GREATER THAN THETA-MAX')
  150 FORMAT(//,1X,'CALCULATION FOR TYPE II INTERFERENCE'/)
  200 FORMAT(/,1X,'FOR THESE CONDITIONS, TRY A TYPE III INTERFERENCE')
  250 FORMAT(/,1X,'FOR THESE CONDITIONS, TRY A TYPE I INTERFERENCE')
  500 FORMAT(/,1X,'NO CONVERGENCE IN TYP2 AFTER 50 ITERATIONS')
      RETURN
      END
C********************************************************C
C
C              TYPE III INTERFERENCE
C
C********************************************************C
      SUBROUTINE TYP3(THETA5A)
      IMPLICIT REAL*16 ( A-H, O-Z )
C
C
C     SUBROUTINE TYP3 USES AN 11-SPECIE EQUILIBRIUM CHEMISTRY MODEL TO
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```
C     CALCULATE GAS PROPERTIES FOR A TYPE III INTERFERENCE PATTERN
C
      REAL*16 M1,M2,M3,M4,M5,M6,M7,M8,M9,MU6,MU7,MU8,MU9
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10),MW(10)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1               MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
      COMMON /BAMAX/ BTM
      COMMON /START/ PRES1,DENS1,VEL1,THEINC
      COMMON /TOTPROP/BUTO,BURHOO,BUPO,BUEO,BUHO,BUSO,BUPRO
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
      EQUIVALENCE (M1,MACHNO(1)),(M2,MACHNO(2)),(M3,MACHNO(3)),
     1            (M4,MACHNO(4)),(M5,MACHNO(5)),(M6,MACHNO(6)),
     2            (M7,MACHNO(7)),(M8,MACHNO(8))
      EQUIVALENCE (T1,TEMP(1)),(T2,TEMP(2)),(T3,TEMP(3)),(T4,TEMP(4)),
     1            (T5,TEMP(5)),(T6,TEMP(6)),(T7,TEMP(7)),(T8,TEMP(8))
      EQUIVALENCE (V1,VEL(1)),(V2,VEL(2)),(V3,VEL(3)),(V4,VEL(4)),
     1            (V5,VEL(5)),(V6,VEL(6)),(V7,VEL(7)),(V8,VEL(8))
      EQUIVALENCE (P1,PRES(1)),(P2,PRES(2)),(P3,PRES(3)),(P4,PRES(4)),
     1            (P5,PRES(5)),(P6,PRES(6)),(P7,PRES(7)),(P8,PRES(8))
      EQUIVALENCE (RHO1,DENS(1)),(RHO2,DENS(2)),(RHO3,DENS(3)),
     1            (RHO4,DENS(4)),(RHO5,DENS(5)),(RHO6,DENS(6)),
     2            (RHO7,DENS(7)),(RHO8,DENS(8))
      EQUIVALENCE (E1,INTER(1)),(E2,INTER(2)),(E3,INTER(3)),
     1            (E4,INTER(4)),(E5,INTER(5)),(E6,INTER(6)),
     2            (E7,INTER(7)),(E8,INTER(8))
      EQUIVALENCE (H1,ENTHA(1)),(H2,ENTHA(2)),(H3,ENTHA(3)),
     1            (H4,ENTHA(4)),(H5,ENTHA(5)),(H6,ENTHA(6)),
     2            (H7,ENTHA(7)),(H8,ENTHA(8))
      EQUIVALENCE (S1,ENTROP(1)),(S2,ENTROP(2)),(S3,ENTROP(3)),
     1            (S4,ENTROP(4)),(S5,ENTROP(5)),(S6,ENTROP(6)),
     2            (S7,ENTROP(7)),(S8,ENTROP(8))
      EQUIVALENCE (SIG1,MW(1)),(SIG2,MW(2)),(SIG3,MW(3)),(SIG4,MW(4)),
     1            (SIG5,MW(5)),(SIG6,MW(6)),(SIG7,MW(7)),(SIG8,MW(8))
      THETA3=THEINC
      TOLER=1.E-4
      API=-1.0
      PI=QACOS(API)
      P1=PRES1
      RHO1=DENS1
      V1=VEL1
      WRITE(2,150)
C
C     SOLVE FOR REGION 3 (WEAK SHOCK SOLUTION)
C
      CALL FINDB(P1,RHO1,V1,P3,RHO3,V3,THETA3,BETA3,2)
      CALL FINDB(P3,RHO3,V3,P4M,RHO4M,V4M,THETA4M,BETA4M,1)
```

```
C
C     SOLVE FOR REGIONS 2 AND 4 WITH THE CONDITIONS THAT :
C          1 - ABSOLUTE THETA (2) EQUALS ABSOLUTE THETA (4)
C          2 - P (2)  EQUALS  P (4)
C          3 - SOLUTION FOR REGION 2 IS SUBSONIC
C          4 - SOLUTION FOR REGION 4 IS SUPERSONIC
C
      CALL NORMAL (P1,RHO1,V1,P2N,RHO2N,V2N)
      THE20=0.000000
      P4=P2N
      CALL FINDB(P1,RHO1,V1,P2M,RHO2M,V2M,THETA2M,BETA2M,1)
      BTM=BETA2M
      ILOOP=0
   10 ILOOP=ILOOP+1
      CALL FINDB(P3,RHO3,V3,P4,RHO4,V4,THETA4,BETA4,7)
      THETA2=THETA3+THETA4
      THEDIF=QABS(THETA2-THE20)
      IF(THEDIF.LT.TOLER) GOTO 20
C     WRITE(2,*)THE20,THETA2
      CALL FINDB(P1,RHO1,V1,P2,RHO2,V2,THETA2,BETA2,5)
      THE20=THETA2
      P4=P2
        IF(ILOOP.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      GOTO 10
   20 CONTINUE
C
C     SOLVE FOR REGION 5
C
C     THETA5A (NEGATIVE ANGLE RELATIVE TO THE FREESTREAM) IS
C     THE ABSOLUTE ANGLE ON THE CYLINDER OF THE SHEAR LAYER
C     AND WILL BE AN INPUT VARIABLE
C
      CALL FINDB(P4,RHO4,V4,P5M,RHO5M,V5M,THETA5M,BETA5M,1)
      THETA4A=THETA4+THETA3
      THETA5=THETA5A-THETA4A
C
C      CHECK FOR A TYPE II INTERFERENCE
C
         IF(THETA5.GT.0.0000) THEN
         WRITE(2,155)
         STOP
         ENDIF
C
C      IF THETA5 > THETA5-MAX  REDEFINE THETA5 = THETA5-MAX
C      TO CONTINUE COMPUTATION
C
C      CHECK FOR A TYPE IV INTERFERENCE
C
         IF (QABS(THETA5).GT.THETA5M) THEN
         WRITE(2,145)
         THETA5=-THETA5M
         BETA5=-BETA5M
```

```
          P5=P5M
          RHO5=RHO5M
          V5=V5M
          GOTO 30
          ENDIF
       BTM=BETA5M
C
C      FIND THE WEAK SHOCK SOLUTION FROM REGION 4 TO 5
C
       CALL FINDB(P4,RHO4,V4,P5,RHO5,V5,THETA5,BETA5,3)
C
C      CALCULATE AND WRITE PROPERTIES OF THE 5 REGIONS
C
   30  CALL PRPROP (T1,RHO1,P1,E1,H1,S1,SIG1)
       SPHEAT(1)=CPP
       CALL PRPROP (T2,RHO2,P2,E2,H2,S2,SIG2)
       SPHEAT(2)=CPP
       CALL PRPROP (T3,RHO3,P3,E3,H3,S3,SIG3)
       SPHEAT(3)=CPP
       CALL PRPROP (T4,RHO4,P4,E4,H4,S4,SIG4)
       SPHEAT(4)=CPP
       CALL PRPROP (T5,RHO5,P5,E5,H5,S5,SIG5)
       SPHEAT(5)=CPP
       CALL SOUND (P1,RHO1,A1)
       CALL SOUND (P2,RHO2,A2)
       CALL SOUND (P3,RHO3,A3)
       CALL SOUND (P4,RHO4,A4)
       CALL SOUND (P5,RHO5,A5)
       M1=V1/A1
       M2=V2/A2
       M3=V3/A3
       M4=V4/A4
       M5=V5/A5
C
C      CALCULATE UNIT REYNOLDS NUMBER PER FOOT
C      AND PRANDLT NUMBER FOR EACH REGION
C
       DO 45 I=1,5
       CALL MUANDK (TEMP(I),VISC(I),TCON(I),SPHEAT(I),MW(I))
          IF (IGAS.EQ.1) THEN
          PRNO(I)=VISC(I)*SPHEAT(I)/TCON(I)
          ELSE
          PRNO(I)=PRNUM
          ENDIF
       REX(I)=(VEL(I)*DENS(I)/VISC(I))/VERTV
   45  CONTINUE
       CALL PRNTOUT(5)
C
C      FORMAT STATEMENTS
C
  145  FORMAT(/,1X,'                ******** NOTE ********',
     1 /,1X,'      INPUT THETA(5) IS GREATER THAN THETA(5)-MAX',
     2 /,1X,'TRY A TYPE IV INTERFERENCE FOR THIS WALL TURNING ANGLE',
     3 /,1X,'          HOWEVER FOR THIS CASE :',
     4 /,1X,'LET THETA(5) EQUAL THETA(5)-MAX TO CONTINUE COMPUTATION',/)
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 150 FORMAT(//,1X,'CALCULATION FOR TYPE III INTERFERENCE',/)
 155 FORMAT(1X,'FOR THESE CONDITIONS, TRY A TYPE II INTERFERENCE')
 500 FORMAT(/,1X,'NO CONVERGENCE IN TYP3 AFTER 50 ITERATIONS')
     RETURN
     END
C***********************************************************C
C
C               TYPE IV INTERFERENCE
C
C***********************************************************C
      SUBROUTINE TYP4
      IMPLICIT REAL*16 ( A-H, O-Z )
C
C
C     SUBROUTINE TYP4 USES AN 11-SPECIE EQUILIBRIUM CHEMISTRY MODEL TO
C     CALCULATE GAS PROPERTIES FOR A TYPE IV INTERFERENCE PATTERN
C
      REAL*16 M1,M2,M3,M4,M5,M6,M7,M8,M9,MU6,MU7,MU8,MU9
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10),MW(10)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1                MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
      COMMON /BAMAX/ BTM
      COMMON /START/ PRES1,DENS1,VEL1,THEINC
      COMMON /TOTPROP/BUTO,BURHOO,BUPO,BUEO,BUHO,BUSO,BUPRO
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
      EQUIVALENCE (M1,MACHNO(1)),(M2,MACHNO(2)),(M3,MACHNO(3)),
     1            (M4,MACHNO(4)),(M5,MACHNO(5)),(M6,MACHNO(6)),
     2            (M7,MACHNO(7)),(M8,MACHNO(8))
      EQUIVALENCE (T1,TEMP(1)),(T2,TEMP(2)),(T3,TEMP(3)),(T4,TEMP(4)),
     1            (T5,TEMP(5)),(T6,TEMP(6)),(T7,TEMP(7)),(T8,TEMP(8))
      EQUIVALENCE (V1,VEL(1)),(V2,VEL(2)),(V3,VEL(3)),(V4,VEL(4)),
     1            (V5,VEL(5)),(V6,VEL(6)),(V7,VEL(7)),(V8,VEL(8))
      EQUIVALENCE (P1,PRES(1)),(P2,PRES(2)),(P3,PRES(3)),(P4,PRES(4)),
     1            (P5,PRES(5)),(P6,PRES(6)),(P7,PRES(7)),(P8,PRES(8))
      EQUIVALENCE (RHO1,DENS(1)),(RHO2,DENS(2)),(RHO3,DENS(3)),
     1            (RHO4,DENS(4)),(RHO5,DENS(5)),(RHO6,DENS(6)),
     2            (RHO7,DENS(7)),(RHO8,DENS(8))
      EQUIVALENCE (E1,INTER(1)),(E2,INTER(2)),(E3,INTER(3)),
     1            (E4,INTER(4)),(E5,INTER(5)),(E6,INTER(6)),
     2            (E7,INTER(7)),(E8,INTER(8))
      EQUIVALENCE (H1,ENTHA(1)),(H2,ENTHA(2)),(H3,ENTHA(3)),
     1            (H4,ENTHA(4)),(H5,ENTHA(5)),(H6,ENTHA(6)),
     2            (H7,ENTHA(7)),(H8,ENTHA(8))
      EQUIVALENCE (S1,ENTROP(1)),(S2,ENTROP(2)),(S3,ENTROP(3)),
     1            (S4,ENTROP(4)),(S5,ENTROP(5)),(S6,ENTROP(6)),
     2            (S7,ENTROP(7)),(S8,ENTROP(8))
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```
      EQUIVALENCE (SIG1,MW(1)),(SIG2,MW(2)),(SIG3,MW(3)),(SIG4,MW(4)),
     1            (SIG5,MW(5)),(SIG6,MW(6)),(SIG7,MW(7)),(SIG8,MW(8))
      THETA3=THEINC
      TOLER=1.E-4
      API=-1.0
      PI=QACOS(API)
      P1=PRES1
      RHO1=DENS1
      V1=VEL1
      WRITE(2,150)
C
C     SOLVE FOR REGION 3 (WEAK SHOCK SOLUTION)
C
      CALL FINDB(P1,RHO1,V1,P3,RHO3,V3,THETA3,BETA3,2)
      CALL FINDB(P3,RHO3,V3,P4M,RHO4M,V4M,THETA4M,BETA4M,1)
C
C     SOLVE FOR REGIONS 2 AND 4 WITH THE CONDITIONS THAT :
C          1 - ABSOLUTE THETA (2) EQUALS ABSOLUTE THETA (4)
C          2 - P (2)  EQUALS  P (4)
C          3 - SOLUTION FOR REGION 2 IS SUBSONIC
C          4 - SOLUTION FOR REGION 4 IS SUPERSONIC
C
      CALL NORMAL (P1,RHO1,V1,P2N,RHO2N,V2N)
      THE20=0.000000
      P4=P2N
      CALL FINDB(P1,RHO1,V1,P2M,RHO2M,V2M,THETA2M,BETA2M,1)
      BTM=BETA2M
      ILOOP1=0
   10 ILOOP1=ILOOP1+1
      CALL FINDB(P3,RHO3,V3,P4,RHO4,V4,THETA4,BETA4,7)
      THETA2=THETA3+THETA4
      THEDIF=QABS(THETA2-THE20)
      IF(THEDIF.LT.TOLER) GOTO 20
C     WRITE(2,*)THE20,THETA2
      CALL FINDB(P1,RHO1,V1,P2,RHO2,V2,THETA2,BETA2,5)
      THE20=THETA2
      P4=P2
        IF(ILOOP1.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      GOTO 10
   20 CONTINUE
C
C     FIND THE APPROXIMATE BODY ANGLE LIMITS
C     FOR THE TYPE IV INTERFERENCE
C
      DEG=180.0000/PI
      CALL FINDB(P4,RHO4,V4,P5M,RHO5M,V5M,THETA5M,BETA5M,1)
      TBODMAX=90.0000-(THETA3+THETA4M)*DEG
      TBODMIN=-90.0000-(THETA3+THETA4-THETA5M)*DEG
      WRITE(2,140)TBODMAX,TBODMIN
C
C     SOLVE FOR REGIONS 5 AND 6 WITH THE CONDITIONS THAT :
C          1 - ABSOLUTE THETA (5) EQUALS ABSOLUTE THETA (6)
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```
C          2 - P (5)  EQUALS  P (6)
C          3 - SOLUTION FOR REGION 5 IS SUBSONIC
C          4 - SOLUTION FOR REGION 6 IS SUPERSONIC
C
      BTM=BETA4M
      CALL NORMAL(P3,RHO3,V3,P5N,RHO5N,V5N)
      THE50=0.0000000
      P6=P5N
      ILOOP2=0
   30 ILOOP2=ILOOP2+1
      CALL FINDB(P4,RHO4,V4,P6,RHO6,V6,THETA6,BETA6,6)
      THETA5=THETA6+THETA4
      THEDIF=QABS(THETA5-THE50)
      IF(THEDIF.LT.TOLER) GOTO 40
C     WRITE(2,*)THE50,THETA5
      CALL FINDB(P3,RHO3,V3,P5,RHO5,V5,THETA5,BETA5,5)
      THE50=THETA5
      P6=P5
        IF(ILOOP2.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      GOTO 30
C
C     SETUP FOR AN ISENTROPIC EXPANSION FROM REGION 6 TO 7
C
   40 P7=P2
      CALL EXPAND (P6,RHO6,V6,P7,RHO7,V7,THETA7)
      CALL PRPROP(T6,RHO6,P6,E6,H6,S6,SIG6)
      SPHEAT(6)=CPP
      CALL PRPROP(T7,RHO7,P7,E7,H7,S7,SIG7)
      SPHEAT(7)=CPP
      CALL SOUND (P6,RHO6,A6)
      CALL SOUND (P7,RHO7,A7)
      M6=V6/A6
      M7=V7/A7
      MU6=-QASIN(1.0000/M6)
      MU7=-(QASIN(1.0000/M7)-THETA7)
      BETA7=0.5000*(MU6+MU7)
C
C     SETUP FOR REGION 8
C
      P8=P5
      CALL FINDB(P7,RHO7,V7,P8,RHO8,V8,THETA8,BETA8,6)
      CALL PRPROP (T1,RHO1,P1,E1,H1,S1,SIG1)
      SPHEAT(1)=CPP
      CALL PRPROP (T2,RHO2,P2,E2,H2,S2,SIG2)
      SPHEAT(2)=CPP
      CALL PRPROP (T3,RHO3,P3,E3,H3,S3,SIG3)
      SPHEAT(3)=CPP
      CALL PRPROP (T4,RHO4,P4,E4,H4,S4,SIG4)
      SPHEAT(4)=CPP
      CALL PRPROP (T5,RHO5,P5,E5,H5,S5,SIG5)
      SPHEAT(5)=CPP
      CALL PRPROP (T8,RHO8,P8,E8,H8,S8,SIG8)
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      SPHEAT(8)=CPP
      CALL SOUND (P1,RHO1,A1)
      CALL SOUND (P2,RHO2,A2)
      CALL SOUND (P3,RHO3,A3)
      CALL SOUND (P4,RHO4,A4)
      CALL SOUND (P5,RHO5,A5)
      CALL SOUND (P8,RHO8,A8)
      M1=V1/A1
      M2=V2/A2
      M3=V3/A3
      M4=V4/A4
      M5=V5/A5
      M8=V8/A8
C
C     CALCULATE UNIT REYNOLDS NUMBER PER FOOT
C     AND PRANDLT NUMBER FOR EACH REGION
C
      DO 45 I=1,8
      CALL MUANDK (TEMP(I),VISC(I),TCON(I),SPHEAT(I),MW(I))
         IF (IGAS.EQ.1) THEN
         PRNO(I)=VISC(I)*SPHEAT(I)/TCON(I)
         ELSE
         PRNO(I)=PRNUM
         ENDIF
      REX(I)=(VEL(I)*DENS(I)/VISC(I))/VERTV
   45 CONTINUE
      CALL PRNTOUT(8)
C
C     CALCULATE BETA9
C
      P9=P2
      CALL EXPAND(P8,RHO8,V8,P9,RHO9,V9,THETA9)
      CALL PRPROP(T9,RHO9,P9,E9,H9,S9,SIG9)
      CALL SOUND (P9,RHO9,A9)
      M9=V9/A9
      MU8=-QASIN(1.0000/M8)
      MU9=-(QASIN(1.0000/M9)-THETA9)
      BETA9=0.50000*(MU8+MU9)
C
C     FORMAT STATEMENTS
C
  140 FORMAT(/,1X,'THE APPROXIMATE BOUNDS FOR THE',
     1       /,1X,'TYPE IV INTERFERENCE ARE :',
     2       /,1X,'   UPPER BODY ANGLE = ',F7.3,' DEGREES',
     3       /,1X,'   LOWER BODY ANGLE = ',F7.3,' DEGREES',/)
  150 FORMAT(//,1X,'CALCULATION FOR TYPE IV INTERFERENCE',/)
  500 FORMAT(/,1X,'NO CONVERGENCE IN TYP4 AFTER 50 ITERATIONS')
      RETURN
      END
C***********************************************************C
C
C                 TYPE V INTERFERENCE
C
C***********************************************************C
      SUBROUTINE TYP5(THEBOD)
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```
      IMPLICIT REAL*16 ( A-H, O-Z )
C
C
C     SUBROUTINE TYP5 USES AN 11-SPECIE EQUILIBRIUM CHEMISTRY MODEL TO
C     CALCULATE GAS PROPERTIES FOR A TYPE V INTERFERENCE PATTERN
C
      REAL*16 M1,M2,M3,M4,M5,M6,M7,M8,M9,MU6,MU7,MU8,MU9
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10),MW(10)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1                MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
      COMMON /BAMAX/ BTM
      COMMON /START/ PRES1,DENS1,VEL1,THEINC
      COMMON /TOTPROP/BUTO,BURHOO,BUPO,BUEO,BUHO,BUSO,BUPRO
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
      EQUIVALENCE (M1,MACHNO(1)),(M2,MACHNO(2)),(M3,MACHNO(3)),
     1            (M4,MACHNO(4)),(M5,MACHNO(5)),(M6,MACHNO(6)),
     2            (M7,MACHNO(7)),(M8,MACHNO(8))
      EQUIVALENCE (T1,TEMP(1)),(T2,TEMP(2)),(T3,TEMP(3)),(T4,TEMP(4)),
     1            (T5,TEMP(5)),(T6,TEMP(6)),(T7,TEMP(7)),(T8,TEMP(8))
      EQUIVALENCE (V1,VEL(1)),(V2,VEL(2)),(V3,VEL(3)),(V4,VEL(4)),
     1            (V5,VEL(5)),(V6,VEL(6)),(V7,VEL(7)),(V8,VEL(8))
      EQUIVALENCE (P1,PRES(1)),(P2,PRES(2)),(P3,PRES(3)),(P4,PRES(4)),
     1            (P5,PRES(5)),(P6,PRES(6)),(P7,PRES(7)),(P8,PRES(8))
      EQUIVALENCE (RHO1,DENS(1)),(RHO2,DENS(2)),(RHO3,DENS(3)),
     1            (RHO4,DENS(4)),(RHO5,DENS(5)),(RHO6,DENS(6)),
     2            (RHO7,DENS(7)),(RHO8,DENS(8))
      EQUIVALENCE (E1,INTER(1)),(E2,INTER(2)),(E3,INTER(3)),
     1            (E4,INTER(4)),(E5,INTER(5)),(E6,INTER(6)),
     2            (E7,INTER(7)),(E8,INTER(8))
      EQUIVALENCE (H1,ENTHA(1)),(H2,ENTHA(2)),(H3,ENTHA(3)),
     1            (H4,ENTHA(4)),(H5,ENTHA(5)),(H6,ENTHA(6)),
     2            (H7,ENTHA(7)),(H8,ENTHA(8))
      EQUIVALENCE (S1,ENTROP(1)),(S2,ENTROP(2)),(S3,ENTROP(3)),
     1            (S4,ENTROP(4)),(S5,ENTROP(5)),(S6,ENTROP(6)),
     2            (S7,ENTROP(7)),(S8,ENTROP(8))
      EQUIVALENCE (SIG1,MW(1)),(SIG2,MW(2)),(SIG3,MW(3)),(SIG4,MW(4)),
     1            (SIG5,MW(5)),(SIG6,MW(6)),(SIG7,MW(7)),(SIG8,MW(8))
      TWO=2.000000000
C
C     DEFINE THE SHOCK GENERATOR ANGLE
C
      THETA2=THEINC
C
C     DEFINE THE BODY ANGLE
C
      THETA3=THEBOD-THETA2
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```
      TOLER=1.E-4
      API=-1.0
      PI=QACOS(API)
      P1=PRES1
      RHO1=DENS1
      V1=VEL1
      WRITE(2,145)
C
C     SOLVE FOR REGION 2 (WEAK SHOCK SOLUTION)
C     AND WRITE A WARNING IF THETA > THETA-MAX
C
      CALL FINDB(P1,RHO1,V1,PM,RHOM,VM,THETAM,BETAM,1)
        IF(THETA2.GT.THETAM) THEN
        WRITE(2,100) 2
        STOP
        ENDIF
      BTM=BETAM
      CALL FINDB(P1,RHO1,V1,P2,RHO2,V2,THETA2,BETA2,3)
C
C     SOLVE FOR REGION 3 (WEAK SHOCK SOLUTION)
C     AND WRITE A WARNING IF THETA > THETA-MAX
C
      CALL FINDB(P2,RHO2,V2,P3M,RHO3M,V3M,THETA3M,BETA3M,1)
C
C     CHECK FOR A TYPE IV INTERFERENCE
C
        IF(THETA3.GT.THETA3M) THEN
        WRITE(2,100) 3
        WRITE(2,150)
        STOP
        ENDIF
      BTM=BETA3M
      CALL FINDB(P2,RHO2,V2,P3,RHO3,V3,THETA3,BETA3,3)
C
C     CHECK FOR A TYPE VI INTERFERENCE
C
        IF(THEBOD.LT.THETAM) THEN
        BTM=BETAM
        CALL FINDB(P1,RHO1,V1,PDUM,RDUM,VDUM,THEBOD,BDUM,5)
          IF(P3.LT.PDUM) THEN
          WRITE(2,155)
          ENDIF
        ENDIF
C
C     SOLVE FOR REGIONS 4 AND 5 WITH THE CONDITIONS THAT :
C          1 - ABSOLUTE THETA (4) EQUALS ABSOLUTE THETA (5)
C          2 - P (4)  EQUALS  P (5)
C          3 - SOLUTION FOR REGION 4 IS SUBSONIC
C          4 - SOLUTION FOR REGION 5 IS SUPERSONIC
C
C
      CALL FINDB(P3,RHO3,V3,P5M,RHO5M,V5M,THETA5M,BETA5M,1)
      THETA5=-THETA5M
      THETA4=THETA3+THETA5
      BTM=BETA3M
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      CALL FINDB(P2,RHO2,V2,P4,RHO4,V4,THETA4,BETA4,5)
      P5=P4
C
C     CONVERGE TO THE GIVEN CONDITIONS
C
      THE40=THETA4
      LOOP1=0
   10 LOOP1=LOOP1+1
      CALL FINDB(P3,RHO3,V3,P5,RHO5,V5,THETA5,BETA5,7)
      THETA4=THETA3+THETA5
      THEDIF=QABS(THETA4-THE40)
      IF(THEDIF.LT.TOLER) GOTO 20
C     WRITE(2,*)THE40,THETA4
        IF(LOOP1.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      CALL FINDB(P2,RHO2,V2,P4,RHO4,V4,THETA4,BETA4,5)
      THE40=THETA4
C
C     CHECK IF A TYPE V SOLUTION EXISTS
C
        IF(P4.GT.P5M) THEN
        WRITE(2,157)
        STOP
        ENDIF
      P5=P4
      GOTO 10
   20 CONTINUE
C
C     SOLVE FOR REGION 6
C
      CALL FINDB(P5,RHO5,V5,P6M,RHO6M,V6M,THETA6M,BETA6M,1)
        IF(THETA6M.LE.QABS(THETA5)) THEN
        CALL NORMAL (P5,RHO5,V5,P6,RHO6,V6)
        THETA6=-THETA5
        BETA6=PI/TWO+THETA6
        ELSE
        THETA6=-THETA5
        BTM=BETA6M
        CALL FINDB(P5,RHO5,V5,P6,RHO6,V6,THETA6,BETA6,3)
        ENDIF
C
C     DEFINE PROPERTIES IN EACH REGION
C
      CALL PRPROP (T1,RHO1,P1,E1,H1,S1,SIG1)
      SPHEAT(1)=CPP
      CALL PRPROP (T2,RHO2,P2,E2,H2,S2,SIG2)
      SPHEAT(2)=CPP
      CALL PRPROP (T3,RHO3,P3,E3,H3,S3,SIG3)
      SPHEAT(3)=CPP
      CALL PRPROP (T4,RHO4,P4,E4,H4,S4,SIG4)
      SPHEAT(4)=CPP
      CALL PRPROP (T5,RHO5,P5,E5,H5,S5,SIG5)
      SPHEAT(5)=CPP
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      CALL PRPROP (T6,RHO6,P6,E6,H6,S6,SIG6)
      SPHEAT(6)=CPP
      CALL SOUND (P1,RHO1,A1)
      CALL SOUND (P2,RHO2,A2)
      CALL SOUND (P3,RHO3,A3)
      CALL SOUND (P4,RHO4,A4)
      CALL SOUND (P5,RHO5,A5)
      CALL SOUND (P6,RHO6,A6)
      M1=V1/A1
      M2=V2/A2
      M3=V3/A3
      M4=V4/A4
      M5=V5/A5
      M6=V6/A6
C
C     CALCULATE UNIT REYNOLDS NUMBER PER FOOT
C     AND PRANDLT NUMBER FOR EACH REGION
C
      DO 45 I=1,6
      CALL MUANDK (TEMP(I),VISC(I),TCON(I),SPHEAT(I),MW(I))
         IF (IGAS.EQ.1) THEN
         PRNO(I)=VISC(I)*SPHEAT(I)/TCON(I)
         ELSE
         PRNO(I)=PRNUM
         ENDIF
      REX(I)=(VEL(I)*DENS(I)/VISC(I))/VERTV
   45 CONTINUE
      CALL PRNTOUT(6)
C
C     FORMAT STATEMENTS
C
  100 FORMAT(/,1X,'******** WARNING ********',/,1X,'THETA(',I1,
     1       ') IS GREATER THAN THETA-MAX')
  145 FORMAT(//,1X,'CALCULATION FOR TYPE V INTERFERENCE'/)
  150 FORMAT(/,1X,'FOR THESE CONDITIONS, TRY A TYPE IV INTERFERENCE')
  155 FORMAT(/,1X,'FOR THESE CONDITIONS, TRY A TYPE VI INTERFERENCE',
     1       /,1X,'HOWEVER, A TYPE V INTERFERENCE SOLUTION MAY EXIST',
     2       /,1X,'THEREFORE, CONTINUE THE CALCULATION',/)
  157 FORMAT(/,1X,'A TYPE V SOLUTION DOES NOT EXIST')
  500 FORMAT(/,1X,'NO CONVERGENCE IN TYP5 AFTER 50 ITERATIONS')
      RETURN
      END
C*******************************************************C
C
C                TYPE VI INTERFERENCE
C
C*******************************************************C
      SUBROUTINE TYP6(THEBOD)
      IMPLICIT REAL*16 ( A-H, O-Z )
C
C
C     SUBROUTINE TYP6 USES AN 11-SPECIE EQUILIBRIUM CHEMISTRY MODEL TO
C     CALCULATE GAS PROPERTIES FOR A TYPE VI INTERFERENCE PATTERN
C
      REAL*16 M1,M2,M3,M4,M5,M6,M7,M8,M9,MU6,MU7,MU8,MU9
```

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      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10),MW(10)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1                MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
      COMMON /BAMAX/ BTM
      COMMON /START/ PRES1,DENS1,VEL1,THEINC
      COMMON /TOTPROP/BUTO,BURHOO,BUPO,BUEO,BUHO,BUSO,BUPRO
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
      EQUIVALENCE (M1,MACHNO(1)),(M2,MACHNO(2)),(M3,MACHNO(3)),
     1            (M4,MACHNO(4)),(M5,MACHNO(5)),(M6,MACHNO(6)),
     2            (M7,MACHNO(7)),(M8,MACHNO(8))
      EQUIVALENCE (T1,TEMP(1)),(T2,TEMP(2)),(T3,TEMP(3)),(T4,TEMP(4)),
     1            (T5,TEMP(5)),(T6,TEMP(6)),(T7,TEMP(7)),(T8,TEMP(8))
      EQUIVALENCE (V1,VEL(1)),(V2,VEL(2)),(V3,VEL(3)),(V4,VEL(4)),
     1            (V5,VEL(5)),(V6,VEL(6)),(V7,VEL(7)),(V8,VEL(8))
      EQUIVALENCE (P1,PRES(1)),(P2,PRES(2)),(P3,PRES(3)),(P4,PRES(4)),
     1            (P5,PRES(5)),(P6,PRES(6)),(P7,PRES(7)),(P8,PRES(8))
      EQUIVALENCE (RHO1,DENS(1)),(RHO2,DENS(2)),(RHO3,DENS(3)),
     1            (RHO4,DENS(4)),(RHO5,DENS(5)),(RHO6,DENS(6)),
     2            (RHO7,DENS(7)),(RHO8,DENS(8))
      EQUIVALENCE (E1,INTER(1)),(E2,INTER(2)),(E3,INTER(3)),
     1            (E4,INTER(4)),(E5,INTER(5)),(E6,INTER(6)),
     2            (E7,INTER(7)),(E8,INTER(8))
      EQUIVALENCE (H1,ENTHA(1)),(H2,ENTHA(2)),(H3,ENTHA(3)),
     1            (H4,ENTHA(4)),(H5,ENTHA(5)),(H6,ENTHA(6)),
     2            (H7,ENTHA(7)),(H8,ENTHA(8))
      EQUIVALENCE (S1,ENTROP(1)),(S2,ENTROP(2)),(S3,ENTROP(3)),
     1            (S4,ENTROP(4)),(S5,ENTROP(5)),(S6,ENTROP(6)),
     2            (S7,ENTROP(7)),(S8,ENTROP(8))
      EQUIVALENCE (SIG1,MW(1)),(SIG2,MW(2)),(SIG3,MW(3)),(SIG4,MW(4)),
     1            (SIG5,MW(5)),(SIG6,MW(6)),(SIG7,MW(7)),(SIG8,MW(8))
      ONE=1.000000000
      TWO=2.000000000
C
C     DEFINE SHOCK GENERATOR ANGLE
C
      THETA3=THEINC
C
C     DEFINE BODY ANGLE
C
      THETA4=THEBOD-THETA3
      TOLER=1.E-4
      API=-ONE
      PI=QACOS(API)
      P1=PRES1
      RHO1=DENS1
      V1=VEL1
```

```
      WRITE(2,145)
C
C     SOLVE FOR REGION 3 (WEAK SHOCK SOLUTION)
C     AND WRITE A WARNING IF THETA > THETA-MAX
C
      CALL FINDB(P1,RHO1,V1,PM,RHOM,VM,THETAM,BETAM,1)
        IF(THETA3.GT.THETAM) THEN
        WRITE(2,100) 3
        STOP
        ENDIF
      BTM=BETAM
      CALL FINDB(P1,RHO1,V1,P3,RHO3,V3,THETA3,BETA3,3)
C
C     SOLVE FOR REGION 4 (WEAK SHOCK SOLUTION)
C     AND WRITE A WARNING IF THETA > THETA-MAX
C
      CALL FINDB(P3,RHO3,V3,P4M,RHO4M,V4M,THETA4M,BETA4M,1)
        IF(THETA4.GT.THETA4M) THEN
        WRITE(2,100) 4
        STOP
        ENDIF
      BTM=BETA4M
      CALL FINDB(P3,RHO3,V3,P4,RHO4,V4,THETA4,BETA4,3)
C
C     CHECK FOR A TYPE V INTERFERENCE
C
        IF(THEBOD.GT.THETAM) THEN
        WRITE(2,150)
        STOP
        ENDIF
      BTM=BETAM
      CALL FINDB(P1,RHO1,V1,PDUM,RDUM,VDUM,THEBOD,BDUM,5)
        IF(PDUM.LT.P4) THEN
        WRITE(2,150)
        STOP
        ENDIF
C
C     SOLVE FOR REGIONS 2 AND 5 WITH THE CONDITIONS THAT :
C         1 - EXPANSION FROM REGION 4 TO 5
C         2 - ABSOLUTE THETA (2) EQUALS ABSOLUTE THETA (5)
C         3 - P (2)  EQUALS  P (5)
C         4 - SOLUTION FOR REGIONS 2 AND 5 ARE SUPERSONIC
C
      BTM=BETAM
      I=1
C
C     SET THE INITIAL LIMITS ON PHI
C
      PHIMAX=THETA3+THETA4
      PHIMIN=PHIMAX
   10 PHI=(PHIMAX+PHIMIN)/TWO
      THETA2=PHI
      CALL FINDB(P1,RHO1,V1,P2,RHO2,V2,THETA2,BETA2,3)
      P5=P2
      CALL EXPAND(P4,RHO4,V4,P5,RHO5,V5,THETA5)
```

```
      PHIEXP=THETA3+THETA4+THETA5
C     WRITE(2,*)PHI,P2
C     WRITE(2,*)PHIEXP,P5,I
      PHICHK=QABS(PHI-PHIEXP)
C     WRITE(2,*)PHICHK
      IF(PHICHK.LT.TOLER) GOTO 20
        IF(I.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      I=I+1
        IF(PHIEXP.GT.PHI) THEN
        PHIMAX=PHIEXP
        PHIMIN=PHI
        ELSE
        PHIMAX=PHI
        PHIMIN=PHIEXP
        ENDIF
      GOTO 10
   20 CONTINUE
C
C     SOLVE FOR EXPANSION FROM REGION 5 TO 6
C     (WAVES INCIDENT ON A SOLID BOUNDARY REFLECT
C      IN A LIKE MANNER)
C
C     ITERATE TO FIND P6, TO START :
C     THE DECREASE IN PRESSURE FROM 4 TO 6 IS TAKEN
C     AS TWICE THE DECREASE FROM 4 TO 5
C
      P6=TWO*P5-P4
      THETA6=THETA5
      PPP=P5
      TPP=0.0
      PIN=P6
      I=1
   25 CALL EXPAND(P5,RHO5,V5,PIN,RHO6,V6,TOUT)
      TCHECK=QABS(THETA6-TOUT)
      IF(TCHECK.LT.TOLER) GOTO 27
        IF(I.GT.50) THEN
        WRITE(2,500)
        STOP
        ENDIF
      I=I+1
      PP=PIN
      TP=TOUT
      PNEW=PP+((PPP-PP)/(TPP-TP))*(THETA6-TP)
C     WRITE(2,*) PIN,PNEW,TOUT,THETA5,I
      PIN=PNEW
      PPP=PP
      TPP=TP
      GOTO 25
   27 P6=PIN
      THETA6=-TOUT
C
C     DEFINE PROPERTIES IN EACH REGION
```

```
C
   30 CALL PRPROP (T1,RHO1,P1,E1,H1,S1,SIG1)
      SPHEAT(1)=CPP
      CALL PRPROP (T2,RHO2,P2,E2,H2,S2,SIG2)
      SPHEAT(2)=CPP
      CALL PRPROP (T3,RHO3,P3,E3,H3,S3,SIG3)
      SPHEAT(3)=CPP
      CALL PRPROP (T4,RHO4,P4,E4,H4,S4,SIG4)
      SPHEAT(4)=CPP
      CALL PRPROP (T5,RHO5,P5,E5,H5,S5,SIG5)
      SPHEAT(5)=CPP
      CALL PRPROP (T6,RHO6,P6,E6,H6,S6,SIG6)
      SPHEAT(6)=CPP
      CALL SOUND (P1,RHO1,A1)
      CALL SOUND (P2,RHO2,A2)
      CALL SOUND (P3,RHO3,A3)
      CALL SOUND (P4,RHO4,A4)
      CALL SOUND (P5,RHO5,A5)
      CALL SOUND (P6,RHO6,A6)
      M1=V1/A1
      M2=V2/A2
      M3=V3/A3
      M4=V4/A4
      M5=V5/A5
      M6=V6/A6
C
C     CALCULATE BETA5(-) AND BETA6(+)
C
      B5EXP1=QASIN(ONE/M4)
      B5EXP2=QASIN(ONE/M5)-THETA5
      BETA5=-(B5EXP1+B5EXP2)/TWO
      B6EXP1=QASIN(ONE/M5)
      B6EXP2=QASIN(ONE/M6)+THETA6
      BETA6=(B6EXP1+B6EXP2)/TWO
C
C     CALCULATE UNIT REYNOLDS NUMBER PER FOOT
C     AND PRANDLT NUMBER FOR EACH REGION
C
      DO 45 I=1,6
      CALL MUANDK (TEMP(I),VISC(I),TCON(I),SPHEAT(I),MW(I))
         IF (IGAS.EQ.1) THEN
         PRNO(I)=VISC(I)*SPHEAT(I)/TCON(I)
         ELSE
         PRNO(I)=PRNUM
         ENDIF
      REX(I)=(VEL(I)*DENS(I)/VISC(I))/VERTV
   45 CONTINUE
      CALL PRNTOUT(6)
C
C     FORMAT STATEMENTS
C
  100 FORMAT(/,1X,'******** WARNING ********',/,1X,'THETA(',I1,
     1       ') IS GREATER THAN THETA-MAX')
  145 FORMAT(//,1X,'CALCULATION FOR TYPE VI INTERFERENCE'/)
  150 FORMAT(/,1X,'FOR THESE CONDITIONS, TRY A TYPE V INTERFERENCE')
```

```
  500 FORMAT(/,1X,'NO CONVERGENCE IN TYP6 AFTER 50 ITERATIONS')
      RETURN
      END
C
C    SUBROUTINE PRNTOUT PRINTS FLOW AND STATE INFORMATION
C    FOR EACH REGION
C
      SUBROUTINE PRNTOUT(J)
      IMPLICIT REAL*16 ( A-H, O-Z )
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10),MW(10)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /TOTPROP/BUTO,BURHOO,BUPO,BUEO,BUHO,BUSO,BUPRO
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      WRITE(2,160)
      WRITE(2,164)0,BUTO,BUPO,BURHOO,BUEO
      DO 50 I=1,J
      BUTEMP=TEMP(I)*VERTT
      BUPRES=PRES(I)*VERTP
      BUDENS=DENS(I)*VERTD
      BUINTER=INTER(I)*VERTE
      WRITE(2,165)I,BUTEMP,BUPRES,BUDENS,BUINTER,REX(I)
   50 CONTINUE
      WRITE(2,170)
      WRITE(2,175)0,0.000,0.000,BUHO,BUSO,BUPRO
      DO 60 I=1,J
      BUVEL=VEL(I)*VERTV
      BUENTH=ENTHA(I)*VERTE
      BUENTR=ENTROP(I)*VERTS
      WRITE(2,175)I,BUVEL,MACHNO(I),BUENTH,BUENTR,PRNO(I)
   60 CONTINUE
C
C     FORMAT STATEMENTS
C
  160 FORMAT(//,1X,'REGION',3X,'TEMPERATURE',5X,'PRESSURE',8X,'DENSITY',
     18X,'INTERNAL',9X,'REX',/,58X,'ENERGY',/,11X,'(RANKINE)',7X,
     2'(PSIA)',6X,'(SLUGS/FT**3)',4X,'(BTU/LBM)',8X,'(1/FT)',/)
  164 FORMAT(3X,I2,1X,4(3X,E12.5))
  165 FORMAT(3X,I2,1X,5(3X,E12.5))
  170 FORMAT(//,1X,'REGION',4X,'VELOCITY',5X,'MACH NUMBER',4X,
     1'ENTHALPY',8X,'ENTROPY',11X,'PR',/,11X,'(FT/SEC)',20X,
     2'(BTU/LBM)',5X,'(BTU/LBM-R)',/)
  175 FORMAT(3X,I2,4X,E12.5,5X,F7.4,1X,3(3X,E12.5))
      RETURN
      END
C
C     SUBROUTINE SBLLOC CALCULATES THE POINT HEATING AT
C     SHOCK AND EXPANSION WAVE / BOUNDARY LAYER INTERACTIONS
C     USING THE METHODS OF NASA TM X-2725 AND NASA TN D-7139
C
      SUBROUTINE SBLLOC (XL,ITY)
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      IMPLICIT REAL*16 ( A-H, O-Z )
      REAL*16 MU6,MU7,GAMMA
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10)
      DIMENSION RTHETA(8),ATHETA(8),RBETA(8),ABETA(8),XJ(6),YJ(6)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1                MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
      COMMON /WALL/ TW,ITYPE
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
      LOOP=6
C
C     LOAD SINGLE VALUE ANGLES INTO ARRAYS
C
      RTHETA(2)=THETA2
      RBETA(2)=BETA2
      RTHETA(3)=THETA3
      RBETA(3)=BETA3
      RTHETA(4)=THETA4
      RBETA(4)=BETA4
      RTHETA(5)=THETA5
      RBETA(5)=BETA5
      RTHETA(6)=THETA6
      RBETA(6)=BETA6
C
C     DEFINE ABSOLUTE THETA AND BETA W.R.T. REGION 1
C
      RTHETA(1)=0.00
      ATHETA(1)=RTHETA(1)
      ATHETA(2)=RTHETA(2)
      ATHETA(3)=RTHETA(3)
      ATHETA(4)=RTHETA(2)+RTHETA(4)
      ATHETA(5)=RTHETA(3)+RTHETA(5)
      ATHETA(6)=ATHETA(4)+RTHETA(6)
      RBETA(1)=0.00
      ABETA(1)=RBETA(1)
      ABETA(2)=RBETA(2)
      ABETA(3)=RBETA(3)
      ABETA(4)=RBETA(4)+(ATHETA(4)-RTHETA(4))
      ABETA(5)=RBETA(5)+(ATHETA(5)-RTHETA(5))
      ABETA(6)=RBETA(6)+(ATHETA(6)-RTHETA(6))
C
C     IF ITY = 2, THEN DEFINE REGIONS 7 AND 8
C
         IF(ITY.EQ.2) THEN
         LOOP=8
         RTHETA(7)=THETA7
         RBETA(7)=BETA7
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        RTHETA(8)=THETA8
        RBETA(8)=BETA8
        ATHETA(5)=ATHETA(4)
        ABETA(5)=RBETA(5)+(ATHETA(5)-RTHETA(5))
        ATHETA(7)=RTHETA(3)+RTHETA(7)
        ABETA(7)=RBETA(7)+(ATHETA(7)-RTHETA(7))
        ATHETA(8)=RTHETA(8)
        ABETA(8)=RBETA(8)+(ATHETA(8)-RTHETA(8))
        ENDIF
C
C     IF ITY = 5, THEN DEFINE REGIONS 7 AND 8
C
        IF(ITY.EQ.5) THEN
        ATHETA(3)=ATHETA(2)+RTHETA(3)
        ATHETA(4)=ATHETA(2)+RTHETA(4)
        ATHETA(5)=ATHETA(3)+RTHETA(5)
        ATHETA(6)=ATHETA(5)+RTHETA(6)
        ABETA(3)=RBETA(3)+(ATHETA(3)-RTHETA(3))
        ABETA(4)=RBETA(4)+(ATHETA(4)-RTHETA(4))
        ABETA(5)=RBETA(5)+(ATHETA(5)-RTHETA(5))
        ABETA(6)=RBETA(6)+(ATHETA(6)-RTHETA(6))
        ENDIF
C
C     IF ITY = 6, THEN DEFINE REGIONS 4, 5, AND 6
C
        IF(ITY.EQ.6) THEN
        ATHETA(4)=RTHETA(3)+RTHETA(4)
        ATHETA(5)=ATHETA(4)+RTHETA(5)
        ATHETA(6)=ATHETA(5)+RTHETA(6)
        ABETA(4)=RBETA(4)+(ATHETA(4)-RTHETA(4))
        ABETA(5)=RBETA(5)+(ATHETA(5)-RTHETA(5))
        ABETA(6)=RBETA(6)+(ATHETA(6)-RTHETA(6))
        ENDIF
C
C     LOAD ANGLES [DEG] INTO REGINFO
C
      ONEN=-1.000000
      PI=QACOS(ONEN)
      CONVERT=180.000000/PI
      DO 5 I=1,LOOP
      ANGTA(I)=ATHETA(I)*CONVERT
      ANGTR(I)=RTHETA(I)*CONVERT
      ANGBA(I)=ABETA(I)*CONVERT
      ANGBR(I)=RBETA(I)*CONVERT
    5 CONTINUE
C
C     WRITE ANGLE INFORMATION
C
      WRITE(2,110)
      DO 10 I1=1,LOOP
      WRITE(2,120)I1,ANGTR(I1),ANGBR(I1),ANGTA(I1),ANGBA(I1)
   10 CONTINUE
C
C     CALCULATE LAMINAR AND TURBULENT HEATING FROM
C     SHOCK / BOUNDARY LAYER INTERACTION
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```
C
      IR2=6
      IF(ITY.EQ.1) IR1=2
      IF(ITY.EQ.2) IR1=2
      IF(ITY.EQ.5) IR1=3
      IF(ITY.EQ.6) IR1=4
C
C     START BY FINDING THE FLAT PLATE HEATING JUST PRIOR TO
C     THE INTERACTION REGION.
C     FOR THE METHOD USED SEE THE TEXT :
C     " CONVECTIVE HEAT AND MASS TRANSFER ", 2ND EDITION,
C     BY KAYS AND CRAWFORD
C
      ZERO=0.0000000
      TWO=2.000000
      ONEO3=1.000000/3.000000
C
C     CONVERGE TO THE WALL CONDITIONS TW AND P2
C
C     START BY GUESSING DENSITY AT THE WALL
C
      RR=8.31441
      I=1
      SIG2=PRES(IR1)/(DENS(IR1)*RR*TEMP(IR1))
      RHOW=PRES(IR1)/(RR*SIG2*TW)
   30 I=I+1
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(TW,RHOW,PW,EW,HW,SW,SIGW)
          ELSE
          CALL SUBR2(TW,RHOW,PW,EW,HW,SW,SIGW)
          ENDIF
C     WRITE(2,300)PW,PRES(IR1)
      IF(QABS((PRES(IR1)-PW)/PRES(IR1)).LT.1.E-7) GOTO 40
          IF(I.GT.50) THEN
          WRITE(2,200)
          STOP
          ENDIF
      RHOW=PRES(IR1)/(RR*SIGW*TW)
      GOTO 30
   40 CPPW=CPP
      CALL MUANDK (TW,VISW,CONW,CPPW,SIGW)
          IF (IGAS.EQ.1) THEN
          PRNOW=VISW*CPPW/CONW
          ELSE
          PRNOW=PRNUM
          ENDIF
C
C     CALCULATE THE ADIABATIC WALL ENTHALPY, HAW, SEE ECKERT'S
C     DISCUSSION IN "JOURNAL OF THE AERONAUTICAL SCIENCES"
C     AUG. 1955, PP. 585-587.
C
      ITOL=1
      DIFTOL=1.E-7
      PRLREF=PRNO(IR1)
      PRTREF=PRNO(IR1)
```

```
   50 CONTINUE
      ITOL=ITOL+1
         IF(ITOL.GT.50) THEN
         WRITE(2,200)
         STOP
         ENDIF
      RFACL=QSQRT(PRLREF)
      HAWL=ENTHA(IR1)+RFACL*VEL(IR1)*VEL(IR1)/TWO
      RFACT=PRTREF**ONE03
      HAWT=ENTHA(IR1)+RFACT*VEL(IR1)*VEL(IR1)/TWO
C
C     CALCULATE THE REFERENCE ENTHALPY, HR
C     ( SEE EQN. 15-42, " CONVECTIVE HEAT AND MASS TRANSFER ",
C       2ND EDITION, BY KAYS AND CRAWFORD )
C
      HRL=ENTHA(IR1)+0.50*(HW-ENTHA(IR1))+0.22*(HAWL-ENTHA(IR1))
      HRT=ENTHA(IR1)+0.50*(HW-ENTHA(IR1))+0.22*(HAWT-ENTHA(IR1))
C
C     FIND THE REF TEMPERATURE, REF DENSITY, AND
C     REF SPECIFIC HEAT
C
      CALL HREF(PRES(IR1),HRL,TRL,RHORL,SIGRL,CPRL)
      CALL HREF(PRES(IR1),HRT,TRT,RHORT,SIGRT,CPRT)
C
C     CALCULATE REYNOLDS NUMBER AND PRANDTL NUMBER AT HR
C
      CALL MUANDK (TRL,VISRL,CONRL,CPRL,SIGRL)
      RENORL=VEL(IR1)*RHORL*XL/VISRL
         IF (IGAS.EQ.1) THEN
         PRNORL=VISRL*CPRL/CONRL
         ELSE
         PRNORL=PRNUM
         ENDIF
      CALL MUANDK (TRT,VISRT,CONRT,CPRT,SIGRT)
      RENORT=VEL(IR1)*RHORT*XL/VISRT
         IF (IGAS.EQ.1) THEN
         PRNORT=VISRT*CPRT/CONRT
         ELSE
         PRNORT=PRNUM
         ENDIF
C
C     UPDATE AND CHECK REFERENCE PRANDTL NUMBER FOR CONVERGENCE
C
      DIFL=QABS((PRLREF-PRNORL)/PRLREF)
      DIFT=QABS((PRTREF-PRNORT)/PRTREF)
         IF(DIFL.LE.DIFTOL.AND.DIFT.LE.DIFTOL) THEN
         GOTO 60
         ELSE
         PRLREF=PRNORL
         PRTREF=PRNORT
         GOTO 50
         ENDIF
   60 CONTINUE
C
C     CALCULATE LAMINAR STANTON NUMBER AT TR
```

```
C     SEE EQNS. 9-10 AND 9-27, KAYS AND CRAWFORD
C
      POWA=-2.00000/3.00000
      STNORL=(PRNORL**POWA)*0.332/QSQRT(RENORL)
C
C     CALCULATE TURBULENT STANTON NUMBER AT TR
C     SEE EQNS. 10-24 AND 12-12, KAYS AND CRAWFORD
C
      POWB=-2.584
      CFBY2=0.185*(QLOG10(RENORT))**POWB
      STNORT=CFBY2/(QSQRT(CFBY2)*(13.2*PRNORT-10.16)+0.9)
C
C     CALCULATE ENTHALPY CONDUCTANCE, SEE PAGES 305 AND 308-309
C
      CONGL=STNORL*VEL(IR1)*RHORL
      CONGT=STNORT*VEL(IR1)*RHORT
C
C     CALCULATE FLAT PLATE HEATING RATE, EQN. 15-41
C     JUST PRIOR TO THE SHOCK INTERACTION REGION
C
      QFPWL=CONGL*(HAWL-HW)
      QFPWT=CONGT*(HAWT-HW)
C
C     CALCULATE PEAK HEATING USING EMPIRICAL CORRELATIONS GIVEN
C     BY MARKARIAN AND USED IN NASA TM X-2725
C
      POWC=1.29
      POWD=0.85
      QWL=QFPWL*((PRES(IR2)/PRES(IR1))**POWC)
      QWT=QFPWT*((PRES(IR2)/PRES(IR1))**POWD)
C
C     CONVERT FROM SI (WATTS/M**2) TO BRITISH (BTU/FT**2-SEC)
C
      QWLFPBU=QFPWL*VERTQ
      QWTFPBU=QFPWT*VERTQ
      QWLBU=QWL*VERTQ
      QWTBU=QWT*VERTQ
C
C     WRITE WALL HEATING RATE FOR THE SHOCK OR EXPANSION
C     WAVE/BOUNDARY LAYER INTERACTION
C
      WRITE(2,350)
      WRITE(2,400)
      BUTW=TW*VERTT
      BUPW=PW*VERTP
      BURHOW=RHOW*VERTD
      WRITE(2,440)BUTW,BUPW,BURHOW,ZERO,PRNOW
      WRITE(2,500)
      WRITE(2,550)QWLFPBU,QWLBU
      WRITE(2,600)
      WRITE(2,550)QWTFPBU,QWTBU
  110 FORMAT(//,1X,'TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH
     1 REGION (DEGREES) '
     2,/,2X,'REGION',10X,'RELATIVE ANGLE',14X,'ABSOLUTE ANGLE',/
     3,15X,'THETA',10X,'BETA',9X,'THETA',10X,'BETA',/)
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```
  120 FORMAT(4X,I2,4X,4(2X,E12.5))
  200 FORMAT(1X,'NO CONVERGENCE IN SBLLOC AFTER 50 ITERATIONS')
  350 FORMAT(/,/,1X,'****** SHOCK / BOUNDARY LAYER INTERACTION',
     1       1X,'******',/)
  400 FORMAT(/,3X,'REGION',5X,'TEMPERATURE',4X,'PRESSURE',4X,'DENSITY',
     16X,'VELOCITY',8X,'PR',/,15X,'(RANKINE)',6X,'(PSIA)',3X,
     2'(SLUGS/FT**3)',2X,'(FT/SEC)')
  440 FORMAT  (1X,'   WALL    ',5(1X,E12.5),/)
  500 FORMAT(/,1X,'LAMINAR SHOCK/BOUNDARY LAYER INTERFERENCE HEATING',/)
  550 FORMAT(1X,'UNDISTURBED HEATING RATE = ',E12.5,1X,'BTU/FT**2-SEC',
     1     /,1X,'       PEAK HEATING RATE = ',E12.5,1X,'BTU/FT**2-SEC')
  600 FORMAT(/,1X,'TURBULENT SHOCK/BOUNDARY LAYER INTERFERENCE HEATING',
     1       /)
      RETURN
      END
C
C     SUBROUTINE HREF CALCULATES TEMPERATURE, DENSITY, AND SPECIFIC
C     HEAT GIVEN AN ENTHALPY AND PRESSURE
C     SUBROUTINE HREF IS USED BY SBLLOC TO CALCULATE REFERENCE
C     CONDITIONS GIVEN A REFERENCE ENTHALPY
C
      SUBROUTINE HREF(P,HR,TR,RHOR,SIGR,CPR)
      IMPLICIT REAL*16 (A-H,O-Z)
      COMMON /E/ CPP
      COMMON /GAS/ IGAS,PRNUM
C
C     ITERATE TO CONVERGE ON REFERENCE TEMPERATURE AT
C     REFERENCE ENTHALPY HR AND PRESSURE P2,
C
      ONE=1.0000
      RHOP=0.0
      RR=8.31441
      SIGR=34.518
      TR=HR/1003.5
C
C     I IS THE OUTER LOOP INDEX
C
      I=1
C
C     GUESS DENSITY USING IDEAL GAS ASSUMPTIONS FOR AIR
C
      RHOR=P/(SIGR*RR*TR)
   15 CONTINUE
C
C     CALCULATE TR AT P AND RHOR
C
      CALL PRPROP(TR,RHOR,P,ER,HDUM,SR,SIGR)
C
C     J IS THE INNER LOOP INDEX
C
      J=1
C
C     MODIFY RHOR AT P AND TR
C
   20 RHOR=P/(SIGR*RR*TR)
```

```
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(TR,RHOR,PDUM,ER,HRP,SR,SIGR)
          ELSE
          CALL SUBR2(TR,RHOR,PDUM,ER,HRP,SR,SIGR)
          ENDIF
      DH=HR-HRP
C
C     COMPUTE AN EFFECTIVE CP
C
      TRP=TR+ONE
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(TRP,RHOR,DUM1,DUM2,HRPP,DUM3,DUM4)
          ELSE
          CALL SUBR2(TRP,RHOR,DUM1,DUM2,HRPP,DUM3,DUM4)
          ENDIF
      CP=(HRP-HRPP)/(TR-TRP)
C
C     MODIFY TR USING THE EFFECTIVE CP
C
      DT=DH/CP
      TR=TR+DT
C     WRITE(2,*)I,J,TR,DT,HR,HRP,DH
        IF(J.GT.50) THEN
        WRITE(2,*)I,J,TR,DT,HR,HRP,DH
        STOP 99
        ENDIF
C
C     CHECK FOR TEMPERATURE CONVERGENCE AT RHOR AND HR
C
      IF(QABS(DT).LT..001) GOTO 30
      J=J+1
      GOTO 20
   30 CONTINUE
C
C     CHECK FOR DENSITY CONVERGENCE
C
      CHECK=QABS((RHOR-RHOP)/RHOR)
      IF(CHECK.LT.1.E-6) GOTO 40
      IF(I.GT.99) STOP 99
      I=I+1
      RHOP=RHOR
      GOTO 15
   40 CONTINUE
      CPR=CPP
      RETURN
      END
      SUBROUTINE SHERLOC (SL12)
      IMPLICIT REAL*16 ( A-H, O-Z )
      REAL*16 MU6,MU7
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10)
      DIMENSION RTHETA(8),ATHETA(8),RBETA(8),ABETA(8),XJ(6),YJ(6)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
```

```
     1                REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1               MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
      COMMON /WALL/ TW,ITYPE
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
C
C     LOAD SINGLE VALUE ANGLES INTO ARRAYS
C
      RTHETA(2)=THETA2
      RBETA(2)=BETA2
      RTHETA(3)=THETA3
      RBETA(3)=BETA3
      RTHETA(4)=THETA4
      RBETA(4)=BETA4
      RTHETA(5)=THETA5
      RBETA(5)=BETA5
C
C     DEFINE ABSOLUTE THETA AND BETA W.R.T. REGION 1
C
      RTHETA(1)=0.00
      ATHETA(1)=RTHETA(1)
      ATHETA(2)=RTHETA(2)
      ATHETA(3)=RTHETA(3)
      ATHETA(4)=RTHETA(3)+RTHETA(4)
      ATHETA(5)=ATHETA(4)+RTHETA(5)
      RBETA(1)=0.00
      ABETA(1)=RBETA(1)
      ABETA(2)=RBETA(2)
      ABETA(3)=RBETA(3)
      ABETA(4)=RBETA(4)-(RTHETA(4)-ATHETA(4))
      ABETA(5)=RBETA(5)-(RTHETA(5)-ATHETA(5))
C
C     LOAD ANGLES [DEG] INTO REGINFO
C
      ONEN=-1.000000
      PI=QACOS(ONEN)
      CONVERT=180.000000/PI
      DO 5 I=1,5
      ANGTA(I)=ATHETA(I)*CONVERT
      ANGTR(I)=RTHETA(I)*CONVERT
      ANGBA(I)=ABETA(I)*CONVERT
      ANGBR(I)=RBETA(I)*CONVERT
    5 CONTINUE
C
C     WRITE ANGLE INFORMATION
C
      WRITE(2,110)
      DO 10 I1=1,5
      WRITE(2,120)I1,ANGTR(I1),ANGBR(I1),ANGTA(I1),ANGBA(I1)
   10 CONTINUE
C
```

```
C     CALCULATE LAMINAR AND TURBULENT HEATING FROM
C     SHEAR LAYER/BOUNDARY LAYER INTERACTION
C
      TWO=2.000000
      ONE03=1.000000/3.000000
      RR=8.31441
      COEFL=0.19
      COEFT=0.021
      POWT=0.20
      SINT5=QABS(QSIN(RTHETA(5)))
      TOLER=1.E-7
C
C     CALCULATE THE SHEAR LAYER LENGTH, SHRLG
C
      ALPHA1=QABS(ABETA(4)-RTHETA(2))
      ALPHA2=PI-QABS(RBETA(5))
      ALPHA3=PI-ALPHA1-ALPHA2
      SHRLG=SL12*(QSIN(ALPHA3)/QSIN(ALPHA2))
C
C     CONVERGE TO THE WALL CONDITIONS TW AND P5
C
C     START BY GUESSING DENSITY AT THE WALL
C
      I=1
      SIG5=PRES(5)/(DENS(5)*RR*TEMP(5))
      RHOW=PRES(5)/(RR*SIG5*TW)
   30 I=I+1
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(TW,RHOW,PW,EW,HW,SW,SIGW)
          ELSE
          CALL SUBR2(TW,RHOW,PW,EW,HW,SW,SIGW)
          ENDIF
C     WRITE(2,300)PW,PRES(5)
      IF(QABS((PRES(5)-PW)/PRES(5)).LT.TOLER) GOTO 40
       IF(I.GT.50) THEN
       WRITE(2,200)
       STOP
       ENDIF
      RHOW=PRES(5)/(RR*SIGW*TW)
      GOTO 30
   40 CPPW=CPP
      CALL MUANDK (TW,VISW,CONW,CPPW,SIGW)
         IF (IGAS.EQ.1) THEN
         PRNOW=VISW*CPPW/CONW
         ELSE
         PRNOW=PRNUM
         ENDIF
C
C     CALCULATE THE ADIABATIC WALL ENTHALPY, HAW, SEE ECKERT'S
C     DISCUSSION IN "JOURNAL OF THE AERONAUTICAL SCIENCES"
C     AUG. 1955, PP. 585-587.
C
      ITOL=1
      DIFTOL=1.E-7
      PRLREF=PRNO(5)
```

```
      PRTREF=PRNO(5)
   50 CONTINUE
      ITOL=ITOL+1
         IF(ITOL.GT.50) THEN
         WRITE(2,200)
         STOP
         ENDIF
      RFACL=QSQRT(PRLREF)
      RFACT=PRTREF**ONEO3
      HAWL=ENTHA(5)+RFACL*(VEL(5)*VEL(5)/TWO)
      HAWT=ENTHA(5)+RFACT*(VEL(5)*VEL(5)/TWO)
C
C     CALCULATE THE REFERENCE ENTHALPY, HR
C     ( SEE EQN. 15-42, " CONVECTIVE HEAT AND MASS TRANSFER ",
C       2ND EDITION, BY KAYS AND CRAWFORD )
C
      HRL=ENTHA(5)+0.50*(HW-ENTHA(5))+0.22*(HAWL-ENTHA(5))
      HRT=ENTHA(5)+0.50*(HW-ENTHA(5))+0.22*(HAWT-ENTHA(5))
C
C     FIND THE REF TEMPERATURE, REF DENSITY, AND
C     REF SPECIFIC HEAT
C
      CALL HREF(PRES(5),HRL,TRL,RHORL,SIGRL,CPRL)
      CALL HREF(PRES(5),HRT,TRT,RHORT,SIGRT,CPRT)
C
C     CALCULATE PRANDTL NUMBER AT HR
C
      CALL MUANDK (TRL,VISRL,CONRL,CPRL,SIGRL)
         IF (IGAS.EQ.1) THEN
         PRNORL=VISRL*CPRL/CONRL
         ELSE
         PRNORL=PRNUM
         ENDIF
      CALL MUANDK (TRT,VISRT,CONRT,CPRT,SIGRT)
         IF (IGAS.EQ.1) THEN
         PRNORT=VISRT*CPRT/CONRT
         ELSE
         PRNORT=PRNUM
         ENDIF
C
C     UPDATE AND CHECK REFERENCE PRANDTL NUMBER FOR CONVERGENCE
C
      DIFL=QABS((PRLREF-PRNORL)/PRLREF)
      DIFT=QABS((PRTREF-PRNORT)/PRTREF)
         IF(DIFL.LE.DIFTOL.AND.DIFT.LE.DIFTOL) THEN
         GOTO 60
         ELSE
         PRLREF=PRNORL
         PRTREF=PRNORT
         GOTO 50
         ENDIF
   60 CONTINUE
C
C     CALCULATE THE SHEAR LAYER THICKNESS AT THE WALL, DEL
C
```

```
      DELL=5.0000*QSQRT((SHRLG*VISC(4))/(DENS(4)*VEL(4)))
      DELT=0.123*SHRLG
C
C     CALCULATE PEAK WALL HEATING FOR LAMINAR AND TURBULENT
C     SHEAR LAYER ATTACHMENT - NASA TN-D-7139
C
      QWL1=COEFL*RHOW*VEL(5)*(HAWL-HW)
      QWL2=QSQRT((VISW*SINT5)/(RHOW*VEL(5)*DELL))
      QWL=QWL1*QWL2
      QWT1=COEFT*RHOW*VEL(5)*(HAWT-HW)
      QWT2=((VISW*SINT5)/(RHOW*VEL(5)*DELT))**POWT
      QWT=QWT1*QWT2
C
C     CONVERT FROM SI (WATTS/M**2) TO BRITISH (BTU/FT**2-SEC)
C
      QWLBU=QWL*VERTQ
      QWTBU=QWT*VERTQ
C
C     CALCULATE LOCAL STANTON NUMBER
C
      STNOL=QWL/(VEL(5)*DENS(5)*(HAWL-HW))
      STNOT=QWT/(VEL(5)*DENS(5)*(HAWT-HW))
C
C     WRITE WALL AND HEATING RATE DATA FOR THE SHEAR LAYER
C
      WRITE(2,350)
      WRITE(2,400)
      BUTW=TW*VERTT
      BUPW=PW*VERTP
      BURHOW=RHOW*VERTD
      WRITE(2,440)BUTW,BUPW,BURHOW,ZERO,PRNOW
      WRITE(2,500)
      WRITE(2,550)QWLBU,STNOL
      WRITE(2,600)
      WRITE(2,550)QWTBU,STNOT
  110 FORMAT(//,1X,'TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH
     1 REGION (DEGREES) '
     2,/,2X,'REGION',10X,'RELATIVE ANGLE',14X,'ABSOLUTE ANGLE',/
     3,15X,'THETA',10X,'BETA',9X,'THETA',10X,'BETA',/)
  120 FORMAT(4X,I2,4X,4(2X,E12.5))
  200 FORMAT(1X,'NO CONVERGENCE IN SHERLOC AFTER 50 ITERATIONS')
  350 FORMAT(/,/,1X,'****** SHEAR LAYER / BOUNDARY LAYER INTERACTION',
     1       1X,'******',/)
  400 FORMAT(/,3X,'REGION',5X,'TEMPERATURE',4X,'PRESSURE',4X,'DENSITY',
     16X,'VELOCITY',8X,'PR',/,15X,'(RANKINE)',6X,'(PSIA)',3X,
     2'(SLUGS/FT**3)',2X,'(FT/SEC)')
  440 FORMAT  (1X,'   WALL    ',5(1X,E12.5),/)
  500 FORMAT(/,1X,'LAMINAR SHEAR LAYER HEATING',/)
  550 FORMAT(1X,'WALL HEATING RATE = ',E12.5,2X,'BTU/FT**2-SEC',
     1     /,1X,'WALL STANTON NUMBER',1X,'= ',E12.5)
  600 FORMAT(/,1X,'TURBULENT SHEAR LAYER HEATING',/)
      RETURN
      END
      SUBROUTINE JETLOC (SL12)
      IMPLICIT REAL*16 ( A-H, O-Z )
```

```
      REAL*16 MU6,MU7
      REAL*16 TEMP(10),DENS(10),PRES(10),INTER(10),VEL(10),
     1        ENTHA(10),ENTROP(10),REX(10),VISC(10),TCON(10),
     2        ANGTA(10),ANGTR(10),ANGBA(10),ANGBR(10),PRNO(10),
     3        MACHNO(10),SPHEAT(10)
      DIMENSION RTHETA(8),ATHETA(8),RBETA(8),ABETA(8),XJ(6),YJ(6)
      COMMON /REGINFO/ TEMP,DENS,PRES,INTER,VEL,ENTHA,ENTROP,
     1                 REX,VISC,TCON,ANGTA,ANGTR,ANGBA,ANGBR,
     2                 PRNO,MACHNO,SPHEAT
      COMMON /ANGLEB/ BETA2,BETA3,BETA4,BETA5,BETA6,BETA7,BETA8,BETA9,
     1                MU6,MU7
      COMMON /ANGLET/ THETA2,THETA3,THETA4,THETA5,THETA6,THETA7,THETA8
C
C     LOAD SINGLE VALUE ANGLES INTO ARRAYS
C
      RTHETA(2)=THETA2
      RBETA(2)=BETA2
      RTHETA(3)=THETA3
      RBETA(3)=BETA3
      RTHETA(4)=THETA4
      RBETA(4)=BETA4
      RTHETA(5)=THETA5
      RBETA(5)=BETA5
      RTHETA(6)=THETA6
      RBETA(6)=BETA6
      RTHETA(7)=THETA7
      RBETA(7)=BETA7
      RTHETA(8)=THETA8
      RBETA(8)=BETA8
C
C     DEFINE ABSOLUTE THETA AND BETA W.R.T. REGION 1
C
      RTHETA(1)=0.00
      ATHETA(1)=RTHETA(1)
      ATHETA(2)=RTHETA(2)
      ATHETA(3)=RTHETA(3)
      ATHETA(4)=RTHETA(3)+RTHETA(4)
      ATHETA(5)=RTHETA(3)+RTHETA(5)
      ATHETA(6)=ATHETA(4)+RTHETA(6)
      ATHETA(7)=ATHETA(6)+RTHETA(7)
      ATHETA(8)=ATHETA(7)+RTHETA(8)
      RBETA(1)=0.00
      ABETA(1)=RBETA(1)
      ABETA(2)=RBETA(2)
      ABETA(3)=RBETA(3)
      ABETA(4)=RBETA(4)-(RTHETA(4)-ATHETA(4))
      ABETA(5)=RBETA(5)-(RTHETA(5)-ATHETA(5))
      ABETA(6)=RBETA(6)-(RTHETA(6)-ATHETA(6))
      ABETA(7)=RBETA(7)-(RTHETA(7)-ATHETA(7))
      ABETA(8)=RBETA(8)-(RTHETA(8)-ATHETA(8))
C
C     LOAD ANGLES [DEG] INTO REGINFO
C
      ONEN=-1.000000
      PI=QACOS(ONEN)
```

```
      CONVERT=180.000000/PI
      DO 5 I=1,8
      ANGTA(I)=ATHETA(I)*CONVERT
      ANGTR(I)=RTHETA(I)*CONVERT
      ANGBA(I)=ABETA(I)*CONVERT
      ANGBR(I)=RBETA(I)*CONVERT
    5 CONTINUE
C
C     CALCULATE X AND Y LOCATIONS OF J1, J2, J3, J4, AND J5
C
C     VALUE OF SL12 IS KNOWN FROM EXPERIMENTAL RESULTS
C
C     LOCATION J1
C
C     WRITE(2,100)
C 100 FORMAT(1X,'ENTER SHOCK DISPLACEMENT LENGTH, SL12, IN FT.')
C     READ(2,*) SL12
      XJ(1)=0.00
      YJ(1)=0.00
C
C     LOCATION J2
C
      XJ(2)=SL12*QCOS(ABETA(4))
      YJ(2)=SL12*QSIN(ABETA(4))
C
C     LOCATION J3
C
      ALPHA1=QABS(ABETA(4)-ATHETA(2))
      ALPHA2=QABS(ABETA(6)-ATHETA(2))
      A4=SL12*QCOS(ALPHA1)
      C4=SL12*QSIN(ALPHA1)
      B4=C4/QTAN(ALPHA2)
      SL13=A4+B4
      XJ(3)=SL13*QCOS(ATHETA(2))
      YJ(3)=SL13*QSIN(ATHETA(2))
C
C     LOCATION J4
C
      SL23=C4/QSIN(ALPHA2)
      ALPHA3=QABS(ABETA(6)-ATHETA(6))
      C6=SL23*QSIN(ALPHA3)
      ALPHA4=QABS(ABETA(7)-ATHETA(6))
      SL34=C6/QSIN(ALPHA4)
      SL24=SL23*QCOS(ALPHA3)+SL34*QCOS(ALPHA4)
      XJ(4)=XJ(2)+SL24*QCOS(ATHETA(6))
      YJ(4)=YJ(2)+SL24*QSIN(ATHETA(6))
C
C     LOCATION J5
C
      ALPHA5=QABS(ABETA(7)-ATHETA(7))
      ALPHA6=QABS(ABETA(8)-ATHETA(7))
      C7=SL34*QSIN(ALPHA5)
      SL45=C7/QSIN(ALPHA6)
      XJ(5)=XJ(4)+SL45*QCOS(ABETA(8))
      YJ(5)=YJ(4)+SL45*QSIN(ABETA(8))
```

```
C
C     CALCULATE JET WIDTH IN REGIONS 7 AND 8
C
      ALPHA7=QABS(ABETA(8)-ATHETA(8))
      C8=SL45*QSIN(ALPHA7)
      WJET7=C7
      WJET8=C8
C
C     LOCATION J6
C
      ALPHA8=QABS(BETA9)
      A8=C8/QTAN(ALPHA7)
      B8=C8/QTAN(ALPHA8)
      SL46=A8+B8
      XJ(6)=XJ(4)+SL46*QCOS(ATHETA(8))
      YJ(6)=YJ(4)+SL46*QSIN(ATHETA(8))
C
C     WRITE ANGLES AND JET INFORMATION
C
      WRITE(2,110)
      DO 10 I1=1,8
      WRITE(2,120)I1,ANGTR(I1),ANGBR(I1),ANGTA(I1),ANGBA(I1)
   10 CONTINUE
C     WRITE(2,130)MU6,MU7
      WRITE(2,140)
      DO 20 I2=1,6
      WRITE(2,150)I2,XJ(I2),YJ(I2)
   20 CONTINUE
      WRITE(2,160)
      WRITE(2,170)7,WJET7
      WRITE(2,170)8,WJET8
C
C     FIND THE STAGNATION HEATING RESULTING FROM
C     JET REGIONS 7 AND 8
C
      WRITE (2,180)
      CALL JETHEAT (PRES(7),DENS(7),VEL(7),WJET7,QJET7)
      WRITE (2,190)
      CALL JETHEAT (PRES(8),DENS(8),VEL(8),WJET8,QJET8)
C
C     WRITE STAGNATION HEATING INFORMATION HERE
C
  110 FORMAT(//,1X,'TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH
     1 REGION (DEGREES) '
     2,/,2X,'REGION',10X,'RELATIVE ANGLE',14X,'ABSOLUTE ANGLE',/
     3,15X,'THETA',10X,'BETA',9X,'THETA',10X,'BETA',/)
  120 FORMAT(4X,I2,4X,4(2X,E12.5))
C 130 FORMAT(/,1X,'MU6 = ',E12.5,6X,'MU7 = ',E12.5)
  140 FORMAT(//,1X,'COORDINATE LOCATIONS OF THE JET',/,2X,'POINT',9X,
     1'XJ',12X,'YJ',/,15X,'[FT]',10X,'[FT]',/)
  150 FORMAT(3X,I2,4X,2(2X,E12.5))
  160 FORMAT(//,2X,'REGION',5X,'JET WIDTH',/,16X,'[FT]',/)
  170 FORMAT(4X,I2,5X,E12.5)
  180 FORMAT(/,1X,'******* REGION 7 *******',/)
  190 FORMAT(/,1X,'******* REGION 8 *******',/)
```

```
      RETURN
      END
      SUBROUTINE JETHEAT (P1,RHO1,V1,WJETFT,QJET)
      IMPLICIT REAL*16 (A-H,O-Z)
      DIMENSION VARI(16),VARD(16)
C
C     VALUES FOR DENSITY RATIO AND SHOCK STANDOFF TO NOSE RADIUS
C     RATIO AS CALCULATED BY HARRIS HAMILTON'S BLUNT BODY SOLVER
C     AT GAMMA = 1.4 FOR FLOW OVER A CYLINDER
C
      COMMON /WALL/ TW,ITYPE
      DATA VARI/.1669,.1687,.1703,.1749,.1998,.2185,.2256,.2343,.2451,
     1          .2586,.2759,.2985,.3287,.3699,.4276,.5092/
      DATA VARD/.3767,.3817,.3864,.3999,.4770,.5396,.5646,.5960,.6361,
     1          .6888,.7603,.8606,1.0086,1.2409,1.6372,2.3941/
      WJETM=WJETFT*0.3048
      CALL NORMAL (P1,RHO1,V1,P2,RHO2,V2)
      RHORAT=RHO1/RHO2
      CALL FTLUP (RHORAT,DELOR,1,16,VARI,VARD)
      DELOW=0.45
      DEL=DELOW*WJETM
      RBSHK=DEL/DELOR
      CALL QSTAG (P1,RHO1,V1,RBSHK,TW,QJET,ITYPE)
      RETURN
      END
      SUBROUTINE FTLUP (X,Y,M,N,VARI,VARD)
      IMPLICIT REAL*16 (A-H,O-Z)
C     ***DOCUMENT DATE  7/7/69    SUBROUTINE REVISED  7/7/69  *********
C        MODIFICATION OF LIBRARY INTERPOLATION SUBROUTINE  FTLUP
      DIMENSION VARI(16), VARD(16), V(3), YY(2)
      DIMENSION II(43)
C      INITIALIZE ALL INTERVAL POINTERS TO -1.0   FOR MONOTONICITY CHECK
      DATA (II(J),J=1,43)/43*-1/
      MA=IABS(M)
C
C     ASSIGN INTERVAL POINTER FOR GIVEN VARI TABLE
C     THE SAME POINTER WILL BE USED ON A GIVEN VARI TABLE EVERY TIME
C
C     LI=MOD(LOCF(VARI(1)),43)+1
      LI=1
      I=II(LI)
      IF (I.GE.0) GO TO 70
      IF (N.LT.2) GO TO 70
C     MONOTONICITY CHECK
      IF (VARI(2)-VARI(1)) 30,30,50
C     ERROR IN MONOTONICITY
C  20 K=LOCF(VARI(1))
   20 K=1
      WRITE(2,180) J,K,(VARI(J),J=1,N),(VARD(J),J=1,N)
      STOP
C     MONOTONIC DECREASING
   30 DO 40 J=2,N
      IF (VARI(J)-VARI(J-1)) 40,20,20
   40 CONTINUE
      GO TO 70
```

```
C     MONOTONIC INCREASING
   50 DO 60 J=2,N
      IF (VARI(J)-VARI(J-1)) 20,20,60
   60 CONTINUE
C     INTERPOLATION
   70 IF (I.LE.0) I=1
      IF (I.GE.N) I=N-1
      IF (N.LE.1) GO TO 80
      IF (MA.NE.0) GO TO 90
C     ZERO ORDER
   80 Y=VARD(1)
      GO TO 170
C     LOCATE I INTERVAL (X(I).LE.X.LT.X(I+1))
   90 IF ((VARI(I)-X)*(VARI(I+1)-X)) 120,120,100
C     IN GIVES DIRECTION FOR SEARCH OF INTERVALS
  100 AFIX=(VARI(I+1)-VARI(I))*(X-VARI(I))
      ONE=1.0
      IN=SIGN(ONE,AFIX)
C     IF X OUTSIDE ENDPOINTS, EXTRAPOLATE FROM END INTERVAL
  110 IF ((I+IN).LE.0) GO TO 120
      IF ((I+IN).GE.N) GO TO 120
      I=I+IN
      IF ((VARI(I)-X)*(VARI(I+1)-X)) 120,120,110
  120 IF (MA.EQ.2) GO TO 130
C     FIRST ORDER
      Y=(VARD(I)*(VARI(I+1)-X)-VARD(I+1)*(VARI(I)-X))/(VARI(I+1)-VARI(I)
     1)
      GO TO 170
C     SECOND ORDER
  130 IF (N.EQ.2) GO TO 20
      IF (I.EQ.(N-1)) GO TO 150
      IF (I.EQ.1) GO TO 140
C     PICK THIRD POINT
      SK=VARI(I+1)-VARI(I)
      IF ((SK*(X-VARI(I-1))).LT.(SK*(VARI(I+2)-X))) GO TO 150
  140 L=I
      GO TO 160
  150 L=I-1
  160 V(1)=VARI(L)-X
      V(2)=VARI(L+1)-X
      V(3)=VARI(L+2)-X
      YY(1)=(VARD(L)*V(2)-VARD(L+1)*V(1))/(VARI(L+1)-VARI(L))
      YY(2)=(VARD(L+1)*V(3)-VARD(L+2)*V(2))/(VARI(L+2)-VARI(L+1))
      Y=(YY(1)*V(3)-YY(2)*V(1))/(VARI(L+2)-VARI(L))
  170 II(LI)=I
      RETURN
C
  180 FORMAT (1H1,50H TABLE BELOW OUT OF ORDER FOR FTLUP  AT POSITION   ,
     1I5,/31H X TABLE IS STORED IN LOCATION ,O6,//(8G15.8))
      END
C
C     SUBROUTINE QSTAG CALCULATES STAGNATION HEATING RATE
C     USING THE FOLLOWING MODELS :
C
C     ITYPE = 1 : 2-D FAY AND RIDDELL
```

```
C     ITYPE = 2 : 3-D FAY AND RIDDELL
C     ITYPE = 3 : 2-D LEES'
C     ITYPE = 4 : 3-D LEES'
C     ITYPE = 5 : 2-D BOEING
C     ITYPE = 6 : 3-D BOEING
C     ITYPE = 7 : 2-D VAN DRIEST
C     ITYPE = 8 : 3-D VAN DRIEST
C
      SUBROUTINE QSTAG (PINF,RHOINF,VINF,R,TW,QW,ITYPE)
      IMPLICIT REAL*16 (A-H,O-Z)
      COMMON /REG1/ T1C,RHO1C,P1C,E1C,H1C,SIG1C
      COMMON /REG2/ T2C,RHO2C,P2C,E2C,H2C,SIG2C
      COMMON /ENTRO/ SC,GAMMA
      COMMON /E/ CPP
      COMMON /UNITS/ VERTT,VERTP,VERTD,VERTE,VERTQ,VERTS,VERTV
      COMMON /GAS/ IGAS,PRNUM
      REAL*16 M1C,GAMMA,LE
      RIDEAL=287.0
      RR=8.31441
      TOLER=1.E-7
      ONE=1.000000
      ONEPTWO=1.200000
      TWO=2.000000
      CALL PRPROP(TINF,RHOINF,PINF,EINF,HINF,SINF,SIGINF)
      CPPINF=CPP
      CALL MUANDK (TINF,VISINF,CONINF,CPPINF,SIGINF)
         IF (IGAS.EQ.1) THEN
         PRNOINF=VISINF*CPPINF/CONINF
         ELSE
         PRNOINF=PRNUM
         ENDIF
      TOTENTH=HINF+VINF*VINF/TWO
C     WRITE(2,99)TOTENTH
   99 FORMAT(/,1X,'TOTAL ENTHALPY = ',E12.5,/)
      CALL NORMAL(PINF,RHOINF,VINF,P1C,RHO1C,V1C)
      CALL PRPROP(T1C,RHO1C,P1C,E1C,H1C,S1C,SIG1C)
      CPP1=CPP
      CALL MUANDK (T1C,VIS1,CON1,CPP1,SIG1C)
         IF (IGAS.EQ.1) THEN
         PRNO1=VIS1*CPP1/CON1
         ELSE
         PRNO1=PRNUM
         ENDIF
      HO=TOTENTH
      PMIN=P1C
      CALL SOUND (P1C,RHO1C,A1C)
      SC=S1C
      GAMMA=A1C*A1C*RHO1C/P1C
      PSTART= P1C+RHO1C*V1C*V1C
      PMAX=PSTART
C
C     CONVERGE TO THE STAGNATION CONDITION AT TOTAL ENTHALPY HO
C     AND ENTROPY BEHIND THE NORMAL SHOCK
C
      I=1
```

```
   10 I=I+1
      P2C=(PMAX+PMIN)/TWO
      CALL CENTRO(1)
C     WRITE(2,100) P2C,PMAX,H2C,HO
      IF(QABS((HO-H2C)/HO).LT.TOLER) GOTO 20
       IF(HO.GT.H2C) THEN
       PMIN=P2C
       ELSE
       PMAX=P2C
       ENDIF
       IF(I.GT.50) THEN
       WRITE(2,200)
       STOP
       ENDIF
      GOTO 10
   20 CPPSTAG=CPP
      PSTAG=P2C
      TSTAG=T2C
      RHOSTAG=RHO2C
      ESTAG=E2C
      HSTAG=H2C
      SIGSTAG=SIG2C
      CALL MUANDK (TSTAG,VISSTAG,CONSTAG,CPPSTAG,SIGSTAG)
         IF (IGAS.EQ.1) THEN
         PRSTAG=VISSTAG*CPPSTAG/CONSTAG
         ELSE
         PRSTAG=PRNUM
         ENDIF
      ZSTAG=PSTAG/(RHOSTAG*RIDEAL*TSTAG)
C
C     CONVERGE TO THE WALL CONDITIONS TW AND PSTAG
C
C     START BY GUESSING DENSITY AT THE WALL
C
      I=1
      RHOW=PSTAG/(RR*SIGSTAG*TW)
   30 I=I+1
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(TW,RHOW,PW,EW,HW,SW,SIGW)
          ELSE
          CALL SUBR2(TW,RHOW,PW,EW,HW,SW,SIGW)
          ENDIF
C     WRITE(2,300)PW,PSTAG
      IF(QABS((PSTAG-PW)/PSTAG).LT.TOLER) GOTO 40
       IF(I.GT.50) THEN
       WRITE(2,200)
       STOP
       ENDIF
      RHOW=PSTAG/(RR*SIGW*TW)
      GOTO 30
   40 CPPW=CPP
      CALL MUANDK (TW,VISW,CONW,CPPW,SIGW)
         IF (IGAS.EQ.1) THEN
         PRNOW=VISW*CPPW/CONW
         ELSE
```

```
            PRNOW=PRNUM
         ENDIF
         ZERO=0.00000
C
C        CONVERT TO BRITISH UNITS AND WRITE TEMPERATURE,
C        PRESSURE, DENSITY, VELOCITY, AND PRANDLT NUMBER
C        FOR PRE-SHOCK, POST-SHOCK, STAGNATION, AND WALL
C        REGIONS
C
         WRITE(2,400)
         BUTINF=TINF*VERTT
         BUPINF=PINF*VERTP
         BURHOIN=RHOINF*VERTD
         BUVINF=VINF*VERTV
         WRITE(2,410)BUTINF,BUPINF,BURHOIN,BUVINF,PRNOINF
         BUT1C=T1C*VERTT
         BUP1C=P1C*VERTP
         BURHO1C=RHO1C*VERTD
         BUV1C=V1C*VERTV
         WRITE(2,420)BUT1C,BUP1C,BURHO1C,BUV1C,PRNO1
         BUTS=TSTAG*VERTT
         BUPS=PSTAG*VERTP
         BURHOS=RHOSTAG*VERTD
         WRITE(2,430)BUTS,BUPS,BURHOS,ZERO,PRSTAG
         BUTW=TW*VERTT
         BUPW=PW*VERTP
         BURHOW=RHOW*VERTD
         WRITE(2,440)BUTW,BUPW,BURHOW,ZERO,PRNOW
         IF(ITYPE.NE.1) GOTO 110
C
C        CALCULATE 2-D STAGNATION LINE HEATING RATE
C        FROM FAY AND RIDDELL ENERGY EQUATION GIVEN BY
C        WIETING IN NASA TM-100484
C
         TWOD=0.567
         TERM1=TWOD*PRNOINF**(-0.60)
         TERM2=(RHOW*VISW)**0.10
         TERM3=(RHOSTAG*VISSTAG)**0.40
         TERM4=HSTAG-HW
         TERM5P=TWO*(PSTAG-PINF)/RHOSTAG
         TERM5=QSQRT((ONE/R)*QSQRT(TERM5P))
         QW=TERM1*(VERTQ*(TERM2*TERM3*TERM4*TERM5))
         WRITE(2,50) QW
      50 FORMAT(/,1X,'2-D FAY AND RIDDELL STAGNATION LINE HEATING = ',/
        1        ,E12.5,' BTU/(FT**2-SEC)',/)
         GOTO 180
     110 IF(ITYPE.NE.2) GOTO 120
C
C        CALCULATE 3-D STAGNATION POINT HEATING RATE
C        FROM FAY AND RIDDELL ENERGY EQUATION GIVEN BY
C        WIETING IN NASA TM-100484
C
         THREED=0.76
         TERM1=THREED*PRNOINF**(-0.60)
         TERM2=(RHOW*VISW)**0.10
```

```
      TERM3=(RHOSTAG*VISSTAG)**0.40
      TERM4=HSTAG-HW
      TERM5P=TWO*(PSTAG-PINF)/RHOSTAG
      TERM5=QSQRT((ONE/R)*QSQRT(TERM5P))
      QW=TERM1*(VERTQ*(TERM2*TERM3*TERM4*TERM5))
      WRITE(2,55) QW
   55 FORMAT(/,1X,'3-D FAY AND RIDDELL STAGNATION POINT HEATING = ',/
     1       ,E12.5,' BTU/(FT**2-SEC)',/)
      GOTO 180
  120 IF(ITYPE.NE.3) GOTO 130
C
C     CALCULATE 2-D STAGNATION LINE HEATING RATE
C     FROM LEES (EQN. 7.46) GIVEN IN "ELEMENTS OF HYPERSONIC
C     AERODYNAMICS" BY COX AND CRABTREE
C
      TWOD=0.47
      TERM1=TWOD*((PRSTAG+PRNOW)/TWO)**(-2.000/3.000)
      TERM2=QSQRT(RHOSTAG*VISSTAG*VINF)*HO
      TERM3P=QSQRT(TWO*(PSTAG-PINF)/RHOINF)
      TERM3=QSQRT(TERM3P/(VINF*R))
      QW=TERM1*(VERTQ*(TERM2*TERM3))
      WRITE(2,60) QW
   60 FORMAT(/,1X,'2-D LEES STAGNATION LINE HEATING = ',/
     1       ,E12.5,' BTU/(FT**2-SEC)',/)
      GOTO 180
  130 IF(ITYPE.NE.4) GOTO 140
C
C     CALCULATE 3-D STAGNATION POINT HEATING RATE
C     FROM LEES (EQN. 7.46) GIVEN IN "ELEMENTS OF HYPERSONIC
C     AERODYNAMICS" BY COX AND CRABTREE
C
      THREED=0.47*QSQRT(TWO)
      TERM1=THREED*((PRSTAG+PRNOW)/TWO)**(-2.000/3.000)
      TERM2=QSQRT(RHOSTAG*VISSTAG*VINF)*HO
      TERM3P=QSQRT(TWO*(PSTAG-PINF)/RHOINF)
      TERM3=QSQRT(TERM3P/(VINF*R))
      QW=TERM1*(VERTQ*(TERM2*TERM3))
      WRITE(2,65) QW
   65 FORMAT(/,1X,'3-D LEES STAGNATION POINT HEATING = ',/
     1       ,E12.5,' BTU/(FT**2-SEC)',/)
      GOTO 180
  140 IF(ITYPE.NE.5) GOTO 150
C
C     CALCULATE 2-D STAGNATION LINE HEATING RATE
C     FROM BOEING RESEARCH DOCUMENT NO. D2-9514
C     "AERODYNAMIC HEAT TRANSFER HANDBOOK - VOL. I", PAGE 5.1
C
      LE=1.4
      TWOD=0.576
      HD=0.0000
      HI=0.0000
      TERM1=TWOD*PRNOW**(-0.60)
      TERM2=(RHOW*VISW)**0.06
      TERM3=(RHOSTAG*VISSTAG)**0.44
      TERM4=HSTAG-HW
```

```
      WRITE(2,*)HO,HSTAG,TOTENTH
      TERM5P=TWO*(PSTAG-PINF)/RHOSTAG
      TERM5=QSQRT((ONE/R)*QSQRT(TERM5P))
C
C     ACCOUNT FOR THE DISSOCIATION AND IONIZATION ENTHALPY
C
         IF(ZSTAG.GT.ONE.AND.ZSTAG.LE.ONEPTWO) THEN
         HD=(7276.0*(ZSTAG-ONE))/VERTE
         ENDIF
         IF(ZSTAG.GT.ONEPTWO.AND.ZSTAG.LE.TWO) THEN
         HD=(1455.0+13940.0*(ZSTAG-ONEPTWO))/VERTE
         ENDIF
         IF(ZSTAG.GT.TWO) THEN
         HD=(1455.0+13940.0*(TWO-ONEPTWO))/VERTE
         HI=21400.0*(ZSTAG-TWO)/VERTE
         ENDIF
      TERM6A=(LE**0.52-ONE)*HD/HSTAG
      TERM6B=HI/HSTAG
      TERM6=ONE+TERM6A+TERM6B
      QW=TERM1*(VERTQ*(TERM2*TERM3*TERM4*TERM5*TERM6))
      WRITE(2,70) QW
   70 FORMAT(/,1X,'2-D BOEING STAGNATION LINE HEATING = ',/
     1       ,E12.5,' BTU/(FT**2-SEC)',/)
      GOTO 180
  150 IF(ITYPE.NE.6) GOTO 160
C
C     CALCULATE 3-D STAGNATION POINT HEATING RATE
C     FROM BOEING RESEARCH DOCUMENT NO. D2-9514
C     "AERODYNAMIC HEAT TRANSFER HANDBOOK - VOL. I", PAGE 4.1
C
      LE=1.4
      THREED=0.793
      HD=0.0000
      HI=0.0000
      TERM1=THREED*PRNOW**(-0.60)
      TERM2=(RHOW*VISW)**0.06
      TERM3=(RHOSTAG*VISSTAG)**0.44
      TERM4=HSTAG-HW
      TERM5P=TWO*(PSTAG-PINF)/RHOSTAG
      TERM5=QSQRT((ONE/R)*QSQRT(TERM5P))
C
C     ACCOUNT FOR THE DISSOCIATION AND IONIZATION ENTHALPY
C
         IF(ZSTAG.GT.ONE.AND.ZSTAG.LE.ONEPTWO) THEN
         HD=(7276.0*(ZSTAG-ONE))/VERTE
         ENDIF
         IF(ZSTAG.GT.ONEPTWO.AND.ZSTAG.LE.TWO) THEN
         HD=(1455.0+13940.0*(ZSTAG-ONEPTWO))/VERTE
         ENDIF
         IF(ZSTAG.GT.TWO) THEN
         HD=(1455.0+13940.0*(TWO-ONEPTWO))/VERTE
         HI=21400.0*(ZSTAG-TWO)/VERTE
         ENDIF
      TERM6A=(LE**0.52-ONE)*HD/HSTAG
      TERM6B=HI/HSTAG
```

```
      TERM6=ONE+TERM6A+TERM6B
      QW=TERM1*(VERTQ*(TERM2*TERM3*TERM4*TERM5*TERM6))
      WRITE(2,75) QW
   75 FORMAT(/,1X,'3-D BOEING STAGNATION POINT HEATING = ',/
     1       ,E12.5,' BTU/(FT**2-SEC)',/)
      GOTO 180
  160 IF(ITYPE.NE.7) GOTO 170
C
C     CALCULATE 2-D STAGNATION LINE HEATING RATE
C     FROM VAN DRIEST ENERGY EQUATION GIVEN BY
C     ANDERSON IN "INTRODUCTION TO HYPERSONIC AERODYNAMICS"
C     CLASS NOTES
C
      TWOD=0.57
      TERM1=TWOD*PRNOINF**(-0.60)
      TERM2=QSQRT(RHOSTAG*VISSTAG)
      TERM3P=TWO*(PSTAG-PINF)/RHOSTAG
      TERM3=QSQRT((ONE/R)*QSQRT(TERM3P))
      HAW=HINF+QSQRT(PRNOINF)*VINF*VINF/TWO
      TERM4=HAW-HW
      QW=TERM1*(VERTQ*(TERM2*TERM3*TERM4))
      WRITE(2,80) QW
   80 FORMAT(/,1X,'2-D VAN DRIEST STAGNATION LINE HEATING = ',/
     1       ,E12.5,' BTU/(FT**2-SEC)',/)
      GOTO 180
  170 IF(ITYPE.NE.8) GOTO 180
C
C     CALCULATE 3-D STAGNATION POINT HEATING RATE
C     FROM VAN DRIEST ENERGY EQUATION GIVEN BY
C     ANDERSON IN "INTRODUCTION TO HYPERSONIC AERODYNAMICS"
C     CLASS NOTES
C
      THREED=0.763
      TERM1=THREED*PRNOINF**(-0.60)
      TERM2=QSQRT(RHOSTAG*VISSTAG)
      TERM3P=TWO*(PSTAG-PINF)/RHOSTAG
      TERM3=QSQRT((ONE/R)*QSQRT(TERM3P))
      HAW=HINF+QSQRT(PRNOINF)*VINF*VINF/TWO
      TERM4=HAW-HW
      QW=TERM1*(VERTQ*(TERM2*TERM3*TERM4))
      WRITE(2,85) QW
   85 FORMAT(/,1X,'3-D VAN DRIEST STAGNATION POINT HEATING = ',/
     1       ,E12.5,' BTU/(FT**2-SEC)',/)
  180 CONTINUE
      CHMAX=(QW/VERTQ)/(RHOINF*VINF*(HO-HW))
C     WRITE(2,800)CHMAX
      GOTO 190
  100 FORMAT(1X,4(5X,E12.5))
  200 FORMAT(1X,'NO CONVERGENCE IN QSTAG AFTER 50 ITERATIONS')
  300 FORMAT(1X,2(5X,E12.5))
  400 FORMAT(/,3X,'REGION',5X,'TEMPERATURE',4X,'PRESSURE',4X,'DENSITY',
     16X,'VELOCITY',8X,'PR',/,15X,'(RANKINE)',6X,'(PSIA)',3X,
     2'(SLUGS/FT**3)',2X,'(FT/SEC)')
  410 FORMAT(/,1X,'PRE-SHOCK  ',5(1X,E12.5))
  420 FORMAT  (1X,'POST-SHOCK ',5(1X,E12.5))
```

```
  430 FORMAT  (1X,'STAGNATION ',5(1X,E12.5))
  440 FORMAT  (1X,'WALL       ',5(1X,E12.5),/)
C 800 FORMAT(1X,'HEAT TRANSFER COEFFICIENT AT THE STAGNATION LINE = ',
C    1       2X,E12.5,/,/)
  190 RETURN
      END
C
C     SUBROUTINE FINDB CALCULATES SHOCK ANGLES GIVEN UPSTREAM
C     FLOW CONDITIONS FOR THE FOLLOWING :
C
C     ITYPE = 1 : USED TO CALCULATE MAXIMUM TURNING ANGLE SOLUTION
C                 (THETA-MAX, BETA, P2, RHO2, AND V2)
C                 GIVEN P1, RHO1, AND V1
C
C     ITYPE = 2 : USED TO CALCULATE THE WEAK SHOCK SOLUTION
C                 (BETA, P2, RHO2, AND V2)
C                 GIVEN P1, RHO1, V1, AND THETA
C
C     ITYPE = 3 : USED TO CALCULATE THE WEAK SHOCK SOLUTION
C                 (BETA, P2, RHO2, AND V2)
C                 GIVEN P1, RHO1, V1, THETA, AND BETA AT THETA-MAX
C
C     ITYPE = 4 : USED TO CALCULATE THE STRONG SHOCK SOLUTION
C                 (BETA, P2, RHO2, AND V2)
C                 GIVEN P1, RHO1, V1, AND THETA
C
C     ITYPE = 5 : USED TO CALCULATE THE STRONG SHOCK SOLUTION
C                 (BETA, P2, RHO2, AND V2)
C                 GIVEN P1, RHO1, V1, THETA, AND BETA AT THETA-MAX
C
C     ITYPE = 6 : USED TO CALCULATE WEAK SHOCK SOLUTION FOR
C                 A POSITIVE TURNING ANGLE
C                 (THETA, BETA, RHO2, AND V2)
C                 GIVEN P1, RHO1, V1, AND P2
C
C     ITYPE = 7 : USED TO CALCULATE WEAK SHOCK SOLUTION FOR
C                 A NEGATIVE TURNING ANGLE
C                 (THETA, BETA, RHO2, AND V2)
C                 GIVEN P1, RHO1, V1, AND P2
C
      SUBROUTINE FINDB(P1,RHO1,V1,P2,RHO2,V2,THETA,BETA,ITYPE)
      IMPLICIT REAL*16 ( A-H, O-Z )
      COMMON /BAMAX/ BTM
      TOLER=1.E-4
       API=-1.0
      PI=QACOS(API)
      IF(ITYPE.GT.5) GOTO 70
      IF(ITYPE.EQ.1) GOTO 5
C     CHECK FOR NEGATIVE THETA AND SET IFLAG
C
      IF(THETA.LT.0.0000) THEN
      THETA=-THETA
      IFLAG=-1
      ELSE
      IFLAG=1
```

```
      ENDIF
      IF(ITYPE.EQ.3) GOTO 25
      IF(ITYPE.EQ.5) GOTO 45
C
C     FIND THETA-MAX USING SUBROUTINE TFIND
C
    5 BETAM=PI/2.0
      DBETAM=-0.10000
      THETAO=0.00000
      PP=P1
   10 BETAM=BETAM+DBETAM
      CALL FINDT(P1,RHO1,V1,BETAM,P2M,RHO2M,V2M,THETAN)
C
C     DIAGNOSTIC WRITE
C     WRITE(2,*)THETAO,THETAN
C
      DIFF1=QABS((PP-P2M)/P2M)
      PP=P2M
      IF(DIFF1.LE.TOLER) GOTO 20
      IF(THETAO.GT.THETAN) DBETAM=-DBETAM/10.00000
      THETAO=THETAN
      GOTO 10
   20 THETAM=THETAN
      IF(ITYPE.EQ.1) THEN
      THETA=THETAM
      BETA=BETAM
      P2=P2M
      RHO2=RHO2M
      V2=V2M
      RETURN
      ENDIF
C
C     CHECK THETA WITH THETA-MAX, IF THETA GREATER THAN THETA-MAX, THEN
C     1 - WRITE ERROR MESSAGE
C     2 - RETURN EXECUTION TO CALLING ROUTINE
C
      IF(THETA.GE.THETAM) THEN
      WRITE(2,200)
      RETURN
  200 FORMAT(1X,'THETA INPUT TO SUBROUTINE FINDB GREATER THAN THETA-MAX'
     1)
      ENDIF
      IF(ITYPE.EQ.4) GOTO 40
C
C     CALCULATE THE WEAK SHOCK SOLUTION IF ITYPE = 2 OR 3
C
      BETAMAX=BETAM
C
C     TRY TO OPTIMIZE FINDB
C
   25 IF(ITYPE.EQ.3) BETAMAX=BTM
      CALL SOUND (P1,RHO1,A1)
      BETAMIN=QASIN(A1/V1)
      PP=P1
      I=1
```

```
   30   IF(I.EQ.1) THEN
        BETAW=(BETAMAX+BETAMIN)/2.0000
        ELSE
        BETAW=BETANEW
        ENDIF
      IF(BETAW.GE.BETAMAX)BETAW=BETAMAX-0.05
      IF(BETAW.LE.BETAMIN)BETAW=BETAMIN+0.05
      CALL FINDT (P1,RHO1,V1,BETAW,P2W,RHO2W,V2W,THETAP)
      DIFF=QABS((PP-P2W)/P2W)
      PP=P2W
      IF(DIFF.LE.TOLER) GOTO 60
      IF(I.GT.50) STOP 500
      I=I+1
      BPOS=BETAW+0.005
      BNEG=BETAW
      CALL FINDT (P1,RHO1,V1,BPOS,PPDUM,RPDUM,VPDUM,TPOS)
      CALL FINDT (P1,RHO1,V1,BNEG,PNDUM,RNDUM,VNDUM,TNEG)
      DBBYDT=(BPOS-BNEG)/(TPOS-TNEG)
      BETANEW=BETAW+(THETA-THETAP)*DBBYDT
      GOTO 30
C*****************************************************************
C  25 IF(ITYPE.EQ.3) BETAMAX=BTM
C     CALL SOUND (P1,RHO1,A1)
C     BETAMIN=QASIN(A1/V1)
C     PP=P1
C  30 BETAW=(BETAMAX+BETAMIN)/2.0000
C     U1=V1*QSIN(BETAW)
C     W1=V1*QCOS(BETAW)
C     CALL NORMAL(P1,RHO1,U1,P2W,RHO2W,U2W)
C     W2W=W1
C     THETAP=BETAW-QATAN2(U2W,W2W)
C
C     DIAGNOSTIC WRITE
C     WRITE(2,*)BETAMAX,BETAMIN
C
C     DIFF=QABS((PP-P2W)/P2W)
C     PP=P2W
C     IF(DIFF.LE.TOLER) GOTO 60
C     IF(THETA.GT.THETAP) THEN
C     BETAMIN=BETAW
C     ELSE
C     BETAMAX=BETAW
C     ENDIF
C     GOTO 30
C********************************************************
   40 CONTINUE
C
C     CALCULATE THE STRONG SHOCK SOLUTION IF ITYPE = 4 OR 5
C
      BETAMIN=BETAM
   45 IF(ITYPE.EQ.5) BETAMIN=BTM
      BETAMAX=PI/2.0000
      PP=P1
   50 BETAS=(BETAMAX+BETAMIN)/2.0000
      U1=V1*QSIN(BETAS)
```

```
      W1=V1*QCOS(BETAS)
      CALL NORMAL (P1,RHO1,U1,P2S,RHO2S,U2S)
      W2S=W1
      THETAP=BETAS-QATAN2(U2S,W2S)
C
C     DIAGNOSTIC WRITE
C     WRITE(2,*)BETAMAX,BETAMIN
C
      DIFF=QABS((PP-P2S)/P2S)
      PP=P2S
      IF(DIFF.LT.TOLER) GOTO 60
      IF(THETA.GT.THETAP) THEN
      BETAMAX=BETAS
      ELSE
      BETAMIN=BETAS
      ENDIF
      GOTO 50
C
C     CHECK IFLAG AND ITYPE
C
   60 IF(ITYPE.EQ.2.OR.ITYPE.EQ.3) THEN
      P2=P2W
      RHO2=RHO2W
C
C     OPTIMIZED VERSION CALCULATES V2
C
C     V2=QSQRT(W2W*W2W+U2W*U2W)
C
      V2=V2W
      BETA=BETAW
      IF(IFLAG.EQ.-1) THEN
      THETA=-THETA
      BETA=-BETA
      ENDIF
C
C     DIAGNOSTIC WRITE
C     WRITE(2,300)THETA,BETA
C 300 FORMAT(1X,'THE WEAK SHOCK SOLUTION CONVERGED',/,1X,'THETA = ',F9.5
C    1,4X,'BETA = ',F9.5)
C
      ELSE
      P2=P2S
      RHO2=RHO2S
      V2=QSQRT(W2S*W2S+U2S*U2S)
      BETA=BETAS
      IF(IFLAG.EQ.-1) THEN
      THETA=-THETA
      BETA=-BETA
      ENDIF
C
C     DIAGNOSTIC WRITE
C     WRITE(2,400)THETA,BETA
C 400 FORMAT(1X,'THE STRONG SHOCK SOLUTION CONVERGED',/,1X,'THETA = ',F9
C    1.5,4X,'BETA = ',F9.5)
C
```

```
      ENDIF
      RETURN
C
C     CALCULATE WEAK SHOCK SOLUTION IF ITYPE > 5
C
   70 CONTINUE
      CALL NORMAL (P1,RHO1,V1,PDUM,RDUM,VDUM)
      RATMAX=1.0000000
      RATMIN=RHO1/RDUM
   80 RHORAT=(RATMAX+RATMIN)/2.00000
      U1SQ=(P2-P1)/(RHO1*(1.000000-RHORAT))
      U1=QSQRT(U1SQ)
      CALL NORMAL (P1,RHO1,U1,P2P,RHO2P,U2P)
      PCHECK=QABS((P2-P2P)/P2)
C
C     DIAGNOSTIC WRITE
C     WRITE(2,*)P2,P2P,PCHECK
C
      IF(PCHECK.LT.TOLER) GOTO 90
        IF(P2P.LT.P2) THEN
        RATMIN=RHORAT
        ELSE
        RATMAX=RHORAT
        ENDIF
      GOTO 80
   90 U2=U2P
      RHO2=RHO2P
      BETA=QASIN(U1/V1)
      SIDE=(U2/U1)*QTAN(BETA)
      BETMTHE=QATAN(SIDE)
      THETA=BETA-BETMTHE
      W2=U2/SIDE
      V2=QSQRT(U2*U2+W2*W2)
C
C     IF ITYPE = 7  BETA AND THETA ARE NEGATIVE
C
      IF(ITYPE.EQ.7) THEN
      BETA=-BETA
      THETA=-THETA
      ENDIF
      RETURN
      END
C
C     SUBROUTINE FINDT CALCULATES THE FLOW DEFLECTION ANGLE, THETA,
C     GIVEN UPSTREAM CONDITIONS AND THE SHOCK ANGLE, BETA.
C
      SUBROUTINE FINDT (P1,RHO1,V1,BETA,P2,RHO2,V2,THETA)
      IMPLICIT REAL*16 ( A-H, O-Z )
      IFLAG=1
      IF(BETA.LT.0.00000) GOTO 1
      GOTO 2
    1 BETA=-BETA
      IFLAG=-1
    2 U1=V1*QSIN(BETA)
      CALL NORMAL (P1,RHO1,U1,P2,RHO2,U2)
```

```
      TBETA=QTAN(BETA)
      BETMTHE=QATAN(TBETA*U2/U1)
      THETA=BETA-BETMTHE
      W1=U1/TBETA
      W2=W1
      V2SQ=U2*U2+W2*W2
      V2=QSQRT(V2SQ)
      IF(IFLAG.EQ.-1) GOTO 3
      GOTO 4
    3 BETA=-BETA
      THETA=-THETA
    4 RETURN
      END
C
C     SUBROUTINE NORMAL CALCULATES CONDITIONS THROUGH
C     A NORMAL SHOCK GIVEN UPSTREAM CONDITIONS
C
      SUBROUTINE NORMAL (P1,RHO1,U1,P2,RHO2,U2)
      IMPLICIT REAL*16 ( A-H, O-Z )
      COMMON /GAS/ IGAS,PRNUM
      REAL*16 M1
      TOLER=1.E-6
C
C     CHECK IF U1 IS SUPERSONIC
C
      CALL SOUND (P1,RHO1,A1)
      CALL PRPROP(DUM1,RHO1,P1,DUM2,H1,DUM3,DUM4)
      M1=U1/A1
      IF(M1.LT.1.0000) THEN
      WRITE(2,100) M1
  100 FORMAT(1X,'SUBSONIC FLOW DETECTED IN SUBROUTINE NORMAL',/
     1,1X,'M1 EQUALS ',E12.5)
      STOP 100
      ENDIF
      GAMMA=1.4
      ONE=1.000000
      TWO=2.000000
      RR=8.31441
C
C     ESTIMATE POST SHOCK DENSITY USING PERFECT GAS RELATIONSHIPS
C
      RHO2=RHO1*(((GAMMA+ONE)*M1*M1)/((GAMMA-ONE)*M1*M1+TWO))
      RHORAT=RHO1/RHO2
C
C     I IS THE OUTER LOOP INDEX
C
      I=1
C
C     START ITERATION BY CALCULATING P2 USING THE MOMENTUM EQUATION
C
   10 P2=P1+RHO1*U1*U1*(ONE-RHORAT)
C
C     CALCULATE T2 FOR P2 AND RHO2
C
      CALL PRPROP(T2,RHO2,P2,E2,H2,S2,SIG2)
```

```
C
C     J IS THE INNER LOOP INDEX
C
      J=1
C
C     MODIFY RHO2 USING P2 AND THE ENERGY EQUATION
C
   20 RHOSUB=P2/(RR*SIG2*T2)
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(T2,RHOSUB,DUM,E2,H2,S2,SIG2)
          ELSE
          CALL SUBR2(T2,RHOSUB,DUM,E2,H2,S2,SIG2)
          ENDIF
      H2EQN=H1+(U1*U1/TWO)*(ONE-RHORAT*RHORAT)
      DH=H2EQN-H2
C
C     COMPUTE AN EFFECTIVE CP
C
      T2P=T2+ONE
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(T2P,RHOSUB,DUM1,DUM2,H2P,DUM3,DUM4)
          ELSE
          CALL SUBR2(T2P,RHOSUB,DUM1,DUM2,H2P,DUM3,DUM4)
          ENDIF
      CPP=(H2-H2P)/(T2-T2P)
C
C     MODIFY T2 USING THE EFFECTIVE CP
C
      DT=DH/CPP
      T2=T2+DT
        IF(J.GT.50) THEN
        WRITE(2,*)T2,DT,H2,H2EQN,DH
        STOP 99
        ENDIF
      IF(QABS(DT).LT..001) GOTO 30
      J=J+1
      GOTO 20
   30 RHO2=RHOSUB
      RATTEMP=RHORAT
      RHORAT=RHO1/RHO2
      CHECK=QABS(RATTEMP-RHORAT)
      IF(CHECK.LT.TOLER) GOTO 40
      IF(I.GT.99) STOP 99
      I=I+1
      GOTO 10
   40 U2=(RHO1*U1)/RHO2
      RETURN
      END
      SUBROUTINE EXPAND (P1,RHO1,V1,P2,RHO2,V2,THETA)
      IMPLICIT REAL*16 ( A-H, O-Z )
      COMMON /REG1/ T1C,RHO1C,P1C,E1C,H1C,SIG1C
      COMMON /BETWEEN/ VB,H0,EB,RHOB,PB
      COMMON /REG2/ T2C,RHO2C,P2C,E2C,H2C,SIG2C
      COMMON /ENTRO/ SC,GAMMA
      REAL*16 M, MB
```

```
      THETA=0.00000
      GAMMA=1.4
      PINC=(P1-P2)/100.0
      VSTART=V1
      P1C=P1
      RHO1C=RHO1
      CALL PRPROP(T1C,RHO1C,P1C,E1C,H1C,SC,SIG1C)
      HO=H1C+V1*V1/2.0000
      DO 10 I=1,101
      IF(I.EQ.1) THEN
C
C     DEFINE INTEGRAND AT THE STARTING POINT
C
      CALL SOUND (P1C,RHO1C,A1C)
      V=V1
      M=V/A1C
      TOP=QSQRT(M*M-1.0000)
      DTDV=TOP/V
      C1=DTDV
      V1=V
C     WRITE(2,100)
C     WRITE(2,110) DTDV,V,M,THETA
      GOTO 10
      ENDIF
C
C     DEFINE INTEGRAND AT THE SUBSEQUENT POINTS
C
      P2C=P1C-PINC
      CALL CENTRO(1)
      V=QSQRT(2.0000*(HO-H2C))
      CALL SOUND (P2C,RHO2C,A2C)
      M=V/A2C
      TOP=QSQRT(M*M-1.0000)
      DTDV=TOP/V
C
C     USE 4TH ORDER RUNGE-KUTTA FOR INTEGRATION TO FIND THETA
C
      V2=V
      C4=DTDV
      DV=V2-V1
      VB=V1+DV/3.0000
      CALL CENTRO(2)
      CALL SOUND (PB,RHOB,AB)
      MB=VB/AB
      TOPB=QSQRT(MB*MB-1.0000)
      C2=TOPB/VB
      VB=V1+2.0000*DV/3.0000
      CALL CENTRO(2)
      CALL SOUND (PB,RHOB,AB)
      MB=VB/AB
      TOPB=QSQRT(MB*MB-1.0000)
      C3=TOPB/VB
      DT=(DV/8.0000)*(C1+C4+3.0000*(C2+C3))
      THETA=THETA+DT
      C1=C4
```

```
      V1=V2
C     WRITE(2,110) DTDV,V,M,THETA
      T1C=T2C
      E1C=E2C
      H1C=H2C
      P1C=P2C
      RHO1C=RHO2C
      SIG1C=SIG2C
   10 CONTINUE
      P2=P2C
      RHO2=RHO2C
      V1=VSTART
C 100 FORMAT(1X,'DTDV',10X,'VELOCITY',7X,'MACH NUMBER',2X,'THETA')
C 110 FORMAT(1X,E10.5,3(5X,E10.5))
      RETURN
      END
C
C     SUBROUTINE CENTRO CALCULATES PROPERTIES THROUGH AN
C     ISENTROPIC EXPANSION FOR THE FOLLOWING CASES :
C
C     ITYPE = 1 : GIVEN RHO1, P1, S1, AND P2
C                 CALCULATES STATE 2 PROPERTIES
C
C     ITYPE = 2 : GIVEN V1, S1, AND V2
C                 CALCULATES STATE 2 PROPERTIES
C
      SUBROUTINE CENTRO(ITYPE)
      IMPLICIT REAL*16 ( A-H, O-Z )
      COMMON /REG1/ T1C,RHO1C,P1C,E1C,H1C,SIG1C
      COMMON /BETWEEN/ VB,H0,EB,RHOB,PB
      COMMON /REG2/ T2C,RHO2C,P2C,E2C,H2C,SIG2C
      COMMON /ENTRO/ SC,GAMMA
      COMMON /E/ CPP
      COMMON /GAS/ IGAS,PRNUM
      TOL=1.E-7
      RUNIV=8.31441
      IF(ITYPE.EQ.1) THEN
C
C     ITYPE = 1
C
C     CALCULATE STARTING VALUES FOR T2 AND RHO2
C
      RHO2P=RHO1C*(P2C/P1C)**(1.0/GAMMA)
      T2P=P2C/(RHO2P*RUNIV*SIG1C)
      J=1
   10 I=1
C
C     COMPUTE ENTROPY AT T2 AND P2
C
   15     IF (IGAS.EQ.1) THEN
          CALL SUBR1(T2P,RHO2P,P2P,E2P,H2P,S2P,SIG2P)
          ELSE
          CALL SUBR2(T2P,RHO2P,P2P,E2P,H2P,S2P,SIG2P)
          ENDIF
      IF(QABS((P2P-P2C)/P2C).LT.TOL) GOTO 20
```

```
      RHO2P=P2C/(T2P*RUNIV*SIG2P)
      I=I+1
      IF(I.GT.25) GOTO 70
      GOTO 15
C
C     COMPUTE AN EFFECTIVE CP
C
   20 RHO2PP=RHO2P
      T2PP=T2P+1.0
      K=1
C
C     CONVERGE TO A CONSTANT PRESSURE AT T = T + 1
C
   25     IF (IGAS.EQ.1) THEN
          CALL SUBR1(T2PP,RHO2PP,P2PP,E2PP,H2PP,S2PP,SIG2PP)
          ELSE
          CALL SUBR2(T2PP,RHO2PP,P2PP,E2PP,H2PP,S2PP,SIG2PP)
          ENDIF
      IF(QABS((P2C-P2PP)/P2C).LT.TOL) GOTO 27
      IF(K.EQ.25) GOTO 70
      K=K+1
      RHO2PP=P2C/(T2PP*RUNIV*SIG2PP)
      GOTO 25
   27 CPEFF=H2PP-H2P
C
C     COMPUTE AND ADD A TEMPERATURE CORRECTION
C
      DT=T2P*(S2P-SC)/CPEFF
      T2P=T2P-DT
C
C     CHECK FOR ENTROPY CONVERGENCE
C
      IF(QABS(DT/T2P).LT.TOL) GOTO 30
      J=J+1
      IF(J.GT.25) GOTO 70
      GOTO 10
   30 T2C=T2P
      RHO2C=RHO2P
      E2C=E2P
      H2C=H2P
      SIG2C=SIG2P
      GAMMA=QLOG(P2C/P1C)/QLOG(RHO2C/RHO1C)
      RETURN
      ELSE
C
C     ITYPE = 2
C
      HB=HO-VB*VB/2.0000
C
C     GUESS STARTING VALUE FOR PRESSURE
C
      K2=1
      PMAX=P1C
      PMIN=P2C
   35 PB=(PMAX+PMIN)/2.0000
```

```
      RHOB=RHO1C*(PB/P1C)**(1.0000/GAMMA)
      TB=PB/(RHOB*RUNIV*SIG1C)
      J2=1
   40 I2=1
C
C     COMPUTE ENTROPY AT TB AND RHOB
C
   45     IF (IGAS.EQ.1) THEN
          CALL SUBR1(TB,RHOB,PBP,EB,HP,SP,SIGB)
          ELSE
          CALL SUBR2(TB,RHOB,PBP,EB,HP,SP,SIGB)
          ENDIF
      IF(QABS((PBP-PB)/PB).LT.TOL) GOTO 50
      RHOB=PB/(TB*RUNIV*SIGB)
      IF(I2.GT.25) GOTO 70
      I2=I2+1
      GOTO 45
C
C     COMPUTE AN EFFECTIVE CP
C
   50 RHOBP=RHOB
      TBP=TB+1.0
      K1=1
C
C     CONVERGE TO A CONSTANT PRESSURE AT T = T + 1
C
   55     IF (IGAS.EQ.1) THEN
          CALL SUBR1(TBP,RHOBP,PBPP,EBP,HPP,SPP,SIGBP)
          ELSE
          CALL SUBR2(TBP,RHOBP,PBPP,EBP,HPP,SPP,SIGBP)
          ENDIF
      IF(QABS((PB-PBPP)/PB).LT.TOL) GOTO 57
      IF(K1.GT.25) GOTO 70
      K1=K1+1
      RHOBP=PB/(TBP*RUNIV*SIGBP)
      GOTO 55
   57 CPBEFF=HPP-HP
C
C     COMPUTE AND ADD A TEMPERATURE CORRECTION
C
      DBT=TB*(SP-SC)/CPBEFF
      TB=TB-DBT
C
C     CHECK FOR ENTROPY CONVERGENCE
C
      IF(QABS(DBT/TB).LT.TOL) GOTO 60
      J2=J2+1
      IF(J2.GT.25) GOTO 70
   60 VP=QSQRT(2.0000*(HO-HP))
      IF(VP.GT.VB) THEN
      PMIN=PB
      ELSE
      PMAX=PB
      ENDIF
      IF(QABS((VP-VB)/VB).LT.TOL) THEN
```

```
      RETURN
      ELSE
      IF(K2.GT.25) GOTO 70
      K2=K2+1
      GOTO 35
      ENDIF
      ENDIF
   70 WRITE(2,100)
  100 FORMAT(/,2X,'DID NOT CONVERGE IN CENTRO IN 25 ITERATIONS')
      STOP 200
      END
C
C     SUBROUTINE SOUND CALCULATES THE EQUILIBRIUM SPEED OF SOUND
C
      SUBROUTINE SOUND (P,RHO,A)
      IMPLICIT REAL*16(A-H,O-Z)
      COMMON /SREG1/ T1C,RHO1C,P1C,E1C,H1C,SIG1C
      COMMON /SREG2/ T2C,RHO2C,P2C,E2C,H2C,SIG2C
      COMMON /SENTRO/ SC,GAMMA
      RR=8.31441
      GAMMA=1.4
      CALL PRPROP (T,RHO,P,E,H,SC,SIG1C)
      TP=T+0.5
      PP=RHO*RR*SIG1C*TP
      P2C=PP
      P1C=P
      RHO1C=RHO
C     WRITE(2,*)P1C,P2C
      CALL SCENTRO
      RHOP=RHO2C
      TM=T-0.5
      PM=RHO*RR*SIG1C*TM
      P2C=PM
C     WRITE(2,*)P1C,P2C
      CALL SCENTRO
      RHOM=RHO2C
      A2=(PP-PM)/(RHOP-RHOM)
      A=QSQRT(A2)
C     WRITE(2,*)GAMMA,RR,SIG1C,T
C     SPEED=QSQRT(GAMMA*RR*SIG1C*T)
C     WRITE(2,*) SPEED
      RETURN
      END
C
C     SUBROUTINE SCENTRO IS USED BY SUBROUTINE SOUND
C     TO CALCULATE A CONSTANT ENTROPY SOLUTION
C
      SUBROUTINE SCENTRO
      IMPLICIT REAL*16 ( A-H, O-Z )
      COMMON /SREG1/ T1C,RHO1C,P1C,E1C,H1C,SIG1C
      COMMON /SREG2/ T2C,RHO2C,P2C,E2C,H2C,SIG2C
      COMMON /SENTRO/ SC,GAMMA
      COMMON /GAS/ IGAS,PRNUM
      TOL=1.E-7
      RUNIV=8.31441
```

```
      ONE=1.000000
      RHO2P=RHO1C*(P2C/P1C)**(ONE/GAMMA)
      T2P=P2C/(RHO2P*RUNIV*SIG1C)
      J=1
   10 I=1
C
C     COMPUTE ENTROPY AT T2 AND P2
C
   15     IF (IGAS.EQ.1) THEN
          CALL SUBR1(T2P,RHO2P,P2P,E2P,H2P,S2P,SIG2P)
          ELSE
          CALL SUBR2(T2P,RHO2P,P2P,E2P,H2P,S2P,SIG2P)
          ENDIF
      IF(QABS((P2P-P2C)/P2C).LT.TOL) GOTO 20
      RHO2P=P2C/(T2P*RUNIV*SIG2P)
      I=I+1
      IF(I.GT.25) GOTO 70
      GOTO 15
C
C     COMPUTE AN EFFECTIVE CP
C
   20 RHO2PP=RHO2P
      T2PP=T2P+1.0
      K=1
C
C     CONVERGE TO A CONSTANT PRESSURE AT T = T + 1
C
   25     IF (IGAS.EQ.1) THEN
          CALL SUBR1(T2PP,RHO2PP,P2PP,E2PP,H2PP,S2PP,SIG2PP)
          ELSE
          CALL SUBR2(T2PP,RHO2PP,P2PP,E2PP,H2PP,S2PP,SIG2PP)
          ENDIF
      IF(QABS((P2C-P2PP)/P2C).LT.TOL) GOTO 27
      IF(K.EQ.25) GOTO 70
      K=K+1
      RHO2PP=P2C/(T2PP*RUNIV*SIG2PP)
      GOTO 25
   27 CPEFF=H2PP-H2P
C
C     COMPUTE AND ADD A TEMPERATURE CORRECTION
C
      DT=T2P*(S2P-SC)/CPEFF
      T2P=T2P-DT
C
C     CHECK FOR ENTROPY CONVERGENCE
C
      IF(QABS(DT/T2P).LT.TOL) GOTO 30
      J=J+1
      IF(J.GT.25) GOTO 70
      GOTO 10
   30 T2C=T2P
      RHO2C=RHO2P
      E2C=E2P
      H2C=H2P
      SIG2C=SIG2P
```

```
      GAMMA=QLOG(P2C/P1C)/QLOG(RHO2C/RHO1C)
      RETURN
   70 WRITE(2,100)
  100 FORMAT(/,2X,'DID NOT CONVERGE IN SCENTRO IN 25 ITERATIONS')
      STOP 200
      END
C
C     SUBROUTINE TOTAL CALCULATES FREESTREAM VARIABLES GIVEN
C     TOTAL TEMPERATURE, TOTAL PRESSURE, AND FREESTREAM VELOCITY
C
      SUBROUTINE TOTAL (T0,RHO0,P0,T1,RHO1,P1,V1,INCON)
      IMPLICIT REAL*16 ( A-H, O-Z )
      TOL=1.E-7
      ONE=1.0000
      TWO=2.0000
        IF(INCON.GE.10) THEN
C
C     IF (INCON .GE. 10) THEN
C     SOLVE FOR THE FREESTREAM CONDITIONS
C
C     FIND TOTAL DENSITY, RHO0
C
        CALL TPPROP(T0,RHO0,P0,E0,H0,S0,SIG0)
        CALL SOUND (P0,RHO0,A0)
        GAMMA=A0*A0*RHO0/P0
        RHOP=RHO0
        TP=T0
        PP=P0
        K=1
        PMAX=P0
        PMIN=0.000
        HFREE=H0-V1*V1/TWO
C
C     GUESS STARTING VALUES FOR TEMPERATURE AND PRESSURE
C
   10   P1=(PMAX+PMIN)/TWO
        T1=T0*(P1/P0)**((GAMMA-ONE)/GAMMA)
C
C     FIND ENTROPY AT T1 AND P1
C
        J=1
   20   CALL TPPROP(T1,RHO1,P1,E1,H1,S1,SIG1)
C     WRITE(2,*)T1,P1,S1,S0
C
C     COMPUTE AN EFFECTIVE CP TO ADJUST TEMPERATURE, T1
C     TO ENTROPY, S0
C
        T1P=T1+ONE
        CALL TPPROP(T1P,RHO1P,P1,E1P,H1P,S1P,SIG1P)
        CPBEFF=H1P-H1
C
C     COMPUTE AND ADD A TEMPERATURE CORRECTION, DT
C
        DT=T1*(S1-S0)/CPBEFF
        T1=T1-DT
```

```
C
C     CHECK FOR ENTROPY CONVERGENCE
C
          IF(QABS(DT/T1).GT.TOL) THEN
          J=J+1
          IF(J.GT.50) GOTO 30
          GOTO 20
          ENDIF
C
C     CHECK FOR FREESTREAM ENTHAPY CONVERGENCE
C
          IF(QABS((H1-HFREE)/HFREE).LT.TOL) THEN
          GOTO 40
          ELSE
          IF(K.GT.50) GOTO 30
          K=K+1
C
C     ADJUST PRESSURE FOR THE COMPUTED FREESTREAM ENTHALPY
C
            IF(HFREE.GT.H1) THEN
            PMIN=P1
            ELSE
            PMAX=P1
            ENDIF
          GAMMA=QLOG(P1/P0)/QLOG(RHO1/RHO0)
          PP=P1
          RHOP=RHO1
          GOTO 10
          ENDIF
        ELSE
C
C     IF (INCON .LT. 10) THEN
C     SOLVE FOR THE TOTAL CONDITIONS
C
C     FIND FREESTREAM DENSITY, RHO1
C
        CALL TPPROP(T1,RHO1,P1,E1,H1,S1,SIG1)
        CALL SOUND (P1,RHO1,A1)
        GAMMA=A1*A1*RHO1/P1
        RHOP=RHO1
        TP=T1
        PP=P1
        K1=1
        HTOT=H1+V1*V1/TWO
        PMAX=-ONE
        PMIN=P1
C
C     GUESS STARTING VALUES FOR TEMPERATURE AND PRESSURE
C
   50   POWER=GAMMA/(GAMMA-ONE)
          IF(PMAX.LT.0.) THEN
            IF(K1.EQ.1) THEN
            P0=P1*(ONE+((GAMMA-ONE)/TWO)*((V1*V1)/(A1*A1)))**POWER
            ELSE
            P0=TWO*P0
```

```
      ENDIF
     ELSE
     P0=(PMAX+PMIN)/TWO
     ENDIF
    T0=TP*(PP/P0)**(-ONE/POWER)
C  WRITE(2,*)T0,P0,S0,S1
C
C  FIND ENTROPY AT T0 AND P0
C
    J1=1
 60 CALL TPPROP(T0,RHO0,P0,E0,H0,S0,SIG0)
C
C  COMPUTE AN EFFECTIVE CP TO ADJUST TEMPERATURE, T0
C  TO ENTROPY, S1
C
    T0P=T0+1.0
    CALL TPPROP(T0P,RHO0P,P0,E0P,H0P,S0P,SIG0P)
    CPBEFF=H0P-H0
C
C  COMPUTE AND ADD A TEMPERATURE CORRECTION, DT
C
    DT=T0*(S0-S1)/CPBEFF
    T0=T0-DT
C
C  CHECK FOR ENTROPY CONVERGENCE
C
     IF(QABS(DT/T0).GT.TOL) THEN
     J1=J1+1
     IF(J1.GT.50) GOTO 30
     GOTO 60
     ENDIF
C
C  CHECK FOR TOTAL ENTHAPY CONVERGENCE
C
     IF(QABS((H0-HTOT)/HTOT).LT.TOL) THEN
     GOTO 40
     ELSE
     IF(K1.GT.50) GOTO 30
     K1=K1+1
C
C  ADJUST PRESSURE FOR THE COMPUTED TOTAL ENTHALPY
C
      IF(H0.GT.HTOT) THEN
      PMAX=P0
      ELSE
      PMIN=P0
      ENDIF
     GAMMA=QLOG(P0/PP)/QLOG(RHO0/RHOP)
     PP=P0
     RHOP=RHO0
     TP=T0
     GOTO 50
     ENDIF
    ENDIF
 30 WRITE(2,100)
```

```
  100 FORMAT(/,2X,'DID NOT CONVERGE IN TOTAL IN 50 ITERATIONS')
      STOP 200
   40 CONTINUE
C     WRITE(2,*)T1,RHO1,P1,E1,H1,S1
C     WRITE(2,*)S0,VP,V1
      RETURN
      END
C
C     SUBROUTINE TPPROP CALCULATES ALL STATE VARIABLES GIVEN T AND P
C
      SUBROUTINE TPPROP(T,RHO,P,E,H,S,SIG)
      IMPLICIT REAL*16 ( A-H, O-Z )
      COMMON /E/ CPP
      COMMON /GAS/ IGAS,PRNUM
      RUNIV=8.31441
      EPS=1.E-7
      SIG=34.51838
      PIN=P
      I=1
   10 RHO=PIN/(RUNIV*SIG*T)
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(T,RHO,P,E,H,S,SIG)
          ELSE
          CALL SUBR2(T,RHO,P,E,H,S,SIG)
          ENDIF
      I=I+1
C     WRITE(2,*)PIN,P
      PCHECK=QABS((P-PIN)/PIN)
      IF(PCHECK.LT.EPS) GOTO 30
      IF(I.GT.50) GOTO 20
      GOTO 10
   20 WRITE(2,100)
  100 FORMAT(/,1X,'NO CONVERGENCE IN TPPROP IN 50 ITERATIONS')
      STOP
   30 RETURN
      END
C
C     SUBROUTINE PRPROP CALCULATES ALL STATE VARIABLES GIVEN P AND RHO
C
      SUBROUTINE PRPROP(T,RHO,P,E,H,S,SIG)
      IMPLICIT REAL*16 ( A-H, O-Z )
      COMMON /E/ CPP
      COMMON /GAS/ IGAS,PRNUM
      RUNIV=8.31441
      EPS=1.E-7
      SIG=34.51838
      TSTART=P/(RHO*RUNIV*SIG)
      IF(TSTART.LT.500.)DT1=10.0
      IF(TSTART.GT.500..AND.TSTART.LT.5000.)DT1=100.0
      IF(TSTART.GT.5000.)DT1=1000.
      DT=DT1
C
C     FIND A TMAX
C
   10 T=TSTART+DT
```

```
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(T,RHO,PP,E,H,S,SIG)
          ELSE
          CALL SUBR2(T,RHO,PP,E,H,S,SIG)
          ENDIF
      IF(PP.GT.P) THEN
      TMAX=T
      ELSE
      DT=DT+DT1
      GOTO 10
      ENDIF
      DT=DT1
C
C     FIND A TMIN
C
   20 T=TSTART-DT
      IF(T.LT.0.00000) THEN
      TMIN=0.00000
      GOTO 30
      ENDIF
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(T,RHO,PP,E,H,S,SIG)
          ELSE
          CALL SUBR2(T,RHO,PP,E,H,S,SIG)
          ENDIF
      IF(PP.LT.P) THEN
      TMIN=T
      ELSE
      DT=DT+DT1
      GOTO 20
      ENDIF
C
C     USE BISECTOR TO CONVERGE ON A TEMPERATURE
C
   30 T=(TMAX+TMIN)/2.00000
          IF (IGAS.EQ.1) THEN
          CALL SUBR1(T,RHO,PP,E,H,S,SIG)
          ELSE
          CALL SUBR2(T,RHO,PP,E,H,S,SIG)
          ENDIF
      IF(QABS((PP-P)/P).LT.EPS) GOTO 40
      IF(PP.GT.P) THEN
      TMAX=T
      ELSE
      TMIN=T
      ENDIF
      GOTO 30
   40 RETURN
      END
c
C
C     SUBROUTINE SUBR1 CALCULATES ALL STATE PROPERTIES GIVEN T AND RHO
C
      SUBROUTINE SUBR1(TKEL,RKGM3,PRESS,EO,HO,ENTO,SUM)
c     this program computes the equilibrium chemical composition of air assuming
```

```
c       (1) the density is constant.
c       (2) the eleven species:  o2, n2, o, no, n, no+, e-, n+, o+, ar, and ar+.
c       (3) curve fitted data received from bonnie j. mcbride.
c       (4) reference temperature is zero kelvin.
c      also computes enthalpy, internal energy, and entropy.
c
      implicit real*16 (a-h, o-z)
      real*16  aa(11,7,5),c(11),h(11),en(11),s(11),e(11),cp(11)
      real*16  k1,k2,k3,k4,k5,k6,k7,ke
      common  / a /  k1,k2,k3,k4,k5,k6,k7,ke
      common  / b /  sn,so,sr,eps
      common  / c /  s
      common  / d /  niter
      common  / e /  cpp
      common  / ef/  aa
      equivalence (s1,s(1)),(s2,s(2)),(s3,s(3)),(s4,s(4)),(s5,s(5))SΩ(),
     1            (s6,s(6)),(s7,s(7)),(s8,s(8)),(s9,s(9)),(sa,s(10)),
     2            (sb,s(11))
c
c      the following constants are obtained from b. j. mcbride,
c      the basic data sources are:
c      (1) tabulated data from: thermodynamic properties of
c          individual substances, academy of sciences, moscow, ussr,
c          1978, vol.1, part 2. (for molecular species,
c          and formation values of all species.)
c      (2) values computed (by mcbride) using statistical data
c          for monatomic species.
c          source of basic statistical data:
c          (a) nsrds nbs volume 35, 1971
c          (b)      nbs 3, section 5, 1975
c          (c)      nbs 3, section 7, 1976
c
c.....      neutral molecular oxygen, o2.
      data ((aa(1,j,k),j=1,7),k=1,5)/
     * .37703733e+01,-.28952206e-02, .95332231e-05,-.92469913e-08,
     * .30191908e-11,-.18859751e+02, .36933495e+01,
     * .28969178e+01, .23736545e-02,-.14917097e-05, .46603392e-09,
     *-.53945166e-13, .82240429e+02, .75019384e+01,
     * .28421112e+01, .13320561e-02,-.33915853e-06, .44652178e-10,
     *-.22914824e-14, .58350386e+03, .86255038e+01,
     * .56821087e+01,-.75300588e-03, .22980075e-06,-.23955920e-10,
     * .80048472e-15,-.24700372e+04,-.98740054e+01,
     *-.27258966e+00, .20115141e-02,-.24547714e-06, .12025200e-10,
     *-.21389859e-15, .76117740e+04, .31631739e+02/
c.....      neutral molecular nitrogen, n2.
      data ((aa(2,j,k),j=1,7),k=1,5)/
     * .34622648e+01, .58202350e-03,-.30525456e-05, .62280057e-08,
     *-.33755957e-11, .87951739e+00, .32192648e+01,
     * .27022403e+01, .19443933e-02,-.89300044e-06, .19739206e-09,
     *-.16967813e-13, .20180222e+03, .72040846e+01,
     * .39143506e+01, .31537108e-03,-.56481043e-07, .36012299e-11,
     * .52359433e-16,-.53551958e+03, .21671998e-01,
     * .12657466e+01, .18269791e-02,-.37583896e-06, .33033716e-10,
     *-.93651108e-15, .31426960e+04, .17943292e+02,
     * .27715943e+02,-.74173486e-02, .82395970e-06,-.35285300e-10,
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     * .49671195e-15,-.56942692e+05,-.17402873e+03/
c.....      neutral monatomic oxygen, o.
      data ((aa(3,j,k),j=1,7),k=1,5)/
     * .32167143e+01,-.37822689e-02, .84746788e-05,-.88658246e-08,
     * .35365597e-11, .29640462e+05, .18526415e+01,
     * .26045368e+01,-.17235464e-03, .11574138e-06,-.36417858e-10,
     * .46011536e-14, .29728962e+05, .45865262e+01,
     * .28101683e+01,-.29039910e-03, .90833347e-07,-.99427817e-11,
     * .37704361e-15, .29536612e+05, .32536467e+01,
     * .19209266e+01, .21776554e-03,-.18288405e-07, .49050959e-12,
     * .28507296e-17, .30783423e+05, .92748629e+01,
     * .19209266e+01, .21776554e-03,-.18288405e-07, .49050959e-12,
     * .28507296e-17, .30783423e+05, .92748629e+01/
c.....      neutral nitric oxide, no.
      data ((aa(4,j,k),j=1,7),k=1,5)/
     * .42064360e+01,-.45098354e-02, .10557385e-04,-.85919382e-08,
     * .24047097e-11, .10888965e+05, .23137934e+01,
     * .27543778e+01, .23093284e-02,-.12823359e-05, .34043524e-09,
     *-.34807544e-13, .11134325e+05, .90789671e+01,
     * .38015418e+01, .49857546e-03,-.12531319e-06, .14093893e-10,
     *-.44820194e-15, .10666566e+05, .31619390e+01,
     * .49133164e+01, .61755267e-06,-.55222382e-07, .11686489e-10,
     *-.54642492e-15, .88453776e+04,-.45786900e+01,
     * .20456654e+02,-.61498079e-02, .86914275e-06,-.50877512e-10,
     * .10624157e-14,-.22955242e+05,-.11561956e+03/
c.....      neutral monatomic nitrogen, n.
      data ((aa(5,j,k),j=1,7),k=1,5)/
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            , .56626706e+05, .41807280e+01,
     * .25075109e+01,-.24797882e-04, .29641517e-07,-.15288108e-10,
     * .28913714e-14, .56624949e+05, .41431864e+01,
     * .26376051e+01,-.87373323e-05,-.64772651e-07, .23473436e-10,
     *-.17396164e-14, .56452267e+05, .32232104e+01,
     * .33720620e+01,-.88554639e-03, .25293270e-06,-.23187896e-10,
     * .70471420e-15, .56270151e+05,-.10563976e+01,
     *-.10205642e+02, .42931347e-02,-.49310664e-06, .24951067e-10,
     *-.46969943e-15, .84933779e+05, .96403744e+02/
c.....      unipositive nitric oxide, no+.
      data ((aa(6,j,k),j=1,7),k=1,5)/
     * .35659323e+01,-.27420307e-03,-.52284273e-06, .30228201e-08,
     *-.19112702e-11, .11841356e+06, .35935691e+01,
     * .27152625e+01, .18998146e-02,-.85346216e-06, .18390288e-09,
     *-.15328469e-13, .11862129e+06, .79369146e+01,
     * .39310989e+01, .30660785e-03,-.56705942e-07, .45573508e-11,
     *-.77762022e-16, .11786296e+06, .70198182e+00,
     * .10656163e+01, .17917961e-02,-.33077778e-06, .25052719e-10,
     *-.54540127e-15, .12214242e+06, .20328302e+02,
     * .31376951e+02,-.78170663e-02, .75437124e-06,-.24734142e-10,
     * .15952361e-15, .48124504e+05,-.20218492e+03/
c.....      electron, e-.
      data ((aa(7,j,k),j=1,7),k=1,5)/
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            ,-.42498957e-01,-.11733917e+02,
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            ,-.42498957e-01,-.11733917e+02,
```

```
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            ,-.42498957e-01,-.11733917e+02,
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            ,-.42498957e-01,-.11733917e+02,
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            ,-.42498957e-01,-.11733917e+02/
c.....    unipositive monatomic nitrogen, n+.
      data ((aa(8,j,k),j=1,7),k=1,5)/
     * .30816977e+01,-.37737512e-02, .96771466e-05,-.11099460e-07,
     * .47248633e-11, .22532807e+06, .24315936e+01,
     * .25347005e+01,-.55067384e-04, .36440013e-07,-.12313199e-10,
     * .19224650e-14, .22539524e+06, .47895586e+01,
     * .28005551e+01,-.29566365e-03, .96649663e-07,-.11053590e-10,
     * .44145151e-15, .22518494e+06, .31305296e+01,
     * .20047667e+01, .19189730e-03,-.15499136e-07, .41165940e-12,
     * .26287640e-17, .22622600e+06, .84634959e+01,
     * .20598363e+01, .18875424e-03,-.18075532e-07, .80284344e-12,
     *-.13089587e-16, .22602766e+06, .80254371e+01/
c.....    unipositive monatomic oxygen, o+.
      data ((aa(9,j,k),j=1,7),k=1,5)/
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            , .18771321e+06, .43801998e+01,
     * .25013354e+01,-.40431297e-05, .43271450e-08,-.19527702e-11,
     * .31632791e-15, .18771288e+06, .43734240e+01,
     * .22258863e+01, .29650143e-03,-.11561144e-06, .18461192e-10,
     *-.89249152e-15, .18791159e+06, .60576133e+01,
     * .41210991e+01,-.86786175e-03, .15337469e-06,-.92260135e-11,
     * .17842049e-15, .18543702e+06,-.66388864e+01,
     * .17349474e+01,-.80710732e-04, .59806317e-07,-.45998476e-11,
     * .10295182e-15, .19107440e+06, .10791908e+02/
c.....    neutral argon, a.
      data ((aa(10,j,k),j=1,7),k=1,5)/
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            ,-.42498957e-01, .43664979e+01,
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            ,-.42498957e-01, .43664979e+01,
     * .25000000e+01,0.            ,0.            ,0.            ,
     *0.            ,-.42498957e-01, .43664979e+01,
     * .26303545e+01,-.77393441e-04, .17219729e-07,-.17028231e-11,
     * .63198847e-16,-.17548010e+03, .34890096e+01,
     *-.91423987e+01, .38508169e-02,-.46800440e-06, .24506918e-10,
     *-.45646899e-15, .27751915e+05, .89461765e+02/
c.....    unipositive monatomic  argon, a.
      data ((aa(11,j,k),j=1,7),k=1,5)/
     * .26818797e+01,-.20720300e-02, .74786002e-05,-.87672013e-08,
     * .34484189e-11, .18287091e+06, .50764556e+01,
     * .24220646e+01, .86346979e-03,-.78459395e-06, .26673998e-09,
     *-.31850590e-13, .18285266e+06, .59236280e+01,
     * .25588416e+01, .89736230e-04,-.50091586e-07, .88298198e-11,
     *-.52371930e-15, .18301380e+06, .55313033e+01,
     * .25014164e+01, .29446558e-04,-.80471729e-08, .77535785e-12,
     *-.25780935e-16, .18325162e+06, .60544022e+01,
     * .25706058e+01,-.20621051e-04, .29786013e-08,-.21101899e-12,
     * .57476758e-17, .18322322e+06, .56165023e+01/
      eps=1.e-8
```

```
      tref=0.0
      rr=8.31441
      p0=1.01325e+05
c
c..... assume air to have o2 : n2 : a = 20.96 : 78.11 : 0.93
c
      so    = 14.4802
      sn    = 53.9620
      sr    =  0.3212
C     IF(TKEL.LT.50.0) WRITE(2,999)
C 999 FORMAT(1X,'***** WARNING *****',/,1X,'TEMPERATURE IS BELOW 50 K',
C    1        /,1X,'THIS GAS MODEL WILL GIVE QUESTIONABLE RESULTS')
C
C     CHECK FOR TKEL < 300.0 K
C
        IF(TKEL .LT. 300.0) THEN
        DO 1010 I=1,11
        S(I)=0.000
 1010   CONTINUE
        S(1)=SO/2.000
        S(2)=SN/2.000
        sa=sr
        GOTO 1020
        ENDIF
C
C.....CHOOSE APPROPRIATE CONSTANTS DEPENDING UPON THE TEMPERATURE.
C
      k=1
      IF(TKEL .GT. 800.0) k=2
      IF(TKEL .GT. 3000.) k=3
      IF(TKEL .GT. 6000.) k=4
      IF(TKEL .GT. 10000.) k=5
      DO 8 I=1,11
      C(I)=DGBYRT(I,k,TKEL)
      H(I)=(ENTH (I,k,TKEL)*TKEL)*RR
      EN(I)=ENTR (I,k,TKEL) *RR
      E(I)=H(I)-RR*TKEL
      CP(I)=RR*CPBYR(I,k,TKEL)
c     WRITE(2,50) J,I,TKEL,C(I),H(I),EN(I)
   50 FORMAT(2I2,7E12.5)
    8 CONTINUE
C**********************************************************************C
C
C.....COMPUTE THE EQUILIBRIUM CONSTANTS FOR THE GIVEN TEMPERATURE
C.....AND DENSITY CONDITIONS.
C
C.....THE REACTIONS ARE:
C
C          O2 = 2 O                (1)
C
C      N2 + O2 = 2 NO              (2)
C
C          N2 = 2 N                (3)
C
C   (NO+) + E- = NO                (4)
```

```
C
C    (N+) + E- = N                           (5)
C
C    (O+) + E- = O                           (6)
C
c   (ar+) + e- = ar                          (7)
c
C******************************************************************************C
      K1=2.0*C(3)-C(1)
      K2=2.0*C(4)-C(1)-C(2)
      K3=2.0*C(5)-C(2)
      K4=C(4)-C(6)-C(7)
      K5=C(5)-C(8)-C(7)
      K6=C(3)-C(9)-C(7)
      k7=c(10)-c(11)-c(7)
      K1=EXXP(-K1)
      K2=EXXP(-K2)
      K3=EXXP(-K3)
      K4=EXXP(-K4)
      K5=EXXP(-K5)
      K6=EXXP(-K6)
      K7=EXXP(-K7)
      K1=K1*PO/(RR*TKEL*RKGM3)
      K3=K3*PO/(RR*TKEL*RKGM3)
      K4=K4/(PO/(RR*TKEL*RKGM3))
      K5=K5/(PO/(RR*TKEL*RKGM3))
      K6=K6/(PO/(RR*TKEL*RKGM3))
      K7=K7/(PO/(RR*TKEL*RKGM3))
      KE = QSQRT(K2/(K1*K3))
C
C..... CALL APPROPRIATE SUBROUTINE DEPENDING UPON THE TEMPERATURE
C......TO COMPUTE THE COMPOSITION.
C
      IF(TKEL .LE. 1600.) GO TO 151
      RLOG = QLOG10(RKGM3)
      TEMP1 = 1000.0*(3.5+10.0*((rlog+6.0)/7.0)**2.5)
      if(tkel .le. temp1) go to 154
      TEMP2=1000.*(5.4+3.2*(rlog+6.)/6.+5.55*(qabs(rlog+6.)/6.)**3.35)
      if(tkel .le. temp2) go to 152
  153 ic = 3
      CALL cubic
      GO TO 156
  152 ic = 2
      CALL qudratc
      GO TO 156
  154 ic = 4
      CALL QUARTIC
      GO TO 156
  151 ic = 1
      CALL LOWTEMP
 1020 CONTINUE
c
c     total mol number
c
  156 SUM = S1+S4+S2+S3+S5+S6+S7+S8+S9+SA+sb
```

```
C
C.....COMPUTE PRESSURE
C
      PBAR = RKGM3*RR*SUM*TKEL/100000.
      PATM = PBAR/1.01325
      PRESS=PBAR*100000.0
c     WRITE(6,101) TKEL,RKGM3,EPS
c     WRITE(6,100) SO,SN,SA
      IF(TKEL .LT. 300.0) GO TO 1030
c     WRITE(6,102) K1,K2,K3,K4,K5,K6,K7,kE
c     IF(IC .EQ. 1) WRITE(6,304) NITER
c     IF(IC .EQ. 2) WRITE(6,307) NITER
c     IF(IC .EQ. 3) WRITE(6,306) NITER
c     IF(IC .EQ. 4) WRITE(6,305) NITER
C*******************************************************************************C
C
C.....COMPUTE THE ENTHALPY, INT. ENERGY, AND ENTROPY  OF THE MIXTURE.
C.....NOTE: ENTHALPY AND INT. ENERGY ARE IN JOULES/KG.
C.....      ENTROPY IS IN JOULES/KG.KELVIN
C
C*******************************************************************************C
      HO = 0.0
      EO = 0.0
      DO 96 I=1,11
      HO = HO+S(I)*H(I)
      EO = EO+S(I)*E(I)
   96 CONTINUE
      ENTO = -RR*SUM*QLOG(PATM/SUM)
      DO 97 I=1,11
      IF(S(I) .EQ. 0.0) GO TO 97
      ENTO = ENTO+S(I)*(EN(I)-RR*QLOG(S(I)))
   97 CONTINUE
C
C     COMPUTE THE CP OF THE MIXTURE
C     NOTE CP OF THE MIXTURE IS IN JOULES/KG-K
C
      CPP=0.00
      DO 10 I=1,11
      CPP=CPP+CP(I)*S(I)
   10 CONTINUE
 1030 CONTINUE
C
C     IF TKEL < 300 K COMPUTE SPECIFIC HEAT, ENTHALPY,
C     INTERNAL ENERGY, AND ENTROPY FOR AIR WITH THREE SPECIES
C     (N2-O2-AR). THE SPECIFIC HEAT IS CALCULATED USING
C     A QUADRATIC CURVE FIT OVER A TEMPERATURE RANGE OF
C     100 K < TKEL < 300 K AND ENTHALPY AND ENTROPY ARE CALCULATED BY
C     THE APPROPRIATE INTEGRATION OF SPECIFIC HEAT WITH TEMPERATURE.
C
C           ******** NOTE-OF-CAUTION ********
C
C     THESE CURVE FITS ARE QUESTIONABLE BELOW 100 K
C     AND SHOULD NOT BE EXTRAPOLATED BELOW ABOUT 50 K.
C
        IF (TKEL.LT.300.0) THEN
```

```
      TSTAR=300.0
      AO2=29.343
      BO2=-0.00354
      CO2=0.0000123
      AN2=29.116
      BN2=-0.000195
      CN2=0.00000075
      AAR=20.7860
C
C     MINOR SPECIE CONTRIBUTION NEGLECTED
C
      DO 1040 I=1,11
      CP(I)=0.000
      H(I)=0.000
      E(I)=0.000
      EN(I)=0.000
 1040 CONTINUE
C
C     CALCULATE SPECIFIC HEAT AT T = TKEL FOR major species.
C
      CP(1)=AO2+BO2*TKEL+CO2*TKEL*TKEL
      CP(2)=AN2+BN2*TKEL+CN2*TKEL*TKEL
      CP(10)=AAR
C
C     CALCULATE ENTHALPY AT 300 K FOR EACH SPECIE
C
C     H(I)=(ENTH (I,j,TKEL)*TKEL)*RR + DH(I)
C
      HO2STAR=(ENTH(1,1,TSTAR)*TSTAR)*RR
      HN2STAR=(ENTH(2,1,TSTAR)*TSTAR)*RR
      HARSTAR=(ENTH(10,1,TSTAR)*TSTAR)*RR
C
C     CALCULATE ENTHALPY AT TKEL FOR EACH SPECIE
C
      H(1)=AO2*(TKEL-TSTAR)+(BO2/2.00)*(TKEL*TKEL-TSTAR*TSTAR)
     1     +(CO2/3.00)*(TKEL**3.000-TSTAR**3.000)+HO2STAR
      H(2)=AN2*(TKEL-TSTAR)+(BN2/2.00)*(TKEL*TKEL-TSTAR*TSTAR)
     1     +(CN2/3.00)*(TKEL**3.000-TSTAR**3.000)+HN2STAR
      H(10)=AAR*(TKEL-TSTAR)+HARSTAR
C
C     CALCULATE INTERNAL ENERGY AT TKEL FOR EACH SPECIE
C
      E(1)=H(1)-RR*(TKEL-TREF)
      E(2)=H(2)-RR*(TKEL-TREF)
      E(10)=H(10)-RR*(TKEL-TREF)
C
C     CALCULATE ENTROPY AT 300 K FOR EACH SPECIE
C
C     EN(I)=ENTR (I,j,TKEL) *RR
C
      ENO2=ENTR(1,1,TSTAR)*RR
      ENN2=ENTR(2,1,TSTAR)*RR
      ENAR=ENTR(10,1,TSTAR)*RR
C
C     CALCULATE ENTROPY AT TKEL FOR EACH SPECIE
```

```
C
         EN(1)=AO2*(QLOG(TKEL)-QLOG(TSTAR))+BO2*(TKEL-TSTAR)+
     1         (CO2/2.000)*(TKEL*TKEL-TSTAR*TSTAR)+ENO2
         EN(2)=AN2*(QLOG(TKEL)-QLOG(TSTAR))+BN2*(TKEL-TSTAR)+
     1         (CN2/2.000)*(TKEL*TKEL-TSTAR*TSTAR)+ENN2
         EN(10)=AAR*(QLOG(TKEL)-QLOG(TSTAR))+ENAR
C
C        STARTING VALUE FOR ENTROPY
C        ENTO = -RR*SUM*QLOG(PATM/SUM)
C
C        MIXING RULE FOR ENTROPY
C        ENTO = ENTO+S(I)*(EN(I)-RR*QLOG(S(I)))
C
C        FIND CPP, HO, EO, AND ENTO FOR THE MIXTURE
C
         CPP=0.000
         HO=0.000
         EO=0.000
         ENTO=-RR*SUM*QLOG(PATM/SUM)
c
         DO 1050 I=1,11
         CPP=CPP+S(I)*CP(I)
         HO=HO+S(I)*H(I)
         EO=EO+S(I)*E(I)
         IF(S(I).LT.0.000001) GOTO 1050
         ENTO=ENTO+S(I)*(EN(I)-RR*QLOG(S(I)))
 1050    CONTINUE
         ENDIF
c      WRITE(2,1060)TKEL,CPP,HO,EO,ENTO
 1060 FORMAT(/,1X,'TEMPERATURE',7X,'CP',8X,'ENTHALPY',1X,
     11X,'INTERNAL ENERGY',1X,'ENTROPY',/,5(1X,E12.5),/)
c      WRITE(6,303) S1,S2,S3,S4,S5,S6,S7,S8,S9,SA,Sb,sUM
c      WRITE(6,318) (H(I),I =1,11)
c      WRITE(6,316) (E(I),I =1,11)
c      WRITE(6,319) (EN(I),I =1,11)
c      WRITE(6,317) HO,ENTO,EO,PBAR
c      WRITE(6,1007) HO,EO,PBAR
 1007 FORMAT(
     1/,2X,29HENTHALPY OF THE MIXTURE    = ,E12.6,11H JOULES/KG.,
     1/,2X,29HINT. ENERGY OF THE MIXTURE = ,E12.6,11H JOULES/KG.,
     1   /,2X,29HPRESSURE                    = ,E12.6,6H (BAR))
  303 FORMAT(/,2X,38HMOLE NUMBERS OF THE SPECIES (MOL/KG):-,
     1/,10X,2HO2, 12X,2HN2,12X,2HO ,12X,2HNO,12X,2HN ,
     1/,10X,3HNO+,11X,2HE-,12X,2HN+,12X,2HO+,12X,2HA ,
     1/,10X,3HAR+,/,/
     12(2X,5E14.5,/),2x,e14.5,/,2X,19HTOTAL MOL NUMBER = ,E14.5)
  304 FORMAT(/,2X,43HSOLUTION BY THE SIMPLE ITERATION PROCEDURE;,
     1  I3,11H ITERATIONS)
  305 FORMAT(/,2X,33HSOLUTION OF THE QUARTIC EQUATION;,
     1  I3,11H ITERATIONS)
  306 FORMAT(/,2X,31HSOLUTION OF THE CUBIC EQUATION;,
     1  I3,11H ITERATIONS)
  307 FORMAT(/,2X,35HSOLUTION OF THE QUADRATIC EQUATION;,
     1  I3,11H ITERATIONS)
  100 FORMAT(/,7H  SO = ,F10.4,7H  SN = ,F10.4,7H  SA = ,F10.4,2X,
```

```
     1      8HMOLES/KG)
  101 FORMAT(/,15H  T (KELVIN) = ,F8.2,22H  DENSITY (KG/M**3) = ,E12.6
     1 ,8H  EPS = ,E10.4)
  204 FORMAT(/,12H  RESIDUES:-,/,2(2X,5E14.5,/))
  102 FORMAT(/,24H EQUILIBRIUM CONSTANTS:-,
     1      /,9H  K(I) = , 4E16.8,/,9X,4E16.8)
  317 FORMAT(
     1/,2X,29HENTHALPY OF THE MIXTURE    = ,E12.6,11H JOULES/KG.,
     1/,2X,29HENTROPY OF THE MIXTURE     = ,E12.6,18H JOULES/KG./KELVIN,
     1/,2X,29HINT. ENERGY OF THE MIXTURE = ,E12.6,11H JOULES/KG.,
     1  /,2X,29HPRESSURE                   = ,E12.6,6H (BAR))
  318 FORMAT(/,2X,38HENTHALPY OF EACH SPECIES(JOULES/MOL):-,/,
     1      2(2X,5E14.5,/))
  316 FORMAT(/,2X,44HINTERNAL ENRGY OF EACH SPECIES(JOULES/MOL):-,/,
     1      2(2X,5E14.5,/))
  319 FORMAT(/,2X,44HENTROPY OF EACH SPECIES(JOULES/MOL/KELVIN):-,/,
     1      2(2X,5E14.5,/))
      RETURN
      END
C
C     DEFINE FUNCTION DGBYRT USED IN SUBR1
C
      REAL*16 FUNCTION DGBYRT(i,k,T)
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 AA(11,7,5)
      COMMON /EF/ AA
      dgbyrt=enth(i,k,t)-entr(i,k,t)
      RETURN
      END
C
C     DEFINE FUNCTION ENTH USED IN SUBR1
C
      REAL*16 FUNCTION ENTH(i,k,T)
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 AA(11,7,5)
      COMMON /EF/ AA
      enth=aa(i,1,k)        +aa(i,2,k)*t   /2.+aa(i,3,k)*t**2/3.
     1    +aa(i,4,k)*t**3/4.+aa(i,5,k)*t**4/5.+aa(i,6,k)/t
      RETURN
      END
C
C     DEFINE FUNCTION ENTR USED IN SUBR1
C
      REAL*16 FUNCTION ENTR(I,k,T)
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 AA(11,7,5)
      COMMON /EF/ AA
      entr=aa(i,2,k)*t      +aa(i,3,k)*t**2/2.+aa(i,4,k)*t**3/3.
     1    +aa(i,5,k)*t**4/4.+aa(i,1,k)*qlog(t)+aa(i,7,k)
      RETURN
      END
C
C     DEFINE FUNCTION CPBYR USED IN SUBR1
C
      REAL*16 FUNCTION CPBYR(I,k,T)
```

```
      IMPLICIT REAL*16 (A-H,O-Z)
      REAL*16 AA(11,7,5)
      COMMON /EF/ AA
      cpbyr=aa(i,1,k)       +aa(i,2,k)*t   +aa(i,3,k)*t**2
     1     +aa(i,4,k)*t**3   +aa(i,5,k)*t**4
      RETURN
      END
      subroutine lowtemp
c
c.....this subroutine computes the composition of air
c.....at low temperatures where there is some dissociation
c.....but very little ionization.
c.....the major species are o2, n2, and ar.
c.....(model i)
c
      implicit real*16 (a-h, o-z)
      common  / a /  k1,k2,k3,k4,k5,k6,k7,ke
      common  / b /  sn,so,sr,eps
      common  / c /  s1,s2,s3,s4,s5,s6,s7,s8,s9,sa,sb
      common  / d /  iter
      real*16 k1,k2,k3,k4,k5,k6,k7,ke
c
c.....initialize and start iterating.
c
      s1p   = so / 2.0
      s2    = sn / 2.0
      sa    = sr
      do    200 iter = 1,20
c
c.....compute the minor species.
c
      s3    = sqrt(k1*s1p)
      s5    = sqrt(k3*s2)
      s4    = ke*s3*s5
c
c.....update the major species.
c
      s1    = (so - s4 - s3) / 2.0
      s2    = (sn - s4 - s5) / 2.0
c
c.....check for convergence.
c
      ds1   = s1 - s1p
      if    (abs(ds1) .le. eps) go to 201
      s1p   = s1
  200 continue
  201 continue
c
c.....compute the trace species.
c
      c3    = s3/k6
      c4    = s4/k4
      c5    = s5/k5
      c6    = sa/k7
      s7    = sqrt(c3 + c4 + c5 + c6)
```

```
      s6    = c4/s7
      s8    = c5/s7
      s9    = c3/s7
      sb    = c6/s7
      return
      end
      subroutine quartic
c
c.....this subroutine computes the composition of air
c.....at moderate temperatures where there is dissociation
c.....but not much ionization.
c.....the major species are o2, n2, o, no, and n.
c.....(model ii)
c
      implicit real*16 (a-h, o-z)
      common  / a /  k1,k2,k3,k4,k5,k6,k7,ke
      common  / b /  sn,so,sr,eps
      common  / c /  s1,s2,s3,s4,s5,s6,s7,s8,s9,sa,sb
      common  / d /  iter
      real*16 k1,k2,k3,k4,k5,k6,k7,ke
c
c.....initialize, determine the initial guess, and start iteration.
c
      s6    = 0.0
      s8    = 0.0
      s9    = 0.0
      sa    = sr
      b4    = (8.0 - k2 - k2) / k1
      b3    = 8.0 - k2 - 2.0*k3*ke
      bb    = k1*(1.0 + sqrt(k2*sn / (k1 + k1)))
      s3    = ( - bb + sqrt(bb*bb + 8.0*so*k1)) / 4.0
      c1    = k1*k3*ke
      do    200 iter = 1,20
      so1   = so - s6 - s9
      sn1   = sn - s6 - s8
      b2    = - 8.0*so1 + k1 + k1 + (so1 - sn1)*k2 - c1
      b1    = so1*( - k1 - k1 - k1 - k1 + c1)
      b0    = 2.0*so1*so1*k1
      f     = b0 + s3*(b1 + s3*(b2 + s3*(b3 + s3*b4)))
      fp    = b1 + s3*(b2 + b2 + s3*(b3 + b3 + b3 + s3*(b4+b4+b4+b4)))
      d3    = - f / fp
      s3    = s3 + d3
c
c.....unravel the rest of the major species.
c
      s5    = (so1 - s3 - 2.0*s3*s3 / k1) / (ke*s3)
      s4    = ke*s5*s3
      s2    = (sn1 - s4 - s5) / 2.0
      s1    = (so1 - s4 - s3) / 2.0
c
c.....compute the minor species.
c
      c3    = s3/k6
      c4    = s4/k4
      c5    = s5/k5
```

[redacted]

```
      c6    = sa/k7
      s7    = sqrt(c3 + c4 + c5 + c6)
      s6    = c4/s7
      s8    = c5/s7
      s9    = c3/s7
      sb    = c6/s7
      sa    = sr - sb
c
c.....check for convergence.
c
      if    (abs(d3) .le. eps) go to 201
  200 continue
  201 continue
      return
      end
      subroutine cubic
c
c.....this subroutine computes the composition of air
c.....at very high temperatures where not many diatomic particles are found.
c.....the major species are o, n, e- , n+ , and o+.
c.....(model iv)
c
      implicit real*16 (a-h, o-z)
      common  / a /  k1,k2,k3,k4,k5,k6,k7,ke
      common  / b /  sn,so,sr,eps
      common  / c /  s1,s2,s3,s4,s5,s6,s7,s8,s9,sa,sb
      common  / d /  iter
      real*16 k1,k2,k3,k4,k5,k6,k7,ke
c
c.....initialize, determine the initial guess, and start iteration.
c
      s1    = 0.0
      s2    = 0.0
      s4    = 0.0
      s6    = 0.0
      sa    = sr
      sb    = 0.0
      s7    = ( sqrt(1.0 + 4.0*sn*k5)-1.0 ) / (k5 + k5)
      s9    = so / (1.0 + k6*s7)
      sb    = sr / (1.0 + k7*s7)
      s7    = s7 + s9 + sb
      b3    = k5*k6
      c2    = k5 + k6
      do    200 iter = 1,20
      so1   = so - s1 - s1 - s4 - s6
      sn1   = sn - s2 - s2 - s4 - s6
      s6p   = s6 + sb
      b2    =  c2 - b3*s6p
      b1    = 1.0 - sn1*k6 - so1*k5 - s6p*c2
      b0    = - sn1 - so1 - s6p
      f     = b0 + s7*(b1 + s7*(b2 + s7*b3))
      fp    = b1 + s7*(b2 + b2 + s7*3.0*b3)
      d7    = - f / fp
      s7    = s7 + d7
c
```

```
c.....unravel the rest of the major species.
c
      s3    = so1*s7*k6 / (1.0 + k6*s7)
      s5    = sn1*s7*k5 / (1.0 + k5*s7)
      sb    = sr / (1.0 + k7*s7)
      sa    = sr - sb
      s9    = s3 / (k6*s7)
      s8    = s5 / (k5*s7)
c
c.....compute the minor species.
c
      s1    = s3*s3 / k1
      s2    = s5*s5 / k3
      s4    = ke*s3*s5
      s6    = s4 / (k4*s7)
c
c.....check for convergence.
c
      if    (abs(d7) .le. eps) go to 201
  200 continue
  201 continue
      return
      end
      subroutine qudratc
c
c.....this subroutine computes the composition of air at intermediate
c.....temperatures where oxygen is almost fully dissociated,
c.....but not much ionization has taken place.
c.....the major species are n2, o, and n.
c.....(model iii)
c
      implicit real*16 (a-h, o-z)
      common  / a /  k1,k2,k3,k4,k5,k6,k7,ke
      common  / b /  sn,so,sr,eps
      common  / c /  s1,s2,s3,s4,s5,s6,s7,s8,s9,sa,sb
      common  / d /  iter
      real*16 k1,k2,k3,k4,k5,k6,k7,ke
c
c.....initialize, determine the initial guess, and start iteration.
c
      s4    = 0.0
      s6    = 0.0
      s8    = 0.0
      sa    = sr
      b1    = k3 / 2.0
      b2    = k1 / 2.0
      s5    = ( - b1 + sqrt(b1*b1 + 4.0*b1*sn )) / 2.0
      s3p   = ( - b2 + sqrt(b2*b2 + 4.0*b2*so )) / 2.0
      do    200 iter = 1,20
      sn1   = sn - s4 - s6 - s8
      f     = - b1*sn1 + s5*(b1 + s5)
      fp    = b1 + s5 + s5
      s5    = s5 - f / fp
      s2    = (sn1 - s5) / 2.0
c
```

```
c.....unravel the remaining species
c
      s1    = s3p*s3p / k1
      s4    = ke*s3p*s5
      c3    = s3p/k6
      c4    = s4/k4
      c5    = s5/k5
      c6    = sa/k7
      s7    = sqrt(c3 + c4 + c5 + c6)
      s6    = c4/s7
      s8    = c5/s7
      s9    = c3/s7
      sb    = c6/s7
      sa    = sr - sb
      s3    = so - s1 - s1 - s4 - s6 - s9
c
c.....check for convergence.
c
      d3    = s3p - s3
      s3p   = s3
      if    (iter .eq. 1) go to 200
      if    (abs(d3) .le. eps) go to 201
  200 continue
  201 continue
      return
      end
      function exxp(x)
      implicit real*16 (a-h, o-z)
      exxp  = 0.0
      if    (x .lt. - 670.0) return
      exxp  = qexp(x)
      return
      end
C
C     SUBR2 IS A CALORICALLY PERFECT IDEAL GAS SUBROUTINE FOR AIR
C     INPUT REQUIRED IS TEMPERATURE AND DENSITY
C
      SUBROUTINE SUBR2(T,RHO,P,E,H,S,SIG)
      IMPLICIT REAL*16 ( A-H, O-Z )
      COMMON /E/ CPP
      RUNIV=8.31441
      CPP=1003.5
      CV=716.5
      RAIR=287.
      SIG=RAIR/RUNIV
      P=T*RHO*RUNIV*SIG
      E=CV*T
      H=CPP*T
      T0=288.15
      P0=101325.
      S0=6828.6678
      S=S0+CPP*QLOG(T/T0)-SIG*RUNIV*QLOG(P/P0)
      RETURN
      END
C
```

```
C     SUBROUTINE MUANDK GIVES A SET OF VALUES FOR VISCOSITY
C     AND THERMAL CONDUCTIVITY USING "THERMOPHYSICAL PROPERTIES
C     OF MATTER" AS A CHECK OVER THE LIMITED TEMPERATURE RANGE
C
C     NOTE : VALUES ARE FOR A LOW DENSITY GAS
C        WITH NO PRESSURE DEPENDENCE
C
      SUBROUTINE MUANDK (TKEL,AIRMU,AIRK,CPP,SUM)
      IMPLICIT REAL*16 (A-H,O-Z)
C
C     COLLISION INTEGRAL, OMEGA, CALCULATED USING NEUFELD'S EMPIRICAL
C     EQUATION  (SEE EQN 9-4.3 TAKEN FROM "THE PROPERTIES OF GASES AND
C     LIQUIDS" BY REID, PRAUSNITZ, AND SHERWOOD (COPYRIGHT 1977))
C
      AA=1.16145
      BB=0.14874
      CC=0.52487
      DD=0.77320
      EE=2.16178
      FF=2.43787
      RR=8.31441
C
C     VALUES FOR SIGMA AND EPS/K TAKEN FROM APPENDIX C FOR AIR
C
      EPSK=78.6
      SIG=3.711
      TSTAR=TKEL/EPSK
      TERM1=AA/(TSTAR**BB)
      TERM2=CC/(QEXP(DD*TSTAR))
      TERM3=EE/(QEXP(FF*TSTAR))
      OMEGA=TERM1+TERM2+TERM3
      SSUM=1000.000/SUM
C
C     VISCOSITY, AIRMUR, CALCULATED USING EQN 9-3.9
C                 UNITS ARE [KG/(M*SEC)]
C
      AIRMUR=(26.69*QSQRT(TKEL*SSUM)/(SIG*SIG*OMEGA))/10.**7
C
C     THERMAL CONDUCTIVITY, AIRKR, CALCULATED USING EQN. 35
C     NASA CR-2550 WHICH USES THE EUCKEN SEMI-EMPIRICAL FORMULA
C                UNITS ARE J/(M*SEC*K)
C
      AIRKR=AIRMUR*(CPP+1.25*RR*SUM)
C
C     VISCOSITY, AIRMUSV, CALCULATED USING EQN 1
C     NASA TR-R-132 UNITS ARE [KG/(M*SEC)]
C
      AIRMUSV=(26.693*QSQRT(TKEL*SSUM)/(SIG*SIG*OMEGA))/10.**7
C
C     THERMAL CONDUCTIVITY, AIRKSV, CALCULATED USING EQN 2
C     NASA TR-R-132 UNITS ARE J/(M*SEC*K)
C
      AIRKSV=AIRMUSV*RR*SUM*(3.75+1.32*(CPP/(RR*SUM)-2.5))
C
C     VISCOSITY, AIRMUSU, AND THERMAL CONDUCTIVITY, AIRKSU,
```

```
C     CALCULATED USING SUTHERLAND'S LAW GIVEN IN
C     "VISCOUS FLUID FLOW" BY WHITE
C     (COPYRIGHT 1974) EQNS. 1-36 AND 1-44B
C
      SMU0=0.1716
      ST0=491.6
      SMUT=199.
      SK0=0.01395
      SKT=350.
      TR=(9.0/5.0)*TKEL
      CONVMU=0.0001
      CONVK=1.7296
      AIRMUSU=(SMU0*(TR/ST0)**(3./2.)*(ST0+SMUT)/(TR+SMUT))*CONVMU
      AIRKSU=(SK0*(TR/ST0)**(3./2.)*(ST0+SKT)/(TR+SKT))*CONVK
C
C     SELECT BEST TRANSPORT PROPERTY VALUE OF THE THREE METHODS
C     USING "THERMOPHYSICAL PROPERTIES OF MATTER"
C     AS A GUIDE OVER THE GIVEN LIMITED TEMPERATURE RANGE
C
      ONE=1.00000
      TMU1=1500.0000
      TMU2=2000.0000
        IF(TKEL.LE.TMU1) THEN
        AIRMU=AIRMUSU
        GOTO 100
        ENDIF
        IF(TKEL.GT.TMU1.AND.TKEL.LT.TMU2) THEN
        PERCENT=(TKEL-TMU1)/500.00
        AIRMU=PERCENT*AIRMUR+(ONE-PERCENT)*AIRMUSU
        GOTO 100
        ENDIF
      AIRMU=AIRMUR
  100 CONTINUE
      TK2=1500.0000
      TK3=2000.0000
        IF(TKEL.LE.TK2) THEN
        AIRK=AIRKSU
        GOTO 200
        ENDIF
        IF(TKEL.GT.TK2.AND.TKEL.LT.TK3) THEN
        PER2=(TKEL-TK2)/500.00
        AIRK=PER2*AIRKR+(ONE-PER2)*AIRKSU
        GOTO 200
        ENDIF
      AIRK=AIRKR
  200 CONTINUE
      RETURN
      END
```

Appendix C

Listing of the Input and Output Files for Six Shock-Wave Interference Examples Given in Tables 1 and 2

Input file for Type I shock-wave interference example.

```
 $names
  ishock=1,
  igas=2,
  incon=30,
  runno=1.,
  t0bu=3000.,
  p0bu=750.,
  v1bu=5631.5098,
  theideg=20.,
  thebdeg=-20.,
  twbu=800.,
  itype=1,
  sl12=.5,
 $
```

Output file for Type I shock-wave interference example.

```
 ***********************************************

  THIS SOLUTION FOR RUN NUMBER   1. IS BASED ON
  A CALORICALLY PERFECT IDEAL GAS MODEL FOR AIR

 ***********************************************

 INPUT  DATA  FROM  NAMELIST  :


 $NAMES
 ISHOCK  =          1,
 INCON   =         30,
 IGAS    =          2,
 RUNNO   =  1.000000000000000000000000000000       ,
 TOBU    =  3000.000000000000000000000000000       ,
 POBU    =  750.0000000000000000000000000000       ,
 RHOOBU  = 0.0000000000000000000000000000000E+0000,

 T1BU    = 0.0000000000000000000000000000000E+0000,
 P1BU    = 0.0000000000000000000000000000000E+0000,
 RHO1BU  = 0.0000000000000000000000000000000E+0000,
 V1BU    =  5631.509800000000000000000000000       ,
 PRNUM   = 0.7200000000000000000000000000000       ,
 THEIDEG =  20.00000000000000000000000000000       ,
 TWBU    =  800.0000000000000000000000000000       ,
 RBODY   =  1.000000000000000000000000000000       ,
 ITYPE   =          1,
```

```
THEBDEG =  -20.00000000000000000000000000000000          ,
SL12    =  0.500000000000000000000000000000000
$END


CALCULATION FOR TYPE I INTERFERENCE

REGION  TEMPERATURE     PRESSURE       DENSITY        INTERNAL        REX
                                                       ENERGY
         (RANKINE)       (PSIA)     (SLUGS/FT**3)    (BTU/LBM)       (1/FT)

   0    0.30000E+04   0.75000E+03   0.20976E-01    0.51338E+03
   1    0.35756E+03   0.44166E+00   0.10364E-03    0.61188E+02    0.21157E+07
   2    0.90423E+03   0.41652E+01   0.38649E-03    0.15474E+03    0.34635E+07
   3    0.90423E+03   0.41652E+01   0.38649E-03    0.15474E+03    0.34635E+07
   4    0.14957E+04   0.17929E+02   0.10057E-02    0.25595E+03    0.55136E+07
   5    0.14957E+04   0.17929E+02   0.10057E-02    0.25595E+03    0.55136E+07
   6    0.21210E+04   0.53450E+02   0.21144E-02    0.36296E+03    0.71829E+07


REGION    VELOCITY    MACH NUMBER    ENTHALPY       ENTROPY           PR
          (FT/SEC)                  (BTU/LBM)    (BTU/LBM-R)

   0    0.00000E+00     0.0000     0.71901E+03   0.17821E+01    0.72000E+00
   1    0.56315E+04     6.0746     0.85698E+02   0.17821E+01    0.72000E+00
   2    0.50153E+04     3.4020     0.21672E+03   0.18506E+01    0.72000E+00
   3    0.50153E+04     3.4020     0.21672E+03   0.18506E+01    0.72000E+00
   4    0.42490E+04     2.2409     0.35848E+03   0.18712E+01    0.72000E+00
   5    0.42490E+04     2.2409     0.35848E+03   0.18712E+01    0.72000E+00
   6    0.32479E+04     1.4386     0.50835E+03   0.18801E+01    0.72000E+00


TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH REGION (DEGREES)
 REGION         RELATIVE ANGLE              ABSOLUTE ANGLE
              THETA          BETA         THETA         BETA

   1       0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
   2      -0.20000E+02  -0.28173E+02  -0.20000E+02  -0.28173E+02
   3       0.20000E+02   0.28173E+02   0.20000E+02   0.28173E+02
   4       0.20000E+02   0.35130E+02   0.00000E+00   0.15130E+02
   5      -0.20000E+02  -0.35130E+02   0.00000E+00  -0.15130E+02
   6      -0.20000E+02  -0.47137E+02  -0.20000E+02  -0.47137E+02


****** SHOCK / BOUNDARY LAYER INTERACTION ******

 REGION     TEMPERATURE   PRESSURE     DENSITY       VELOCITY         PR
             (RANKINE)     (PSIA)    (SLUGS/FT**3)   (FT/SEC)
  WALL      0.80000E+03  0.41652E+01  0.43684E-03  0.00000E+00  0.72000E+00

LAMINAR SHOCK/BOUNDARY LAYER INTERFERENCE HEATING

UNDISTURBED HEATING RATE =  0.83752E+01 BTU/FT**2-SEC
       PEAK HEATING RATE =  0.22528E+03 BTU/FT**2-SEC
```

```
TURBULENT SHOCK/BOUNDARY LAYER INTERFERENCE HEATING

UNDISTURBED HEATING RATE =  0.43919E+02 BTU/FT**2-SEC
       PEAK HEATING RATE =  0.38435E+03 BTU/FT**2-SEC


*****  STAGNATION CONDITIONS WITHOUT INTERFERENCE  *****


  REGION      TEMPERATURE    PRESSURE    DENSITY      VELOCITY       PR
               (RANKINE)      (PSIA)   (SLUGS/FT**3)  (FT/SEC)

PRE-SHOCK     0.35756E+03  0.44166E+00  0.10364E-03  0.56315E+04  0.72000E+00
POST-SHOCK    0.29052E+04  0.18942E+02  0.54708E-03  0.10668E+04  0.72000E+00
STAGNATION    0.30000E+04  0.21194E+02  0.59275E-03  0.00000E+00  0.72000E+00
WALL          0.80000E+03  0.21194E+02  0.22228E-02  0.00000E+00  0.72000E+00


2-D FAY AND RIDDELL STAGNATION LINE HEATING =
0.63560E+02 BTU/(FT**2-SEC)
```

Input file for Type II shock-wave interference example.

```
 $names
  ishock=2,
  igas=2,
  incon=30,
  runno=1.,
  t0bu=3000.,
  p0bu=750.,
  v1bu=5631.5098,
  theideg=20.,
  thebdeg=-30.,
  twbu=800.,
  itype=1,
  sl12=.5,
 $
```

Output file for Type II shock-wave interference example.

```
 ***********************************************

  THIS SOLUTION FOR RUN NUMBER   1. IS BASED ON
  A CALORICALLY PERFECT IDEAL GAS MODEL FOR AIR

 ***********************************************

 INPUT  DATA  FROM  NAMELIST  :

 $NAMES
 ISHOCK  =          2,
```

```
 INCON    =          30,
 IGAS     =           2,
 RUNNO    =  1.00000000000000000000000000000000      ,
 TOBU     =  3000.00000000000000000000000000000      ,
 POBU     =  750.000000000000000000000000000000      ,
 RHOOBU   = 0.000000000000000000000000000000000E+0000,
 T1BU     = 0.000000000000000000000000000000000E+0000,
 P1BU     = 0.000000000000000000000000000000000E+0000,
 RHO1BU   = 0.000000000000000000000000000000000E+0000,

 V1BU     =  5631.5098000000000000000000000000      ,
 PRNUM    = 0.7200000000000000000000000000000000      ,
 THEIDEG  =  20.0000000000000000000000000000000      ,
 TWBU     =  800.000000000000000000000000000000      ,
 RBODY    =  1.00000000000000000000000000000000      ,
 ITYPE    =           1,
 THEBDEG  = -30.0000000000000000000000000000000      ,
 SL12     = 0.50000000000000000000000000000000000
 $END


CALCULATION FOR TYPE II INTERFERENCE


 REGION   TEMPERATURE     PRESSURE       DENSITY        INTERNAL         REX
                                                         ENERGY
           (RANKINE)       (PSIA)     (SLUGS/FT**3)    (BTU/LBM)        (1/FT)

   0      0.30000E+04    0.75000E+03    0.20976E-01    0.51338E+03
   1      0.35756E+03    0.44166E+00    0.10364E-03    0.61188E+02    0.21157E+07
   2      0.14277E+04    0.80186E+01    0.47126E-03    0.24431E+03    0.27186E+07
   3      0.90423E+03    0.41652E+01    0.38649E-03    0.15474E+03    0.34635E+07
   4      0.18563E+04    0.18864E+02    0.85264E-03    0.31766E+03    0.35748E+07
   5      0.28946E+04    0.18864E+02    0.54681E-03    0.49533E+03    0.53454E+06
   6      0.23293E+04    0.39975E+02    0.14400E-02    0.39860E+03    0.40459E+07
   7      0.15342E+04    0.18942E+02    0.10360E-02    0.26254E+03    0.55193E+07
   8      0.29051E+04    0.18942E+02    0.54708E-03    0.49715E+03    0.50599E+06


 REGION    VELOCITY     MACH NUMBER    ENTHALPY       ENTROPY           PR
           (FT/SEC)                   (BTU/LBM)     (BTU/LBM-R)


   0      0.00000E+00      0.0000     0.71901E+03    0.17821E+01    0.72000E+00
   1      0.56315E+04      6.0746     0.85698E+02    0.17821E+01    0.72000E+00
   2      0.43441E+04      2.3450     0.34217E+03    0.19152E+01    0.72000E+00
   3      0.50153E+04      3.4020     0.21672E+03    0.18506E+01    0.72000E+00
   4      0.37047E+04      1.7539     0.44491E+03    0.19195E+01    0.72000E+00
   5      0.11249E+04      0.4266     0.69374E+03    0.20260E+01    0.72000E+00
   6      0.28369E+04      1.1990     0.55826E+03    0.19224E+01    0.72000E+00
   7      0.41945E+04      2.1844     0.36770E+03    0.18735E+01    0.72000E+00
   8      0.10670E+04      0.4038     0.69628E+03    0.20266E+01    0.72000E+00
```

```
TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH REGION (DEGREES)
 REGION         RELATIVE ANGLE              ABSOLUTE ANGLE
             THETA          BETA         THETA          BETA

    1       0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
    2      -0.30000E+02 -0.40718E+02 -0.30000E+02 -0.40718E+02
    3       0.20000E+02  0.28173E+02  0.20000E+02  0.28173E+02
    4       0.14841E+02  0.38802E+02 -0.15159E+02  0.88019E+01
    5      -0.15159E+02 -0.86316E+02 -0.15159E+02 -0.86316E+02
    6      -0.14841E+02 -0.52947E+02 -0.30000E+02 -0.68106E+02
    7      -0.20936E+02 -0.36218E+02 -0.93626E+00 -0.16218E+02
    8      -0.93626E+00 -0.89819E+02 -0.93626E+00 -0.89819E+02


****** SHOCK / BOUNDARY LAYER INTERACTION ******


  REGION     TEMPERATURE    PRESSURE    DENSITY       VELOCITY        PR
              (RANKINE)      (PSIA)   (SLUGS/FT**3)  (FT/SEC)
   WALL      0.80000E+03  0.80186E+01  0.84099E-03  0.00000E+00  0.72000E+00


LAMINAR SHOCK/BOUNDARY LAYER INTERFERENCE HEATING

UNDISTURBED HEATING RATE =  0.11016E+02 BTU/FT**2-SEC
       PEAK HEATING RATE =  0.87505E+02 BTU/FT**2-SEC

TURBULENT SHOCK/BOUNDARY LAYER INTERFERENCE HEATING

UNDISTURBED HEATING RATE =  0.62974E+02 BTU/FT**2-SEC
output file 'sjout.dat'        PEAK HEATING RATE =  0.24672E+03 BTU/FT**2-SEC

*****  STAGNATION CONDITIONS WITHOUT INTERFERENCE  *****

  REGION     TEMPERATURE    PRESSURE    DENSITY       VELOCITY        PR
              (RANKINE)      (PSIA)   (SLUGS/FT**3)  (FT/SEC)

PRE-SHOCK    0.35756E+03  0.44166E+00  0.10364E-03  0.56315E+04  0.72000E+00
POST-SHOCK   0.29052E+04  0.18942E+02  0.54708E-03  0.10668E+04  0.72000E+00
STAGNATION   0.30000E+04  0.21194E+02  0.59275E-03  0.00000E+00  0.72000E+00
WALL         0.80000E+03  0.21194E+02  0.22228E-02  0.00000E+00  0.72000E+00


2-D FAY AND RIDDELL STAGNATION LINE HEATING =

0.63560E+02 BTU/(FT**2-SEC)
```

Input file for Type III shock-wave interference example.

```
$names
 ishock=3,
 igas=2,
```

```
  incon=1,
  runno=25.,
  p1bu=.1248893,
  rho1bu=4.773146e-5,
  v1bu=5848.971,
  theideg=12.5,
  thebdeg=-30.,
  twbu=533.5,
  rbody=1.5,
  itype=1,
  sl12=.16055046,
  $
```

Output file for Type III shock-wave interference example.

```
 ***********************************************

  THIS SOLUTION FOR RUN NUMBER  25. IS BASED ON
  A CALORICALLY PERFECT IDEAL GAS MODEL FOR AIR

 ***********************************************


 INPUT  DATA  FROM  NAMELIST  :
 $NAMES
 ISHOCK   =         3,
 INCON    =         1,
 IGAS     =         2,
 RUNNO    =  25.0000000000000000000000000000000      ,
 TOBU     = 0.000000000000000000000000000000000E+0000,
 POBU     = 0.000000000000000000000000000000000E+0000,
 RHOOBU   = 0.000000000000000000000000000000000E+0000,
 T1BU     = 0.000000000000000000000000000000000E+0000,
 P1BU     = 0.124889300000000000000000000000000      ,

 RHO1BU   = 4.773146000000000000000000000000000E-0005,
 V1BU     =  5848.97100000000000000000000000000      ,
 PRNUM    = 0.720000000000000000000000000000000      ,
 THEIDEG  =  12.5000000000000000000000000000000      ,
 TWBU     =  533.500000000000000000000000000000      ,
 RBODY    =  1.50000000000000000000000000000000      ,
 ITYPE    =         1,
 THEBDEG  = -30.0000000000000000000000000000000      ,
 SL12     = 0.160550460000000000000000000000000
 $END
```

```
CALCULATION FOR TYPE III INTERFERENCE

REGION   TEMPERATURE     PRESSURE        DENSITY        INTERNAL          REX
                                                        ENERGY
          (RANKINE)       (PSIA)      (SLUGS/FT**3)    (BTU/LBM)        (1/FT)

  0      0.30700E+04    0.12655E+04    0.34586E-01    0.52535E+03
  1      0.21953E+03    0.12489E+00    0.47731E-04    0.37568E+02    0.15819E+07
  2      0.29713E+04    0.94041E+01    0.26555E-03    0.50846E+03    0.24667E+06
  3      0.46991E+03    0.89107E+00    0.15910E-03    0.80413E+02    0.25703E+07
  4      0.12772E+04    0.94041E+01    0.61780E-03    0.21856E+03    0.40815E+07
  5      0.18058E+04    0.27823E+02    0.12927E-02    0.30903E+03    0.57929E+07

REGION    VELOCITY     MACH NUMBER    ENTHALPY       ENTROPY            PR
          (FT/SEC)                   (BTU/LBM)     (BTU/LBM-R)

  0      0.00000E+00      0.0000     0.73579E+03    0.17518E+01    0.72000E+00
  1      0.58490E+04      8.0517     0.52616E+02    0.17518E+01    0.72000E+00
  2      0.10884E+04      0.4073     0.71213E+03    0.20800E+01    0.72000E+00
  3      0.55862E+04      5.2562     0.11262E+03    0.17995E+01    0.72000E+00
  4      0.46385E+04      2.6474     0.30610E+03    0.18776E+01    0.72000E+00
  5      0.38950E+04      1.8696     0.43281E+03    0.18863E+01    0.72000E+00

TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH REGION (DEGREES)
 REGION          RELATIVE ANGLE                  ABSOLUTE ANGLE
              THETA           BETA            THETA          BETA

   1       0.00000E+00    0.00000E+00    0.00000E+00    0.00000E+00
   2      -0.12415E+02   -0.87195E+02   -0.12415E+02   -0.87195E+02
   3       0.12500E+02    0.18100E+02    0.12500E+02    0.18100E+02
   4      -0.24915E+02   -0.35218E+02   -0.12415E+02   -0.22718E+02
   5      -0.17585E+02   -0.38185E+02   -0.30000E+02   -0.50600E+02

****** SHEAR LAYER / BOUNDARY LAYER INTERACTION ******

  REGION     TEMPERATURE    PRESSURE     DENSITY       VELOCITY        PR
              (RANKINE)      (PSIA)    (SLUGS/FT**3)   (FT/SEC)
   WALL      0.53350E+03  0.27823E+02  0.43757E-02  0.00000E+00  0.72000E+00


LAMINAR SHEAR LAYER HEATING

WALL HEATING RATE =  0.16419E+03  BTU/FT**2-SEC
WALL STANTON NUMBER =  0.18020E-02

TURBULENT SHEAR LAYER HEATING

WALL HEATING RATE =  0.35781E+03  BTU/FT**2-SEC
WALL STANTON NUMBER =  0.38286E-02
```

```
*****  STAGNATION CONDITIONS WITHOUT INTERFERENCE  *****


  REGION       TEMPERATURE    PRESSURE    DENSITY       VELOCITY         PR
                (RANKINE)      (PSIA)   (SLUGS/FT**3)  (FT/SEC)

PRE-SHOCK     0.21953E+03  0.12489E+00  0.47731E-04  0.58490E+04  0.72000E+00
POST-SHOCK    0.29779E+04  0.94267E+01  0.26560E-03  0.10511E+04  0.72000E+00
STAGNATION    0.30700E+04  0.10486E+02  0.28657E-03  0.00000E+00  0.72000E+00
WALL          0.53350E+03  0.10486E+02  0.16491E-02  0.00000E+00  0.72000E+00


2-D FAY AND RIDDELL STAGNATION LINE HEATING =
0.42771E+02 BTU/(FT**2-SEC)
```

Input file for Type IV shock-wave interference example.

```
$names
 ishock=4,
 igas=2,
 incon=3,
 runno=21.,
 p1bu=.12744,
 t1bu=219.57,
 v1bu=5841.0,
 theideg=12.5,
 twbu=529.,
 rbody=1.5,
 itype=1,
 sl12=.061110999,
 $
```

Output file for Type IV shock-wave interference example.

```
***********************************************

 THIS SOLUTION FOR RUN NUMBER  21. IS BASED ON
 A CALORICALLY PERFECT IDEAL GAS MODEL FOR AIR

***********************************************


INPUT  DATA  FROM  NAMELIST  :

$NAMES
ISHOCK   =           4,
INCON    =           3,
IGAS     =           2,
RUNNO    =   21.0000000000000000000000000000000      ,
TOBU     =  0.000000000000000000000000000000000E+0000,
POBU     =  0.000000000000000000000000000000000E+0000,
RHOOBU   =  0.000000000000000000000000000000000E+0000,
```

```
T1BU     =    219.57000000000000000000000000000       ,
P1BU     =  0.12744000000000000000000000000000        ,
RHO1BU   =  0.00000000000000000000000000000000E+0000,

V1BU     =    5841.0000000000000000000000000000       ,
PRNUM    =  0.72000000000000000000000000000000        ,
THEIDEG  =    12.500000000000000000000000000000       ,
TWBU     =    529.00000000000000000000000000000       ,
RBODY    =    1.5000000000000000000000000000000       ,
ITYPE    =             1,
THEBDEG  =    1.0000000000000000000000000000000       ,
SL12     =  6.1110999000000000000000000000000E-0002
$END


CALCULATION FOR TYPE IV INTERFERENCE


THE APPROXIMATE BOUNDS FOR THE
TYPE IV INTERFERENCE ARE :
   UPPER BODY ANGLE =  36.002 DEGREES
   LOWER BODY ANGLE = -46.347 DEGREES


REGION   TEMPERATURE     PRESSURE        DENSITY        INTERNAL          REX
                                                         ENERGY
          (RANKINE)        (PSIA)      (SLUGS/FT**3)   (BTU/LBM)         (1/FT)

     0    0.30623E+04    0.12793E+04    0.35051E-01    0.52403E+03
     1    0.21957E+03    0.12744E+00    0.48699E-04    0.37574E+02    0.16115E+07
     2    0.29638E+04    0.95684E+01    0.27088E-03    0.50718E+03    0.25176E+06
     3    0.46942E+03    0.90735E+00    0.16218E-03    0.80330E+02    0.26184E+07
     4    0.12752E+04    0.95684E+01    0.62956E-03    0.21822E+03    0.41566E+07
     5    0.29593E+04    0.29021E+02    0.82284E-03    0.50640E+03    0.78304E+06
     6    0.18205E+04    0.29021E+02    0.13375E-02    0.31154E+03    0.59120E+07
     7    0.13255E+04    0.95684E+01    0.60568E-03    0.22683E+03    0.38471E+07
     8    0.18923E+04    0.29021E+02    0.12868E-02    0.32381E+03    0.53954E+07
  REGION      TEMPERATURE     PRESSURE     DENSITY       VELOCITY        PR


REGION    VELOCITY     MACH NUMBER    ENTHALPY       ENTROPY           PR
          (FT/SEC)                   (BTU/LBM)     (BTU/LBM-R)

0      0.00000E+00     0.0000     0.73394E+03    0.17504E+01    0.72000E+00
    1      0.58410E+04     8.0401     0.52625E+02    0.17504E+01    0.72000E+00

    2      0.10871E+04     0.4074     0.71034E+03    0.20782E+01    0.72000E+00
    3      0.55784E+04     5.2516     0.11251E+03    0.17980E+01    0.72000E+00
    4      0.46311E+04     2.6452     0.30563E+03    0.18760E+01    0.72000E+00
    5      0.11119E+04     0.4170     0.70925E+03    0.20017E+01    0.72000E+00
    6      0.38605E+04     1.8456     0.43633E+03    0.18853E+01    0.72000E+00
    7      0.45656E+04     2.5578     0.31768E+03    0.18853E+01    0.72000E+00
    8      0.37475E+04     1.7573     0.45352E+03    0.18946E+01    0.72000E+00
```

```
TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH REGION (DEGREES)
 REGION         RELATIVE ANGLE              ABSOLUTE ANGLE
             THETA          BETA         THETA          BETA

    1      0.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
    2     -0.12424E+02 -0.87195E+02 -0.12424E+02 -0.87195E+02
    3      0.12500E+02  0.18108E+02  0.12500E+02  0.18108E+02
    4     -0.24924E+02 -0.35238E+02 -0.12424E+02 -0.22738E+02
    5     -0.68666E+01 -0.88265E+02  0.56334E+01 -0.75765E+02
    6      0.18057E+02  0.38758E+02  0.56334E+01  0.26334E+02
    7      0.18413E+02 -0.18705E+02  0.24046E+02 -0.13071E+02
    8      0.18554E+02  0.40347E+02  0.42600E+02  0.64393E+02


COORDINATE LOCATIONS OF THE JET
 POINT        XJ            YJ
             (FT)          (FT)

   1      0.00000E+00   0.00000E+00
   2      0.56362E-01  -0.23620E-01
   3      0.72025E-01  -0.15867E-01
   4      0.90790E-01  -0.20224E-01
   5      0.98550E-01  -0.40319E-02
   6      0.11669E+00   0.35907E-02


 REGION      JET WIDTH
               (FT)

    7     0.11625E-01
    8     0.66662E-02

******* REGION 7 *******


  REGION      TEMPERATURE    PRESSURE    DENSITY       VELOCITY        PR
               (RANKINE)      (PSIA)   (SLUGS/FT**3)  (FT/SEC)

PRE-SHOCK     0.13255E+04  0.95684E+01  0.60568E-03  0.45656E+04  0.72000E+00
POST-SHOCK    0.29120E+04  0.71450E+02  0.20587E-02  0.13432E+04  0.72000E+00

STAGNATION    0.30623E+04  0.85200E+02  0.23344E-02  0.00000E+00  0.72000E+00
WALL          0.52900E+03  0.85200E+02  0.13513E-01  0.00000E+00  0.72000E+00


2-D FAY AND RIDDELL STAGNATION LINE HEATING =
0.53153E+03 BTU/(FT**2-SEC)


******* REGION 8 *******

  REGION      TEMPERATURE    PRESSURE    DENSITY       VELOCITY        PR
               (RANKINE)      (PSIA)   (SLUGS/FT**3)  (FT/SEC)

PRE-SHOCK     0.18923E+04  0.29021E+02  0.12868E-02  0.37475E+04  0.72000E+00
```

```
POST-SHOCK   0.28392E+04  0.99714E+02  0.29467E-02  0.16365E+04  0.72000E+00
STAGNATION   0.30624E+04  0.12991E+03  0.35593E-02  0.00000E+00  0.72000E+00
WALL         0.52900E+03  0.12991E+03  0.20605E-01  0.00000E+00  0.72000E+00


2-D FAY AND RIDDELL STAGNATION LINE HEATING =
0.11990E+04 BTU/(FT**2-SEC)



*****  STAGNATION CONDITIONS WITHOUT INTERFERENCE  *****


  REGION      TEMPERATURE    PRESSURE    DENSITY       VELOCITY        PR
               (RANKINE)      (PSIA)   (SLUGS/FT**3)  (FT/SEC)

PRE-SHOCK    0.21957E+03  0.12744E+00  0.48699E-04  0.58410E+04  0.72000E+00
POST-SHOCK   0.29704E+04  0.95914E+01  0.27093E-03  0.10499E+04  0.72000E+00
STAGNATION   0.30623E+04  0.10669E+02  0.29233E-03  0.00000E+00  0.72000E+00
WALL         0.52900E+03  0.10669E+02  0.16922E-02  0.00000E+00  0.72000E+00


2-D FAY AND RIDDELL STAGNATION LINE HEATING =
0.43082E+02 BTU/(FT**2-SEC)
```

Input file for Type V shock-wave interference example.

```
$names
 ishock=5,
 igas=2,
 incon=30,
 runno=1.,
 t0bu=900.,
 p0bu=400.,
 v1bu=3081.4077,
 theideg=5.,
 thebdeg=35.,
 twbu=550.,
 itype=1,
 sl12=.25,
$
```

Output file for Type V shock-wave interference example.

```
***********************************************

 THIS SOLUTION FOR RUN NUMBER   1. IS BASED ON
 A CALORICALLY PERFECT IDEAL GAS MODEL FOR AIR

***********************************************
```

```
INPUT  DATA  FROM  NAMELIST  :

$NAMES
ISHOCK  =           5,
INCON   =          30,
IGAS    =           2,
RUNNO   =   1.0000000000000000000000000000000000      ,
T0BU    =   900.00000000000000000000000000000000      ,
P0BU    =   400.00000000000000000000000000000000      ,
RHO0BU  =  0.00000000000000000000000000000000000E+0000,
T1BU    =  0.00000000000000000000000000000000000E+0000,
P1BU    =  0.00000000000000000000000000000000000E+0000,
RHO1BU  =  0.00000000000000000000000000000000000E+0000,

V1BU    =   3081.4077000000000000000000000000000      ,
PRNUM   =  0.72000000000000000000000000000000000      ,
THEIDEG =   5.0000000000000000000000000000000000      ,
TWBU    =   550.00000000000000000000000000000000      ,
RBODY   =   1.0000000000000000000000000000000000      ,
ITYPE   =           1,
THEBDEG =   35.000000000000000000000000000000000      ,
SL12    =  0.25000000000000000000000000000000000
$END


CALCULATION FOR TYPE V INTERFERENCE


FOR THESE CONDITIONS, TRY A TYPE VI INTERFERENCE
HOWEVER, A TYPE V INTERFERENCE SOLUTION MAY EXIST
THEREFORE, CONTINUE THE CALCULATION


REGION    TEMPERATURE       PRESSURE          DENSITY          INTERNAL          REX
                                                              ENERGY
           (RANKINE)         (PSIA)        (SLUGS/FT**3)      (BTU/LBM)          (1/FT)

   0      0.90000E+03      0.40000E+03      0.37291E-01      0.15401E+03
   1      0.10886E+03      0.24800E+00      0.19114E-03      0.18629E+02      0.70306E+07
   2      0.13435E+03      0.49993E+00      0.31220E-03      0.22991E+02      0.89215E+07
   3      0.45530E+03      0.72734E+01      0.13404E-02      0.77913E+02      0.91844E+07
   4      0.86709E+03      0.16438E+02      0.15906E-02      0.14838E+03      0.18381E+07
   5      0.58386E+03      0.16438E+02      0.23623E-02      0.99913E+02      0.11244E+08
   6      0.73624E+03      0.35351E+02      0.40287E-02      0.12599E+03      0.11643E+08


REGION     VELOCITY       MACH NUMBER      ENTHALPY          ENTROPY             PR
           (FT/SEC)                       (BTU/LBM)       (BTU/LBM-R)

   0      0.00000E+00        0.0000       0.21570E+03      0.15366E+01      0.72000E+00
   1      0.30814E+04        6.0239       0.26091E+02      0.15366E+01      0.72000E+00
   2      0.30313E+04        5.3342       0.32201E+02      0.15390E+01      0.72000E+00
   3      0.23102E+04        2.2084       0.10912E+03      0.16480E+01      0.72000E+00
   4      0.62844E+03        0.4353       0.20782E+03      0.17465E+01      0.72000E+00
   5      0.19478E+04        1.6442       0.13993E+03      0.16517E+01      0.72000E+00
```

```
   6     0.14017E+04       1.0537      0.17646E+03    0.16548E+01     0.72000E+00

 TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH REGION (DEGREES)
  REGION          RELATIVE ANGLE               ABSOLUTE ANGLE
               THETA           BETA         THETA          BETA

     1       0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
     2       0.50000E+01   0.13123E+02   0.50000E+01   0.13123E+02
     3       0.30000E+02   0.41740E+02   0.35000E+02   0.46740E+02
     4       0.15300E+02   0.86097E+02   0.20300E+02   0.91097E+02
     5      -0.14700E+02  -0.40773E+02   0.20300E+02  -0.57733E+01
     6       0.14700E+02   0.58996E+02   0.35000E+02   0.79296E+02


 ****** SHOCK / BOUNDARY LAYER INTERACTION ******

   REGION      TEMPERATURE     PRESSURE    DENSITY       VELOCITY         PR
                (RANKINE)       (PSIA)    (SLUGS/FT**3)  (FT/SEC)
    WALL      0.55000E+03  0.72734E+01  0.11096E-02  0.00000E+00  0.72000E+00


 LAMINAR SHOCK/BOUNDARY LAYER INTERFERENCE HEATING

 UNDISTURBED HEATING RATE =  0.17914E+01 BTU/FT**2-SEC
       PEAK HEATING RATE =  0.13771E+02 BTU/FT**2-SEC

 TURBULENT SHOCK/BOUNDARY LAYER INTERFERENCE HEATING

 UNDISTURBED HEATING RATE =  0.10814E+02 BTU/FT**2-SEC
       PEAK HEATING RATE =  0.41460E+02 BTU/FT**2-SEC


 *****  STAGNATION CONDITIONS WITHOUT INTERFERENCE  *****


   REGION      TEMPERATURE     PRESSURE    DENSITY       VELOCITY         PR
                (RANKINE)       (PSIA)    (SLUGS/FT**3)  (FT/SEC)

 PRE-SHOCK    0.10886E+03  0.24800E+00  0.19114E-03  0.30814E+04  0.72000E+00
 POST-SHOCK   0.87149E+03  0.10459E+02  0.10070E-02  0.58491E+03  0.72000E+00
 STAGNATION   0.90000E+03  0.11705E+02  0.10912E-02  0.00000E+00  0.72000E+00
 WALL         0.55000E+03  0.11705E+02  0.17856E-02  0.00000E+00  0.72000E+00


 2-D FAY AND RIDDELL STAGNATION LINE HEATING =
 0.67390E+01 BTU/(FT**2-SEC)
```

Input file for Type VI shock-wave interference example.

```
 $names
  ishock=6,
  igas=2,
  incon=30,
```

```
 runno=1.,
 t0bu=900.,
 p0bu=400.,
 v1bu=3081.4077,
 theideg=5.,
 thebdeg=15.,
 twbu=550.,
 itype=1,
 sl12=.25,
$
```

Output file for Type VI shock-wave interference example.

```
**********************************************
THIS SOLUTION FOR RUN NUMBER   1. IS BASED ON
 A CALORICALLY PERFECT IDEAL GAS MODEL FOR AIR

**********************************************


INPUT  DATA  FROM  NAMELIST  :


$NAMES
ISHOCK  =          6,
INCON   =         30,
IGAS    =          2,
RUNNO   =   1.000000000000000000000000000000      ,
T0BU    =   900.0000000000000000000000000000      ,
P0BU    =   400.0000000000000000000000000000      ,
RHO0BU  =  0.000000000000000000000000000000E+0000,
T1BU    =  0.000000000000000000000000000000E+0000,
P1BU    =  0.000000000000000000000000000000E+0000,
RHO1BU  =  0.000000000000000000000000000000E+0000,

V1BU    =   3081.407700000000000000000000000      ,
PRNUM   =  0.7200000000000000000000000000000      ,
THEIDEG =   5.000000000000000000000000000000      ,
TWBU    =   550.0000000000000000000000000000      ,
RBODY   =   1.000000000000000000000000000000      ,
ITYPE   =          1,
THEBDEG =   15.00000000000000000000000000000      ,
SL12    =  0.2500000000000000000000000000000
$END


CALCULATION FOR TYPE VI INTERFERENCE

REGION   TEMPERATURE      PRESSURE       DENSITY        INTERNAL         REX
                                                         ENERGY
          (RANKINE)        (PSIA)      (SLUGS/FT**3)   (BTU/LBM)        (1/FT)
```

```
   0     0.90000E+03    0.40000E+03    0.37291E-01    0.15401E+03
   1     0.10886E+03    0.24800E+00    0.19114E-03    0.18629E+02    0.70306E+07
   2     0.21759E+03    0.15632E+01    0.60277E-03    0.37236E+02    0.98598E+07
   3     0.13435E+03    0.49993E+00    0.31220E-03    0.22991E+02    0.89215E+07
   4     0.19694E+03    0.16216E+01    0.69087E-03    0.33702E+02    0.12661E+08
   5     0.19489E+03    0.15632E+01    0.67301E-03    0.33350E+02    0.12483E+08
   6     0.19284E+03    0.15066E+01    0.65551E-03    0.33000E+02    0.12306E+08


REGION    VELOCITY     MACH NUMBER    ENTHALPY       ENTROPY            PR
          (FT/SEC)                   (BTU/LBM)    (BTU/LBM-R)

   0     0.00000E+00     0.0000     0.21570E+03    0.15366E+01    0.72000E+00
   1     0.30814E+04     6.0239     0.26091E+02    0.15366E+01    0.72000E+00
   2     0.28618E+04     3.9571     0.52151E+02    0.15764E+01    0.72000E+00
   3     0.30313E+04     5.3342     0.32201E+02    0.15390E+01    0.72000E+00
   4     0.29048E+04     4.2219     0.47201E+02    0.15500E+01    0.72000E+00
   5     0.29091E+04     4.2503     0.46708E+02    0.15500E+01    0.72000E+00
   6     0.29133E+04     4.2790     0.46218E+02    0.15500E+01    0.72000E+00


TURNING ANGLE, THETA, AND SHOCK ANGLE, BETA, AT EACH REGION (DEGREES)
 REGION          RELATIVE ANGLE              ABSOLUTE ANGLE
              THETA          BETA          THETA          BETA

   1       0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
   2       0.15341E+02   0.23011E+02   0.15341E+02   0.23011E+02
   3       0.50000E+01   0.13123E+02   0.50000E+01   0.13123E+02
   4       0.10000E+02   0.18693E+02   0.15000E+02   0.23693E+02
   5       0.34419E+00  -0.13482E+02   0.15344E+02   0.15176E+01
   6      -0.34402E+00   0.13389E+02   0.15000E+02   0.28734E+02


****** SHOCK / BOUNDARY LAYER INTERACTION ******


  REGION     TEMPERATURE    PRESSURE    DENSITY       VELOCITY         PR
              (RANKINE)      (PSIA)   (SLUGS/FT**3)  (FT/SEC)
   WALL      0.55000E+03  0.16216E+01  0.24738E-03  0.00000E+00  0.72000E+00


LAMINAR SHOCK/BOUNDARY LAYER INTERFERENCE HEATING

UNDISTURBED HEATING RATE =  0.83136E+00 BTU/FT**2-SEC
       PEAK HEATING RATE =  0.75609E+00 BTU/FT**2-SEC

TURBULENT SHOCK/BOUNDARY LAYER INTERFERENCE HEATING

UNDISTURBED HEATING RATE =  0.38766E+01 BTU/FT**2-SEC
       PEAK HEATING RATE =  0.36416E+01 BTU/FT**2-SEC


*****  STAGNATION CONDITIONS WITHOUT INTERFERENCE  *****
```

```
  REGION     TEMPERATURE    PRESSURE    DENSITY        VELOCITY        PR
              (RANKINE)      (PSIA)   (SLUGS/FT**3)   (FT/SEC)

PRE-SHOCK    0.10886E+03  0.24800E+00  0.19114E-03  0.30814E+04  0.72000E+00
POST-SHOCK   0.87149E+03  0.10459E+02  0.10070E-02  0.58491E+03  0.72000E+00
STAGNATION   0.90000E+03  0.11705E+02  0.10912E-02  0.00000E+00  0.72000E+00
WALL         0.55000E+03  0.11705E+02  0.17856E-02  0.00000E+00  0.72000E+00


2-D FAY AND RIDDELL STAGNATION LINE HEATING =
0.67390E+01 BTU/(FT**2-SEC)
```

References

1. Morris, Dana J.; and Keyes, J. Wayne: *Computer Programs for Predicting Supersonic and Hypersonic Interference Flow Fields and Heating.* NASA TM X-2725, 1973.
2. Anderson, John D., Jr.: *Modern Compressible Flow—With Historical Perspective.* McGraw-Hill, Inc., c.1982.
3. Prabhu, Ramadas K.; and Erickson, Wayne D.: *A Rapid Method for the Computation of Equilibrium Chemical Composition of Air to 15 000 K.* NASA TP-2792, 1988.
4. Reid, Robert C.; Prausnitz, John M.; and Sherwood, Thomas K.: *The Properties of Gases and Liquids,* Third ed. McGraw-Hill Book Co., c.1977.
5. Miner, E. W.; and Lewis, Clark H.: *Hypersonic Ionizing Air Viscous Shock-Layer Flows Over Nonanalytic Blunt Bodies.* NASA CR-2550, 1975.
6. Edney, Barry: *Anomalous Heat Transfer and Pressure Distributions on Blunt Bodies at Hypersonic Speeds in the Presence of an Impinging Shock.* FFA Rep. 115, Aeronautical Research Inst. of Sweden, 1968.
7. Fay, J. A.; and Riddell, F. R.: Theory of Stagnation Point Heat Transfer in Dissociated Air. *J. Aeronaut. Sci.*, vol. 25, no. 2, Feb. 1958, pp. 73–85, 121.
8. *VAX/VMS User's Manual.* Order No. AI-Y517A-TE, Digital Equipment Corp., Apr. 1986.
9. Wieting, Allan R.: *Experimental Study of Shock Wave Interference Heating on a Cylindrical Leading Edge.* NASA TM-100484, 1987.
10. Hiers, Robert S.; and Loubsky, William J.: *Effects of Shock-Wave Impingement on the Heat Transfer on a Cylindrical Leading Edge.* NASA TN D-3859, 1967.
11. Bushnell, Dennis M.: *Effects of Shock Impingement and Other Factors on Leading-Edge Heat Transfer.* NASA TN D-4543, 1968.
12. Keyes, J. Wayne; and Morris, Dana J.: Correlations of Peak Heating in Shock Interference Regions at Hypersonic Speeds. *J. Spacecr. & Rockets*, vol. 9, no. 8, Aug. 1972, pp. 621–623.
13. Hains, F. D.; and Keyes, J. Wayne: Shock Interference Heating in Hypersonic Flows. *AIAA J.*, vol. 10, no. 11, Nov. 1972, pp. 1441–1447.
14. Keyes, J. Wayne; and Hains, Frank D.: *Analytical and Experimental Studies of Shock Interference Heating in Hypersonic Flows.* NASA TN D-7139, 1973.
15. Markarian, C. Franklyn: *Heat Transfer in Shock Wave-Boundary Layer Interaction Regions.* NWC TP 4485, U.S. Navy, Nov. 1968. (Available from DTIC as AD 849 532.)
16. Back, L. H.; and Cuffel, R. F.: Changes in Heat Transfer From Turbulent Boundary Layers Interacting With Shock Waves and Expansion Waves. *AIAA J.*, vol. 8, no. 10, Oct. 1970, pp. 1871–1873.
17. Holden, M. S.: Shock Wave-Turbulent Boundary Layer Interaction in Hypersonic Flow. AIAA Paper 72-74, Jan. 1972.
18. Johnson, Charles B.; and Kaufman, Louis G., II: *Interference Heating From Interactions of Shock Waves With Turbulent Boundary Layers at Mach 6.* NASA TN D-7649, 1974.
19. Kaufman, Louis G., II; and Johnson, Charles B.: *Weak Incident Shock Interactions With Mach 8 Laminar Boundary Layers.* NASA TN D-7835, 1974.
20. Holden, Michael S.: A Study of Flow Separation in Regions of Shock Wave-Boundary Layer Interaction in Hypersonic Flow. AIAA Paper 78-1169, July 1978.
21. Schlichting, Hermann (J. Kestin, transl.): *Boundary-Layer Theory,* Seventh ed. McGraw-Hill Book Co., c.1979.
22. Shapiro, Ascher H.: *The Dynamics and Thermodynamics of Compressible Fluid Flow.* Ronald Press Co.
    Volume I. c.1953.
    Volume II. c.1954.
23. Cox, R. N.; and Crabtree, L. F.: *Elements of Hypersonic Aerodynamics.* Academic Press, Inc., 1965.
24. Anderson, John D., Jr.: *Hypersonic and High Temperature Gas Dynamics.* McGraw-Hill Book Co., c.1989.
25. Eckert, E. R. G.: Engineering Relations for Friction and Heat Transfer to Surfaces in High Velocity Flow. *J. Aeronaut. Sci.*, vol. 22, no. 8, Aug. 1955, pp. 585–587.
26. Kays, W. M.; and Crawford, M. E.: *Convective Heat and Mass Transfer,* Second ed. McGraw-Hill, Inc., c.1980.
27. Bushnell, Dennis M.; and Weinstein, Leonard M.: Correlation of Peak Heating for Reattachment of Separated Flows. *J. Spacecr. & Rockets*, vol. 5, no. 9, Sept. 1968, pp. 1111–1112.
28. Birch, Stanley F.; and Keyes, J. Wayne: Transition In Compressible Free Shear Layers. *J. Spacecr. & Rockets*, vol. 9, no. 8, Aug. 1972, pp. 623–624.
29. Van Dyke, Milton D.; and Gordon, Helen D.: *Supersonic Flow Past a Family of Blunt Axisymmetric Bodies.* NASA TR R-1, 1959.
30. Hayes, Wallace D.; and Probstein, Ronald F.: *Hypersonic Flow Theory, Volume I—Inviscid Flows,* Second ed. Academic Press, Inc., 1966.
31. Glass, Christopher E.; Holden, Michael S.; and Wieting, Allan R.: Effect of Leading Edge Sweep on Shock-Shock Interference at Mach 8. AIAA Paper 89-0271, Jan. 1989.
32. Glass, Christopher E.: Experimental Study of Pressure and Heating Rate on a Swept Cylindrical Leading Edge Resulting From Swept Shock Wave Interference. M.S. Thesis, Old Dominion University, 1989. (Available as NASA CR-185326.)
33. Jackson, L. Robert: *An Accelerator Airplane Concept for Single-Stage-To-Orbit Flight.* NASA TM-101563. 1989.
34. *U.S. Standard Atmosphere,* 1976. NOAA, NASA, and U.S. Air Force, Oct. 1976.
35. Van Wylen, Gordon J.; and Sonntag, Richard E.: *Fundamentals of Classical Thermodynamics—SI Version,* Second ed., Revised printing. John Wiley & Sons, Inc. c.1978.
36. White, Frank M.: *Viscous Fluid Flow.* McGraw-Hill, Inc., c.1974.

Table 1. Predicted Maximum Pressure and Heat Flux From Morris and Keyes Computer Programs[1] and EASI Computer Program for Calorically Perfect Air

Interference type	Morris and Keyes		EASI	
	$p_{\max}$, psia	$q_{\max}$, Btu/ft^2-sec	$p_{\max}$, psia	$q_{\max}$, Btu/ft^2-sec
I				
Laminar	54.07	226.03	53.45	225.28
Turbulent		420.16		384.35
II				
Laminar	40.51	88.04	39.98	87.50
Turbulent		270.60		246.72
III				
Laminar	27.70	163.73	27.82	164.19
Turbulent		356.70		357.81
IV				
Region 7	85.12	526.70	85.20	531.53
Region 8	141.62	1218.10	129.91	1199.00
V				
Laminar	35.77	13.86	35.35	13.77
Turbulent		45.46		41.46
VI				
Laminar	1.53	0.76	1.51	0.76
Turbulent		3.95		3.64

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[1] NASA TM X-2725.

Table 2. Free-Stream Conditions and Model Geometry for Predictions Shown in Table 1

Interference type	T_1, °R	p_1, psia	V_1, ft/sec	θ_i, deg	θ_b, deg	L, ft	r_b, in.
I	357.6	0.442	5631.5	20.0	20.0	0.5	
II	357.6	.442	5631.5	20.0	30.0	.5	
III	219.5	.125	5849.0	12.5	30.0	.16	1.5
IV	219.6	.127	5841.0	12.5		.06	1.5
V	108.9	.248	3081.4	5.0	35.0	.25	
VI	108.9	.248	3081.4	5.0	15.0	.25	

Table 3. Predictions From EASI Computer Program for Chemically Reacting Equilibrium Air

[See figs. 10 to 12]

Interference type	p_o, psia	q_o, Btu/ft^2-sec	$p_{\max}/p_o$	$q_{\max}/q_o$
III (run 26)	10.556	41.130		
Laminar			2.994	4.488
Turbulent			2.994	9.738
IV (run 21)	10.757	40.276		
Region 7			8.154	12.789
Region 8			12.854	28.637
IV (run 43)	4.155	45.020		
Region 7			14.108	13.547
Region 8			28.847	35.442

Table 4. Test Conditions of Shock-Wave Interference Data Shown in Figures 10 to 12

Interference type	T_1, °R	p_1, psia	V_1, ft/sec	θ_i, deg	θ_b, deg	L, ft	r_b, in.
III (run 26)	224.9	0.125	5911	12.5	33.0	2.06	1.5
IV (run 21)	219.6	.127	5841	12.5		.71	1.5
IV (run 43)	94.1	.012	7768	10.0		1.12	1.5

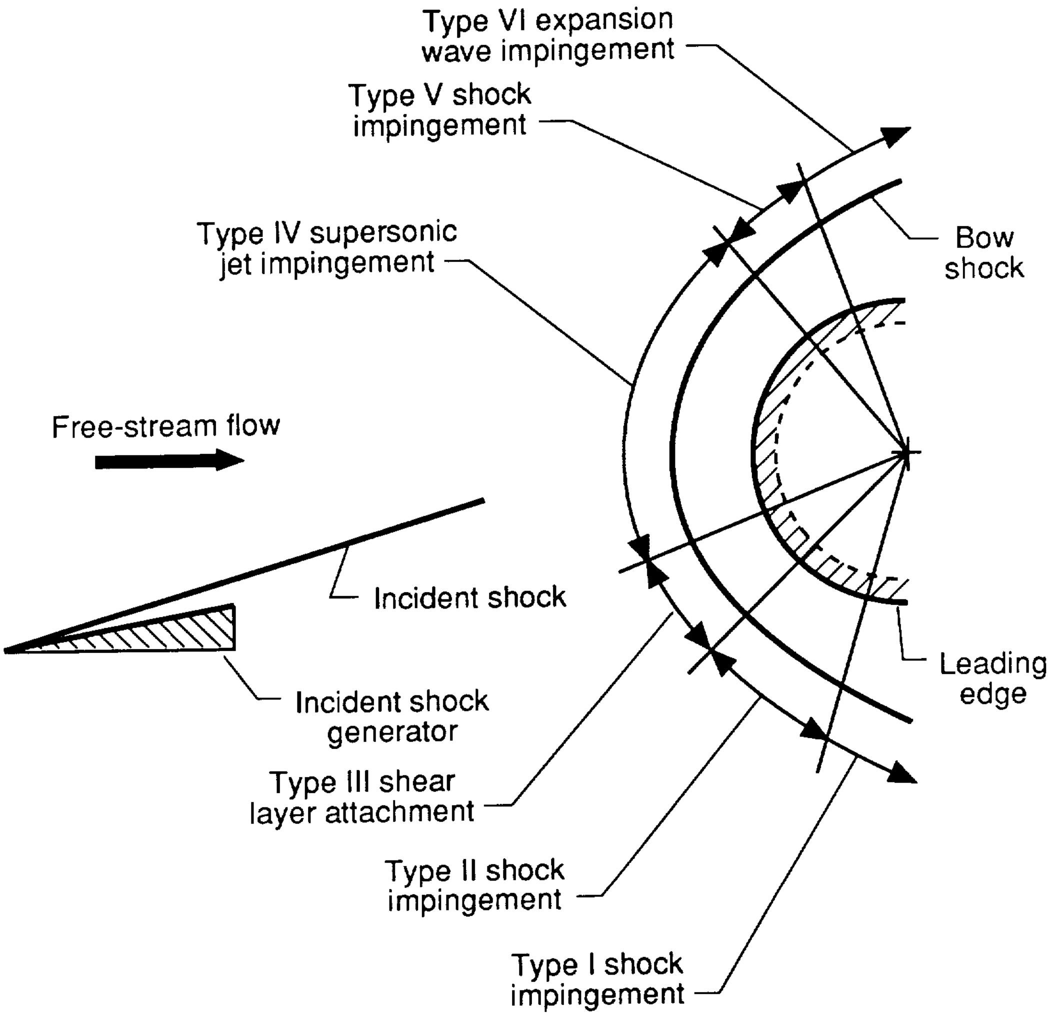
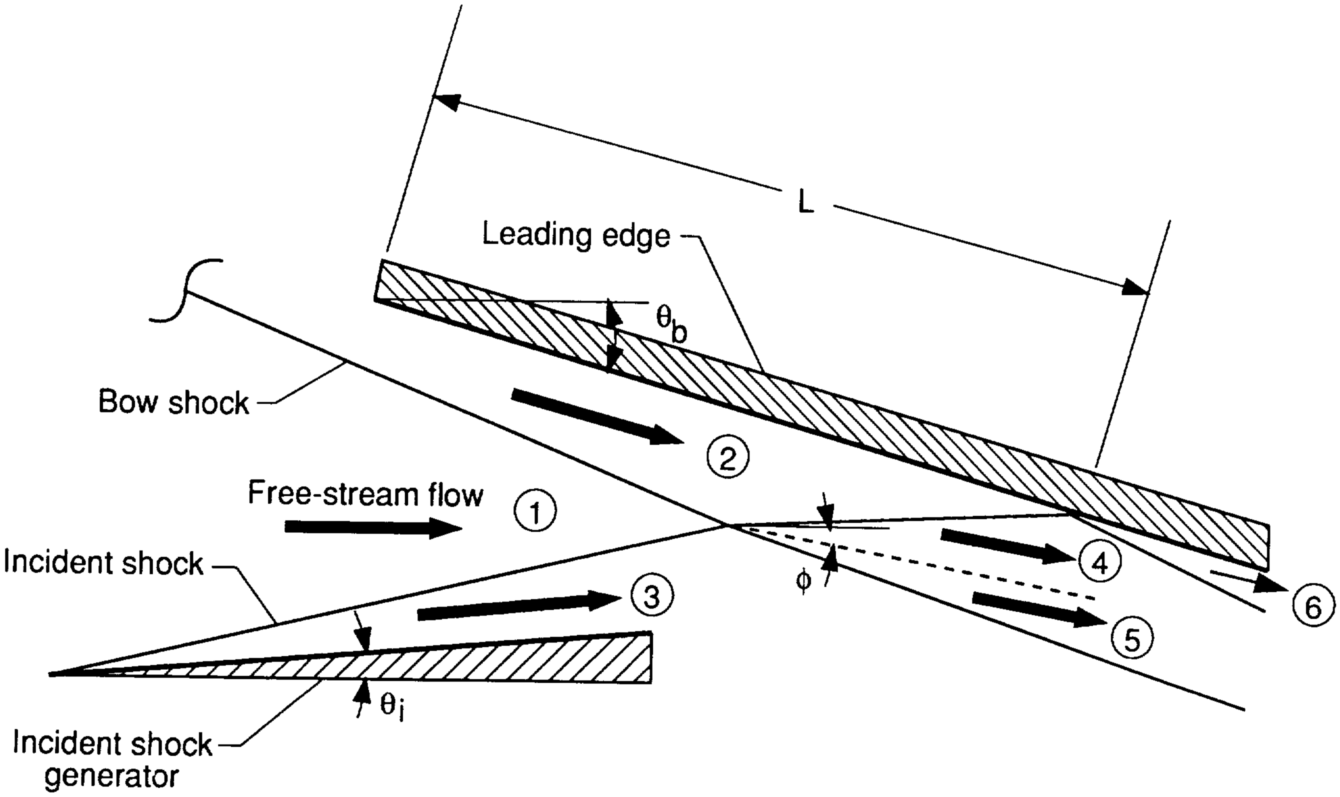
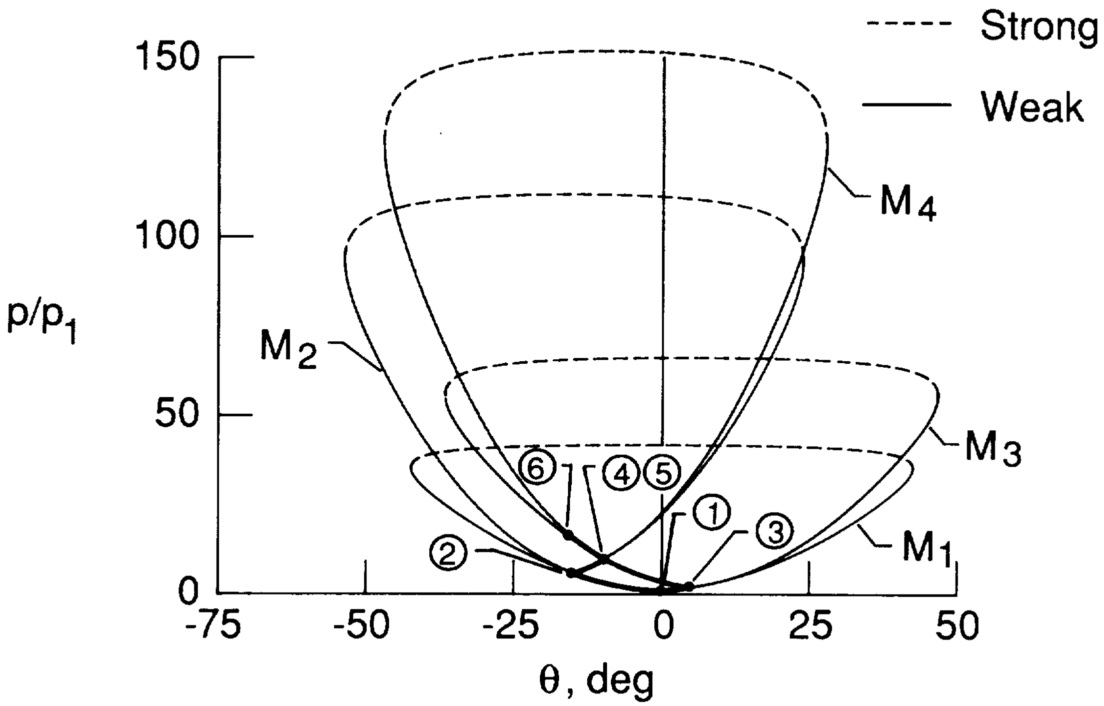


Figure 1. Location of six shock-wave interference patterns on leading edge.

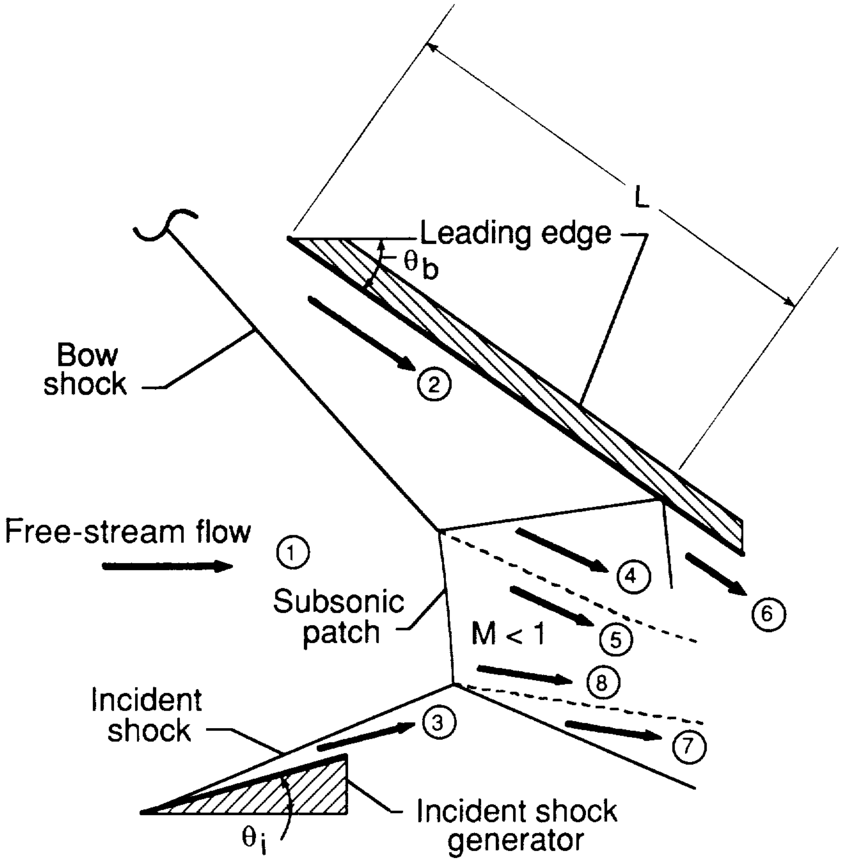


(a) Schematic diagram.

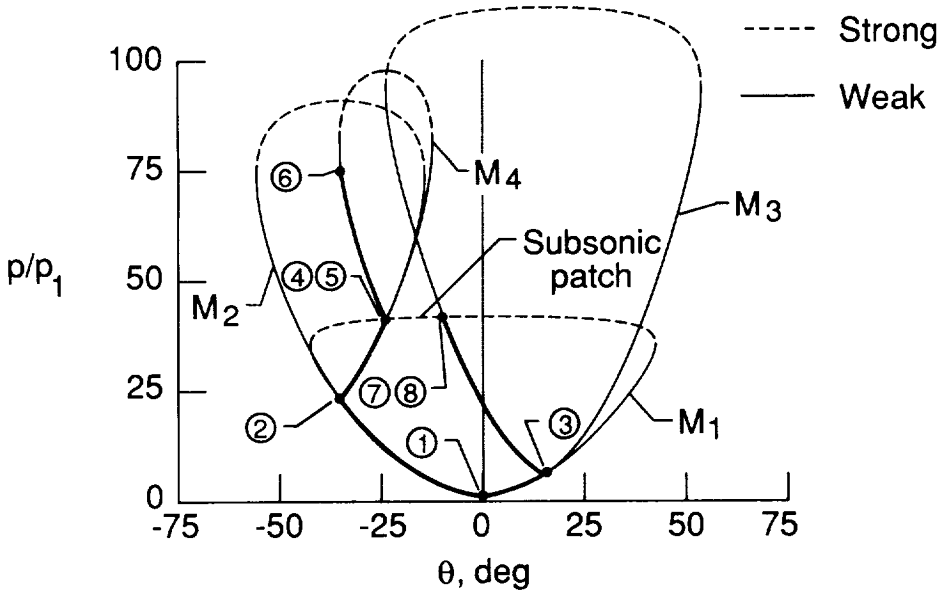


(b) Pressure-deflection diagram.

Figure 2. Type I shock-wave interference pattern.

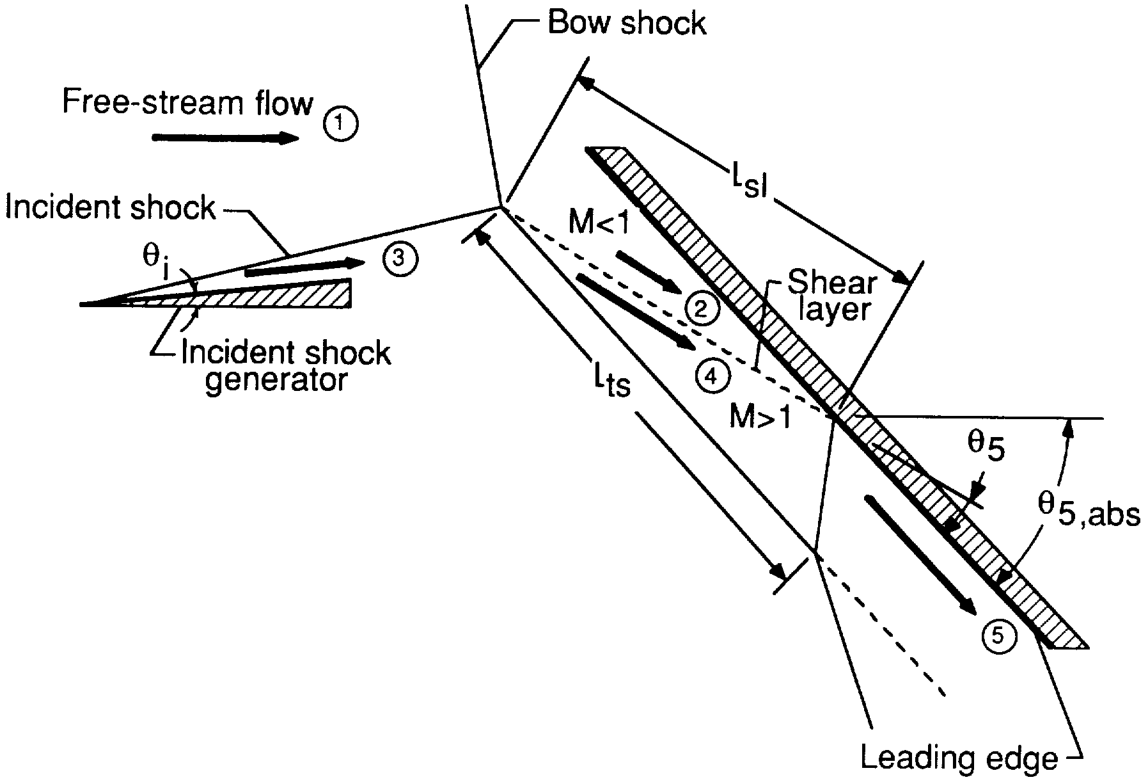


(a) Schematic diagram.

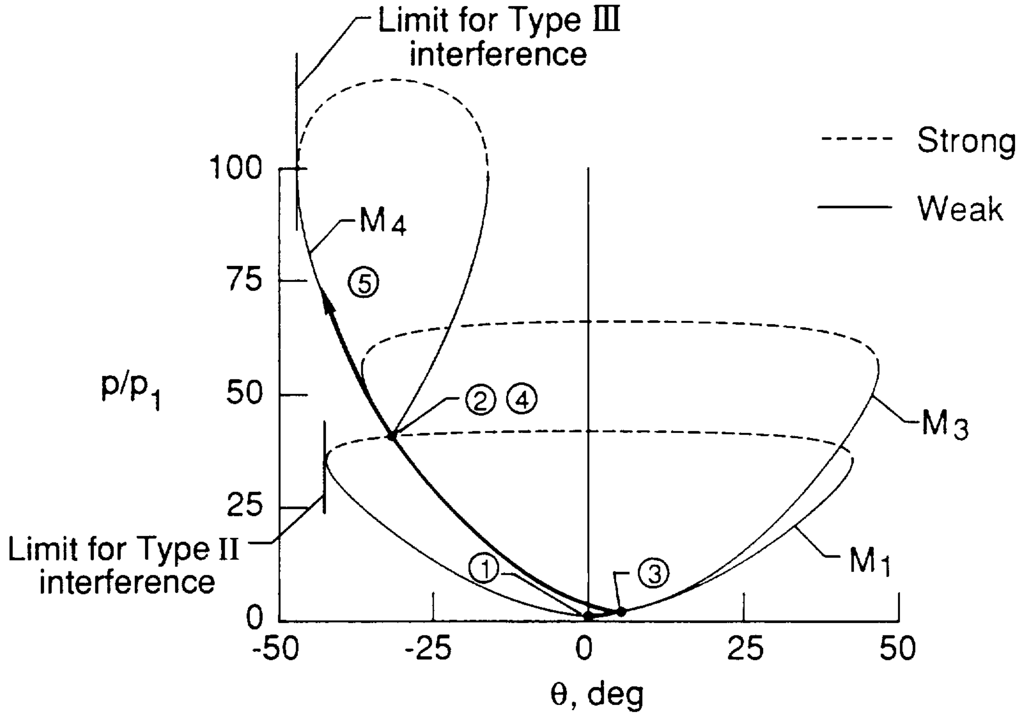


(b) Pressure-deflection diagram.

Figure 3. Type II shock-wave interference pattern.

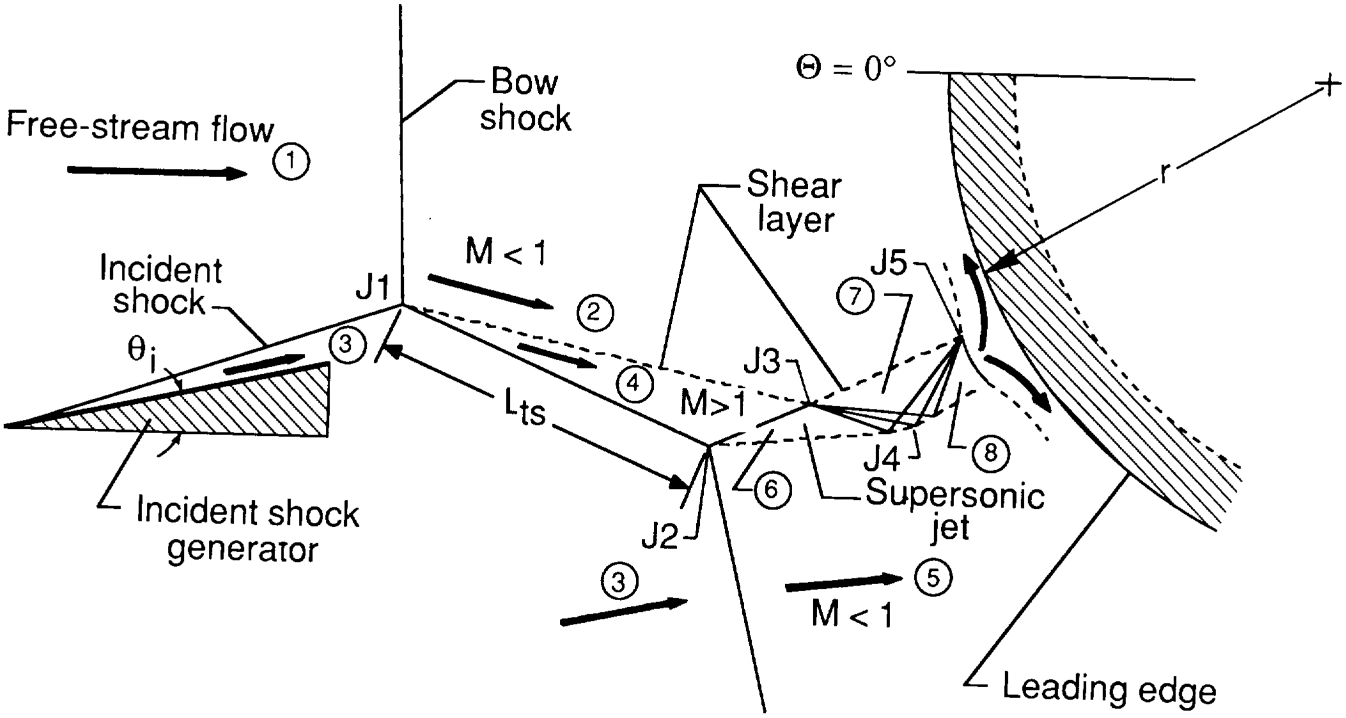


(a) Schematic diagram.

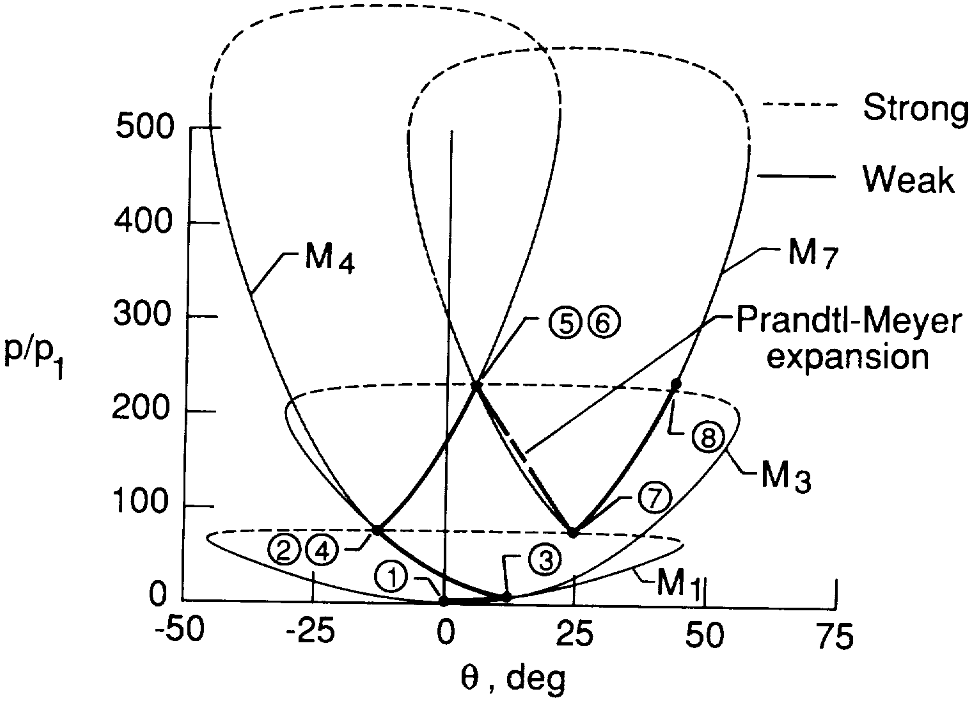


(b) Pressure-deflection diagram.

Figure 4. Type III shock-wave interference pattern.

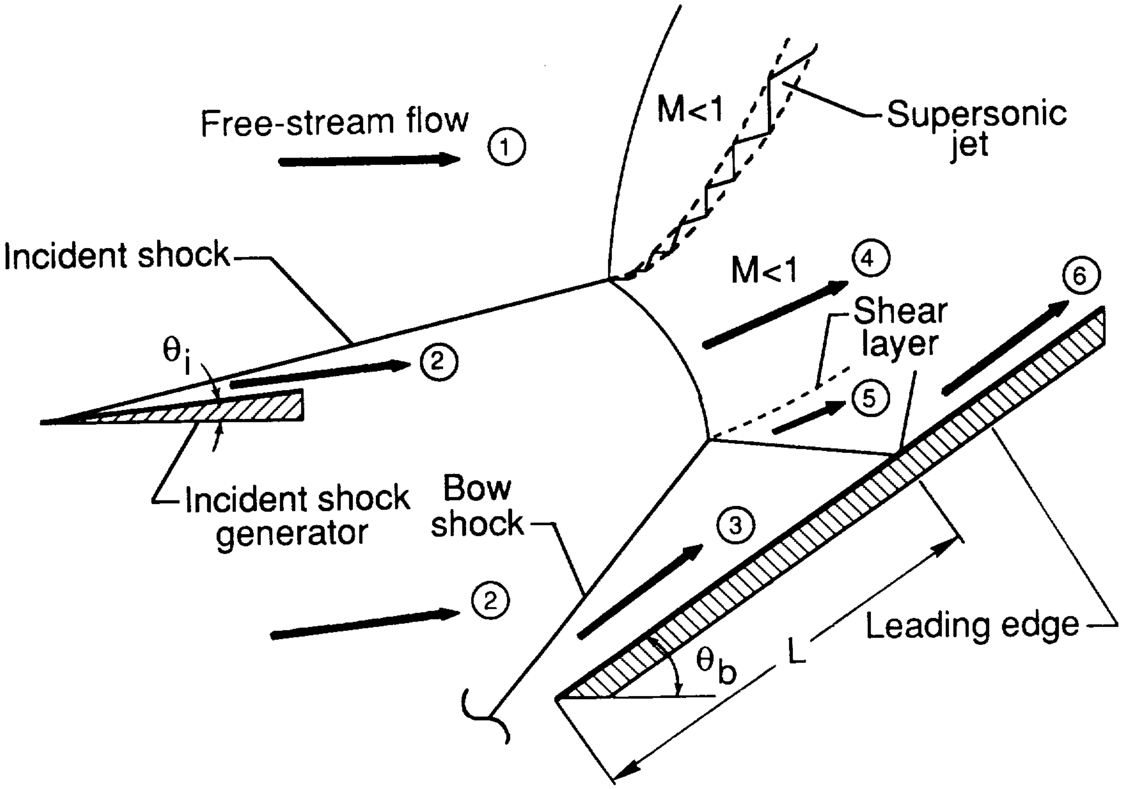


(a) Schematic diagram.

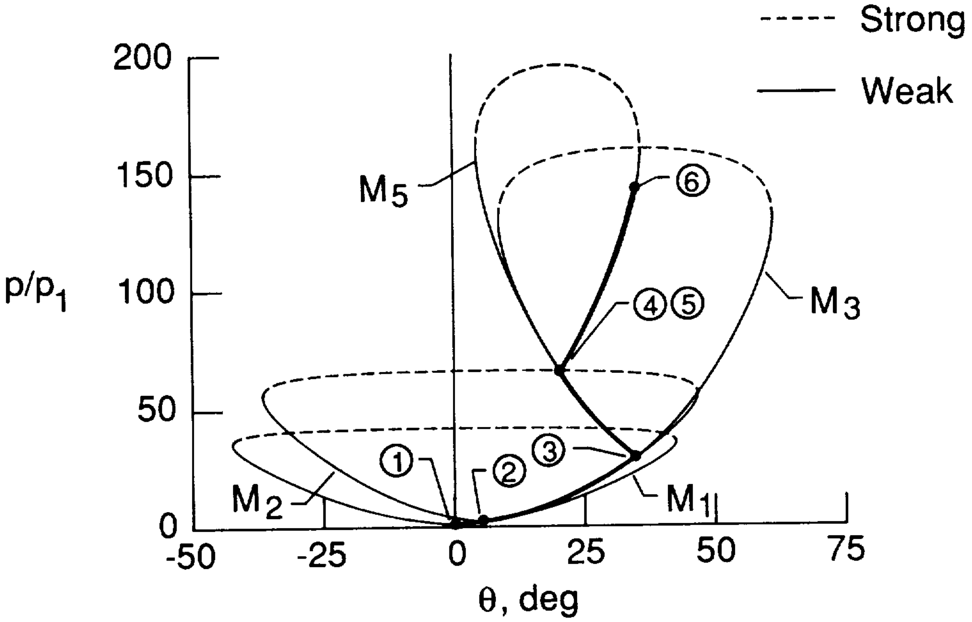


(b) Pressure-deflection diagram.

Figure 5. Type IV shock-wave interference pattern.

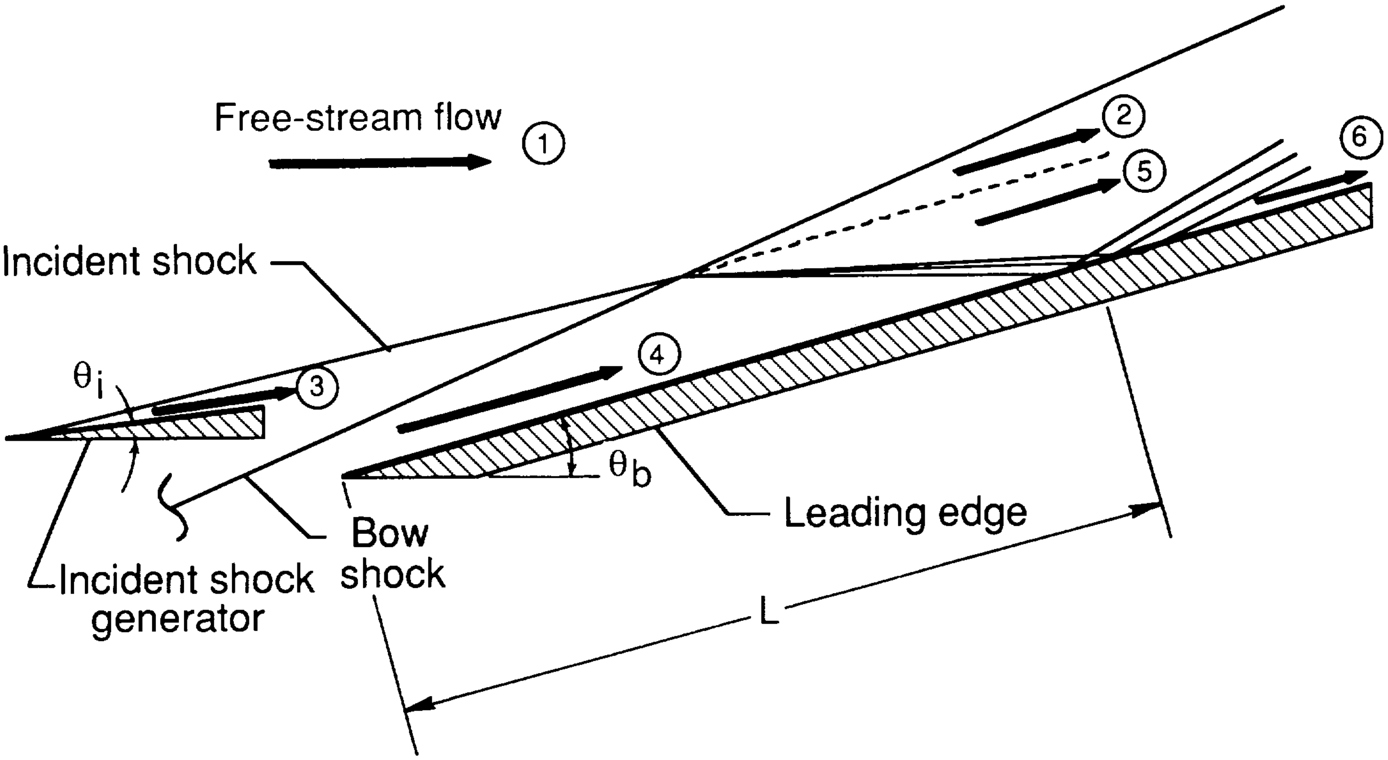


(a) Schematic diagram.

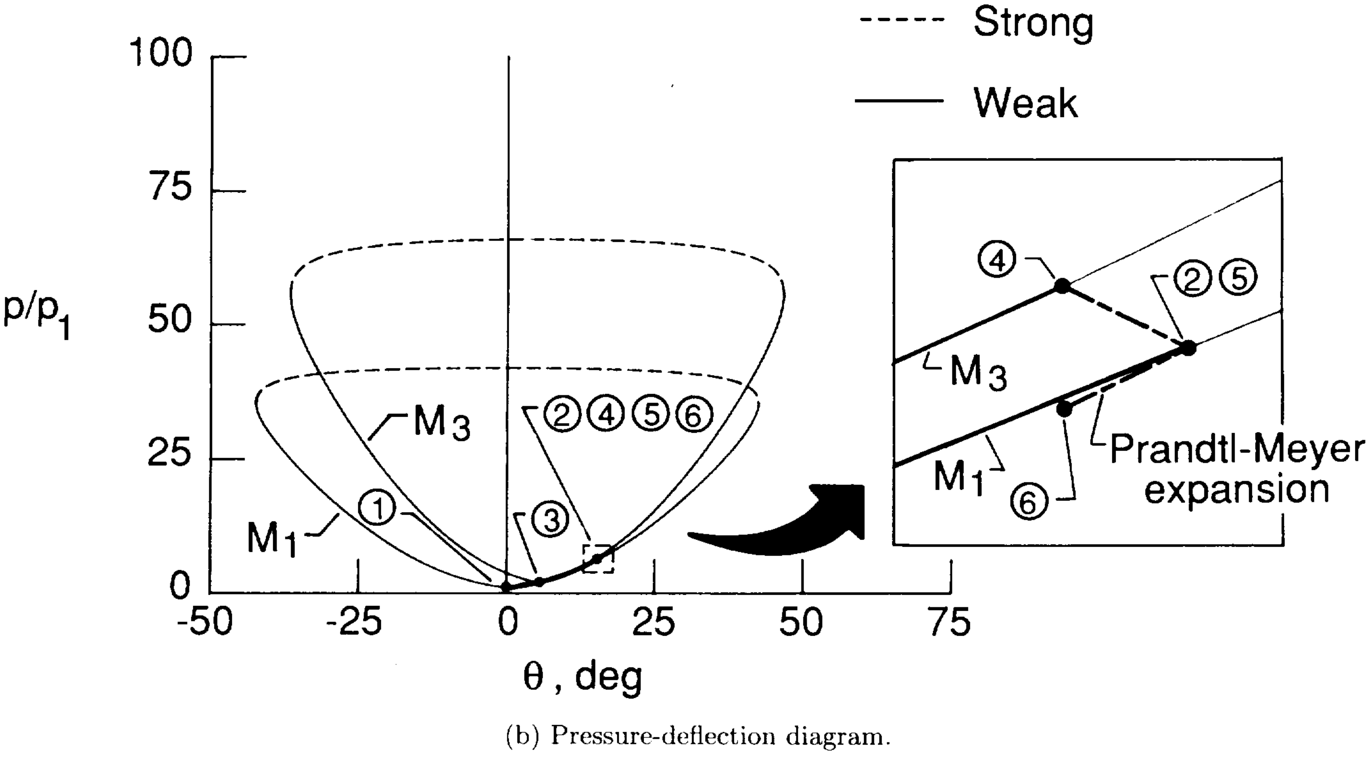


(b) Pressure-deflection diagram.

Figure 6. Type V shock-wave interference pattern.



(a) Schematic diagram.



(b) Pressure-deflection diagram.

Figure 7. Type VI shock-wave interference pattern.

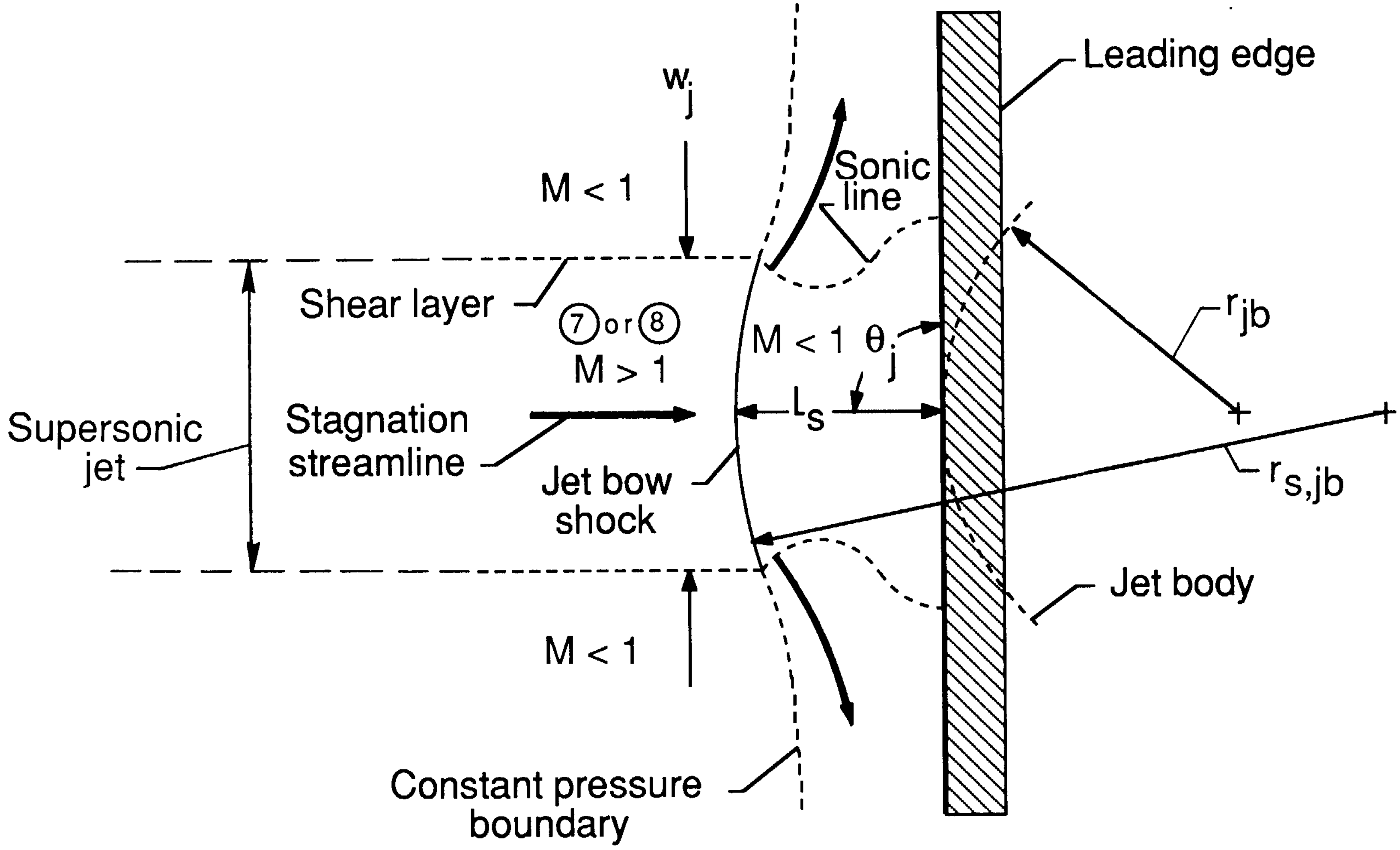


Figure 8. Schematic diagram of Type IV supersonic jet impingement region. (From reference 1.)

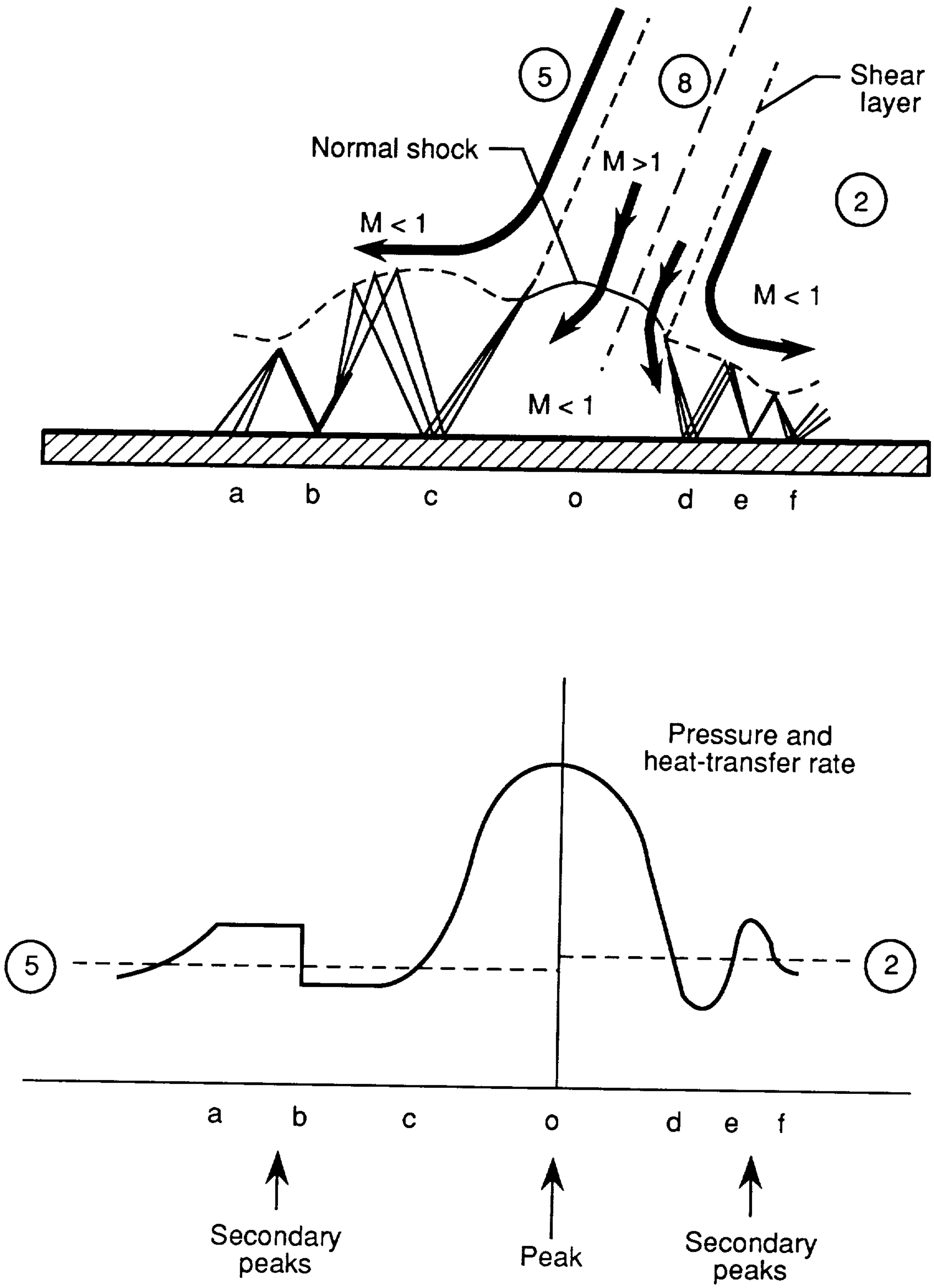


Figure 9. Type IV supersonic jet impingement and resulting pressure and heat-transfer rate distributions. (From reference 6.)

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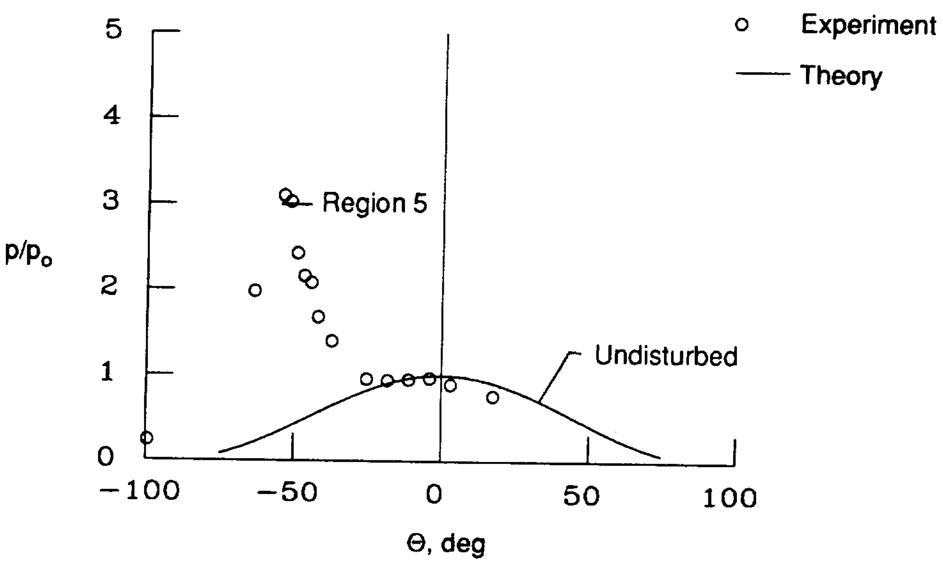
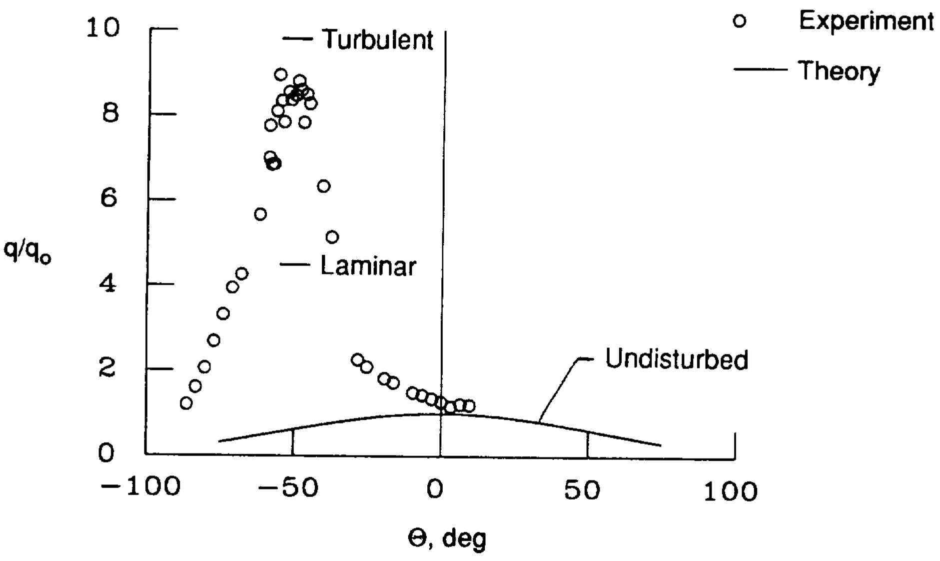
L-90-28

(a) Schlieren photograph.

Figure 10. Experimental results and EASI prediction for Type III interference flow field for Calspan run 26, $M_1 = 8.03$, $L_{ts} = 2.06$ in., and $\mathrm{Re}_1 = 1.482 \times 10^6$.

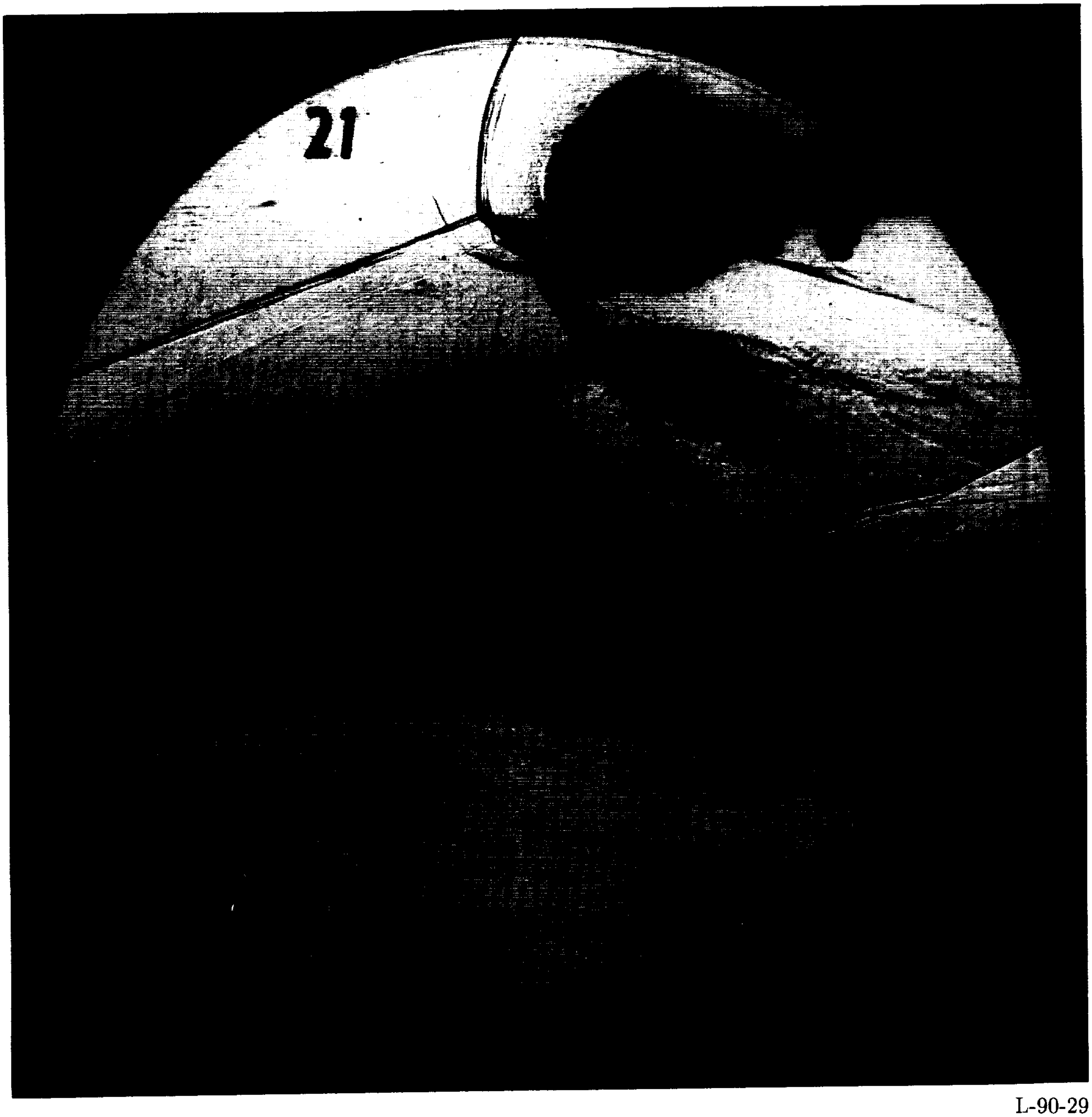


(b) Pressure distribution.



(c) Heat-flux distribution.

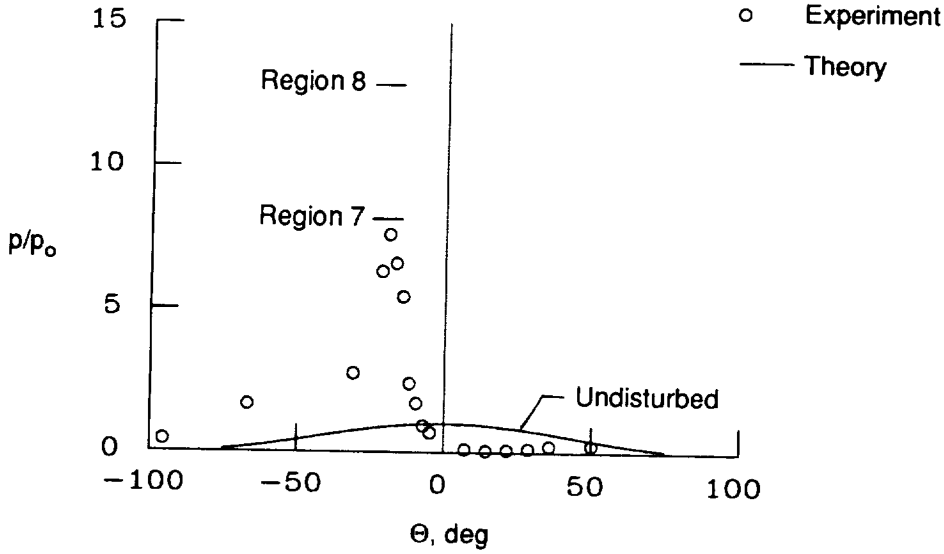
Figure 10. Concluded.



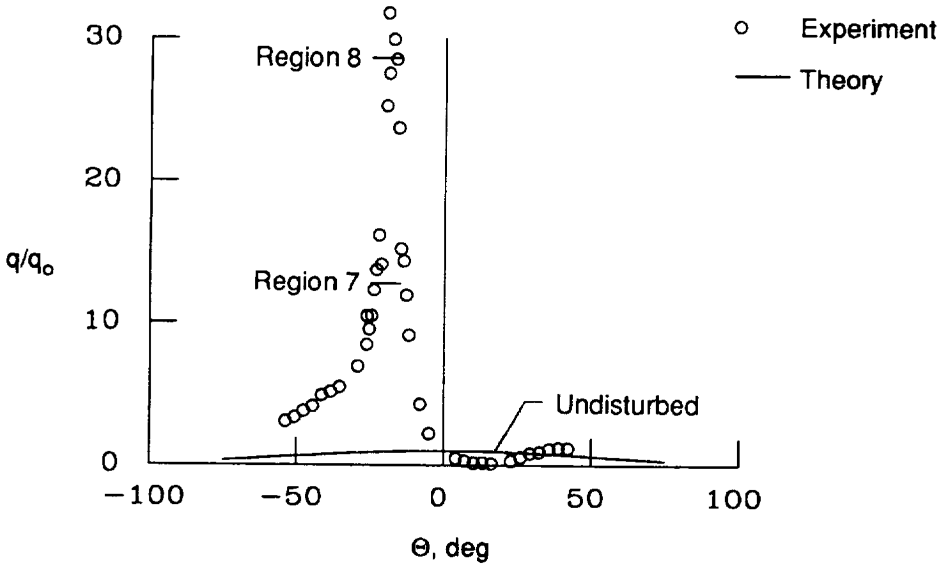
L-90-29

(a) Schlieren photograph.

Figure 11. Experimental results and EASI prediction for Type IV interference flow field for Calspan run 21, $M_1 = 8.04$, $L_{ts} = 0.71$ in., and $\mathrm{Re}_1 = 1.564 \times 10^6$.



(b) Pressure distribution.



(c) Heat-flux distribution.

Figure 11. Concluded.

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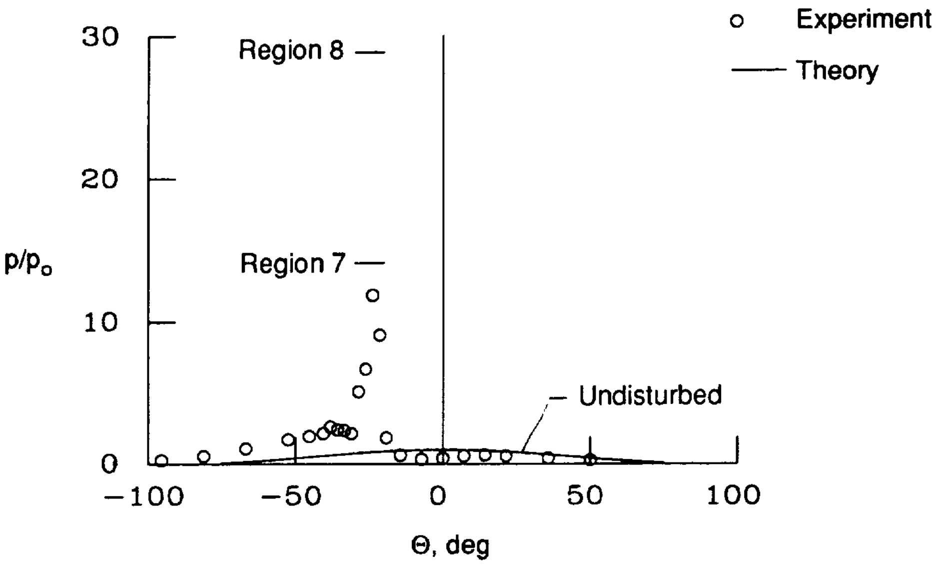
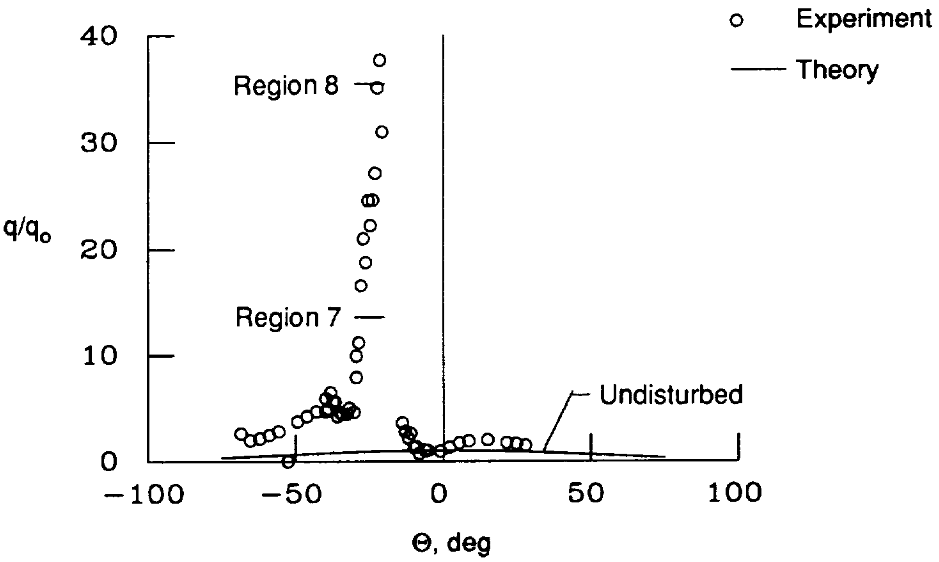
L-90-30

(a) Schlieren photograph.

Figure 12. Experimental results and EASI prediction for Type IV interference flow field for Calspan run 43, $M_1 = 16.33$, $L_{ts} = 1.12$ in., and $\mathrm{Re}_1 = 1.041 \times 10^6$.

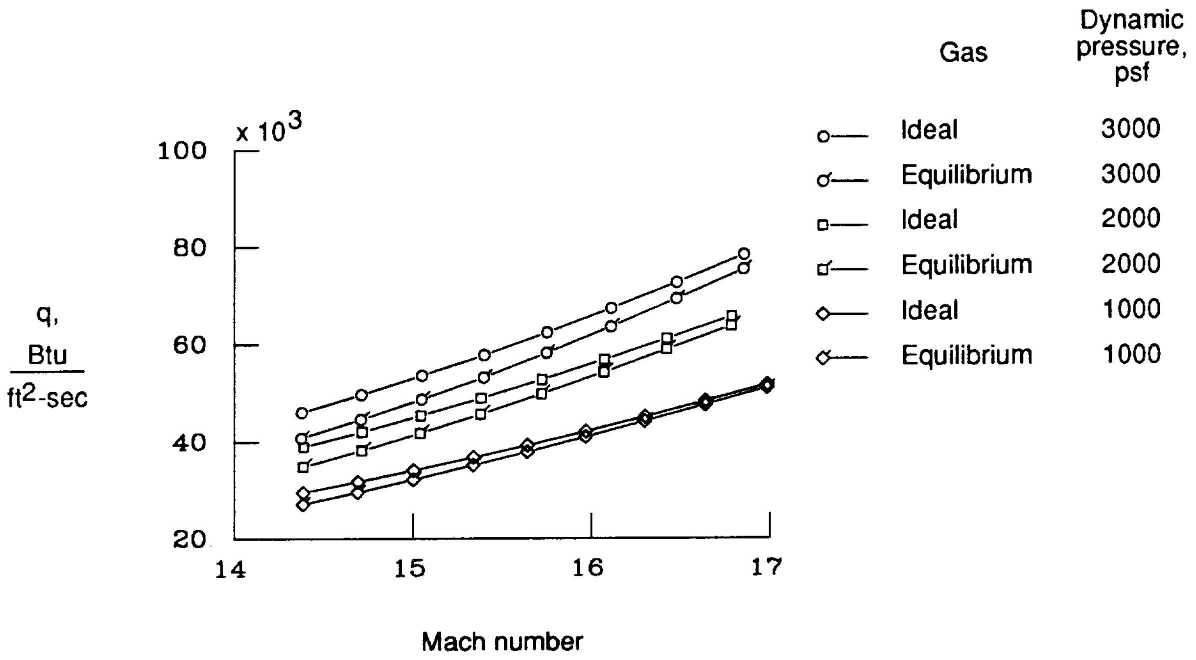


(b) Pressure distribution.

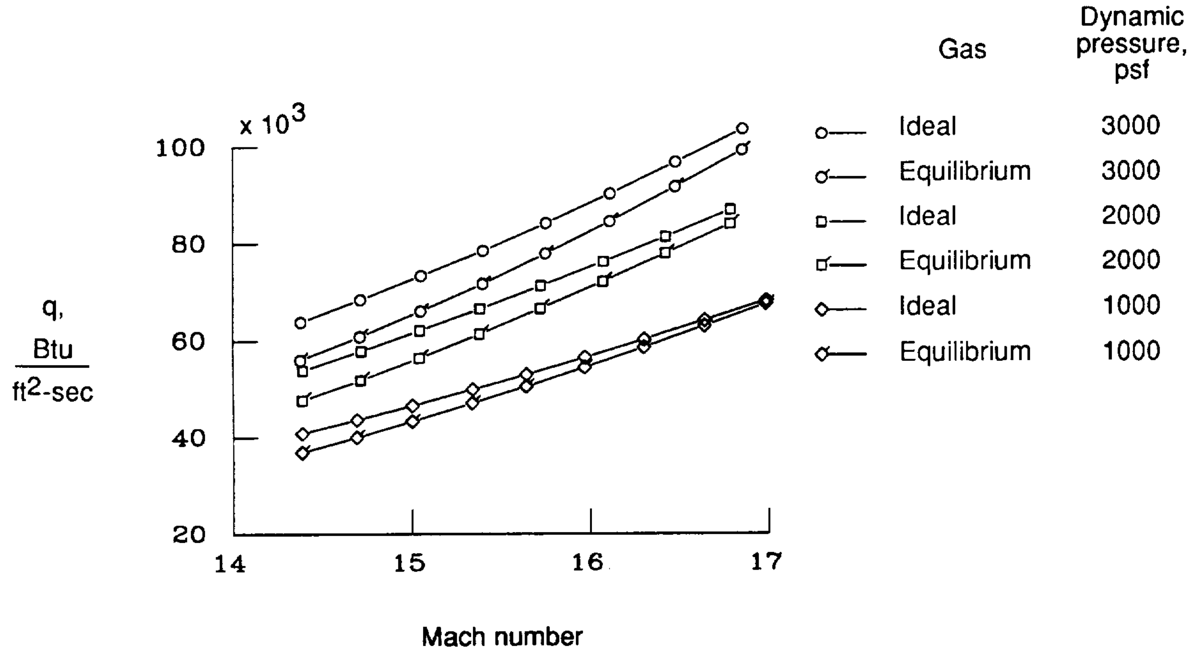


(c) Heat-flux distribution.

Figure 12. Concluded.



(a) Incident shock-wave flow-turning angle θ_i of 5°.



(b) Incident shock-wave flow-turning angle θ_i of 10°.

Figure 13. EASI maximum heating prediction for 0.25-in-diameter leading edge subjected to Type IV, region 8 supersonic jet impingement.

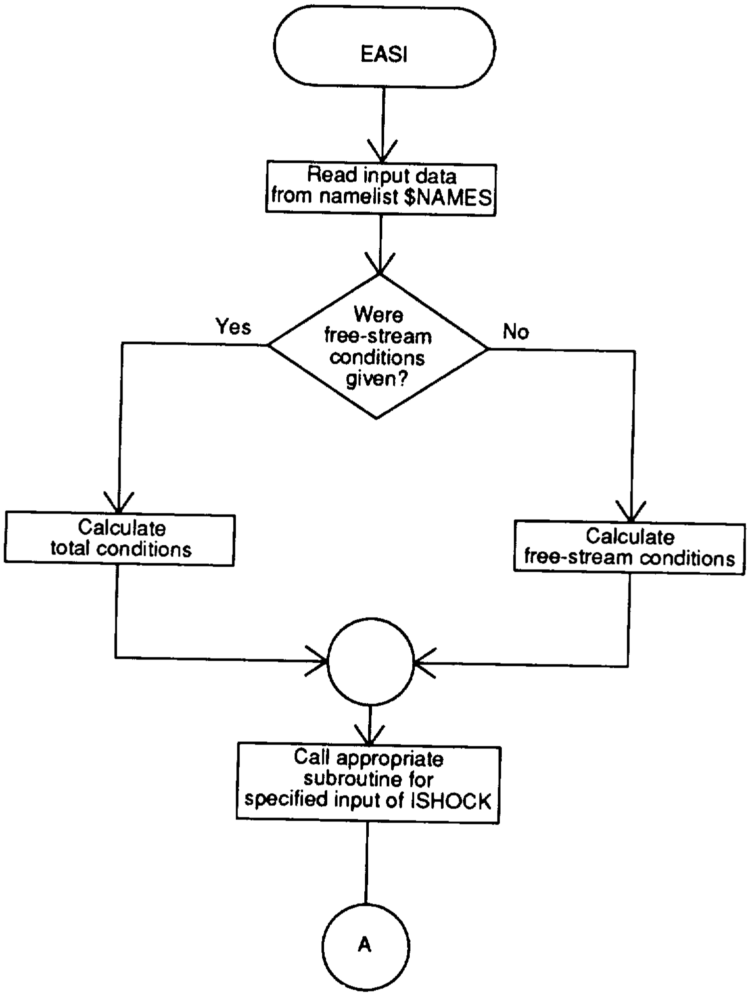


Figure 14. Flowchart of program EASI execution sequence.

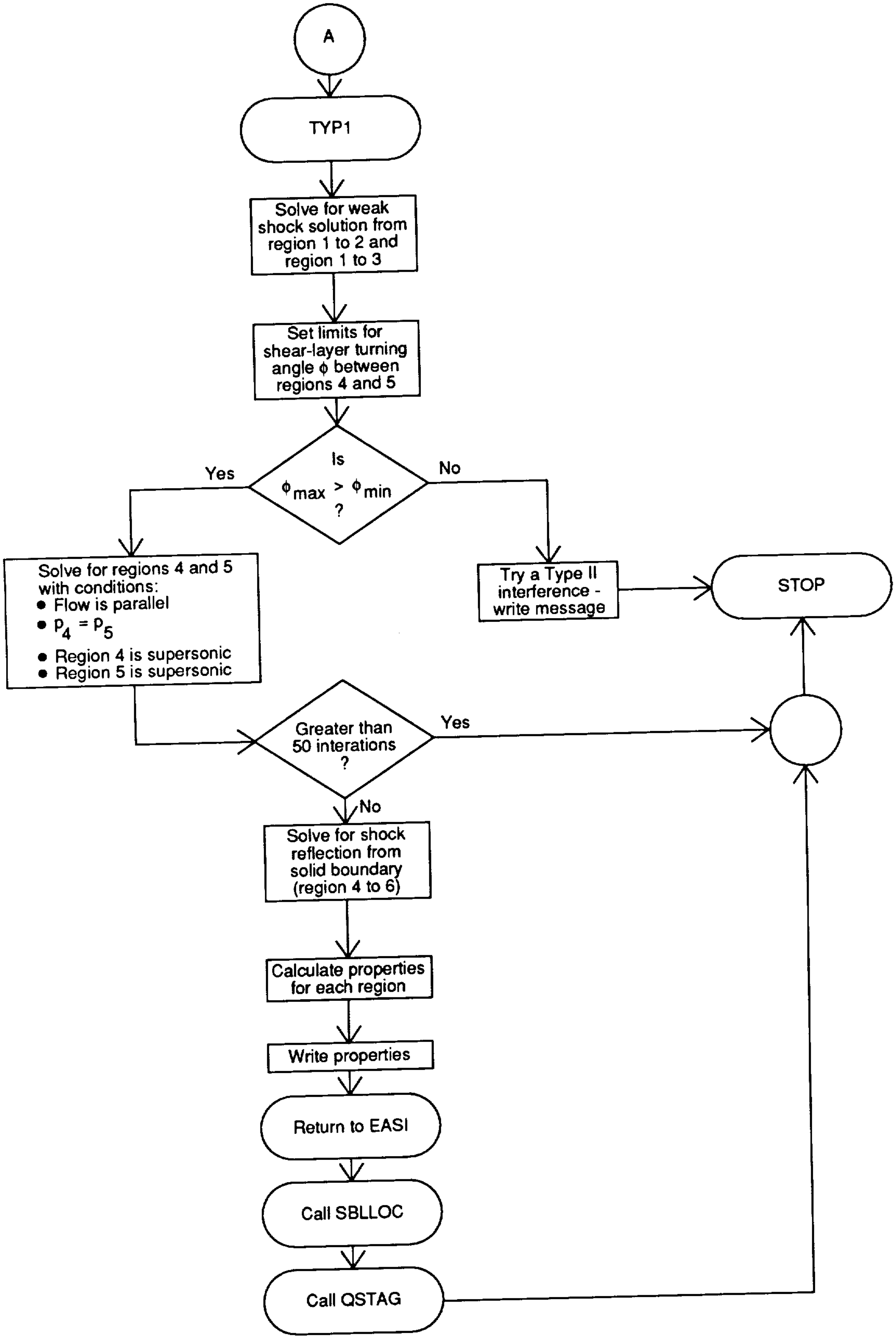


Figure 15. Flowchart of the Type I interference execution sequence.

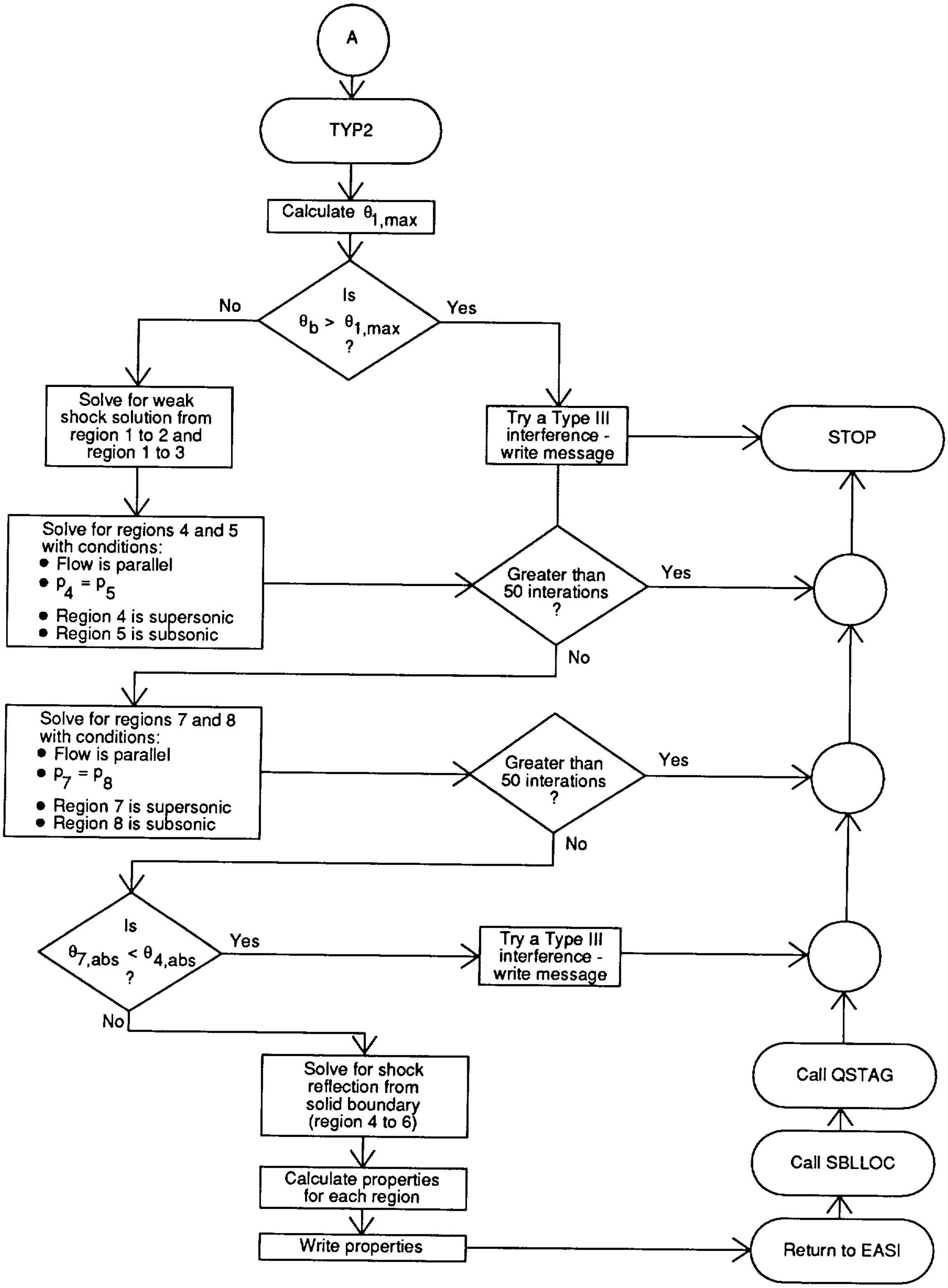


Figure 16. Flowchart of the Type II interference execution sequence.

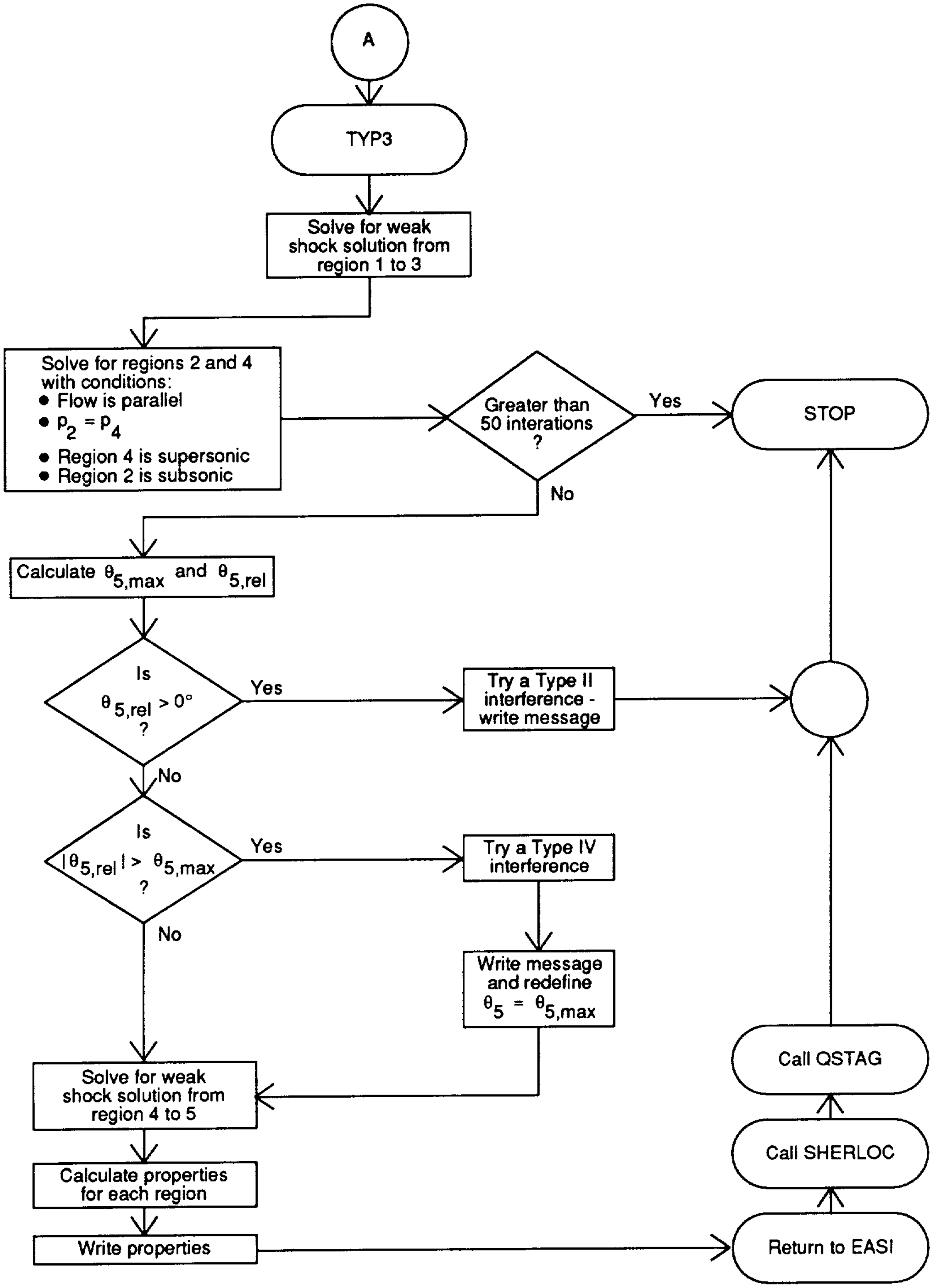


Figure 17. Flowchart of the Type III interference execution sequence.

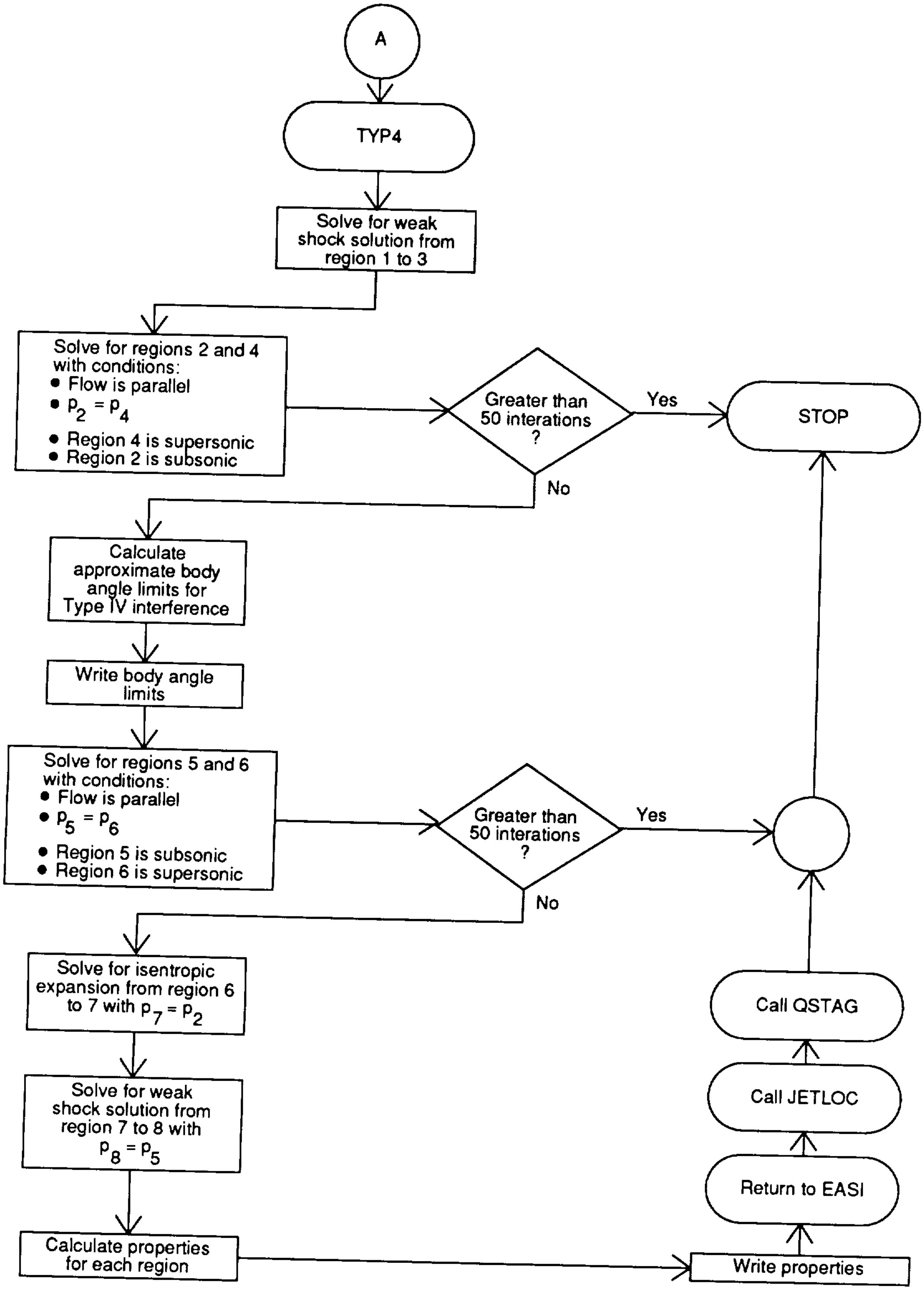


Figure 18. Flowchart of the Type IV interference execution sequence.

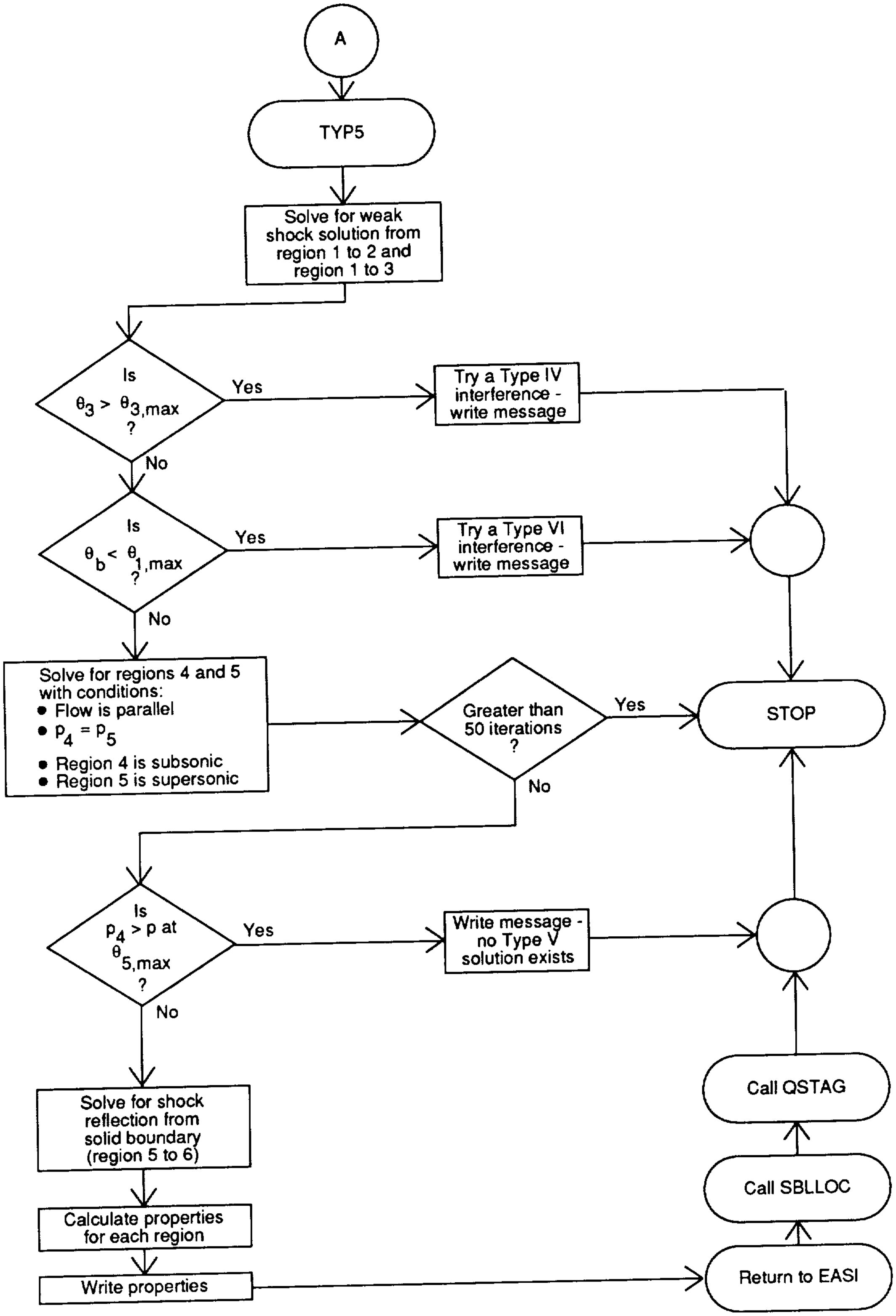


Figure 19. Flowchart of the Type V interference execution sequence.

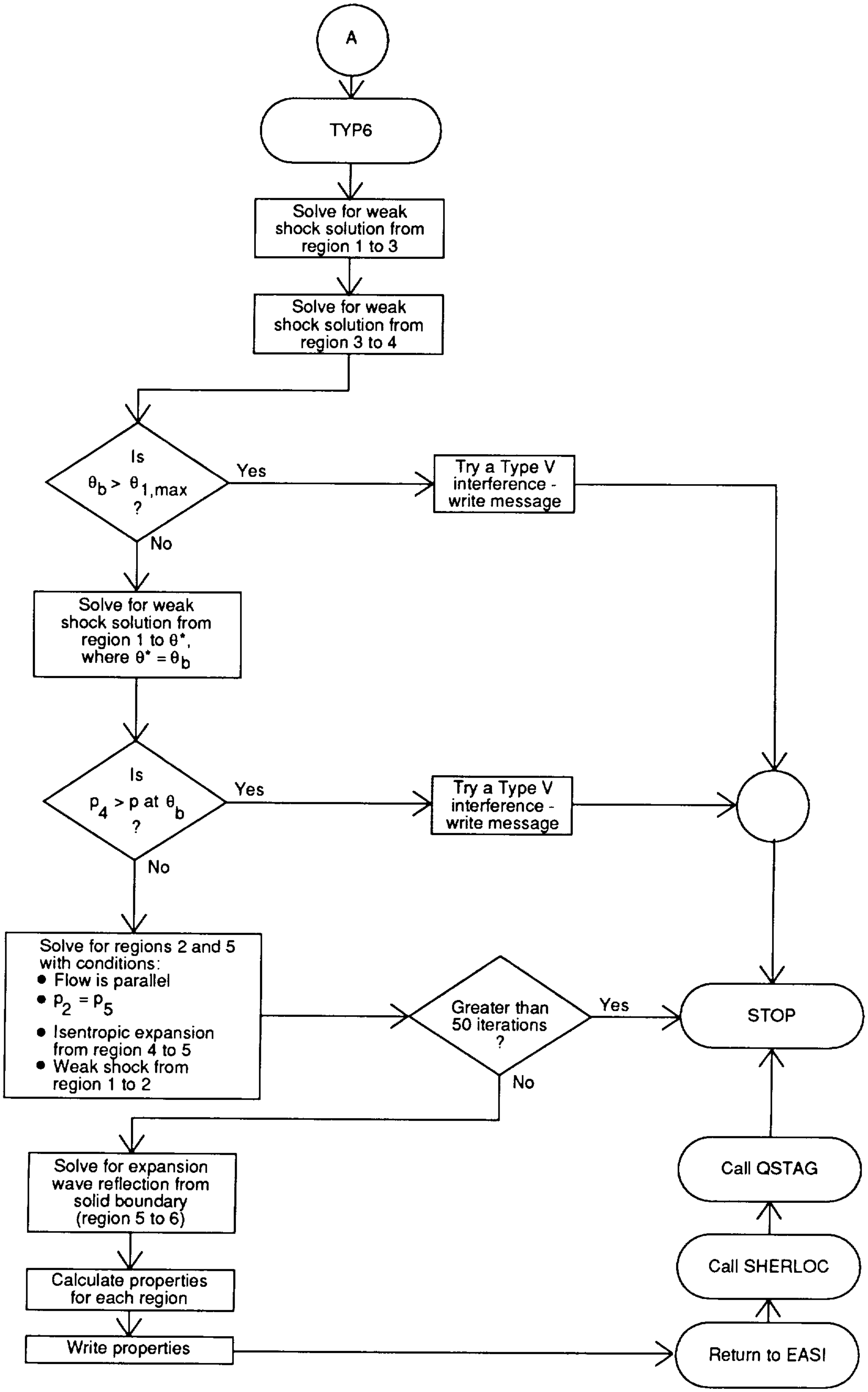


Figure 20. Flowchart of the Type VI interference execution sequence.

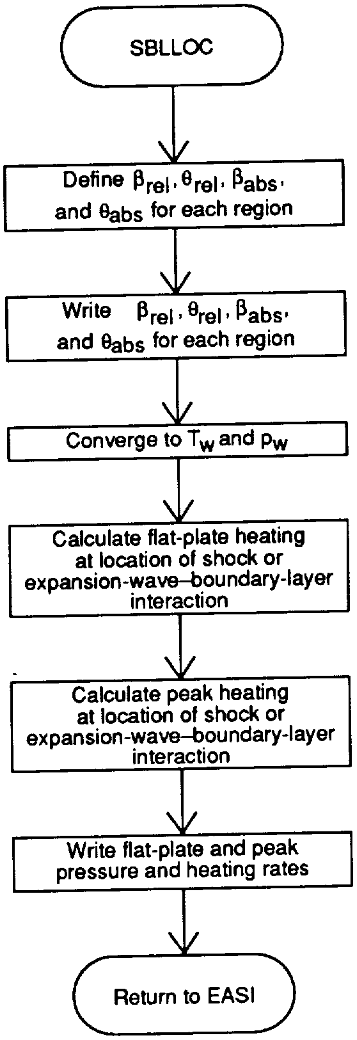


Figure 21. Flowchart of subroutine SBLLOC execution sequence.

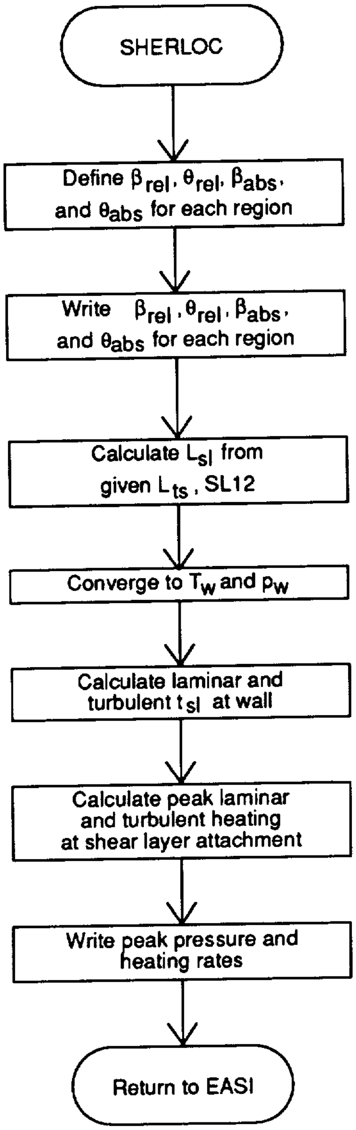


Figure 22. Flowchart of subroutine SHERLOC execution sequence.

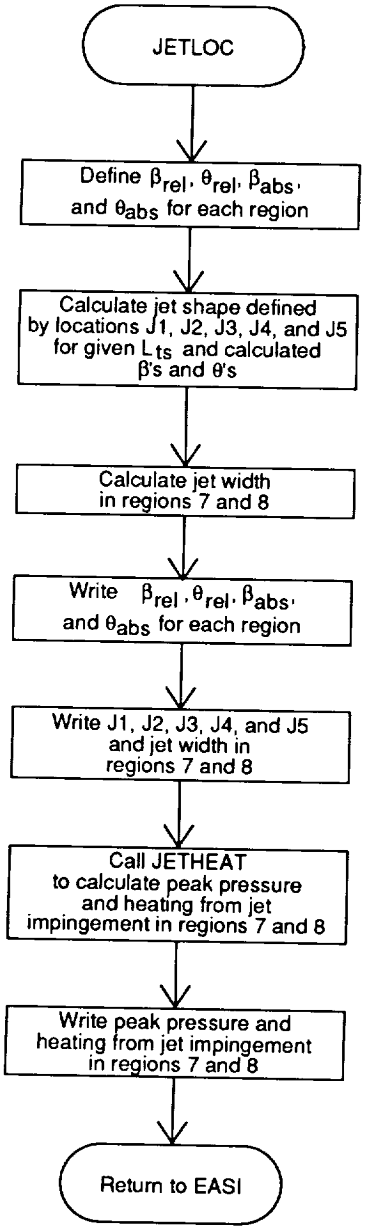


Figure 23. Flowchart of subroutine JETLOC execution sequence.

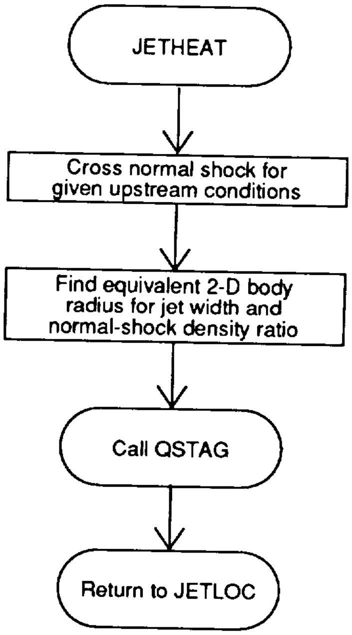


Figure 24. Flowchart of subroutine JETHEAT execution sequence.

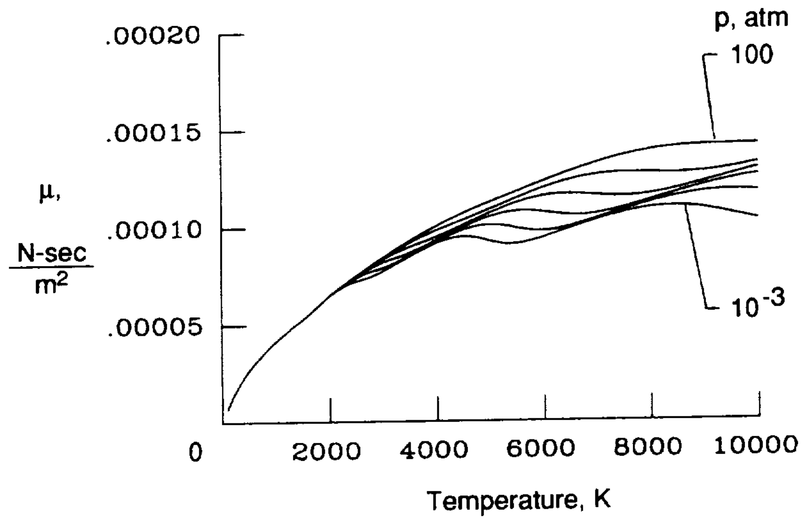


Figure 25. Viscosity μ as a function of pressure and temperature.

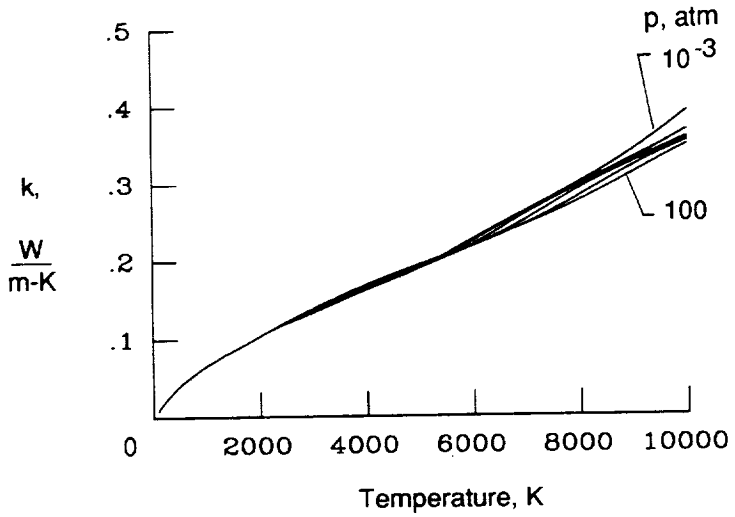


Figure 26. Thermal conductivity k as a function of pressure and temperature.

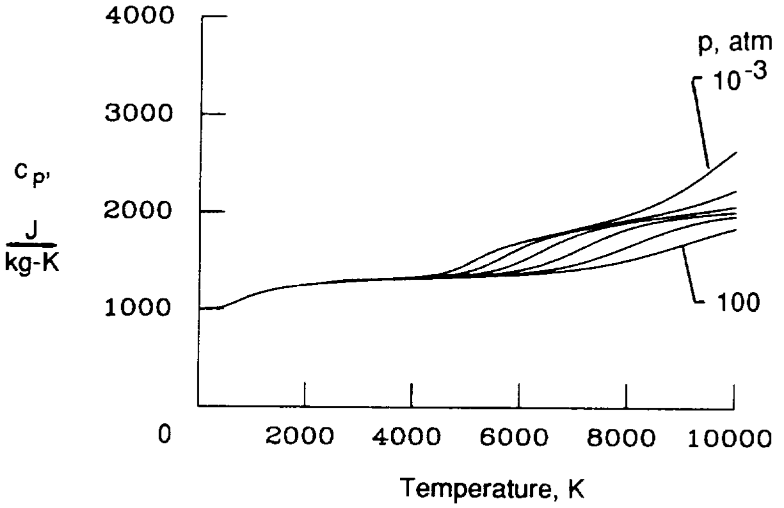


Figure 27. Specific heat c_p as a function of pressure and temperature.

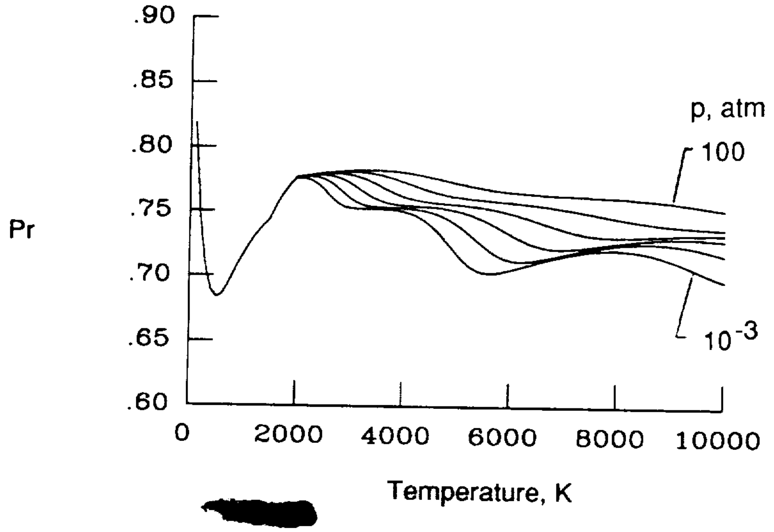


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Figure 28. Prandtl number Pr as a function of pressure and temperature.

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16. Abstract
The computer program EASI, Equilibrium Air Shock Interference, has been developed to calculate the inviscid flow field, the maximum surface pressure, and the maximum heat flux produced by six shock-wave interference patterns on a two-dimensional cylindrical configuration. Thermodynamic properties of the inviscid flow field are determined with either an 11-specie, 7-reaction equilibrium chemically reacting air model or a calorically perfect air model. The inviscid flow field is solved with the integral form of the conservation equations. Surface heating calculations at the impingement point for the equilibrium chemically reacting air model use variable transport properties and specific heat. However, for the calorically perfect air model, heating rate calculations use a constant Prandtl number. Sample calculations of the six shock-wave interference patterns, a listing of the computer program, and flowcharts of the programming logic are included.

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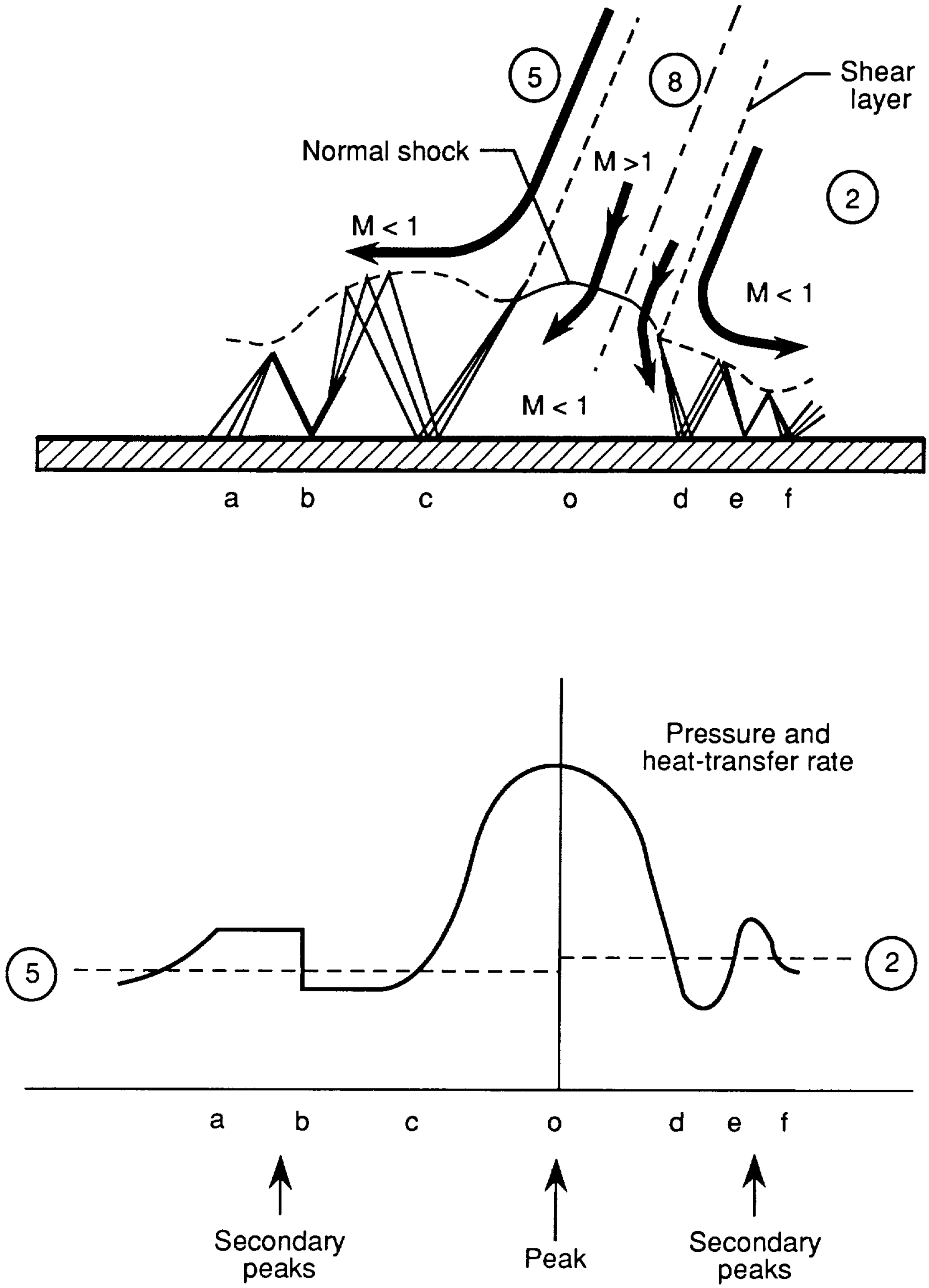
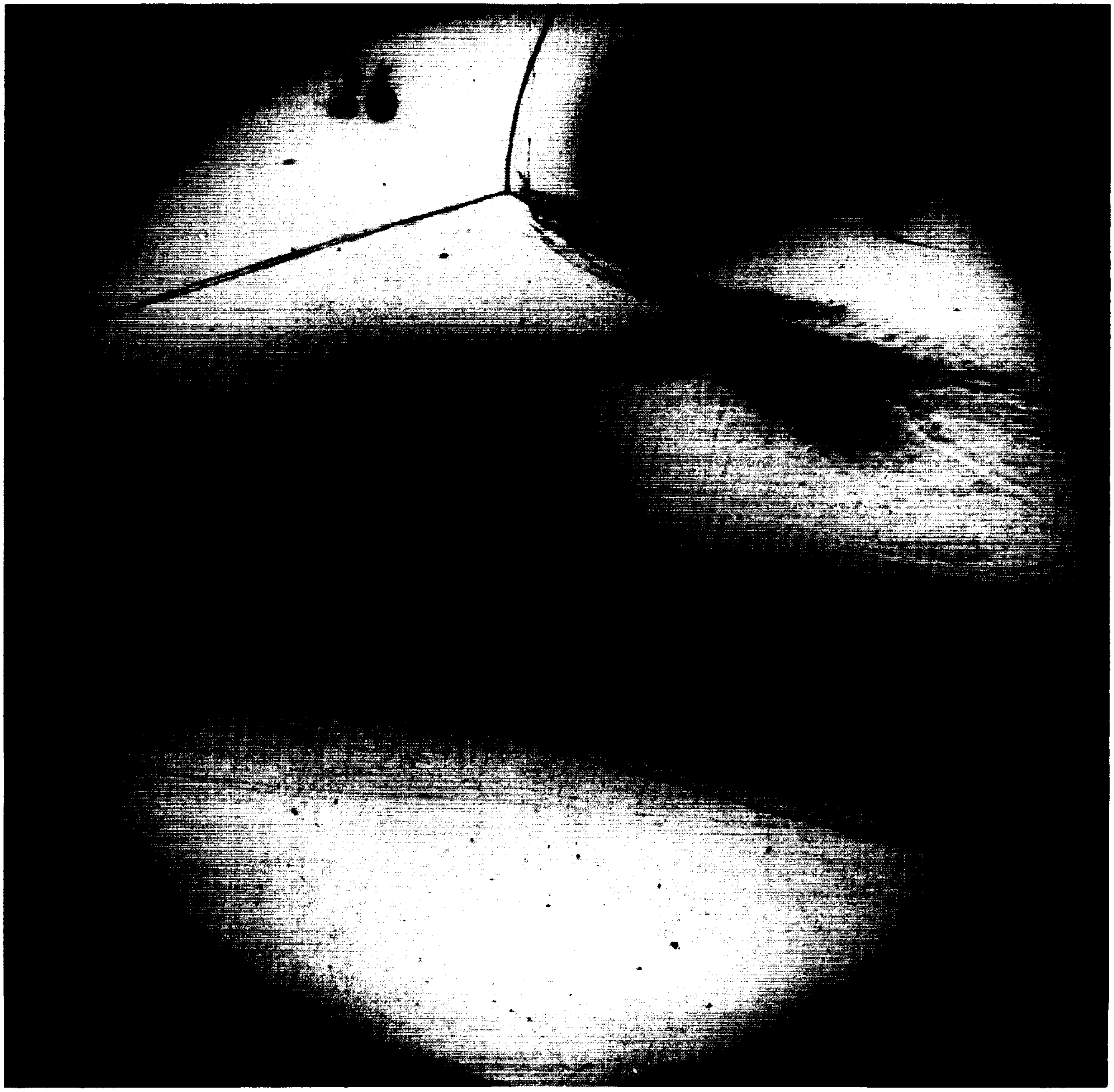


Figure 9. Type IV supersonic jet impingement and resulting pressure and heat-transfer rate distributions. (From reference 6.)



L-90-28

(a) Schlieren photograph.

Figure 10. Experimental results and EASI prediction for Type III interference flow field for Calspan run 26, $M_1 = 8.03$, $L_{ts} = 2.06$ in., and $\mathrm{Re}_1 = 1.482 \times 10^6$.