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TEMPEST

A Three-Dimensional Time-Dependent Computer Program for Hydrothermal Analysis

Volume 1: Numerical Methods and Input Instructions

D. S. Trent L. L. Eyler

Code Version N, Mod 31
January 1989

Prepared for the U.S. Department of Energy
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NOTICE

TEMPEST

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VOLUME I: NUMERICAL METHODS AND INPUT INSTRUCTIONS

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Richland, Washington 99352

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TEMPEST
A THREE-DIMENSIONAL TIME-DEPENDENT COMPUTER PROGRAM FOR HYDROTHERMAL ANALYSIS
VOLUME I: NUMERICAL METHODS AND INPUT INSTRUCTIONS

1.0 SUMMARY

TEMPEST offers simulation capabilities over a wide range of hydrothermal problems that are definable by input instructions. These capabilities are summarized by categories as follows:

- Modeling Capabilities
    - full three-dimensional
    - time-dependent with transient approach to steady state
    - turbulence models (k-ϵ model)
    - Cartesian or cylindrical coordinates
    - heat diffusion in solid regions
    - mass transport in flow regions
    - full implicit solution to the thermal energy equation (all scalar equations)
    - direct solution for thermal steady state
    - multiple flow regions (may be connected through conduction heat transfer)
    - arbitrary orientation of solution coordinate system (wrt gravity)
    - variable grid spacing along all/any coordinate direction
    - use of specified or precomputed flow regions
    - internal heat generation (20 time-dependent tables possible)
    - fifty different material types
    - inflow/outflow boundaries specified or computed
    - time-dependent flow and thermal boundary condition tables (20 tables possible)
    - variable materials properties (thermal conductivity, density, specific heat and viscosity)

  - single-cell width and zero width wall logic
  - drag coefficient correlations for each direction of each cell (98 different coefficient types available from input specification)
  - film coefficient for each direction of each cell
  - partial material properties table built in

- Program Control

  - hydrodynamics only
  - solids heat transfer only
  - decoupled hydrodynamics (no buoyancy effects)
  - fully coupled hydrodynamics and heat transfer
  - inviscid hydrodynamics
  - variable viscosity/thermal properties
  - variable eddy transport coefficients (e.g., 2-equation turbulence model
  - steady-state thermal solution
  - ability to obtain steady-state thermal solution at each hydrodynamic time step
  - internal wave stability control
  - automatic time stepping and stability control
  - restart at any filed time
  - computation in either the U.S. Customary System of engineering units or the International System (SI) of units.

- I/O Control

  - input debug output and control (limited)
  - internal bookkeeping debug output options
  - cell type/material type maps
  - intermediate output including heat transfer connectors, cell continuity, density, thermal conductivity, molecular viscosity, eddy viscosity, turbulence quantities, heat flux map, numerical stability map and heat generation
  - all primary variables with either R-Z, R-X, or Z-X arrays on page
  - ability to specify print/file time

  - input data may be supplied in either the Engineering or SI system of units for the same run
  - partial skip of printing
  - result and execution time monitoring
  - postprocessing graphics (including contours, vectors, and line plots).

- Limitations of the current version are as follows:
  - incompressible flow only
  - computational cell structure must be in rows/columns/tiers
  - Cartesian or cylindrical coordinate only (region cannot have mixed coordinates)
  - hydrodynamic solution is explicit in time--no direct solution for steady state
  - pressure boundary conditions are not available
  - curved boundaries (except circular) must be stair-stepped.

2.0 GOVERNING EQUATIONS AND SOLUTION TECHNIQUE

Equations governing momentum, heat, and mass transport solved by TEMPEST are based on the following conservation laws:

1. conservation of mass (continuity)
2. conservation of momentum (Newton's Second Law)
3. conservation of energy (First Law of Thermodynamics).

Thermodynamic state relationships of the form

$$\rho = f(P_o, T) \tag{2.1}$$

are required in addition to other relationships necessary for definition of temperature-dependent materials properties. Empirical relationships are needed to describe drag and film coefficients for certain simulations.

For constituent transport, mixture values are computed for the density, ρ_m, and the specific heat, C_{pm},. Gaseous constituents are treated as perfect gases. The relations are:

$$R_m = \sum_{i=1}^{n} C_i R_i \quad ; \quad n < 9 \tag{2.2}$$

$$C_{pm} = \sum_{i=1}^{n} C_i C_{pi} \quad ; \quad n < 0 \tag{2.3}$$

and

$$\rho_m = P_o / R_m T \tag{2.4}$$

The reference system pressure is P_o; the system reference (absolute) temperature is T; and R_m is the mixture gas constant.

In the current version of TEMPEST, turbulent flow Reynolds stresses are modeled through an effective viscosity. The Prandtl-Kolmogorov hypothesis is used to relate the effective viscosity to a velocity and a length scale. In this approach, transport equations for the turbulent kinetic energy (k) and the dissipation of turbulent kinetic energy (ϵ) are solved to determine the effective turbulent viscosity as

$$\mu_T = C_\mu \, \rho \, k^2/\epsilon \qquad (2.5)$$

The diffusivity of a constituent is treated one of several ways based on user input. Molecular diffusion is based on the viscosity of the base fluid or on a Sutherland or Schmidt number for turbulent flow. For dilute mixtures this is a good approximation. Multicomponent computation of molecular diffusivities has been considered but has not been implemented. One approach considered is that of White (1974) where a mixture viscosity is computed as

$$\mu_m = \sum_{i=1}^{n} \frac{x_i \mu_i}{\sum_{i=1}^{n} x_j \phi_{i,j}} \qquad (2.6)$$

where

$$\phi_{i,j} = \frac{[(1 + \mu_i/\mu_j)^{\frac{1}{2}} \, (M_j/M_i)^{\frac{1}{4}}]^2}{(8 + 8\, M_i/M_j)^{\frac{1}{2}}} \qquad (2.7)$$

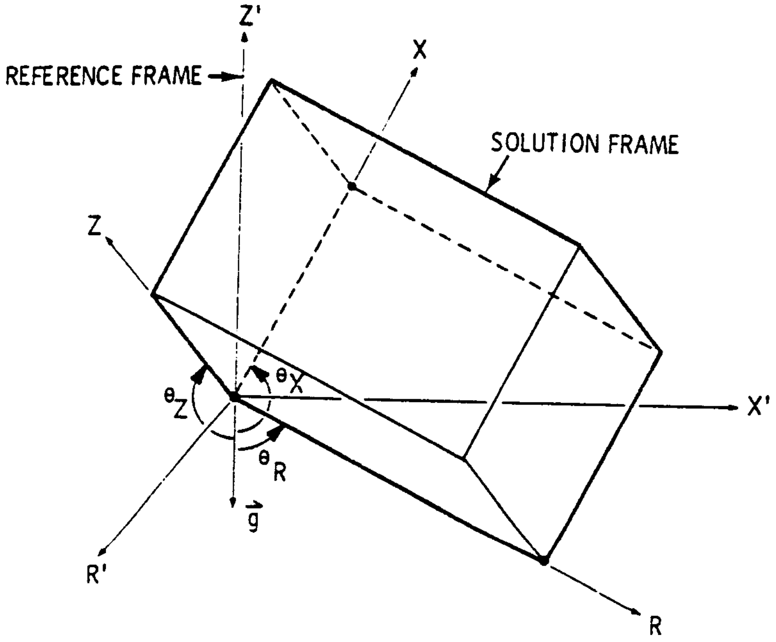
M_i is the molecular weight, and x_i is the component mole fraction of the ith component.

2.1 COORDINATE SYSTEM

The coordinate system used is either Cartesian (R,X,Z) or cylindrical (R,θ,Z). In either case (R',X',Z') refers to a reference coordinate arrangement in which Z' is perpendicular to the geopotential surface (vertical and positive upward). A Cartesian solution frame (R,X,Z), whose rotations within the reference frame are defined by the direction angles θ_R, θ_Z, and θ_X, is illustrated in Figure 2.1.

For this tilted configuration, the solution frame gravitational components are given as:

$$g_R = |g| \cos \theta_R$$
$$g_Z = |g| \cos \theta_Z$$
$$g_X = |g| \cos \theta_X$$



GRAVITATIONAL COMPONENTS: $g_R = |g| \cos(\theta_R)$
$g_Z = |g| \cos(\theta_Z)$
$g_X = |g| \cos(\theta_X)$

FIGURE 2.1. Tilted Solution Frame in Cartesian Coordinates

2.2 PRINCIPAL ASSUMPTIONS

The TEMPEST code simulates flow and thermal fields subject to the following assumptions and/or restrictions:

- The fluid is single phase and incompressible.
- The body forces other than gravity are not considered. Forces resulting from planetary acceleration are included.
- The fluid is Newtonian (for laminar situations, Navier-Stokes equations apply).
- The turbulent flow conservation equations are time averaged and Reynolds stresses are incorporated through appropriate eddy viscosity models.
- The viscous dissipation is eliminated.
- The Boussinesq approximation holds.

For low-speed flows that involve small density variations (i.e., $|\Delta\rho/\rho_0| \ll 1$), the well-known Boussinesq approximation is valid. This approximation is commonly used in natural convection simulations involving either liquids or gases. While the approximation is consistent with the accuracy of other approximations required for numerical simulation, its validity is questionable if density changes considered are large compared to local fluid density. Whereas most simulations involving liquid systems are within validity of this approximation, care should be exercised in gaseous systems, where temporal and spatial temperature changes may be large. The obvious reason for invoking the Boussinesq approximation in TEMPEST is that some simplification of the governing equations is possible by treating density as constant in all terms except the body force terms of the momentum equations.

Additional limitations and assumptions applicable to the mass transport version of TEMPEST are as follows:

- The system pressure, P_0, is assumed to remain constant through the simulation. This assumption is consistent with the incompressible form of the solved transport equations, which does not allow for density change through pressurization. This assumption is valid for situations where the amount of species injection is small relative to total system volume and where open flow boundaries are present. It is anticipated that this assumption will be removed in future versions.

- The current version does not accommodate droplet/aerosol transport where there is slip between the gas phase and a liquid or solid phase (e.g., particulates). One exception is that settling in the vertical direction is allowed if the coordinate system is aligned with the z-axis parallel to the gravitational vector. Complete description of the physics of this system of settling solids has not been fully implemented yet.
- Condensation or phase change of one constituent, such as steam, cannot be accommodated in the current version.
- Insofar as treatment of thermal and mass diffusivities are concerned, only dilute mixtures are treated. Turbulent diffusivities may be specified as constant or computed using the k-ϵ turbulence model. Use of the k-ϵ turbulence model is strictly valid in this version only for dilute mixtures because it uses the base component viscosity to compute wall functions governing boundary conditions for turbulent kinetic energy and dissipation. Computation of molecular diffusivities of component mixtures adds complexity to the computation and for this reason has been omitted from the present version. Removal of this limitation is considered for future versions.

2.3 CONSERVATION EQUATIONS

Continuity

The equation describing the conservation of mass is

$$\frac{1}{R^\beta}\frac{\partial R^\beta U}{\partial R} + \frac{1}{R^\beta}\frac{\partial W}{\partial X} + \frac{\partial V}{\partial Z} = 0 \qquad (2.8)$$

where

β = 1 for cylindrical coordinates

β = 0 for Cartesian coordinates

In the cylindrical [coordinate system, x refers to the azimuthal independent variable (commonly 0)]. Symbols U, W, and V refer to velocity components in the R, X, and Z directions, respectively.

Momentum

The equations describing the conservation of momentum in each of the three coordinate directions are:

R- direction component, U:

$$\frac{\partial U}{\partial t} + \frac{1}{R^{\beta}} \frac{\partial}{\partial R} (R^{\beta}UU) + \frac{1}{R^{\beta}} \frac{\partial}{\partial X} (WU) + \frac{\partial}{\partial Z} (VU) - \beta \left(\frac{\rho}{\rho_o}\right) \frac{W^2}{R}$$

$$= \frac{1}{\rho_o} \left[- \frac{\partial P}{\partial R} + \rho g_R + \frac{1}{R^{\beta}} \frac{\partial}{\partial R} \left(R^{\beta}\xi \frac{\partial U}{\partial R}\right) + \frac{1}{R^{2\beta}} \frac{\partial}{\partial X} \left(\xi \frac{\partial U}{\partial X}\right) + \frac{\partial}{\partial Z} \left(\xi \frac{\partial U}{\partial Z}\right) + S_R\right] \tag{2.9}$$

where

$$S_R = - \beta\xi\left(\frac{U}{R^2} + \frac{2}{R^2} \frac{\partial W}{\partial X}\right) + \frac{\partial \xi}{\partial R} \frac{\partial U}{\partial R} + \frac{\partial \xi}{\partial X} \frac{\partial}{\partial R} \left(\frac{W}{R^{\beta}}\right) + \frac{\partial \xi}{\partial Z} \frac{\partial V}{\partial R} - F_R(U)$$

and

$\xi = \mu + \mu_T$

μ = dynamic viscosity

μ_T = turbulent (eddy) viscosity

$F_R(U)$ = R-direction flow drag

X - direction component, W:

$$\frac{\partial W}{\partial t} + \frac{1}{R^{\beta}} \frac{\partial}{\partial R} (R^{\beta}UW) + \frac{1}{R^{\beta}} \frac{\partial}{\partial X} (WW) + \frac{\partial}{\partial Z} (VW) + \beta\left(\frac{\rho}{\rho_o}\right) \frac{UW}{R} +$$

$$= \frac{1}{\rho_o} [- \frac{1}{R^\beta} \frac{\partial P}{\partial X} + \rho g_X + \frac{1}{R^\beta} \frac{\partial}{\partial R} (R^\beta \xi \frac{\partial W}{\partial R}) + \frac{1}{R^{2\beta}} \frac{\partial}{\partial X} (\xi \frac{\partial W}{\partial X}) + \frac{\partial}{\partial Z} (\xi \frac{\partial W}{\partial Z}) + S_X] \quad (2.10)$$

where

$$S_X = \frac{\beta\xi}{R^2} (2 \frac{\partial U}{\partial X} - W) + \frac{1}{R^\beta} \frac{\partial \xi}{\partial R} (\frac{\partial U}{\partial X} - \beta W)$$

$$+ \frac{1}{R^{2\beta}} \frac{\partial \xi}{\partial X} (\frac{\partial W}{\partial X} + 2\beta U) + \frac{1}{R^\beta} \frac{\partial \xi}{\partial Z} \frac{\partial V}{\partial X} - F_X(W)$$

Z - direction component, V:

$$\frac{\partial V}{\partial t} + \frac{1}{R^\beta} \frac{\partial}{\partial R} (R^\beta UV) + \frac{1}{R^\beta} (WV) + \frac{\partial}{\partial Z} (VV)$$

$$= \frac{1}{\rho_o} [- \frac{\partial P}{\partial Z} + \rho g_Z + \frac{1}{R^\beta} \frac{\partial}{\partial R} (R^\beta \xi \frac{\partial V}{\partial R}) + \frac{1}{R^{2\beta}} \frac{\partial}{\partial X} (\xi \frac{\partial V}{\partial X}) + \frac{\partial}{\partial Z} (\xi \frac{\partial V}{\partial Z}) + S_Z]$$

(2.11)

where

$$S_Z = \frac{\partial \xi}{\partial R} \frac{\partial U}{\partial Z} + \frac{1}{R^\beta} \frac{\partial \xi}{\partial X} \frac{\partial W}{\partial Z} + \frac{\partial \xi}{\partial Z} \frac{\partial V}{\partial Z} - F_Z(V)$$

Thermal Energy

The equation describing the conservation of thermal energy is:

$$\rho_o c [\frac{\partial T}{\partial t} + \frac{1}{R^\beta} \frac{\partial}{\partial R} (R^\beta UT) + \frac{1}{R^\beta} \frac{\partial}{\partial X} (WT) + \frac{\partial}{\partial Z} (VT)]$$

$$= \frac{1}{R^\beta} \frac{\partial}{\partial R} (\sigma R^\beta \frac{\partial T}{\partial R}) + \frac{1}{R^{2\beta}} + \frac{\partial}{\partial X} (\sigma \frac{\partial T}{\partial X}) + \frac{\partial}{\partial Z} (\sigma \frac{\partial T}{\partial Z} + \dot{Q} \quad (2.12)$$

where

$\sigma = \kappa + \kappa_T$

κ = thermal conductivity

κ_T = turbulent (eddy) thermal conductivity

c = specific heat

$\dot{Q}$ = volumetric heat generation rate

2.4 TURBULENCE EQUATIONS

Modeled transport equations for turbulent kinetic energy, k, and dissipation of turbulent kinetic energy, ϵ, are solved to obtain the turbulent effective viscosity, μ_T. The modeled forms of the equations are:

Turbulent Kinetic Energy

$$\rho_o \left[\frac{\partial k}{\partial t} + \frac{1}{R^\beta} \frac{\partial}{\partial R} (R^\beta U k) + \frac{1}{R^\beta} \frac{\partial}{\partial X} (Wk) + \frac{\partial}{\partial Z} (Vk)\right]$$

$$= \frac{1}{R^\beta} \frac{\partial}{\partial R} \left(R^\beta \xi_k \frac{\partial k}{\partial R}\right) + \frac{1}{R^{2\beta}} \frac{\partial}{\partial X} \left(\xi_k \frac{\partial k}{\partial X}\right) + \frac{\partial}{\partial Z} \left(\xi_k \frac{\partial k}{\partial Z}\right) - \rho\epsilon + S_k \tag{2.13}$$

where

$$\xi_k = \mu + \frac{\mu_T}{\sigma_k}$$

$$S_k = P_k + G_k$$

Shear production:

$$P_k = \mu_T \{2[(\frac{\partial U}{\partial R})^2 + (\frac{1}{R^\beta} \frac{\partial W}{\partial X} + \beta \frac{U}{R})^2 + (\frac{\partial V}{\partial Z})^2]$$

$$+ \left(\frac{1}{R^\beta}\frac{\partial U}{\partial X} + \frac{\partial W}{\partial R} - \beta\frac{W}{R}\right)^2 + \left(\frac{\partial U}{\partial Z} + \frac{\partial V}{\partial R}\right)^2 + \left(\frac{\partial W}{\partial Z} + \frac{1}{R^\beta}\frac{\partial V}{\partial X}\right)^2\}$$

Buoyant production:

$$G_k = \frac{\mu_T}{\rho\sigma_T}\left(\frac{\partial \rho}{\partial R} g_R + \frac{1}{R^\beta}\frac{\partial \rho}{\partial X} g_X + \frac{\partial \rho}{\partial Z} g_Z\right)$$

Dissipation of Turbulent Kinetic Energy

$$\rho_o \left[\frac{\partial \epsilon}{\partial t} + \frac{1}{R^\beta}\frac{\partial}{\partial R}(R^\beta U\epsilon) + \frac{1}{R^\beta}\frac{\partial}{\partial X}(W\epsilon) + \frac{\partial}{\partial Z}(V\epsilon)\right]$$

$$= \frac{1}{R^\beta}\frac{\partial}{\partial R}\left(R^\beta \xi_\epsilon \frac{\partial \xi}{\partial R}\right) + \frac{1}{R^{2\beta}}\frac{\partial}{\partial X}\left(\xi_\epsilon \frac{\partial \epsilon}{\partial X}\right) + \frac{\partial}{\partial Z}\left(\xi_\epsilon \frac{\partial \epsilon}{\partial Z}\right)$$

$$+ \frac{1}{k}(S_\epsilon - \rho C_{\epsilon 2}\epsilon)\epsilon \qquad (2.14)$$

where

$$\xi_\epsilon = \mu + \frac{\mu_T}{\sigma_\epsilon}$$

$$S_\epsilon = C_{\epsilon 1}P_k + C_{\epsilon 3}G_k$$

The turbulent viscosity, μ_T, is computed using the Prandtl-Kolmogorov hypothesis:

$$\mu_T = C_\mu \, \rho \, k^2/\epsilon \qquad (2.15)$$

Recommended turbulent model constants (Jones and Launder 1973) are

$\sigma_T = 0.9$ $\quad C_{\epsilon 1} = 1.44$ $\quad C_\mu = 0.09$

$\sigma_k = 1.0$ $\quad C_{\epsilon 2} = 1.92$

$\sigma_\epsilon = 1.3$ $\quad C_{\epsilon 3} = 1.44$

2.5 SPECIES EQUATIONS

TEMPEST accommodates constituent transport by solving the additional partial differential equations:

$$\frac{\partial C_i}{\partial t} + \frac{1}{R^\beta}\frac{\partial}{\partial R}(R^\beta U C_i) + \frac{\partial (W C_i)}{\partial x} + \frac{\partial}{\partial Z}(V C_i)$$

$$= \frac{1}{R^\beta}\frac{\partial}{\partial R}\left(D R^\beta \frac{\partial C_i}{\partial R}\right) + \frac{1}{R^{2\beta}}\left(D\frac{\partial C_i}{\partial X}\right) + \frac{\partial}{\partial Z}\left(D\frac{\partial C_i}{\partial Z}\right) + \dot{C}_i \qquad (2.16)$$

where C_i is the mass fraction of the ith constituent, D is the mass diffusion coefficient, and $\dot{C}_i$ is the mass generation rate. Note that TEMPEST must be redimensioned to accommodate mass transport (see Section 4.3).

The mass diffusivity is determined as

$$D = \mu + \frac{\mu_T}{\rho_m Sc} \qquad (2.17)$$

2.6 SOLUTION PROCEDURE

The TEMPEST solution procedure is a semi-implicit time marching finite-difference procedure with all governing equations solved sequentially. At each time step the momentum equations are solved explicitly and the pressure equations implicitly; temperature, turbulent kinetic energy and dissipation, and other scalar transport equations are solved using an implicit continuation procedure. Thus, the solution proceeds in the three phases as follows:

- Phase I - Tilde Phase. The three momentum equations are advanced in time $(t + \Delta t)$ to obtain approximate (Tilde) velocities, $\tilde{U}$, $\tilde{V}$, and $\tilde{W}$, based on the previous time values of pressure and density, P and ρ. Although these values of the velocity components satisfy the momentum equations based on current values of P and ρ, continuity will usually not be satisfied.
- Phase II - Implicit Phase. The velocity component and pressure corrections (U', V', W', and P') are obtained such that the equations $U^{n+1} = \tilde{U} + U'$, $V^{n+1} = \tilde{V} + V'$, $W^{n+1} = \tilde{W} + W'$, and $P^{n+1} = P^n + P'$ satisfy continuity.
- Phase III - Scalar Phase. Using the previously computed values of U^{n+1}, V^{n+1}, and W^{n+1}, the advanced time $(t + \Delta t)$ values of temperature T^{n+1} and other scalar quantities are computed as required.

The solution is advanced step by step in time by continued application of the above three solution phases.

As indicated above, the Phase II computational procedure corrects the Tilde velocity field that was obtained in the Phase I operation to ensure continuity and also to compute the new time pressure. That is:

$$\vec{U}^{n+1} = \vec{\tilde{U}} + \vec{U}' \tag{2.18}$$

and

$$P^{n+1} = P^n + P' \tag{2.19}$$

where

$\vec{U}^{n+1}$ = divergence-free velocity vector field at time $t + \Delta t$

$\vec{\tilde{U}}$ = Tilde velocity vector field obtained from Phase I

$\vec{U}'$ = irrotational correction velocity vector field to be computed in Phase II

P^{n+1} = pressure field at time t + Δt

P^n = pressure field at time t

P' = pressure change during Δt computed in Phase II

The divergence of Equation (2.18) yields

$$\nabla \bullet \vec{U}^{n+1} = \nabla \bullet \vec{\tilde{U}} + \nabla \bullet \vec{U}' = 0 \tag{2.20}$$

in principle. Thus,

$$\nabla \bullet \vec{U}' = - \nabla \bullet \vec{\tilde{U}} = - \tilde{D} \tag{2.21}$$

where $\tilde{D}$ is computed from results of the Tilde Phase I. Since $\nabla \times U' = 0$ (irrotational), a scalar potential, ϕ, may be defined by

$$\vec{U}' = - \nabla\phi \tag{2.22}$$

To illustrate the procedure, consider the R-direction momentum Equation (2.9). A semi-implicit finite-difference discretization of this equation, using evenly spaced cells, can be expressed as

$$(\tilde{U}_j + U'_j) - U^n_j = - \frac{\Delta t}{\rho_o \Delta R_j} [(P^n + P')_{j+1} - (P^n + P')_j]$$

$$- \Delta t \, K_R |U_j|^n (\tilde{U}_j + U'_j) + \Delta t \, S^n_R \tag{2.23}$$

where it is assumed for illustrative purposes that flow drag has the form $F_j = K_R U_j^2$ and that S_R^n contains all other terms that are evaluated explicitly at the time step n, including appropriate spatial differencing of advective and diffusion terms and gravitational forces. At the beginning of time step n+1, $\nabla \bullet \overrightarrow{U}^n = 0$ to within some convergence criterion, E. Then $U' \equiv 0$ and $P' \equiv 0$ by definition.

Thus, for Phase I

$$(1 + \Delta t K_R |U_j|^n)\, \tilde{U}_j - U_j^n + \frac{\Delta t}{\rho_o \Delta R_j} (P_{j+1}^n - P_j^n) - \Delta t\, S_R^n = 0 \qquad (2.24)$$

Once Phase I has been completed, the explicit form of the momentum equations has been satisfied, but $\nabla \bullet \overrightarrow{\tilde{U}} \neq 0$. To complete the solution at time step n+1 (Phase II), we combine Equations (2.23) and (2.24) to arrive at

$$U_j' = -\frac{\Delta t}{\rho_o \Delta R_j} (P_{j+1}' - P_j') - \Delta t\, K_R |U_j|^n\, U_j' \qquad (2.25)$$

where U_j' and P_j' are to be determined. Thus

$$(1 + \Delta t\, K_R |U_j|^n) U_j' = -\frac{\Delta t}{\rho_o \Delta R_j} (P_{j+1}' - P_j') \qquad (2.26)$$

From Equation 2.21

$$U_j' = -\, L_r \frac{\partial \phi}{\partial R} \qquad (2.27)$$

where

$$L_r = \frac{1}{1 + \Delta t\, K_R |U_j|^n}$$

and

$$\phi = \Delta t P'/\rho_o$$

Substituting Equation (2.27) along with similar expressions for the X- and Z-directions into Equation (2.21), and making use of the expression for continuity (Equation (2.1)), yields

$$\frac{1}{R^\beta}\frac{\partial}{\partial R}\left(R^\beta L_r \frac{\partial \phi}{\partial R}\right) + \frac{1}{R^{2\beta}}\frac{\partial}{\partial X}\left(L_x \frac{\partial \phi}{\partial X}\right) + \frac{\partial}{\partial Z}\left(L_z \frac{\partial \phi}{\partial Z}\right) = \tilde{D} \qquad (2.28)$$

Equation (2.28) forms the essence of the semi-implicit technique used in TEMPEST. Once the scalar field ϕ has been determined

$$P^{n+1} = P^n + \rho_o \phi/\Delta t \qquad (2.29)$$

and

$$\vec{U}^{n+1} = \vec{\tilde{U}}^n - L\nabla\phi \qquad (2.30)$$

The computation proceeds to Phase III with a velocity field that satisfies $\nabla \bullet \vec{U}^{n+1} = 0$ to within a prescribed convergence criterion, E.

It would, of course, be possible to increase the degree of implicitness of Equation (2.24) through iteration between Phase I and Phase II using current iterative values of P. However, this procedure would increase computation costs without significant benefits of increased accuracy, at least in TEMPEST.

2.7 DISCRETE FORMS OF THE GOVERNING EQUATIONS

This section describes discrete forms of the governing equations given in Sections 2.3 and 2.4. Discretization of the equations of motion is achieved through use of state-of-the-art finite-difference techniques (Roache 1972) common to computational fluid dynamics. Discrete cell balance methods are applied to the scalar equations rather than finite differences.

2.7.1 Computational Cell Structure and Subscripting Convention

The computational cell structure is illustrated for cylindrical coordinates in Figure 2.2. Although the cell structure shown indicates regular size, variable spacing may be used along any or all of the three coordinates as long as row/column/tier (R,Z,X; tiers building in the X-direction) structure is maintained.

Note the subscripts in Figure 2.2. The subscripting convention used in this work is to denote all quantities related to cell j,k,i by a single subscript p, keeping in mind that velocities are cell-faced quantities and that all other quantities are cell centered (special cases are noted). Further, all subscripting is suppressed except for those indices that are different from p (or j,k,i). Examples are given in Figures 3.2 and 3.3. Other examples are:

$U_{j,k,i}$	is denoted by	U_p	(velocity at cell east face)
$U_{j-1,k,i}$	is denoted by	U_{j-1}	(velocity at cell west face)
$V_{j-1,k,i-1}$	is denoted by	$V_{j-1,i-1}$	(velocity at cell j-1, i-1 north face)
$T_{j,k,i}$	is denoted by	T_p	(temperature at cell center)
$P_{j,k,i}$	is denoted by	P_p	(pressure at cell center)

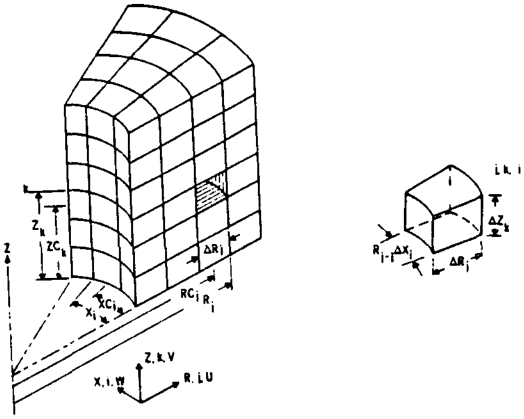


FIGURE 2.2. Computational Cell Structure

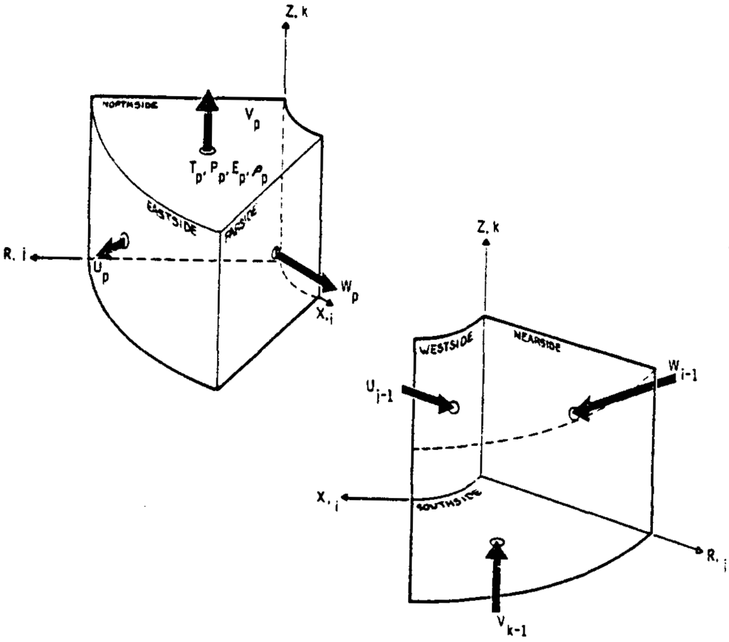


FIGURE 2.3. Computational Cell Nomenclature

This convention is much less confusing, is as descriptive as other conventions that use three subscripts and fractional subscripts, and is directly applicable in programming. One must, however, keep in mind each variable's position associated with a cell. Further descriptions of cellular position are obtained by denoting:

Cell east side = Positive R (or j) cell face

Cell north side = Positive Z (or k) cell face

Cell far side = Positive X (or i) cell face.

Opposite cell faces are the west, south, and near sides, corresponding to R,Z,X (j-1, k-1, i-1), respectively. The superscript n is used to denote that quantities are evaluated at current time t. The superscript n+1 is used to indicate evaluation at t + Δt.

2.7.2 Viscosity Location

Equations 3.2 and 3.4 demand discrete resolution of variable viscosities and associated gradients. In discrete representation, evaluation of these quantities causes some degree of difficulty in that the discretization scheme cell-centers the viscosity, μ, whereas ϵ and its gradients must be evaluated at the six cell faces and six cell edges. Thus, weighted averages usually involving four cells for each viscosity value are needed to obtain viscosities at 12 locations for each cell, in addition to interpolation required at solid walls. To aid in discretization logic, auxiliary viscosities located at the cell edges are used in addition to the cell-centered values, as shown in Figure 2.4. The cell-centered values are denoted by E_p, whereas the cell edge quantities obtained by four-cell-weighted averaging are denoted by ER_p, EX_p, and EZ_p.

2.7.3 Weighting Constants

Discretization of the conservation equations described in Sections 2.3, 2.4, and 2.6 is achieved by applying three-point finite-difference forms wherever possible, except in the advective terms, where donor cell differencing is

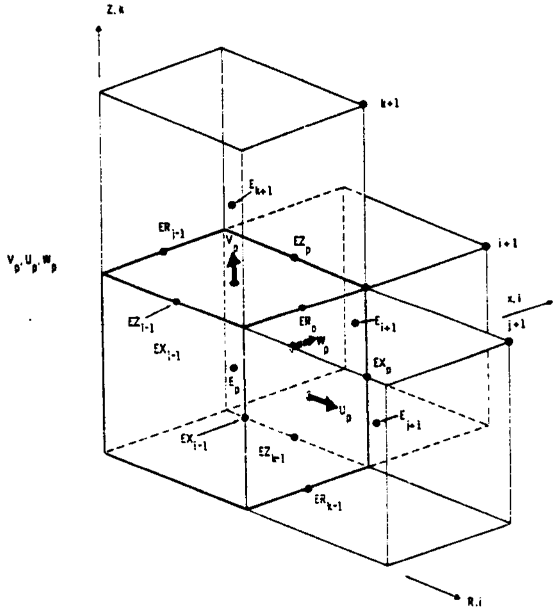


FIGURE 2.4. Variable Viscosity Discretization Pattern

applied. Other forms are, of course, possible, but the forms used are felt to be adequate and consistent with the requirements of this code version.

The following weighting constants are defined for convenience in writing difference expressions for unequally spaced derivatives:

$$SR1 = \frac{\Delta R_{j+1}}{\Delta R_{j+1}+\Delta R_j} , \qquad SR2 = \frac{\Delta R_j}{\Delta R_{j+1}+\Delta R_j}$$

$$SX1 = \frac{\Delta X_{i+1}}{\Delta X_{i+1}+\Delta X_i} , \qquad SX2 = \frac{\Delta X_i}{\Delta X_{i+1}+\Delta X_i}$$

$$SZ1 = \frac{\Delta Z_{k+1}}{\Delta Z_{k+1}+\Delta Z_k} , \qquad SZ2 = \frac{\Delta Z_k}{\Delta Z_{k+1}+\Delta Z_k}$$

$$SR3 = \frac{SR2}{\Delta R_{j+1}} , \qquad SR4 = \frac{SR1}{\Delta R_j} , \qquad SR5 = \frac{\Delta R_{j+1}-\Delta R_j}{\Delta R_j \bullet \Delta R_{j+1}}$$

$$SX3 = \frac{SX2}{\Delta X_{i+1}} , \qquad SX4 = \frac{SX1}{\Delta X_i} , \qquad SX5 = \frac{\Delta X_{i+1}-\Delta X_i}{\Delta X_i \bullet \Delta X_{i+1}}$$

$$SZ3 = \frac{SZ2}{\Delta Z_{k+1}} , \qquad SZ4 = \frac{SZ1}{\Delta Z_k} , \qquad SZ5 = \frac{\Delta Z_{k+1}-\Delta Z_k}{\Delta Z_k \bullet \Delta Z_{k+1}}$$

2.7.4 Phase I - Momentum-Difference Equations

R-direction momentum, U:

$$DUU = \frac{1}{R^\beta} \frac{\partial}{\partial R} (R^\beta UU) \qquad (2.31A)$$

$$\mathrm{DUU} = \frac{1}{2R_j^{\beta}\ (\Delta R_{j+1}+\Delta R_j)}\ \{RC_{j+1}^{\beta}\ [|U_p + U_{j+1}|(U_p - U_{j+1}) + (U_p + U_{j+1})^2]$$

$$+ RC_j^{\beta}\ [|U_p + U_{j-1}|(U_p - U_{j-1}) - (U_p + U_{j-1})^2]\} \tag{2.31B}$$

$$\mathrm{DWU} = \frac{1}{R^{\beta}}\frac{\partial}{\partial X}\ (WU) \tag{2.32A}$$

$$\mathrm{DWU} = \frac{1}{2R^{\beta}\ \Delta X}\ \{|SR2 \bullet W_{j+1} + SR1 \bullet W_p|\ (U_p - U_{i+1})$$

$$+ |SR2 \bullet W_{j+1,i-1} + SR1 \bullet W_{i-1}|\ (U_p - U_{i-1})$$

$$+ (SR2 \bullet W_{j+1} + SR1 \bullet W_p)\ (U_p + U_{i+1})$$

$$- (SR2 \bullet W_{j+1,i-1} + SR1 \bullet W_{i-1})\ (U_p + U_{i-1})] \tag{2.32B}$$

$$\mathrm{DVU} = \frac{\partial}{\partial Z}\ (VU) \tag{2.33A}$$

$$\mathrm{DVU} = \frac{1}{2\Delta Z_k}\ \{|SR2 \bullet V_{j+1} + SR1 \bullet V_p|\ (U_p - U_{k+1})$$

$$+ |SR2 \bullet V_{j+1,k-1} + SR1 \bullet V_{k-1}|\ (U_p - U_{k-1})$$

$$+ (SR2 \bullet V_{j+1} + SR1 \bullet V_p)\ (U_p + U_{k+1})$$

$$- (SR2 \bullet V_{j+1,k-1} + SR1 \bullet V_{k-1})\ (U_p + U_{k-1})] \tag{2.33B}$$

$$DCU = -\beta\left(\frac{\rho}{\rho_o}\right)\frac{W^2}{R} \qquad 34(2.34A)$$

$$DCU = \frac{-\beta}{4\rho_o R_j}\left[SR2 \bullet \rho_{j+1} + SR1 \bullet \rho_j\right]\left[SR2\ (W_{j+1,i-1} + W_{j+1}) + SR1\ (W_{i-1} + W_p)\right]^2 \qquad (2.34B)$$

$$VISR = \frac{1}{R^\beta}\frac{\partial}{\partial R}\left(\xi R^\beta \frac{\partial U}{\partial R}\right) + \frac{1}{R^{2\beta}}\frac{\partial}{\partial X}\left(\xi\frac{\partial U}{\partial X}\right) + \frac{\partial}{\partial Z}\left(\xi\frac{\partial U}{\partial Z}\right) \qquad (2.35A)$$

$$\begin{aligned} VISR = {} & \frac{2E_{j+1}\ RC_{j+1}^{\beta}\ (U_{j+1}-U_p)}{R_j^{\beta}\Delta R_{j+1}\ (\Delta R_{j+1}+\Delta R_j)} - \frac{2E_p RC_j^{\ \beta}(U_p-U_{j-1})}{R_j^{\beta}\Delta R_j\ (\Delta R_{j+1}+\Delta R_j)} \\ & + \frac{2EX_p\ (U_{i+1}-U_p)}{R_j^{2\beta}\Delta X_i(\Delta X_{i+1}+\Delta X_i)} - \frac{2EX_{i-1}\ (U_p-U_{i-1})}{R_j^{2\beta}\Delta X_i\ (\Delta X_{i-1}+\Delta X_i)} \\ & + \frac{2ER_p(U_{k+1}-U_p)}{\Delta Z_k\ (\Delta Z_{k+1}+\Delta Z_k)} - \frac{2ER_{k-1}\ (U_p-U_{k-1})}{\Delta Z_k\ (\Delta Z_{k-1}+\Delta Z_k)} \end{aligned} \qquad (2.35B)$$

$$SRR = -\beta\ \left(\frac{2\xi}{R^2}\right)\frac{\partial W}{\partial X} \qquad (2.36A)$$

$$SRR = = \beta\frac{E_p+E_{k-1}}{R_j^2\ \Delta X_i}\left[SR2\ (W_{j+1} - W_{j+1,i-1}) + SR1\ (W_p - W_{i-1})\right] \qquad (2.36B)$$

$$SRU = -\frac{\beta\xi}{R^2} \qquad (2.37A)$$

$$SRU = -\beta\frac{(E_p+E_{k-1})}{2\ R_j^2} \qquad (2.37B)$$

$$SRV = \frac{\partial \xi}{\partial R} \frac{\partial U}{\partial R} + \frac{\partial \xi}{\partial X} \frac{\partial}{\partial R} \left(\frac{W}{R^{\beta}}\right) + \frac{\partial \xi}{\partial Z} \frac{\partial V}{\partial R} \tag{2.38A}$$

$$SRV = 2 \frac{(E_{j+1} - E_p)}{\Delta R_j + \Delta R_{j+1}} (SR3 \bullet U_{j+1} - SR4 \bullet U_{j-1} - SR5 \bullet U_p)$$

$$+ \frac{EX_p - EX_{i-1}}{\Delta X_i \; (\Delta R_j + \Delta R_{j+1})} \left[\frac{1}{RC^{\beta}_{j+1}} (W_{j+1} + W_{j+1,i-1}) - \frac{1}{RC^{\beta}_j} (W_p + W_{i-1})\right]$$

$$+ \frac{ER_p - ER_{k-1}}{\Delta Z_k \; (\Delta R_j + \Delta R_{j+1})} [(V_{j+1} + V_{j+1,k-1}) - (V_p + V_{k-1})] \tag{2.38B}$$

$$FRN = KR_p |U_p|^{N_p - 1} + SRU \tag{2.39}$$

$$DPR = - \frac{2}{\rho_o} \left[\frac{P_{j+1} - P_p}{\Delta R_{j+1} + \Delta R_j}\right] \tag{2.40}$$

$$UC = DUU + DWU + DVU + DCU \tag{2.41}$$

$$UVIS = (VISR + SRR + SRV)/\rho_o \tag{2.42}$$

X-direction momentum, W:

$$DUW = \frac{1}{R^{\beta}} \frac{\partial}{\partial R} (R^{\beta} UW) \tag{2.43A}$$

$$DUW = \frac{1}{2\ RC_j^{\beta}\Delta R_j}\ [R_j^{\beta}|SX2 \bullet U_{i+1} + SX1 \bullet U_p|(W_p - W_{j+1})$$

$$+ R_{j-1}^{\beta}|SX2 \bullet U_{j-1,i+1} + SX1 \bullet U_{j-1}|(W_p - W_{j-1})$$

$$+ R_j^{\beta}(SX2 \bullet U_{i+1} + SX1 \bullet U_p)\ (W_p + W_{j+1})$$

$$- R_{j-1}^{\beta}(SX2 \bullet U_{j-1,i+1} + SX1 \bullet U_{j-1})\ (W_p + W_{j+1})] \tag{2.43B}$$

$$DWW = \frac{1}{R^{\beta}}\frac{\partial}{\partial X}\ (WW) \tag{2.44A}$$

$$DWW = \frac{1}{2RC_j^{\beta}\ (\Delta X_{i+1}+\Delta X_i)}\ \{|W_{i+1} + W_p|(W_p - W_{i+1}) + |W_{i-1} + W_p|(W_p - W_{i-1})$$

$$+ W_{i+1}^2 - W_{i-1}^2 + 2(W_{i+1} - W_{i-1})\ W_p\} \tag{2.44B}$$

$$DVW = \frac{\partial}{\partial Z}\ (VW) \tag{2.45A}$$

$$DVW = \frac{1}{2\Delta Z_k}\ \{|SX2 \bullet V_{i+1} + SX1 \bullet V_p|(W_p - W_{k+1})$$

$$+ |SX2 \bullet V_{i+1,k-1} + SX1 \bullet V_{k-1}|(W_p - W_{k-1})$$

$$+ (SX2 \bullet V_{i+1} + SX1 \bullet V_p)(W_p + W_{k+1})$$

$$- (SX2 \bullet V_{i+1,k-1} + SX1 \bullet V_{k-1})(W_p + W_{k-1})\} \tag{2.45B}$$

$$\mathrm{DCW} = \beta\left(\frac{\rho}{\rho_o}\right)\left(\frac{U}{R}\right) \tag{2.46A}$$

$$\mathrm{DCW} = \frac{\beta}{\rho_o RC_j}\left[SX2 \bullet \rho_{i+1}\left(U_{i+1} + U_{j-1,i+1}\right) + SX1 \bullet \rho_p\left(U_p + U_{j-1}\right)\right] \tag{2.46B}$$

$$\mathrm{VISX} = \frac{1}{R^{\beta}}\frac{\partial}{\partial R}\left(\xi R^{\beta}\frac{\partial W}{\partial R}\right) + \frac{1}{R^{2\beta}}\frac{\partial}{\partial X}\left(\xi\frac{\partial W}{\partial X}\right) + \frac{\partial}{\partial Z}\left(\xi\frac{\partial W}{\partial Z}\right) \tag{2.47A}$$

$$\begin{aligned}\mathrm{VISX} = {} & \frac{2EX_p R_j^{\beta}\left(W_{j+1}-W_p\right)}{RC_j^{\beta}\,\Delta R_j\left(\Delta R_{j+1}+\Delta R_j\right)} - \frac{2EX_{j-1}R_{j-1}^{\beta}\left(W_p-W_{j-1}\right)}{RC_j^{\beta}\,\Delta R_j\left(\Delta R_{j-1}+\Delta R_j\right)} \\ & + \frac{2E_{i+1}\left(W_{i+1}-W_p\right)}{RC_j^{2\beta}\,\Delta X_{i+1}\left(\Delta X_{i+1}+\Delta X_i\right)} - \frac{2E_p\left(W_p-W_{i-1}\right)}{RC_j^{2\beta}\,\Delta X_i\left(\Delta X_{i+1}+\Delta X_i\right)} \\ & + \frac{2EZ_p\left(W_{k+1}-W_p\right)}{\Delta Z_k\left(\Delta Z_{k+1}+\Delta Z_k\right)} - \frac{2EZ_{k-1}\left(W_p-W_{k-1}\right)}{\Delta Z_k\left(\Delta Z_{k-1}+\Delta Z_k\right)}\end{aligned} \tag{2.47B}$$

$$\mathrm{SXX} \quad \frac{2\beta\xi}{R^2}\frac{\partial U}{\partial X} \tag{2.48A}$$

$$\mathrm{SXX} = \beta\frac{\left(E_p+E_{j-1}\right)}{RC_j^2}\left[\frac{U_{i+1}+U_{j-1,i+1}-\left(U_p+U_{j-1}\right)}{\Delta X_{i+1}+\Delta X_i}\right] \tag{2.48B}$$

$$\mathrm{SXW} = -\frac{\beta}{R}\left(\frac{\xi}{R} + \frac{\partial\xi}{\partial R}\right) \tag{2.49A}$$

$$\mathrm{SXW} = \frac{\beta}{RC_j}\left[\frac{\left(E_p + E_{j-1}\right)}{RC_j} + \frac{\left(EX_p - E_{j-1}\right)}{\Delta R_j}\right] \tag{2.49B}$$

$$SXV = \frac{1}{R^{\beta}} \frac{\partial\xi}{\partial R} \frac{\partial U}{\partial X} + \frac{1}{R^{2\beta}} \frac{\partial\xi}{\partial X} \left(\frac{\partial W}{\partial X} + 2\beta U\right) + \frac{1}{R^{\beta}} \frac{\partial\xi}{\partial Z} \frac{\partial V}{\partial X} \tag{2.50A}$$

$$\begin{aligned} SXV = {} & \frac{1}{RC_j^{\beta}} \frac{EX_p+E_{j-1}}{\Delta R_j} \left[\frac{U_{i+1}+U_{j-1,i+1}-(U_p+U_{j-1})}{\Delta X_{i+1}+\Delta X_i}\right] \\ & + \frac{2}{RC_j^{2\beta}} \frac{E_{i+1}-E_p}{(\Delta X_{i+1}+\Delta X_i)} \{[SX3 \bullet W_{i+1} - SX4 \bullet W_{i-1} - SX5 \bullet W_p] \\ & + \beta[SX2 \; (U_{i+1} + U_{j-1,i+1}) + SX1 \; (U_p + U_{j-1})]\} \\ & + \frac{1}{RC_j^{\beta}} \frac{EZ_p-EZ_{k-1}}{\Delta Z_k} \left[\frac{V_{i+1}+V_{i+1,k-1}-(V_p+V_{k-1})}{\Delta X_{i+1}+\Delta X_i}\right] \end{aligned} \tag{2.50B}$$

$$FXN = KX_p|W_p|^{N_p-1} + DCW + SXW \tag{2.51}$$

$$DPX = \frac{-2 \; (P_{i+1}-P_p)}{\rho_o RC_j^{\beta} \; (\Delta X_{i+1}+\Delta X_i)} \tag{2.52}$$

$$WC = DWW + DUW + DCW \tag{2.53}$$

$$WVIX = (VISX + SXX + SXV)/\rho_o \tag{2.54}$$

<u>Z-direction momentum, V:</u>

$$DUV = \frac{1}{R^{\beta}} \frac{\partial}{\partial R} \left(R^{\beta} UV\right) \tag{2.55A}$$

$$\begin{aligned} DUV = \frac{1}{2RC_j^{\beta}\Delta R_j} \{ & R_j^{\beta}|SZ2 \bullet U_{k+1} + SZ1 \bullet U_p|(V_p - V_{j+1}) \\ & + R_{j-1}^{\beta}|SZ2 \bullet U_{j-1,k+1} + SZ1 \bullet U_{j-1}|(V_p - V_{j-1}) \\ & + R_j^{\beta} (SZ2 \bullet U_{k+1} + SZ1 \bullet U_p)(V_p + V_{j+1}) \\ & - R_{j-1}^{\beta} (SZ2 \bullet U_{j-1,k+1} + SZ1 \bullet U_{j-1})(V_p + V_{j-1})\} \end{aligned} \tag{2.55B}$$

$$DWV = \frac{1}{R^{\beta}} \frac{\partial}{\partial X} (WV) \tag{2.56A}$$

$$\begin{aligned} DWV = \frac{1}{2\ RC_j^{\beta}\ \Delta X_i} \{ & |SZ2 \bullet W_{k+1} + SZ1 \bullet W_p|(V_p - V_{i+1}) \\ & + |SZ2 \bullet W_{i-1,k+1} + SZ1 \bullet W_{k-1}|(V_p - V_{i-1}) \\ & + (SZ2 \bullet W_{k+1} + SZ1 \bullet W_p)(V_p + V_{i+1}) \\ & - (SZ2 \bullet W_{i-1,k+1} + SZ1 \bullet W_{i-1})(V_p + V_{i-1})\} \end{aligned} \tag{2.56B}$$

$$DVV = \frac{\partial}{\partial Z} (VV) \tag{2.57A}$$

$$\begin{aligned} DVV = \frac{1}{2\ (\Delta Z_{k+1} + \Delta Z_k)} \{ & |V_{k+1} + V_p|(V_p - V_{k+1}) + |V_{k-1} + V_p|(V_p - V_{k-1}) \\ & + V_{k+1}^2 - V_{k-1}^2 + 2\ (V_{k+1} - V_{k-1})\ V_p\} \end{aligned} \tag{2.57B}$$

$$\mathrm{VISZ} = \frac{1}{R^{\beta}} \frac{\partial}{\partial R} (\xi \; R^{\beta} \frac{\partial V}{\partial R}) + \frac{1}{R^{2\beta}} \frac{\partial}{\partial X} (\xi \frac{\partial V}{\partial X}) + \frac{\partial}{\partial Z} (\xi \frac{\partial V}{\partial Z}) \tag{2.58A}$$

$$\begin{aligned} \mathrm{VISZ} = {} & \frac{2ER_p R_j^{\beta} \; (V_{j+1} - V_p)}{RC_j^{\beta} \; \Delta R_j \; (\Delta R_{j+1} + \Delta R_j)} - \frac{2ER_{j-1}^{\beta} R_j \; (V_p - V_{j-1})}{RC_j^{\beta} \; \Delta R_j \; (\Delta R_{j-1} + \Delta R_j)} \\ & + \frac{2EZ_p \; (V_{i+1} - V_p)}{RC_j^{2\beta} \; \Delta X_i \; (\Delta X_{i+1} + \Delta X_i)} - \frac{2EZ_{i-1} \; (V_p - V_{i-1})}{RC_j^{2\beta} \; \Delta X_i \; (\Delta X_{i-1} + \Delta X_i)} \\ & + \frac{2E_{k+1} \; (V_{k+1} - V_p)}{\Delta Z_{k+1} \; (\Delta Z_{k+1} + \Delta Z_k)} - \frac{2E_p \; (V_p - V_{k-1})}{\Delta Z_k \; (\Delta Z_{k+1} + \Delta Z_k)} \end{aligned} \tag{2.58B}$$

$$\mathrm{SZV} = \frac{\partial \xi}{\partial R} \frac{\partial U}{\partial Z} + \frac{1}{R^{\beta}} \frac{\partial \xi}{\partial X} \frac{\partial W}{\partial Z} + \frac{\partial \xi}{\partial Z} \frac{\partial V}{\partial Z} \tag{2.59A}$$

$$\begin{aligned} \mathrm{SZV} = {} & \frac{ER_p - ER_{j-1}}{\Delta R_j} \; [\frac{U_{k+1} + U_{j-1,k+1} - (U_p + U_{j-1})}{\Delta Z_{k+1} + \Delta Z_k}] \\ & + \frac{EZ_p - EZ_{i-1}}{RC_j^{\beta} \; \Delta X_i} \; [\frac{W_{k+1} + W_{i-1,k+1} - (W_p + W_{i-1})}{\Delta Z_{k+1} + \Delta Z_k}] \\ & + \frac{2(E_{k+1} - E_p)}{\Delta Z_{k+1} + \Delta Z_k} \; [SZ3 \bullet V_{k+1} - SZ4 \bullet V_{k-1} - SZ5 \bullet V_p] \end{aligned} \tag{2.59B}$$

$$\mathrm{FZN} = KZ_p |V_p|^{N_p - 1} \tag{2.60}$$

$$\mathrm{VC} = \mathrm{DVV} + \mathrm{DUV} + \mathrm{DMV} \tag{2.61}$$

$$\mathrm{VVIS} = (\mathrm{VISZ} + \mathrm{SZV}) / \rho_o \tag{2.62}$$

$$\mathrm{DPZ} = -\frac{2\,(P_{k+1}-P_p)}{\rho_o\,(\Delta Z_{k+1}+\Delta Z_k)} \tag{2.63}$$

Tilde velocities in Phase I are computed as:

$$\tilde{U}_p^{n+1} = \frac{1}{(1+\Delta t \bullet \mathrm{FRN})}\{U_p + \Delta t\,(\mathrm{DPR} + \mathrm{GR}_p - \mathrm{UC} + \mathrm{UVIS})\} \tag{2.64}$$

$$\tilde{W}_p^{n+1} = \frac{1}{(1+\Delta t \bullet \mathrm{FXN})}\{W_p + \Delta t\,(\mathrm{DPX} + \mathrm{GX}_p - \mathrm{WC} + \mathrm{WVIS})\} \tag{2.65}$$

$$\tilde{V}_p^{n+1} = \frac{1}{(1+\Delta t \bullet \mathrm{FZN})}\{V_p + \Delta t\,(\mathrm{DPZ} + \mathrm{GZ}_p - \mathrm{VC} + \mathrm{VVIS})\} \tag{2.66}$$

The quantities GR, GX, and GZ are gravitational body force contributions and may be either in the form $G = (\rho_p/\rho_o)g$ or $G = [(\rho_p - \rho_o)/\rho_0]g$. The latter form is the usual form of the Boussinesq approximation regarding small density variations and may be obtained by subtracting the hydrostatic pressure contribution based on constant reference density ρ_o from the equation of motion (e.g., $\frac{\partial P}{\partial Z} = -\rho_o g$).

2.7.5 Phase II - Continuity/Pressure Difference Equation

Equation (2.28) is the primary equation to be solved in the Phase II computation and is restated here for reference:

$$\frac{2}{R^\beta}\frac{\partial}{\partial R}\left(R^\beta L_r \frac{\partial \phi}{\partial R}\right) + \frac{1}{R^{2\beta}}\frac{\partial}{\partial X}\left(L_x \frac{\partial \phi}{\partial X}\right) + \frac{\partial}{\partial Z}\left(L_z \frac{\partial \phi}{\partial Z}\right) = \tilde{D} \tag{2.67}$$

The solution to this equation is not formulated by applying differencing techniques; rather, the equation is reformulated in terms of connector logic to give the following expression

$$\sum_{s=1}^{6} KC_{p,s} \; (\phi_s - \phi_p) = \tilde{D}_p v_p \tag{2.68}$$

where

v_p = volume of Cell p

$KC_{p,s}$ = flow conductance between Cell p and Side s

The summation applies over the six cell faces.

Flow connectors are defined as follows:

$$KC_{p,1} = KC_E = \frac{2\ R_j^{\beta}\ \Delta X_i \Delta Z_i}{(\Delta R_{j+1} + \Delta R_j)} \bullet \frac{1}{(1 + \Delta t \bullet FRN_p)} \qquad \text{East}$$

$$KC_{p,2} = KC_W = \frac{2\ R_{j-1}^{\beta}\ \Delta X_i \Delta Z_i}{(\Delta R_{j-1} + \Delta R_j)} \bullet \frac{1}{(1 + \Delta t \bullet FRN_{j-1})} \qquad \text{West}$$

$$KC_{p,3} = KC_N = \frac{2\ R_j^{\beta}\ \Delta X_i \Delta R_j}{(\Delta Z_{k+1} + \Delta Z_k)} \bullet \frac{1}{(1 + \Delta t \bullet FZN_p)} \qquad \text{North}$$

$$KC_{p,4} = KC_S = \frac{2\ RC_j^{\beta}\ \Delta X_i \Delta R_j}{(\Delta Z_{k-1} + \Delta Z_k)} \bullet \frac{1}{(1 + \Delta t \bullet FZN_{k-1})} \qquad \text{South}$$

$$KC_{p,5} = KC_F = \frac{2\ \Delta R_j\ \Delta Z_k}{RC_j^{\beta}\ (\Delta X_{i+1} + \Delta X_i)} \bullet \frac{1}{(1 + \Delta t \bullet FXN_p)} \qquad \text{Far Side}$$

$$KC_{p,6} = KC_{NR} = \frac{2\ \Delta R_j\ \Delta Z_k}{RC_j^{\beta}\ (\Delta X_{i-1} + \Delta X_i)} \bullet \frac{1}{(1 + \Delta t \bullet FXN_{i-1})} \qquad \text{Near Side}$$

The generating function $\tilde{D}_p v_p$ is evaluated by first computing the divergence using Equation (2.1) and Phase I velocities. Thus,

$$\tilde{D} = \frac{1}{R^{\beta}} \frac{\partial R^{\beta} \tilde{U}}{\partial R} + \frac{1}{R^{\beta}} \frac{\partial \tilde{W}}{\partial X} + \frac{\partial \tilde{V}}{\partial Z} \tag{2.69}$$

In discrete form, the above equation becomes

$$\tilde{D}_p = \frac{R_j^{\beta}\, \tilde{U}_j - R_{j-1}^{\beta}\, \tilde{U}_{j-1}}{RC_j^{\beta}\, \Delta R_j} + \frac{\tilde{W}_i - \tilde{W}_{i-1}}{RC_j^{\beta}\, \Delta X_i} + \frac{\tilde{V}_k - \tilde{V}_{k-1}}{\Delta Z_k} \tag{2.70}$$

The cell volume is

$$v_p = RC_j^{\beta}\, \Delta R_j\, \Delta x_i\, \Delta Z_k \tag{2.71}$$

TEMPEST first computes $\tilde{D}_p$ using Equation (2.70) which is then multiplied by the cell volume for use in Equation (2.68).

The solution to Equation (2.68) can be obtained by any number of iterative procedures (or possibly, by direct inversion). TEMPEST allows the user to select either an alternating direction LSOR or Gauss-Siedel SOR procedure.

Once ϕ_p is obtained for the flow field, the corrected new time velocities are computed by

$$U_p^{n+1} = \tilde{U}_p - \frac{2\,(\phi_{j+1} - \phi_p)}{(\Delta R_j + \Delta R_{j+1})} \bullet \frac{1}{(1 + \Delta t \bullet FRN_p)} \tag{2.72}$$

$$W_p^{n+1} = \tilde{W}_p \quad \frac{2\,(\phi_{i+1} - \phi_p)}{R_j^{\beta}\,(\Delta X_i + \Delta X_{i+1})} \bullet \frac{1}{(1 + \Delta t \bullet FXN_p)} \tag{2.73}$$

$$V_p^{n+1} = \tilde{V}_p - \frac{2\,(\phi_{k+1}-\phi_p)}{(\Delta Z_k+\Delta Z_{k+1})} \bullet \frac{1}{(1+\Delta t \bullet FZN_p)} \tag{2.74}$$

New time pressure is computed by

$$p^{n+1} = p^n + (\rho_o\phi)_p/\Delta t \tag{2.75}$$

2.7.6 Phase III - Scalar Equation Solution Procedure

The scalar phase of TEMPEST obtains the solutions to transport equations for T, k, and ϵ. Since these Equations ((2.12), (2.13), (2.14)) all have the same form, a general solution procedure is developed and implemented in TEMPEST. As in the case of the pressure/continuity solution, these transport equations are discretized using the control volume approach.

2.7.6.1 General Transport Equation

The discrete form of the balance equation for Cell p, whether solid or fluid, is given by the implicit equation

$$\Gamma_p^{n+1} - \Gamma_p^n = \tau F \sum_{s=1}^{6} (KS_{p,s}\Gamma_s^{n+1} - KP_{p,s}\Gamma_p^{n+1})$$

$$+ \tau(1 - F) \sum_{s=1}^{6} (KS_{p,s}\Gamma_s^n - KP_{p,s}\Gamma_p^n) + \tau\dot{\Gamma} + \tau C\Gamma^{n+1} \tag{2.76}$$

where

Γ = transported quantity

$\tau = \frac{\Delta t}{V_p^*}$

F = implicit weighting factor (F = 0.5, Crank-Nicholson)

V_p^* = cell volume parameter

C = constant

and $KS_{p,s}$ and $KP_{p,s}$ are the transport connectors (defined later). If $\tau C\Gamma^n$ is subtracted from both sides of the above equation and $\Delta\Gamma_p^{n+1}$ is the change of Γ during time increment Δt defined as

$$\Delta\Gamma_p^{n+1} = \Gamma_p^{n+1} - \Gamma_p^n \tag{2.77}$$

then Equation (2.76) may be recast in the following form:

$$\Delta\Gamma_p^{n+1} = \theta F \sum_{s=1}^{6} (KS_{p,s}\Delta\Gamma_s^{n+1} - KP_{p,s}\Delta\Gamma_p^{n+1}) + \Delta\Gamma_E^{n+1} \tag{2.78}$$

where

$$\Delta\Gamma_E^{n+1} = \theta[\sum_{s=1}^{6} (KS_{p,s}\Gamma_s^n - KP_{p,s}\Gamma_p^n) + \dot{\Gamma} + C\Gamma^n] \tag{2.79}$$

$$\theta = \frac{\tau}{1-C\tau}$$

and $\Delta\Gamma^{n+1}$ is the change that one would obtain through an explicit computation.

Equation (2.78) may be solved by a number of different techniques, including direct iteration. However, it is imperative that the selected algorithm be computationally efficient, accurate, and independent of modeling complexities such as geometry, flow, and materials. The method chosen is the Douglas and Gunn three-step algorithm described in Richtmeyer and Morton (1967) with modification in that $\Delta\Gamma_p$ is solved for instead of Γ_p.

Through minor algebraic manipulation, one may cast Equation (2.78) in the following Douglas and Gunn format:

Step 1

$$\Delta\Gamma^{*}_{p} = \theta F[KS_{p,1}\Delta\Gamma_{j-1} - (KP_{p,1} + KP_{p,2})\ \Delta\Gamma^{*}_{p} + KS_{p,2}\Delta\Gamma_{j+1}] + \Delta\Gamma^{n+1}_{E} \tag{2.80}$$

Step 2

$$\Delta\Gamma^{**}_{p} = \theta F[KS_{p,3}\Delta\Gamma^{**}_{k-1} - (KP_{p,3} + KP_{p,4})\ \Delta\Gamma^{**}_{p} + KS_{p,4}\Delta\Gamma_{k+1}] + \Delta\Gamma^{*}_{p} \tag{2.81}$$

Step 3

$$\Delta\Gamma^{n+1}_{p} = \theta F[KS_{p,5}\Delta\Gamma^{n+1}_{i-1} - (KP_{p,5} + KP_{p,6})\ \Delta\Gamma^{n+1}_{p} + KP_{p,6}\Delta\Gamma^{n+1}_{i+1}] + \Delta\Gamma^{**}_{p} \tag{2.82}$$

Finally, the transported quantities are computed at time step n+1 by

$$\Gamma^{n+1}_{p} = \Gamma^{n}_{p} + \Delta\Gamma^{n+1}_{p} \tag{2.83}$$

The above algorithm is very efficient because computation may be performed through repeated application of tridiagonal Gauss elimination. Only one array is required for storage of the $\Delta\Gamma$'s other than the storage required by a single line segment.

One particularly attractive feature of the above algorithm, as currently used in TEMPEST, is that the implicit part of the computation may be bypassed if $\Delta\Gamma^{n+1}_{E}$, the explicit computation, is stable. Explicit time step stability is easily computed as

$$(\theta \sum_{s=1}^{6} KP_{p,s})_{max} \leq 1 \tag{2.84}$$

Thus, in TEMPEST the implicit continuation is performed only if the stability criterion, Equation (2.84), is unsatisfied after merging with the $\Delta\Gamma_E^{n+1}$ array.

2.7.6.2 Thermal Energy

The system temperature distribution is obtained through the solution procedure described in Section 2.7.6.1 with the following definitions:

$$\Gamma_p = T_p$$

$$v_p^* = (\rho c v)_p$$

$$\Gamma_p^* = \dot{Q} \text{ (volumetric heat generation rate)}$$

$$C = 0$$

So that $\tau = \dfrac{\Delta t}{(\rho c v)_p}$

and $\theta = \tau$

The thermal connectors $K_{p,s}$ and $KP_{p,s}$ are described as follows:

$$KD_{p,s} = \frac{1}{\sum_{\ell}^{m} R_{\ell,s}}$$

where $R_{\ell,s}$ is the thermal resistance between the cell center of node p and the cell center of the node adjacent side s of node p (electrical analogy, Figure 2.5).

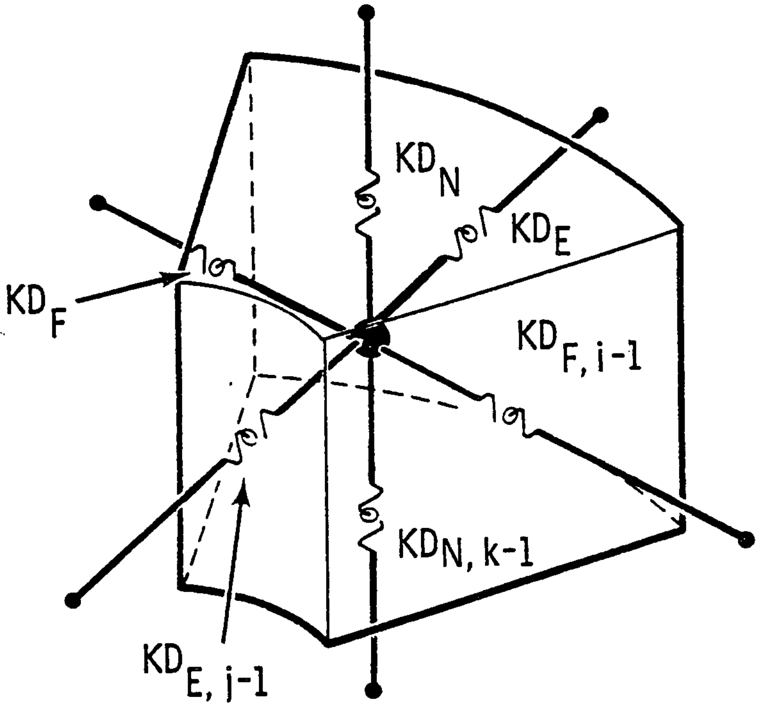


FIGURE 2.5. Thermal Diffusion Cell Connectors

These connectors (conductances) are summarized in both cylindrical and Cartesian coordinates as follows:

Cartesian Coordinates ($\beta = 0$)

$$KD_E = KD_j = \frac{2\ \Delta x_i\ \Delta Z_k}{\frac{\Delta R_j}{\sigma_p} + \frac{\Delta R_{j+1}}{\sigma_{j+1}} + \frac{2}{H_E}} \qquad \text{East Side}$$

$$KD_N = KD_k = \frac{2\ \Delta x_i\ \Delta R_j}{\frac{\Delta Z_k}{\sigma_p} + \frac{\Delta Z_{k+1}}{\sigma_{k+1}} + \frac{2}{H_N}} \qquad \text{North Side}$$

$$KD_F = KD_i = \frac{2\ \Delta x_i\ \Delta Z_k}{\frac{\Delta X_i}{\sigma_p} + \frac{\Delta X_{i+1}}{\sigma_{i+1}} + \frac{2}{H_F}} \qquad \text{Far Side}$$

Cylindrical Coordinates ($\beta = 1$)

$$KD_E = KD_j = \frac{\Delta X_i\ \Delta Z_k}{\frac{\ell n(R_j/RC_j)}{\sigma_p} + \frac{\ell n(RC_{j+1}/R_j)}{\sigma_{j+1}} + \frac{1}{H_E R_j}} \qquad \text{East Side}$$

$$KD_N = KD_k = \frac{2\ \Delta X_i\ \Delta R_j\ RC_j}{\frac{\Delta Z_k}{\sigma_p} + \frac{\Delta Z_{k+1}}{\sigma_{k+1}} + \frac{2}{H_N}} \qquad \text{North Side}$$

$$KD_F = KD_i = \frac{2\ \Delta R_j\ \Delta Z_k}{RC_j\ (\frac{\Delta X_i}{\sigma_p} + \frac{\Delta X_{i+1}}{\sigma_{i+1}}) + \frac{2}{H_F}} \qquad \text{Far Side}$$

$H_E = H_{p,E}$ = Film/contact coefficient cell East Side
$H_N = H_{p,N}$ = Film/contact coefficient cell North Side
$H_F = H_{p,F}$ = Film/contact coefficient cell Far Side

Flow Connectors. Flow connectors for donor cell differencing are expressed as follows:

$$KFP_j = \Delta X_i\ \Delta Z_k\ R_j^{\beta}\ (|U_p| + U_p)\rho c/2$$

$$KPF_k = \Delta X_i\ \Delta R_j\ RC_j^{\beta}\ (|V_p| + V_p)\rho c/2$$

$$KFP_i = \Delta R_k\ \Delta Z_k\ (|W_p| + W\ )\rho c/2$$

$$KFM_j = \Delta X_i \ \Delta Z_K R_j^{\beta} \ (|U_p| - U_p)\rho c/2$$

$$KFM_k = \Delta X_i \ \Delta R_j RC_j^{\beta} \ (|V_p| - V_p)\rho c/2$$

$$KFM_i = \Delta R_j \ \Delta Z_k \ (|W_p| - W_p)\rho c/2$$

Combined Connectors. The combined flow and conduction connectors become:

$KS_{p,1} = KD_{j-1} + KFP_{j-1}$ West Side

$KS_{p,2} = KD_j + KFM_j$ East Side

$KS_{p,3} = KD_{k-1} + KFP_{k-1}$ South Side

$KS_{p,4} = KD_k + KFM_k$ North Side

$KS_{p,5} = KD_{i-1} + KFP_{i-1}$ Near Side

$KS_{p,6} = KD_i + KFM_i$ Far Side

$KP_{p,1} = KD_{j-1} + KFM_{j-1}$ Center West

$KP_{p,2} = KD_j + KFP_j$ Center East

$KP_{p,3} = KD_{k-1} + KFP_{k-1}$ Center South

$KP_{p,4} = KD_k + KFP_k$ Center North

$KP_{p,5} = KD_{i-1} + KFM_{i-1}$ Center Near

$KP_{p,6} = KD_i + KFP_i$ Center Far

2.7.6.3 Turbulent Kinetic Energy Equation

The turbulent kinetic energy equation is discretized and solved as described in Section 2.7.6.1 using the following definitions:

$$\Gamma_p = k_p$$

$$v_p^* = (\rho v)_p$$

$$\dot{\Gamma} = (PK + GK - \rho\epsilon)_p$$

The dissipation term in the explicit change of kinetic energy could be evaluated directly. However, TEMPEST uses an alternative formulation which improves the solution stability. Solving for ϵ in the effective viscosity definition,

$$\rho\epsilon = \frac{\rho^2 C_\mu k^2}{\mu_T} \tag{2.85}$$

This expression is further evaluated as

$$\rho\epsilon = \frac{\rho^2 C_\mu k^n k^{n+1}}{\mu_T} \tag{2.86}$$

Thus, we may redefine $\dot{\Gamma}$ as

$$\dot{\Gamma} = (PK_p + GK_p) v_p \tag{2.87}$$

and the constant C, as

$$C = \left(\frac{\rho^2 C_\mu k^n v}{\mu_T}\right)_p \tag{2.88}$$

where v is the cell volume.

Finally, the new time turbulent kinetic energy is computed as

$$k_p^{n+1} = k_p^n + \Delta k_p^{n+1} \tag{2.89}$$

Diffusion Connectors. The diffusion connectors for the turbulent kinetic equation are computed for Cartesian and cylindrical coordinates as:

Cartesian Coordinates ($\beta = 0$)

$$KD_E = KD_j = \frac{2\Delta X_i \Delta Z_k}{\frac{\Delta R_j}{\gamma_p} + \frac{\Delta R_{j+1}}{\gamma_{j+1}}} \qquad \text{East Side}$$

$$KD_N = KD_k = \frac{2\Delta X_i \Delta R_j}{\frac{\Delta Z_k}{\gamma_p} + \frac{\Delta Z_{k+1}}{\gamma_{k+1}}} \qquad \text{North Side}$$

$$KD_F = KD_i = \frac{2\Delta R_j \Delta Z_k}{\frac{\Delta X_i}{\gamma_p} + \frac{\Delta X_{i+1}}{\gamma_{i+1}}}$$

Cylindrical Coordinates ($\beta = 1$)

$$KD_E = KD_j = \frac{\Delta X_i \Delta Z_k}{\frac{\ell n(R_j/RC_j)}{\gamma_p} + \frac{\ell n(RC_{j+1}/R_j)}{\gamma_{j+1}}} \qquad \text{East Side}$$

$$KD_N = KD_k = \frac{2\Delta X_i \Delta R_j}{\frac{\Delta Z_k}{\gamma_p} + \frac{\Delta Z_{k+1}}{\gamma_{k+1}}}$$ North Side

$$KD_F = KD_i = \frac{2\Delta R_j \Delta Z_k}{\frac{\Delta X_i}{\gamma_p} + \frac{\Delta X_{i+1}}{\gamma_{i+1}}}$$ Far Side

Cylindrical Coordinates (β = 1)

$$KD_E = KD_j = \frac{\Delta X_i \Delta Z_k}{\frac{\ell n(R_j/RC_j)}{\gamma_p} + \frac{\ell n(RC_{j+1}/R_j)}{\gamma_{j+1}}}$$ East Side

$$KD_N = KD_k = \frac{2\Delta X_i \Delta R_j RC_j}{\frac{\Delta Z_k}{\gamma_p} + \frac{\Delta Z_{k+1}}{\gamma_{k+1}}}$$ North Side

$$KD_F = KD_i = \frac{2\Delta R_j \Delta Z_k}{RC_j\left(\frac{\Delta X_i}{\gamma_p} + \frac{\Delta X_{i+1}}{\gamma_{i+1}}\right)}$$ Far Side

The effective diffusion coefficients, γ, are determined from the viscosities and kinetic energy diffusion constant, σ_k, as:(a)

$$\gamma_p = (\mu + \frac{\mu_T}{\sigma_k})_p$$

(a) The subscript k on σ refers to kinetic energy and should not be confused with the Z-direction counter k used elsewhere.

$$\gamma_{j+1} = (\mu + \frac{\mu_T}{\sigma_k})_{j+1}$$

$$\gamma_{k+1} = (\mu + \frac{\mu_T}{\sigma_k})_{k+1}$$

$$\gamma_{i+1} = (\mu = \frac{\mu_T}{\sigma_k})_{i+1}$$

Flow Connectors. The flow connectors for the turbulent kinetic energy equation are the same as the flow connectors given in Section 2.7.6.2.

Combined Connectors. The combined connectors for the discrete turbulent kinetic energy equation are the sum of the diffusion connectors given above and the flow connectors given in Section 2.7.6.2. They are combined as discussed in Section 2.7.6.2.

Kinetic Energy Production. In the present formulation and solution technique, the production and dissipation of turbulent kinetic energy appear in the explicit change of turbulent kinetic energy given by Equation (2.87). These are the production caused by mean flow shear (PK_p) and density gradients (GK_p).

The shear production term is given in Section 2.4. The discrete mean velocity gradients are evaluated as:

$$DUDR = \frac{\partial U}{\partial R} = \frac{U_j - U_{j-1}}{\Delta R_j}$$

$$DVDZ = \frac{\partial V}{\partial Z} = \frac{V_k - V_{k-1}}{\Delta Z_k}$$

$$DWDX = \frac{1}{R^{\beta}} \frac{\partial W}{\partial X} = \frac{W_i - W_{i-1}}{RC_j^{\beta} \Delta X_i}$$

$$UOR = \beta\frac{U}{R} = \beta\frac{(U_j + U_{j-1})}{2RC_j}$$

$$DUDX = \frac{1}{R^{\beta}} \frac{\partial U}{\partial X}$$

$$= \frac{SX2(U_{i+1} + U_{j-1,i+1}) - SX1_{i-1}(U_{i-1} + U_{j-1,i-1}) + (SX1 - SX2_{i-1})(U_j + U_{j-1})}{2\ RC_j^{\beta}\ \Delta X_i}$$

$$DWDR = \frac{\partial W}{\partial R}$$

$$= \frac{SR2(W_{j+1} + W_{j+1,i-1}) - SR1_{j-1}(W_{j-1} + W_{j-1,i-1}) + (SR1 - SR2_{j-1})\ (W_i + W_{i-1})}{2\ \Delta R_j}$$

$$WOR = \beta\frac{W}{R} = \beta\frac{(W_j + W_{j-1})}{2RC_j}$$

$$DUDZ = \frac{\partial U}{\partial Z}$$

$$= \frac{SZ2(U_{k+1} + U_{j-1,k+1}) - SZ1_{k-1} + (U_{k-1} + U_{j-1,k-1}) + (SZ1 - SZ2_{k-1})(U_j + U_{j-1})}{2\ \Delta Z_k}$$

$$DVDR = \frac{\partial V}{\partial R}$$

$$= \frac{SR2(V_{j+1} + V_{j+1,k-1}) - SR_{j-1}(V_{j-1} + V_{j-1,k-1}) + (SR1 - SR2_{j-1})(V_k + V_{k-1})}{2\ \Delta R_j}$$

$$DWDZ = \frac{\partial W}{\partial Z}$$

$$= \frac{SZ2(W_{k+1} + W_{k+1,i-1}) - SZ1_{k-1}(W_{k-1} + W_{k-1,i-1}) + (SZ1 - SZ2_{k-1})(W_i + W_{i-1})}{2\ \Delta Z_k}$$

$$DVDZ = \frac{1}{R^{\beta}} \frac{\partial V}{\partial X}$$

$$= \frac{SX2(V_{i+1} + V_{k-1,i+1}) - SX1_{i-1}(V_{i-1} + V_{k-1,i-1}) + (SX1 - SX2_{i-1})(V_k + V_{k-1})}{2\ \Delta X_i\ RC_j^{\beta}}$$

Finally,

$$PK_p = \mu_T\{2[(DUDR)^2 + (DWDX + UOR)^2 + (DVDX)^2]$$

$$+ (DUDX + DWDR - WOR)^2 + (DUDZ + DVDR)^2 + (DWDZ + DVDX)^2\} \qquad (2.90)$$

The buoyancy source term, GK_p, is also given in Section 2.4. In TEMPEST, G_k is evaluated using the previously determined diffusion coefficients (KD_j, KD_k, KD_i) and is given as

$$GK_p = \frac{\mu_T}{2\rho\sigma_T} \{[KD_j(\rho_{j+1} - \rho_p) + KD_{j-1}(\rho_p - \rho_{j-1})]\ \Delta R_j g_R$$

$$+ [KD_k(\rho_{k+1} - \rho_p) + KD_{k-1}(\rho_p - \rho_{k-1})]\ \Delta Z_k g_Z$$

$$+ [KD_i(\rho_{i+1} - \rho_p) + KD_{i-1}(\rho_p - \rho_{i-1})] \, \Delta X_i RC_j^\beta \, g_x\} \qquad (2.91)$$

2.7.6.4 Dissipation Equation

The modeled transport equation for dissipation of turbulent kinetic energy, ϵ, is given by Equation (2.14) and solved as described in Section 2.7.6.1 with the following definitions:

$$\Gamma_p = \epsilon_p$$

$$\tau = (\frac{\Delta t}{\rho v})_p$$

$$\dot{\Gamma} = \{\frac{\rho C_\mu k^{n+1}}{\mu_T} (C_{\epsilon 1} PK + C_{\epsilon 3} GK) v\}_p$$

$$C = (\frac{\rho C_{\epsilon 2} \epsilon^n}{k^{n+1}} v)_p$$

then $\theta = \frac{\tau}{1 - C\tau}$

Finally, the new time dissipation is computed as

$$\epsilon_p^{n+1} = \epsilon_p^n + \Delta\epsilon_p^{n+1} \qquad (2.92)$$

The combined flow and diffusion connectors, $KS_{p,s}$ and $KP_{p,s}$, are computed for the dissipation equation in exactly the same manner as for the kinetic energy equations. The only exception is the effective diffusion coefficients. These are computed as

$$\gamma_p = (\mu + \frac{\mu_T}{\sigma_\epsilon})_p$$

$$\gamma_{j+1} = (\mu + \frac{\mu_T}{\sigma_\epsilon})_{j+1}$$

$$\gamma_{k+1} = (\mu + \frac{\mu_T}{\sigma_\epsilon})_{k+1}$$

$$\gamma_{i+1} = (\mu + \frac{\mu_T}{\sigma_\epsilon})_{i+1}$$

2.7.6.5 Turbulence Equation Boundary Conditions

Boundary conditions must be applied to the turbulent kinetic energy equation and the dissipation equation at inflow and outflow boundaries, lines of symmetry, and solid walls. In the current version of TEMPEST, inflow boundary values of k and ϵ may be defaulted to simulate no inlet turbulence. They can be specified on the input file to prescribe known inlet conditions. At outflow boundaries, a computed zero gradient condition is imposed. For lines of symmetry, such as a pipe centerline, or at a free shear boundary, the zero-gradient condition is imposed.

At solid walls, a modified law-of-the-wall formulation is used to relate the level of turbulence to the mean shear. This expression takes the form

$$\frac{U_p}{(\tau/\rho)_w} (C_\mu^{1/2} k_p)_w^{1/2} = \frac{1}{\kappa} \ell n[E\ y_p \frac{\rho(C_\mu^{1/2} k_p)_w^{1/2}}{\mu}] \tag{2.93}$$

where $\kappa = 0.42$ and $E = 9.793$. The rationale behind this modified law-of-the-wall formulation is explained by Launder and Spalding (1972). It incorporates the features of the universal law of the wall in a region where uniform shear stress prevails and generation and dissipation of kinetic energy are in balance there.

Equation (2.93) is used in two ways. In the first application, it is used to model the drag on fluid near a solid wall by solving for $(\tau/\rho)_w$. This is a drag on fluid in a cell next to a wall and is applied in the solution of the momentum equations.

In the second application, Equation (2.93) is used to model the production of turbulence near a wall in the production source term, P_k. In this application, turbulent shear stress in the analytical expression for P_k (in Cartesian tensor notation)

$$P_k = \tau\ell_m \left(\frac{\partial U_\ell}{\partial x_m}\right) \tag{2.94}$$

is modeled by equating $(\tau/\rho)_w$ to the shear stress on the wall side of the fluid cell. The velocity U_p in Equation (2.93) becomes the vector quantity parallel to the wall in the three-dimensional flows.

The dissipation used in the kinetic energy equation at wall cells is determined as an integrated average value across the wall cell. This is done to accommodate the nonlinearity of the local dissipation near a wall.

A turbulent heat transfer model is used to determine a local heat transfer coefficient at a wall. The basis for the model is a modified-temperature law-of-the-wall expression. The local heat transfer coefficient is defined as

$$h = \frac{\rho C_p (C_\mu^{1/2} k_p)^{1/2}}{\sigma_{T,o}\left[\left(\frac{U_p}{(\tau/\rho)_w}\right) + P_j\right]} \tag{2.95}$$

This h is defined locally based on $T_w - T_p$ where T_p is the temperature in the computational cell next to a wall. P_j is the so-called P-function discussed by Jayatelleke (1969) and White (1974). The quantity $\sigma_{T,o}$ is a turbulent (thermal) Prandtl number equal to 0.9, according to Jayatelleke.

For fluids with a low Prandtl number, an additional P-function modification is made to account for the enhanced conduction region near a wall. This modification utilizes a slope/intercept matching approach of the near wall and far field. This approach was developed based on extensive data available in mercury and sodium pipe flows.

2.8 STABILITY

The computational stability of TEMPEST is governed by stability criteria associated with classical explicit techniques. The scalar equation solutions, however, contain an implicit continuation procedure which eliminates time step size stability restrictions for the Phase III portion of the computation. Time step size is thus limited by the momentum equation's stability criteria which are based on the cellwise Courant number and momentum diffusivity.

2.8.1 TEMPEST Procedure

TEMPEST has a provision for computing the stable time step automatically, an option that may be requested by specifying the input variable, PACE,. If the PACE, option is called, TEMPEST will compute a stable time step for Δt_s^{n+1}, based on information available at t^n, before proceeding with computation for the new time, T^{n+1}. If the time step is unstable, the momentum solution at Δt^{n+1} is "backed up" and recomputed using the new computed stable time step. The time step computed may not be stable for an explicit energy equation solution (or other scalar transport solutions); thus the scalar Phase III procedure is to first compute the scalar field explicitly, check for stability, and continue with an implicit procedure if the explicit criteria are violated. If the time step is stable, the explicit computation is accepted for the scalar field at t^{n+1}.

TEMPEST computational stability is also sensitive to the celerity of internal waves caused by density perturbations in quiescent, stratified fluids. In this case, the wave speed is related to the Brunt-Väisälä frequency, N, where

$$N^2 = - \left(\frac{g}{\rho_o}\right)\left(\frac{d\rho}{dZ}\right) \qquad (2.96)$$

Resolution of the wave form, as well as computational stability, requires that the time step be less than the wave quarter period. The program control parameter DENL, limits the time step to less than the wave speed quarter period, whereas the parameter DAMP, will damp out density perturbations and allow normal time-step control. The user can reduce the size of the input parameter CMAX, which reduces the time step size computed according to the stability criteria. Normally, CMAX = 0.99 (default value), but it may be set to any decimal fraction less than the default value. If the DENL, option is used, CMAX should be less than about 0.5 to resolve the internal wave shape.

2.8.2 Stability Criteria

Development of usable stability criteria may be found in Roache (1972). The automatic time-stepping procedure used in TEMPEST computes the stable time step for the next time advance using principles of the following simplified criterion:

$$\Delta t \le \min \left[\frac{1}{\sum_{i=1}^{3} \left(\frac{2\xi}{\rho \Delta x_i^2} + \frac{|U_i|}{\Delta x_i} \right)_p} \right. \qquad (2.97)$$

where, in this equation, the index i represents each of the three coordinate directions, R, Z, and X, and the subscript p denotes cell p. Equation (2.62) is, of course, a simplistic prescriptor which becomes somewhat more complex for the case of unequal cell sizes, cylindrical coordinates, and variable diffusivity.

The TEMPEST procedure is to apply expressions similar to Equation (2.62) to each computational cell for each transport equation, which then establishes the maximum time step for the entire system of equations. For the purpose of illustration, the stable time step for the R-direction momentum equation is estimated as follows:

$$\frac{1}{\Delta t_p} \geq E_p \{\frac{2}{\Delta R_{j+1}(\Delta R_j + \Delta R_{j-1})} + \frac{2}{\Delta R_j(\Delta R_j + \Delta R_{j+1})}$$

$$+ \frac{1}{R_j^{2\beta}} [\frac{2}{\Delta X_i(\Delta X_i + \Delta X_{i+1})} + \frac{2}{\Delta X_{i+1}(\Delta X_i + \Delta X_{i-1})}]$$

$$+ \frac{2}{\Delta Z_k(\Delta Z_k + \Delta Z_{k+1})} + \frac{2}{\Delta Z_{k+1}(\Delta Z_k + \Delta Z_{k-1})}$$

$$+ \frac{|U_p|}{\frac{1}{2}\,(\Delta R_j + \Delta R_{j+1})} + \frac{|W_p|}{\frac{1}{2}\,RC_j^{\beta}\,(\Delta X_i + \Delta X_{i+1})} + \frac{|V_p|}{\frac{1}{2}\,(\Delta Z_k + \Delta Z_{k+1})}\} \qquad (2.98)$$

3.0 TEMPEST INPUT DESCRIPTION

Input for TEMPEST is arranged in four major groups of cards[a] as follows:

Group 1. Initialization and numerical control parameters
Group 2. Alphanumeric control parameters
Group 3. Integer data
Group 4. Floating-point data

Each group must be ended by a blank card and arranged in the above order. The blank card signals the end of input for that particular card group and directs the computer to proceed to the next group. The end of Group 4 signals the end of all input. Each card within each group has either a numerical or alphanumerical key, so that data cards within any one group can be arranged in any order. The first cards in the entire data file must, however, be simulation label cards.

There are two special concerns the user has to be aware of. One is case sensitivity, the other is blank filling. The TEMPEST source code (normally) is distributed in lower case. Thus all alphanumeric comparisons are done in lower case. Throughout this manual, however, alphanumeric input is described in upper case type. In opening the "INPUT" file, the standard mode of 'BLANK = "ZERO"' is used. Experience has shown, however, that not all compilers recognize this. As such, on certain input records where integer input is requested in the middle of a field (e.g., in space 3 of an I5 field), the user may have to "zero" fill the field.

TEMPEST is designed to run in a normal mode using engineering units from the U.S. Customary System or the International System (SI) of units. The default mode uses the U.S. Customary System of units. Computation using SI units may be made by specifying SISY, on the CONT, Card, as explained in Section 3.2.1. Regardless of which system of units is to be used during a given execution, input data may be supplied using either system on a card-by-card basis (see Section 3.4). Table 3.1 gives the system of consistent units that is to be used for TEMPEST input.

---

[a] The word "card" is used to denote an 80-character input record.

TABLE 3.1. Input Data Units for TEMPEST

Quantity	Engineering System (ES)	International Standard (SI)
Length	feet (ft)	metre (m)
Mass	lb_m	kg
Density	lb_m/ft^3	kg/m^3
Velocity	ft/s	m/s
Acceleration	ft/s^2	m/s^2
Kinematic viscosity	ft^2/s	m^2/sec
Dynamic viscosity	$lb_m/s\text{-}ft$	kg/m-sec
Temperature	°F	°C
Absolute temperature	°R	°K
Thermal conductivity	Btu/ft-hr-°F	W/m-°K
Specific heat	Btu/lb_m-°F	J/kg-°K
Film/contact coefficient	Btu/ft^2-hr-°F	W/m^2-°K
Heat generation rate	Btu/ft^3-hr	W/m^3
Pressure	$lb_f/in.^2$ (psia)	Pa (Pascal)
Gas constant, R	Btu/lb_m-°R	J/kg-°K
Salinity		
Electric potential	volts	volts
Electric Conductivity	$(ohms\text{-}ft)^{-1}$	$(ohms\text{-}m)^{-1}$

---

a. The consistent "internal" unit of time is the second.

b. Certain engineering input data are required to be in hours.

c. For the purpose of I/O convenience, the user may specify the time unit (see TIME, Card). Only I/O time data are affected. Quantities in the above table are used with units as listed.

d. TEMPEST input requires temperatures for SI to be in degrees Celsius rather than Kelvin and angles to be in degrees rather than radians.

e. Pressure in the engineering system is used internally in lb_f/ft^2.

f. Options are provided for the input of certain data with units of inches or centimeters.

Two-dimensional simulations require a noded region that is only one cell in depth. However, the input is set up for three dimensions. For the user's convenience, indices that refer to the third dimension may be defaulted.

TEMPEST requires that certain files be available before execution can begin. During execution, additional I/O scratch files are used. Upon normal termination of a run, the user may create other files containing restart data and/or postprocessing data, depending on user-selected control options. A description of files utilized or created is presented in Section 4.2.

SIMULATION LABEL

Simulation labels begin the input. They may be any label occupying Columns 2-80 and any number of labels may be used. Any non-blank character occurring in Column 1 indicates the last label.

EXAMPLE LABEL CARDS:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
    This is a sample label
    followed by another, and
*   finally ended.
```

3.1 CARD GROUP 1: INITIALIZATION AND NUMERICAL CONTROL PARAMETERS

FORMAT (A4,1X,14F5.0,A4)

Each card is keyed by four alpha characters in Columns 1 to 4 and a comma in Column 5. The following card types are available.

SIZE,√	size parameters
TIME,√	time parameters
PRNT,√	printer output parameters
REST,	restart file parameters
PRES,	pressure/continuity iterations parameters
MISC,	miscellaneous parameters
POST,	postprocessing parameters
SEAL,	steady-state heat transfer parameters
TEMP,	transient heat transfer parameters
MOVY,	movie post-processing parameters

Notes:

1. The √ indicates required cards. The others are optional.
2. The comma in Column 5 is a separator and is used herein consistently. A space would serve the same purpose; however, it is suggested that the user always use a comma.

3.1.1 SIZE, Card: Setup Simulation Size

Field	Column	Data	Description
1	1 - 5	SIZE,	Card type key.
2	6 - 10	NR	Number of cells, R-direction. Default is 1.
3	11 - 15	NZ	Number of cells, Z-direction. Default is 1.
4	16 - 20	NX	Number of cells, X-direction. Default is 1.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
SIZE,   40   10    6
```

This card is required; its omission will abort execution.

SIZE,: The alpha word SIZE, must always occupy the first five columns. The comma is the separator.

NR,NZ,NX: Number of cells in the R, Z, and X directions, respectively. Data must be right-justified.

The modeled region must be divided into finite-difference cells arranged in rows/columns/tiers as indicated by Figure 3.1. The number of cells specified in each direction must always include an extra plane of cells on each side to accommodate boundary conditions, except in the third dimension of a two-dimensional case as explained below. Thus, a modeled region containing 5 x 5 x 5 computational cells must be specified as 7 x 7 x 7 (NR*NZ*NX) to accommodate boundary values on each side of the modeled region. An important exception to this requirement is that an additional plane of cells must be provided if a computed flow boundary (cell type 40) occurs on the west, south, or near side of the modeled region. If the sample region has a computed flow boundary on the south side, the size would be 7 x 8 x 7.

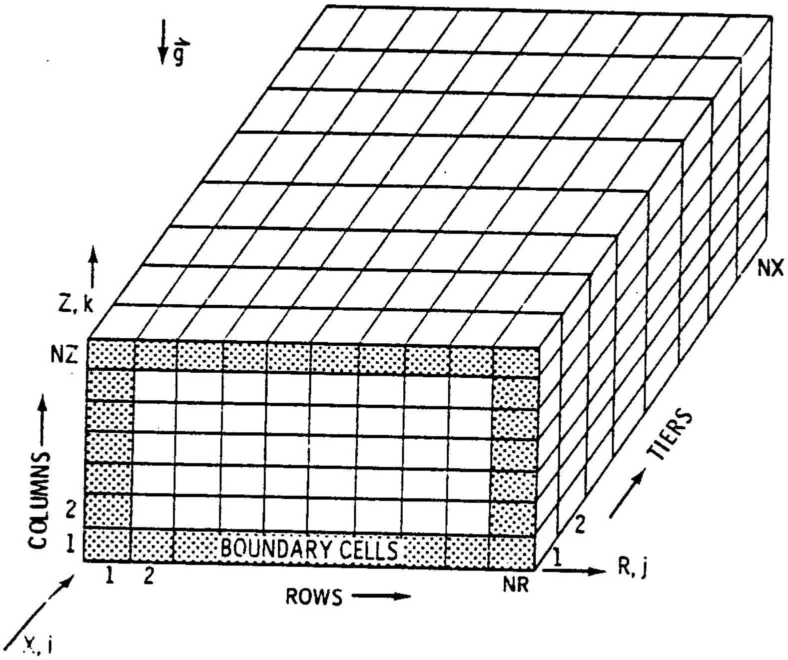


FIGURE 3.1. General Finite-Difference Cell Structure

TEMPEST has the capability to compute solutions for two-dimensional problems; that capability can be activated simply by setting the appropriate value of NR, NZ, or NX equal to 1 (or defaulted). A one-dimensional solution requires at least three rows of cells in the current version.

For application of TEMPEST in simulating geophysical flows, the Z coordinate should be parallel to the gravitational vector (perpendicular to the geopotential surface) as shown in Figure 3.2. If Coriolis forces are to be included, the inclination angle of the coordinate system with respect to the planetary equator is measured from the R-direction axis. For further information, see Section 3.4.3.2.

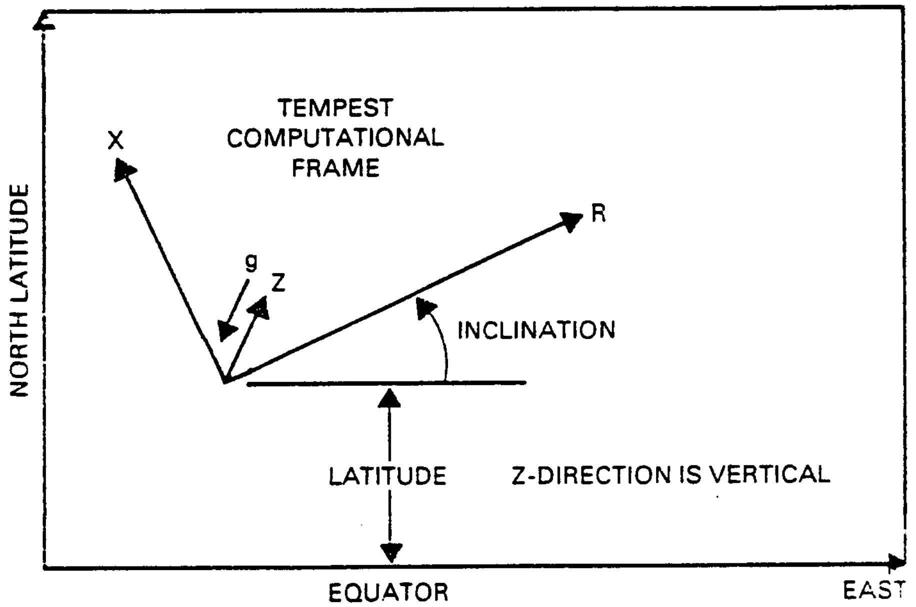


FIGURE 3.2. Geophysical Flow Coordinate System

3.1.2 TIME, Card: Time Parameters

Field	Column	Data	Description
1	1 - 5	TIME,	Card type key.
2	6 - 10	DT	Time step, seconds.* May be 0 if automatic time step requested (PACE,).
3	11 - 15	NSTEPS	Number of time steps.
4	16 - 20	TSTOP	Total simulation time, seconds.* Default: TSTOP = 10^{15} sec.
5	21 - 25	CMAX	Time step multiplier $0 < \text{CMAX} \leq 0.99$. Default = 0.99.
6	26 - 30	TADD	A time increment that may be added or subtracted from the restart time, seconds.*
7	31 - 35	CPULIM	CPU time limit check. Simulation is halted if CPU time is greater than CPULIM, decimal seconds. Default = 10^{15} seconds.
8	36 - 40	Blank	
9	41 - 45	DAMP	Damping parameter factor.
10-15	46 - 75	Blank	
16	76 - 80	TYMUNT	Time units for I/O. Default is seconds.

*Note: Units of minutes, hours, days, or years may also be used. The values must be consistent with the TYMUNT specification.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
TIME, .050  100    0  .95    0   20                                        HOURS
```

This card is required; its omission will abort execution.

TIME,: The alpha word TIME, must always occupy the first time columns.

DT: Simulation time step. TEMPEST will accommodate a fixed time step or compute a variable time step if PACE, is requested on the CONT, Card in Card Group 2. If PACE, is requested, the value of DT specified will be used for the first time step and thereafter recomputed internally. If DT is specified to be 0 or if the case is a restart, the first time step will be computed internally. It may be advantageous to specify the initial time step to prevent a very large initial step from being computed, especially in certain initially stagnant buoyancy-driven problems. A brief discussion dealing with computational stability and automatic time stepping is presented in Section 3.8.

NSTEPS: Number of time steps requested for this simulation. If TSTOP is nonzero, NSTEPS will default to the value of the internal constant, LARGE (LARGE = 10^6). If NSTEPS = TSTOP = 0, TEMPEST executes the setup routines and prints the debug options requested but terminates before executing the solution to the governing equations.

TSTOP: Total simulation time requested. A nonzero value will override NSTEPS as discussed above. If TSTOP = 0, it will default to the value of the internal constant BIG (BIG = 10^{15} in this version).

CMAX: Time step multiplier, ($0 < \mathrm{CMAX} \leq 0.99$). The default value for CMAX is 0.99. TEMPEST multiplies the time step Δt^n by CMAX when the time step is computed automatically. That is, $\Delta t^n = \mathrm{CMAX} * \Delta t^n$ where Δt^n is computed by stability criteria.

TADD: A time increment specified that may be added to the restart time. Thus, results on a restart file may be used to initiate a transient at a different starting time. Two situations are of interest: 1) when transient boundary conditions are used, one may begin at some time into the transient; and 2) when a steady-state initial condition is achieved through a transient simulation, all time parameters may be reset to zero to begin a transient simulation. By specifying TADD = 99999 all time parameters are reset to zero.

CPULIM: CPU time limit check, decimal seconds. Simulation will be terminated in a normal mode if CPU time is greater than CPULIM. The default value for CPULIM is BIG (10^{15}). CPULIM should be set 1 to 5 seconds less than the decimal time equivalent specified on the job control card (the job control card may require time in octal seconds). For small simulations, allowing 1 to 2 seconds should provide enough time for normal termination. For large and long-running-time jobs, it is best to be on the safe side by providing 5 to perhaps 10 seconds to ensure a normal termination. Normal termination is required to construct postprocessing and/or a restart file at the end of the simulation.

DAMP: A damping factor used in conjunction with control option DAMP, (see CONT, Card, Group 2) for elimination of internal (gravity) waves. The larger the value, the greater the damping of internal waves. Default = 1.

TYMUNT: An alpha word for the time units to be used for selected input/output. The default units are seconds. The available input data are the alpha names:

MINUT - Time units are in minutes.
HOURS - Time units are in hours.
DAYSS - Time units are in days.
YEARS - Time units are in years.

Time unit names must be specified exactly as indicated above and located in Columns 76 - 80. This option is only to obtain selected input/output in convenient units for long-term transport processes. Internal computations are executed using seconds for all cases.

3.1.3 PRNT, Card: Printer Output Control Parameters

Field	Column	Data	Description
1	1 - 5	PRNT,	Card type key.
2	6 - 10	TBPRT	Simulation time between printing output arrays, seconds.* Default = 10^{15} seconds.
3	11 - 15	NOUT	Number of time steps between printing output arrays. Default = 10^6.
4	16 - 20	NSOUT	Number of time steps between printing special array output. Default = 10^6.
5	21 - 25	IST	Array tier output start (Default = 1).
6	26 - 30	IEND	Array tier output end (Default = NX).
7	31 - 35	IOUT	Number of tiers between printer output. (Default = all levels between IST and IEND.)
8	36 - 40	KSKIP	Number of K levels between printer output. (Default = all levels.)
9	41 - 45	MSKIP	Number of time steps between monitor output. (Default = all time steps.)
10	46 - 50	Blank	
11	51 - 55	TBTPRT	Simulation time between print temperature arrays only. Default = 10^{15} seconds.

*Note: This value must be consistent with the time units on the TIME, Card.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
PRNT,    5    0    0    2   10    0    0    5
```

This card is required; its omission will abort execution.

PRNT,: The alpha word PRNT, must always occupy the first five columns.

TBPRT: Simulation time in seconds between printing output arrays. For example, if TBPRT = 10 seconds and the time step $\Delta t = 3$ seconds, the sequence of time steps used would be 3,3,3,1. Note that the last time step is adjusted internally from 3 to 1 second to obtain printing of simulation results at the specified time. Internally, TBPRT is used to set up an array called PTIME(N) which contains the print times. TBPRT is used only when the printing time increment is constant. Card Type 20 defined in Card Group 4 allows the user to specify an arbitrary sequence of printing times (PTIME(N)) and may be used in conjunction with TBPRT for selective printing. For instance, by specifying TBPRT = 2 a sequence of print times would be set up such as 2, 4, 6, 8, 10...seconds, up to the dimensions of PTIME(N). Values can be selectively added to the sequence using Card Type 20 to obtain a sequence such as 2, 4, 6, 6.1, 6.2, 6.8, 8, 10... . The default value for TBPRT is BIG sec (where BIG = 10^{15}).

NOUT: Number of time steps between printing output arrays. Default value is NOUT = LARGE (10^6). A non-zero value of TBPRT will default NOUT.

NSOUT: Number of time steps between printing special output arrays (for debugging purposes). The default value for NSOUT is LARGE (where LARGE = 10^6). If, however, special output is requested by the DBUG, card (Card Group 2) arrays will be written at normal print times governed by TBPRT, PTIME(N), or NOUT. The value specified here may be overwritten in Card Group 3, Card Type 6, to achieve successive debug outputs at selected time steps during execution.

IST, IEND, and IOUT: These parameters are used to control the output array printing. On an output page, the arrays may be written for either R-Z, R-X, or Z-X planes. R-Z plane arrays are the normal output mode. R-X plane arrays may be obtained by specifying RXIO, on the CONT, card in Card Group 2. Alternatively, Z-X planes may be obtained by specifying ZXIO, on the CONT, card in Card Group 2. IST is the plane in the third dimension where printing is to begin and IEND is the last plane to be printed. IOUT allows one to skip planes. The default values are IST = 1, IEND = NX (or NZ if RXIO), and IOUT = 1. For example, if IST = 2, IEND = 10, and IOUT = 2, printing would begin at the second plane (I = 2) and end at the tenth plane (I = 10), and only those planes that are evenly divisible by 2 would be printed. If IOUT = 1, every plane from 2 through 10 would be printed. If IOUT = 3, planes 2, 3, 6 and 9 would be printed.

KSKIP: This parameter serves a purpose similar to IOUT except that it provides for skipping lines of output on a page. Only numbers that are evenly divisible by KSKIP will be printed. The default value is KSKIP = 1 which permits all lines to be printed.

MSKIP: This parameter causes monitor output to be printed every MSKIP time steps. The default for MSKIP is 1. It is very useful in limiting printer output in long simulations.

TBTPRT: Simulation time in seconds between printing of temperature array only. This printing complements TBPRT for simulations in which temperature field is of primary interest. The default value is BIG sec (where BIG = 10^{15}).

<u>Notes</u>:

1. It is important to keep in mind that TEMPEST is capable of printing an enormous amount of output. The PRNT, card parameters, PTIME(N) (Card Group 4) and LSKAN(N) (Card Group 3) parameters, along with the KSKIP and MSKIP parameters, allow the user to select and control the output volume.
2. If ZXIO, is specified on the CONT, Card in Card Group 2, the Z-X plane will be output. For this mode, the above description of IST, IEND, and IOUT applies to the levels in the R-direction.

3. If RXIO, is specified on the CONT, card in Card Group 2, the R-X plane will be output. For this mode, the above description of IST, IEND, and IOUT applies to the levels in the Z-direction.

3.1.4 REST, Card: Restart File Parameters

Field	Column	Data	Description
1	1 - 5	REST,	Card type key.
2	6 - 10	TBTD	Simulation time between file dumps, seconds.* Default = 10^{15}.
3	11 - 15	ITPDST	File/tape dump number to restart (i.e., can restart at any record saved).
4	16 - 20	ITPDSV	Number of previous file/tape dumps on restart file (total specified on previous run output if saved) to be eliminated for file to be created this run. Default = 0.

*Note: This value must be consistent with the time units specified on the TIME, card.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
REST,   10    5    4
```

- Field 2: Dump every 10 seconds of simulation time
- Field 3: Restart simulation at Dump Number 5
- Field 4: Total number time dumps on saved file/tape (from previous run(s)) eliminated on new file (i.e., eliminate first four dumps and start new file with fifth dump)

This card may be omitted if the run is not restarting.

REST,: The alpha word REST, must always occupy first five columns.

TBTD: Simulation time between file dumps. TBTD is used to control file writing in exactly the same fashion that TBPRT (see PRNT, Card) is used for printing control. A specified file time sequence is constructed in increments of TBTD seconds and loaded to the FTIME(N) array. Arbitrary file times can be loaded into the FTIME(N) array in Card Group 4, Type 21. The default value for TBTD is BIG (10^{15}).

ITPDST: TEMPEST will restart from any file record number saved. For example, on a previous run file dumps may have been made at 10, 25, 35, 70, and 100 seconds. By setting ITPDST = 3, the simulation can be restarted at 35 seconds. ITPDST must always be specified for a restart.

ITPDSV: When restarting, TEMPEST will read all old records from the restart file up to and including the file designated by ITPDST (see above). These files will all be rewritten on the new file unless the value of ITPDSV is specified. In the above example card case, ITPDSV = 4 is specified, which will cause the first four dumps to be deleted from the new file; only time dump 5 will be written from the old restart to the new restart file. If ITPDSV = 0 for all restarts during a continued simulation, the last file will have all previous time dumps on it. If ITPDSV = ITPDST, then all previous time dumps are omitted from the new restart file.

3.1.5 PRES, Card: Pressure Iteration Control Parameters

Field	Column	Data	Description
1	1 - 5	PRES,	Card type key.
2	6 - 10	ITMAX	Maximum number of pressure iterations. (Default = 20)
3	11 - 15	ITMIN	Minimum number of pressure iterations . (Default = 1)
4	16 - 20	PAC	Pressure iteration acceleration factor (0 < PAC < 2.0). (Default = 1.5)
5	21 - 25	SMAX	Continuity or pressure iteration convergence criterion. (Default = 10^{-5})
6	26 - 30		Blank
7	31 - 35	DEXT	Sequential time step ratio limiter (not currently used).
8	36 - 40	IPRBL	Iteration interval to perform rebalancing. (Default = 5)
9	41 - 45	PERROR	Steady-state pressure error limit (not currently used).

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
PRES,   10    0    0  1-6
```

This card may be omitted if all default values are permissible.

PRES,: The alpha word PRES, must always occupy the first five columns.

ITMAX: Maximum number of pressure iterations to be taken during the Phase II calculation. A default value of 20 has been set for this version and will generally be more than sufficient to obtain a cellwise divergence of less than about 10^{-5}/sec. A notable exception to the general convergence rates is for the case of a labyrinth-type system where considerably more pressure iterations may be required.

ITMIN: Minimum number of continuity/pressure iterations to be taken during Phase II. The default value is 1, which is satisfactory for most all cases.

PAC: Continuity/pressure iteration acceleration factor ($0 < PAC < 2$). The default value is 1.5. The best value for PAC is problem dependent and not easily defined. Only a small amount of experience has been accumulated in using values other than 1.5. This experience has demonstrated that the rate of convergence is not largely influenced by different values of PAC, and 1.5 seems to be a reasonable value. In some tests the number of iterations has been reduced by 20% to 30%. Values both larger than and less than 1.5 may be tried. The user is encouraged to try different values, especially if several cases are to be run using the same geometry and similar flow conditions.

SMAX: The continuity/pressure iteration convergence criterion. The default value is 10^{-5}. The value of SMAX is checked against the cellwise change of the potential function Φ during one complete iteration. $\mathrm{MAX}|\Delta\Phi_p^i|$ is the maximum change of the cellwise value of Φ during iteration i. $\mathrm{MAX}|\Delta\Phi_p^i|$ is used for a convergence criterion because of convenience and, unfortunately, is not an absolute measure of the continuity error for the TEMPEST iteration techniques. The normal mode in TEMPEST is to use a modified LSOR technique with coarse mesh balancing. In the normal mode SMAX will be on the same order of magnitude as the absolute cellwise continuity error. That is, SMAX = 10^{-5} will generally give a cellwise continuity error of less than 10^{-4}/second. A very tight convergence is usually achieved with SMAX = 10^{-6}, although certain simulations may require SMAX to be less than 10^{-8} or so. The Gauss-Siedel method usually gives a larger discrepancy between SMAX and the continuity error, the absolute cellwise continuity error being about two orders of magnitude greater than SMAX. A cell-by-cell continuity check can be made by requesting special output in Card Group 2. If TEMPEST is run in the SI mode, SMAX will need to be set smaller by a factor of approximately 30. The default in the SI mode is set to 3×10^{-7}.

DEXT:	Sequential time step ratio limiter (not currently used).
IPRBL	Iteration interval to perform rebalancing. Rebalancing will be performed at each iteration evenly divisible by IPRBL. Default is 5.
PERROR	Steady-state pressure error limit (not currently used).

3.1.6 MISC, Card: Miscellaneous Parameters

Field	Column	Data	Description
1	1 - 5	MISC,	Card type key.
2	6 - 10	SFACT	Boundary velocity slip factor. ($-1 \leq \text{SFACT} \leq +1$, Default = -1). If SFACT = +1, boundary velocities are full slip; if SFACT = -1, boundary velocities are full no-slip.
3	11 - 15	NSP	Number of species. Default = 0.
4	16 - 20	Blank	
5	21 - 25	NVPR	(Not currently used.)
6	26 - 30	NVPZ	(Not currently used.)
7	31 - 35	NVPX	(Not currently used.)
8	36 - 40	TDAMP	(Not currently used.)
9	41 - 45	Blank	
10	46 - 50	TENM10	Constant = 10^{-10}.
11	51 - 55	LSTEPS	Number of steps between momentum solution. Default = 1.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
MISC,    1
```

This card may be omitted.

MISC,: The alpha word MISC, must always occupy the first five columns.

SFACT: Boundary velocity slip factor for all solid surfaces (except Type 20) ($-1 \leq \text{SFACT} \leq +1$). The default value is -1. If SFACT = -1, all fluid/solid boundaries are full "no slip"; if SFACT = +1 all boundaries are full "slip" except as noted.

NSP: Number of species simulated in mass transport version. Up to nine species may be treated.

NPVR, NPVZ, NPVX: Not currently used.

TDAMP: Not currently used.

TENM10: A constant = 10^{-10}, useful on certain computers where small differences between numbers are important to determining time step increments. Values typically equal to 10^{-6} or 10^{-7} may be required on some 32-bit machines.

LSTEPS: Number of time steps between solution of momentum equations. This parameter signals momentum solution at each integral multiple of LSTEPS. It is useful for certain slow hydrodynamic transients with weak thermal coupling. Default = 1.

Note:

1. SFACT value may be selectively overridden by input on Card Type 4, Group 3. Input is not needed for regions using the turbulence modeling.

3.1.7 SEAL, Card: Energy Equation Solution Control Parameters

This card is primarily for control of the steady-state heat transfer option which may be exercised for heat-transfer-only solutions or for obtaining a steady-state heat transfer solution at each hydrodynamic time step.

Field	Column	Data	Description
1	1 - 5	SEAL,	Card type key.
2	6 - 10	LITMAX	Maximum number of steady-state iterations. (Default = 20).
3	11 - 15	DTAC	Temperature iteration acceleration parameter.
4	16 - 20	TMAX	Temperature change convergence criterion. (Default = 0.001°).
5	21 - 25	QERROR	Steady-state heat balance check. If $\sum_{i=1}^{N} \lvert \mathrm{residual} \rvert_i \le \mathrm{QERROR}$ a steady-state temperature field has been attained. Used only if steady state desired. Default = 0.001 Btu/sec or 1.0 watt.
6	26 - 30	RESEMB	Temperature change required to re-evaluate thermal properties. (Default = 5°).
7	31 - 35	Blank	
8	36 - 40	IHRBL	Interval to perform energy equation rebalancing (not currently used).

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
SEAL,   10  1.6  .01    0    0
```

Card Group 1: SEAL, Card

This card may be omitted.

SEAL,: The alpha word SEAL, must always occupy the first five columns.

LITMAX: Maximum number of iterations to be taken in the steady-state heat transfer solution. A default value of 20 iterations has been set for this version of TEMPEST.

DTAC: Steady-state thermal solution acceleration factor ($0 < \text{DTAC} < 2$). The default value is 1.7 for pure conduction problems. The best value of DTAC is problem dependent and not easily defined. Very little experience has been obtained regarding the best value, and the user is encouraged to experiment with values other than the default value. A value greater than 1.0 may cause the solution to diverge in the presence of advection and is limited to a value of 0.99 in the present version.

TMAX: Convergence criterion for steady-state thermal solution temperature change. The default value is 0.001° (consistent units). If the temperature change during successive iterations is less than or equal to TMAX, TEMPEST will proceed with a heat balance convergence check (see QERROR). If the heat balance criterion is not satisfied, TMAX will be reduced by an order of magnitude (TMAX - 0.1*TMAX) and iteration will continue. This process will continue until both the TMAX and QERROR criteria have been satisfied or the number of iterations exceeds LITMAX.

QERROR: Convergence criterion for steady-state heat balance. If

$$\sum_{i=1}^{N} |\text{residual}|_i \leq \text{QERROR}$$

a thermal steady state has been reached. Again, very little experience has been gained using the QERROR criterion, so little guidance regarding the magnitude of QERROR can be offered. The default value is 0.001 Btu/sec or 1.0 watt.

RESEMB: The cumulative temperature change during iteration required to re-evaluate the temperature-dependent thermal properties. Currently TEMPEST takes the first five iterations without properties re-evaluation, regardless of the RESEMB criterion. The default value is 5° (consistent units). This option is not used for constant properties.

IHRBL: Interval to perform energy equation rebalancing. (Not currently used in this version.) Default = 5.

3.1.8 POST, Card: Postpocessing File Parameters

Field	Column	Data	Description
1	1 - 5	POST,	Card type key.
2	6 - 10	TPOST	Simulation time between postprocessing fill dumps, seconds.* (Default = 10^{15})
3	11 - 15	IPLSTR	Postprocess file dump number at which to start writing to new dump file. (Default = 1)
4	16 - 20	IPLSTP	Postprocessing file dump number at which to stop writing to new dump file. IPLSTP=0 (default) will cause all old dump files beginning with IPLSTR to be written to the new file.
5	21 - 25	Blank	
6	26 - 30	TBTTD	Time between temperature tape dumps. (Default = 10^{15} seconds).
7	31 - 35	NSTART	Filed temperature tape dump number to begin reading.

EXAMPLE CARD:

```
                                 Columns

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
POST,    5    3    5
```

Parameters on this card instruct TEMPEST to:

- Field 2: create a postprocessing record at every 5 seconds.
- Field 3: start the new file (REPOST) containing file dumps from the old file (INPOST) beginning with the third file dump on the old file.
- Field 4: place files up to and including the fifth dump on the new file (REPOST).

For this example, files 3, 4, and 5 from the old file INPOST will be written to the new file REPOST. Thus there will be three files on REPOST and new file dumps from the current run will begin as file number 4. This card may be omitted if a previously created file will not be read.

POST,: The alpha word POST, must always occupy first five columns.

TPOST: Simulation time between postprocessing file dumps. TPOST is used to control file writing in exactly the same manner that TBPRT (see PRNT, Card) is used for printing control. A specified file time sequence is constructed in increments of TBTD seconds and loaded into the PPTIME(N) array. Arbitrary file times can be loaded into the PPTIME(N) array in Card Group 4, Type 22. The default value of TPODST is BIG (10^{15}).

IPLSTR and IPLSTP: The starting and stopping file dump numbers, respectively, which are to be read from a previously created postprocessing file and written to the new postprocessing file. PRED, (CONT, Card, Group 2) must be specified in order to read from an old file, and PSAV, (CONT, Card, Group 2) must be specified in order to write to a new file. Files from IPLSTR (Default = 1) to IPLSTP inclusive will be read and written. IPLSTP (Default = 0) will cause all old file dumps to be written to the new file. If IPLSTP = 0 and IPLSTR > 0, all dump file numbers from IPLSTR on will be written to the postprocessing file.

TBTTD: Time between temperature tape dump. This is useful for more frequent dumping of temperature field data to temperature field post-processing file. Default is 10^{15} seconds. (Not currently used.)

NSTART: Filed temperature tape dump number to begin reading. (Not currently used.)

3.1.9 TEMP, Card: Implicit Transient Heat Transfer Solution Parameters

Field	Column	Data	Description
1	1 - 5	TEMP,	Card type key.
2	6 - 10	FRNK	Implicit factor for transient solution. (Default = 0.6).
3	11 - 15	LIMP	Time step limiter (default = 5.00). $\Delta t = LIMP*\Delta t_E$ where Δt_E is the maximum stable explicit time step.
4	16 - 20	DTIMAX	Implicit time step limiter.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
TEMP, 0.6    3
```

This card may be omitted.

TEMP,: The alpha word TEMP, must always occupy the first five columns.

FRNK: Transient solution implicit factor ($0 \leq FRNK \leq 1.0$) where FRNK = 1.0 is full implicit. FRNK = 0.5 is Crank-Nicholson. Default is 0.6.

LIMP: Parameter used to limit the computation time step based on the maximum stable explicit time step. Frequently during the startup of a natural convection problem, the maximum stable time step for the momentum solution is very large. This is especially true for fluids of low viscosity where the computational cells are large and the velocities are zero everywhere. Since the initial time step is governed by the momentum solution, the computed time step may be 10s, 100s, or even 1000s of times greater than that allowed by the thermal explicit solution stability criterion. Thus, the temperature changes computed during the first few time steps can be very dramatic, inaccurate, and can lead to instability and/or poor convergence in the momentum solution. For such situations, it may be necessary to limit the advance of the thermal solution. Alternately a very large value may be useful in computing long simulation time, slow thermal transients.

DTIMAX: Implicit time step limiter. This is the maximum time step which may be taken in the implicit (viscosity) mode. Default is DT, the initial time step, if used, or 10^{15}, if not. (Only enabled if CONT,SCIM, selected and the appropriate coding module is in place.

3.1.10 ELEC, Card: Not Used

3.1.11 MOVY, Card: Movie Data Dumping Parameters

Field	Column	Data	Description
1	1 - 5	MOVY	Card type key.
2	6 - 10	IDIR	Indicator for viewing direction (may not be defaulted).
3	11 - 15	IPLNO	Indicator for plane number of data to dump. (Default = 1.)
4	16 - 20	TNTRVL	Time interval in consistent units for dumping movie data.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
MOVY,    1    3
```

Notes:

1. Data are dumped at each TNTRVL step; thus there is a potential for creating a very large file. Be cautious in its use.
2. Currently only data in one plane may be dumped for later post processing. Because no read/write of previous data are done, the user must use care during simulations in which restarting is done.

MOVY: The alpha word MOVY, must always occupy the first five columns.

IDIR: Indicator for identifying viewing direction. Possible values are:

= 1-View is parallel to X axis (e.g., viewing plane is R-Z).

= 2-View is parallel to Z axis (e.g., viewing plane is R-X).

= 3-View is parallel to R axis (e.g., viewing plane is Z-X).

IPLNO: Indicator for identifying plane number (along viewing axis) for viewing plane. Default is 1.

TNTRVL: Time interval for dumping movie data.

3.2 CARD GROUP 2: ALPHANUMERIC CONTROL PARAMETERS

FORMAT (16(A4,1X))

Each card within Card Group 2 is keyed by four alpha characters in Column 1 to 4 and a separator in Column 5. The following card types are available:

CONT,√	program control options
AOUT,√	printer output options
DBUG,	debugging options
PLOT,	postprocessing file options
FILM,	film (movie) control options
SEDI,	sediment (marine) transport options.

Notes:

1. The √ indicates required cards. The other cards are optional.
2. A comma is used herein as a separator. Any other separator may be used, but a comma is recommended for consistency.

3.2.1 CONT, Card: Program Control Options

CONT,: The alpha word CONT, (including comma or any other separator) must always occupy the first five columns.

The following options may appear in any order on the CONT, card. More than one CONT, card may be used if required or convenient. Commas (or any other separator) must be included.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
CONT,CYLN,HEAT,TESS,TURB,SAVE,SISY,
```

CYLN,: Used to specify cylindrical coordinates. This should be omitted from control list if Cartesian coordinates are to be used.

HEAT,: Used to call for solution to the energy equation.

MAST,: Selection of this option indicates that mass transport of species is to be computed.

SALT,: When selected with MAST, this option enables computation of salt water concentration distribution.

TESS,: Used in conjunction with hydrodynamic simulation to obtain a steady-state energy equation solution at each hydrodynamic time step. This option is useful for achieving steady state in flow systems that are thermally slow in responding. Do not use with the SEAL, option.

SEAL,: Steady-state heat transfer option. To be used for heat-transfer-only computations. A fixed flow field may be used. Do not use with the TESS, option.

UNCP,: Specify UNCP, in the control list if thermal effects do not interact with the hydrodynamic solution through the action of buoyancy. Use UNCP, where natural convection or buoyancy may be eliminated from consideration. Omit the option if simulation is thermally coupled.

INVS,: Specify INVS, in the control list if the hydrodynamic solution is inviscid. INVS, will cause all viscous terms, both laminar and turbulent, to be suppressed in the solution to the momentum equations. Omit this option to suppress it. Note that use of INVS, does not yield potential flow, since the flow field can contain vorticity. The flow field is simply nondiffusive (except for numerical diffusion).

BESQ: If BESQ, is specified, the hydrostatic pressure field is subtracted from the momentum equation, and the resulting calculated pressure field is the deviation from the reference hydrostatic. The hydrostatic distribution for each flow region is computed from the density corresponding to the reference temperature specified on the materials card, Card Group 4, Type 6. This option is useful for simulation in a free environment where the boundary flow condition is computed (e.g., flow about a heated cylinder in a free space). Omit this option to obtain a total pressure field.

VFIX: Specification of the control option VFIX, fixes the velocity field throughout the modeled regions regardless of cell types. This option is particularly convenient for cases in which the velocity field is to be computed and then held constant.

VVIS,: Use of the VVIS, control option directs TEMPEST to include temperature-dependent molecular viscosity terms in the computation. Viscosity values are computed from either the built-in library or table input. Subroutine VISSET will be called for table lookup and spatial interpolation, and the entire Tilde phase computation will require about 30% more CPU time. Omit this option to suppress it.

TURB,: Use of the TURB, control option directs TEMPEST to include variable turbulent viscosities in the computation. The current version of TEMPEST includes a two-equation turbulence model. Subroutine VISSET will be called to spatially interpolate cell-centered values of turbulent viscosity to cell edges. It is possible to put a simple algebraic model into the code at the beginning of subroutine VISSET. Omit this option to suppress it.

VKAY,: Use of the VKAY, control option directs TEMPEST to use temperature-dependent thermal conductivity in the energy equation solution. Properties are obtained from the built-in library or from tabular input. Omit this option if thermal properties for all materials are to be treated as constant in the energy equation solution.

DAMP,: This control option permits the user to suppress internal wave perturbations so that the automatic time stepping is not limited by the Brunt-Väisälä frequency. Use DAMP, only in cases of stratification where velocities are expected to be very small (near quiescent) and the effects of internal waves are unimportant. Omit this option otherwise. Do not use DAMP, if the DENL, option is to be used.

DENL,: This control option should be used only if the TEMPEST automatic time stepping procedure is to use Brunt-Väisälä frequency criteria as an additional time step limiter. DENL, should be used if the motion of internal waves is to be predicted. If internal waves are to be computed, the user should also set CMAX (see TIME, Card) to 0.5 or less for improved accuracy in computing the wave form. Omit this option for normal time stepping or when DAMP, is used.

NBAL,: If NBAL, is specified, <u>all</u> coarse mesh balancing will be suppressed. This mode is <u>not</u> suggested but has been included as an option for experimentation. Unless the simulation is an experiment, always omit this option. Certain labyrinth flow path problems may, however, converge faster when this option is used.

BALR, BALZ, BALX,: Include these options to use coarse mesh balancing along the R-, Z-, and X-directions, respectively. Any combination may be used. Omitting all balancing options including NBAL, will default to balancing in all directions possible, which is the normal mode of operation. TEMPEST will not balance in a given direction unless the region to be balanced is greater than three fluid cells in the direction indicated. A two-dimensional simulation will thus balance only along the coordinates used. Special cases where the flow is nearly one dimensional may benefit from balancing only in the direction of flow. If this is the R-direction, one may obtain a slight decrease in running time by specifying only BALR,.

MONT,: Specify this control option if it is desired to monitor velocities, pressures, and temperatures at every time step. The MONT, option is used in conjunction with Card Group 3, Type 5, where <u>up to 16</u> sets of cell indices may be specified. Omit this option to suppress printing of monitor data.

DTIM,: The DTIM, control option monitors and prints the code execution time summary. The time summary includes the CPU time required for each of the major computational phases and the total time required for the current time step on a millisecond/time-step-cell basis. This is a very useful option for determining CPU time distribution and the CPU time penalties required for activating options that may not be required. The time step size, number of continuity/pressure iterations required for the current time step, and scalar potential, Φ, error is also printed. Omit this option to suppress it.

PACE,: Use of this control option will activate the TEMPEST automatic time-stepping logic. Omit this for a constant time step.

SCAL,: Use of this option scales the initial first 15 time steps of a simulation by factors of N/15 times the explicit table value. It may be useful for startup of buoyancy-induced flows from rest. However, automatic time-stepping logic in TEMPEST (including a time-step backup, if necessary) will handle startup of most all problems.

FORM,: The normal format for the printed arrays is 1PE11.3. If FORM, is specified the temperature and velocity arrays will be printed with an F11.4 format. Omit this option for the normal 1PE11.3 format.

RXIO,: The normal form of the output arrays is to print R-Z planes (for a constant position in the X-direction). It is often useful to print R-X planes or arrays with a constant position in the Z-direction (e.g., cross sections of a pipe). By specifying the control option RXIO), R-X plane array printing is obtained. Omit this option to obtain R-Z planes.

ZXIO,: By specifying the control option ZXIO), Z-X plane array printing is obtained. Omit this option to obtain R-Z planes.

SISY,: Specify SISY, if the normal computational mode is to be in the International System of Units. Omission of this option will default to the U.S. Customary Engineering System (see Table 3.1).

The following options control the reading/writing of restart and postprocessing files. The user is referred to Section 3.5 for a description of these utility files.

READ,: This control option directs TEMPEST to restart from a previously saved restart file. Control parameters are specified on the REST, card in Card Group 1. Omit this option if the run is not a restart.

SAVE,: Create restart files. SAVE, is to be used in conjunction with parameters specified on the REST, card in Card Group 1. A file will be saved at the end of a normal termination. Omit this option if no saved files are desired.

PRED,: Specify this option to read a previously written postprocessing file. Omission of the option suppresses it.

PSAV,: Specify this option to write postprocessing file. Omission of the option suppresses it.

MSAV,: Specifying this option directs TEMPEST to write the monitor output to a postprocessing file called MONSAV. If the option is not specified, writing is suppressed. See Card Group 3, Type 5, monitor cell specification, for further information.

SAVT,: Specifying this option causes temperature field (only) results to be saved on a file called TAPE22 according to parameters TBTTD specified on the POST, card, Card Group 1.

REDT,: Specifying this option causes previously saved temperature field (only) data to be read on restart from TAPE21.

MOVY,: Specifying this option causes data to be dumped to a file called MOVDAT according to parameters specified on the MOVY, Card, Group 1.

The following control options are module specific. Their selection is only appropriate if logic is in place for the code version being run. At present none are available in the base version N, Mod 31.

THEX,:	Selection of this option enables treatment of (real) gases as thermally expanding (but not a function of pressure).
COMP,:	Selection of this option enables computation of fully compressible flow. The real gas assumption is invoked for gases. Requires required additional inclusion of state conditions at this time.
PINX,:	Disables hydrostatic pressure initialization and allows initial pressure fields to be set by input.
PORE,:	Selection of this option enables treatment of computational cells with a volume porosity and surface permeability model.
EMFR,:	This option enables electric field solution.
SURF,:	This option enables computation of moving free surface.
MULT,:	Selection of this option enables rebalancing in multiple regions.
FREZ,:	This option enables selective "freezing" of subregions of the computational domain. In "frozen" regions, momentum changes are not computed, but scalar variables may be advected through them.
SETL,:	Selection of this option enables settling solids to be treated. Fixed settling velocities must be prescribed. (This is a simplified model to complement marine version sedimentation models.)
SEDT,:	This option enables marine sedimentation models.
LAMR,:	CONTRL(3). (Not currently used.)
TDIM,:	CONTRL(24). Two-dimensional flag.
STDY,:	CONTRL(25). Firm solution flag.
TSTD,:	Enable steady-state solution of turbulence model equations at each hydrodynamic time step. (Not currently used.)

TEBL,: CONTRL(34). Enable energy equation rebalancing. (Rebalancing not currently enabled.)

PASS,: CONTRL(35). Passive contaminant flag.

QRAD,: CONTRL(37). (Not currently used.)

PFLO,: CONTRL(40). Potential flow flag.

MRED,: Enable reading of previous monitor file data on restart. (Not currently used.)

NCOS,: CONTRL(47). Nonconservative differencing flag. (Not currently used.)

NOEB,: Specifying the option turns off coarse mesh balancing of the electric field solution.

MINP,: CONTRL(57). Flag to skip MAXIMP check.

PSLT,: Specification indicates that the "power-split" option of the electric field solution is to be enabled. This is a specialty option coded to treat a special dual electrode pair configuration.

3.2.2 AOUT, Card: Output Control Options

AOUT,: The alphanumeric word AOUT, (including comma or any other separator) must always occupy the first five columns.

The following options are used for selecting the output arrays to be printed. The options may be arranged in any order, and multiple cards may be used as necessary or convenient.

EXAMPLE CARD:

```
                                   Columns

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
AOUT,VELR,VELZ,VELX,PRES,TEMP,TKIN,TDIS,COND,
```

VELR,: R-direction velocity array to be printed. Omit this option to suppress printing.

VELZ,: Z-direction velocity array to be printed. Omit this option to suppress printing.

VELX,: X-direction velocity array to be printed. Omit this option to suppress printing.

PRES,: Pressure distribution to be printed. Omit this option to suppress printing.

DELP,: Print pressure difference, $P-P_O$ (local pressure minus reference pressure). Omit this option to suppress printing.

TEMP,: Temperature distribution to be printed. Omit this option to suppress printing.

TKMN,: Print turbulence monitor quantities. Omit this option to suppress printing.

TKIN,: Turbulent kinetic energy distribution to be printed. Omit this option to suppress printing.

TDIS,: Dissipation of turbulent kinetic energy distribution to be printed. Omit this option to suppress printing.

EDDY,:*(a)	Turbulent viscosity distribution to be printed. Omit this option to suppress printing.
KVIS,:*	Molecular viscosity to be printed. Omit this option to suppress printing. Values are the sum of molecular and turbulent viscosities if the TURB, option on the CONT, card is selected.
QGEN,:*	Heat generation rate array to be printed. Omit this option to suppress printing.
DENS,:*	Density array to be printed. Omit this option to suppress printing.
DIVG,:*	Cell continuity error to be printed. Omit this option to suppress printing.
COND,:*	Material thermal conductivity to be printed. Omit this option to suppress printing.
FLUX,:*	Cell face heat flux to be printed. Omit this option to suppress printing.
VOLF,:	Species volume fraction to be printed. Omit to suppress printing.
MASF,:	Species mass fraction to be printed. Omit to suppress printing.
C(#),:	Species concentration number to be printed. Only those selected will be printed (# is an integer from 1 to 9).
SPMN,:	Enable monitor printing of species concentrations at selected cells. Omit to suppress printing.

Following output options are module specific.

SURF,:	Surface height to be printed. Omit this option to suppress printing.
VSMN,:	Enable monitor printing of surface velocity and parameters at selected cells. Omit to suppress printing.
EMFR,:	Enable printing of electric field potential. Omit to suppress printing.

(a) Special output controlled by NSOUT (PRNT, Card) or LSKAN array (Card Group 3, Type 6).

AMPS,:	Enable printing of electric current. Omit to suppress printing.
RESI,:*	Enable printing of electrical resistivity. Omit to suppress printing.
EFMN,:	Enable monitor printing of electric potential at selected cells. Omit to suppress printing.
QJMN,:*	Enable printing of Joule heating array. Omit to suppress printing.
ECMN,:	Enable monitor printing of electric current flux. Omit to suppress printing.
MCRO,:	Enable printing of (output) units in miles or kilometers. Omit to suppress printing.

3.2.3 DBUG, Card: Debug Control Options

DBUG,: The alphanumeric word DBUG, (including comma or any other separator) must always occupy the first five columns.

TEMPEST debug output control options include selections that are useful for both debugging code modifications and for normal output. Generally, debug options that deal with internal indices bookkeeping are useful only if one understands the coding structure and should not be called for as normal output. The options INIT, PROP, TTBL, MTYP, DCID, FCID, HTCN, DATA, CFDG, CFHT, and perhaps SIZE, are options for normal use.

EXAMPLE CARD:

```
                                     Columns

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
DBUG,INDX,SCON,PROP,DATA
```

Coding Debug Options:

BUGS,: By specifying this debug option, *all* debug options are activated. Omit this option to selectively activate options.

INDX,: Prints all cell bookkeeping indices and data. This information will *not* be of value to the casual user but is of value for code modification debugging. Omit this option to suppress it.

SCON,: Prints out values in the SC(N) array. Again, information is valuable only for internal modification and debugging. Omit this option to suppress it.

ADIP,: Prints out alternating direction method bookkeeping data. This option is for internal debugging only. Omit this option to suppress it.

BALI,: Prints out coarse mesh balancing bookkeeping indices. This option is for internal debugging only. Omit this option to suppress it.

HTCN,:(a)* Prints out heat transfer connectors computed in subroutine SEMBLE. These connectors have values as described in Section 3.4.6. Omit this option to suppress it.

DRAG,:* Prints out drag factors computed in subroutine MOMENT. These values are $(1 + \Delta t \bullet FRN_p)^{-1}$, $(1 + \Delta t \bullet FZN_p)^{-1}$ and $(1 + \Delta t \bullet FXN_p)^{-1}$. Omit this option to suppress it.

TILD,: Prints out TILDE phase velocity field (result of momentum solution but before continuity correction). Omit this option to suppress it.

Normal Options:

SIZE,: Prints out array sizes required for simulations. This option is useful for determining dimensions of arrays that are problem dependent; it also gives entry points for INDEX(N) and TEXT(N) arrays for debugging purposes. Omit this option to suppress it.

INIT,: Prints initial condition arrays (U, V, W, T, etc.) or restart arrays. Omit this option to suppress it.

PROP,: Prints out material properties as computed for direct look-up tables. Temperature evaluation points are preset in the code. Omit this option to suppress it.

TTBL,: Prints out transient boundary condition tables. TTBL, should be called for if boundary condition tables are used to provide a record of the simulation. Omit this option to suppress it.

MTYP,: Prints out the cellwise materials type map. This option is very useful when a complex model is initially set up and should always be used until the user has checked all cell material types. Omit this option to suppress it.

(a) Special output controlled by NSOUT (PRNT, Card) or LSKAN array (Card Group 3, Type 6).

NTYP,: Prints out the cellwise node type map. This option is very useful when a complex model is initially set up and should always be used until the user has checked all cell types. Omit this option to suppress it.

DCID,: Prints out the cellwise flow drag coefficient identifiers. The identifiers are those specified on Card Type 4 (Card Group 3) and/or those determined internally for turbulent law-of-the-wall drag. Omit this option to suppress it.

FCID,: Prints out the cellwise heat transfer coefficient identifiers. The identifiers are those specified in Card Type 4 (Card Group 3). Output for cells with no heat transfer coefficient specified will contain asterisk(*) to enhance visual locations. Omit this option to suppress it.

CFDG,: Prints out a listing of the coefficients of flow drag and corresponding identification numbers, as specified on Card Type 17 (Card Group 4). Omit this option to suppress it.

CFHT: Prints out listing of the coefficients of heat transfer and corresponding identification numbers as specified on Card Type 18 (Card Group 4). Omit this option to suppress it.

DATA,: Prints out a listing of the input data file (exactly as typed). This is a very useful option and perhaps should be exercised for every run to log the input file. It is also useful for identifying input errors. Omit this option to suppress it.

TCON,: Prints turbulence modeling constants. Omit this option to suppress it.

STAR,:(a) Prints out momentum solution phase stability map (explicit stability). The results have units of seconds. The map will illustrate the maximum stable time step size for each computational cell. This includes both Courant and viscous contributions. Omit this option to suppress it.

(a) Special output controlled by NSOUT (PRNT, Card) or LSKAN array (Card Group 3, Type 6).

CELL,: Same as BUGS,.

PCON,: Prints out the pressure connectors. Omit this option to suppress it.

ADIH,: (Not currently used.)

VPOR,: Enable printing of cell-wise volume porosity.

APOR,: Enable printing of cell-wise surface area permeability.

3.2.4 PLOT, Card: Postprocessing Output Control Options

PLOT,: The alphanumeric word PLOT, (including a comma or any other separator) must always occupy the first five columns.

Output options are as follows:

EXAMPLE CARD:

```
                                    Columns

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
PLOT,VELR,VELZ,TEMP,
```

VELR,: R-direction velocity record to be created
VELZ,: Z-direction velocity record to be created
VELX,: X-direction velocity record to be created
TEMP,: Temperature record to be created
QGEN,: Heat generation record to be created
PRES,: Pressure record to be created
DENS,: Fluid density record to be created
TKIN,: Turbulent kinetic energy record to be created
TDIS,: Dissipation record to be created
EDDY,: Turbulent viscosity record to be created
MASF,: Species mass fraction record to be created
VOLF,: Species volume fraction record to be created. Note: MASF, and VOLF, are mutually exclusive; only one may be selected. VOLF takes precedence if both are selected.

The following are module-dependent options.

EMFR,: Electric field potential record to be created.
JOUL,: Joulian heat generation record to be created.
AMPR,: R-direction current density record to be printed.
AMPZ,: Z-direction current density record to be printed.
AMPX,: X-direction current density record to be printed.

3.2.5 FILM, Card: Movie Control Parameters

FILM,: The alphanumeric word FILM, (including comma or other separator, must occupy the first five columns).

The option selected on this card enables scaling of color or intensity according to a scalar variable.

EXAMPLE CARD:

```
                                Columns

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
FILM,TEMP,
```

Options are:

PRES,:	Pressure is to be the scalar variable used for scaling with color or intensity.
TEMP,:	Temperature is to be the scalar variable used for scaling with color or intensity.
CONC,:	Concentration (mass fraction) is to be the scalar variable used for scaling with color or intensity.
NONE,:	No color or intensity scaling is to be done. This is default. Particle tracking of flow is to be a uniform color or intensity.

3.3 CARD GROUP 3: INTEGER INPUT

Card Group 3 provides integer input for the following information:

- cell types
- material types
- boundary value table identification numbers
- source value table identification numbers
- film/contact coefficient identification numbers
- flow drag coefficient identification numbers
- special output array flags and cell monitor indices identification.

Cards may be arranged in any order within the group, but caution must be used when overwriting. All data in this card group are input with the following format:

FORMAT (14I5)

On certain card types, more than one piece of information is contained within a given I5 field. In using these fields, the user should be aware of whether his computer "blank fills" or "zero fills" trailing blanks in the field.

Throughout this card group, notation "array (N)" is used in conjunction with specifying (J, K, I) indexing. The latter describes cell location in terms of:

J-index (R-direction) location
K-index (Z-direction) location
I-index (X-direction) location

for a regular (column, row, tier) cell structure. Internal bookkeeping logic converts the three index counters (J,K,I) to a corresponding one-dimensional array storage location (N) according to the size of the simulation (NR,NZ,NX) and vice versa.

3.3.1 Card Type 1: Cell Types, Material Types, and Boundary Value Table Identification

This card type provides for defining cell type and corresponding material, boundary, and source term table identifiers.

Field	Column	Data	Description
1	1 - 5	NT(N)	Cell node type of array.
	6 - 8	MT2(N)	Secondary cell material type of array.
2	9 - 10	MT(N)	Cell material type of array.
	11	MR	R-direction momentum source flag.
	12	MZ	Z-direction momentum source flag.
	13	MX	X-direction momentum source flag.
3	14 - 15	NTAB	Boundary value table number for this array of cells.
4	16 - 20	NTABQ	Heat generation table number for this array of cells.
5	21 - 25	J1	J-index at start of array.
6	26 - 30	J2	J-index at end of array.
7	31 - 35	K1	K-index at start of array.
8	36 - 40	K2	K-index at end of array.
9	41 - 45	I1	I-index at start of array.
10	46 - 50	I2	I-index at end of array.
11	51 - 55	JM	If reflective cell in K,I plane, specify J-index of opposite (mutual) K,I plane.
12	56 - 60	KM	If reflective cell in J,I plane, specify K-index of opposite (mutual) J,I plane.
13	61 - 65	IM	If reflective cell in J,K plane, specify I-index of opposite (mutual) J,K plane.
14	70	KIND	Always the integer 1.
	73 - 80		Identification if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   30    1    1        1    6    1    1    2    5                   1  NODETYPE
```

3.3.1.1 Cell Types (Field 1)

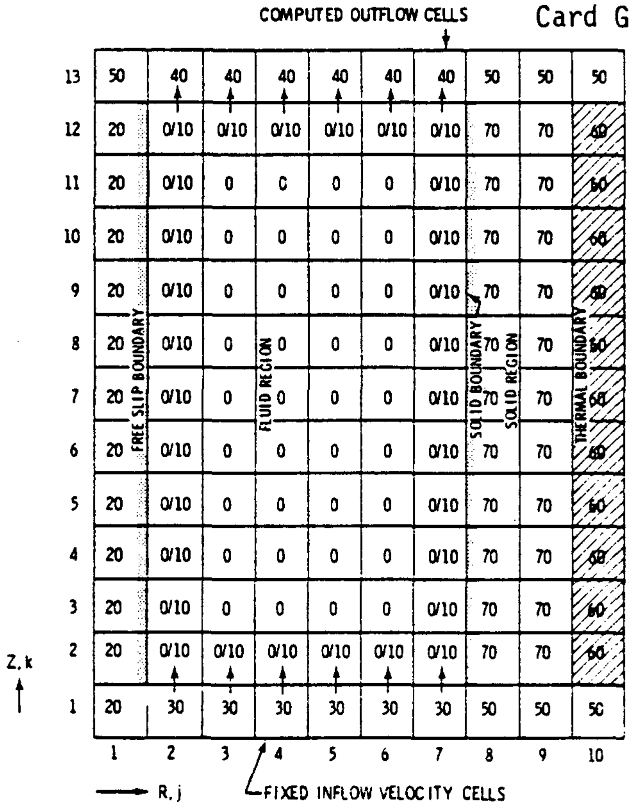
Also see Figure 3.1.

The following cell types are available for use in TEMPEST except as noted:

Type 0: The Type 0 (zero) cell is a fluid computational cell that does not lie on any boundary. The momentum equations are applied to these cells as is the energy equation if HEAT, is called for and other scalar equations. In Figure 3.3, J = 2 through J = 7, K = 2 through K = 12, and I = 1 through I = 1 would be Type 0. The internal cell typing will change all Type 0 specifications made at input to Type 10 if a boundary cell is adjacent. This is shown in Figure 3.3 by 0/10, indicating that the user specifies 0 and TEMPEST changes the type to 10.

Type 20: Type 20 cells are rigid, free-slip boundary cells. Flow is not allowed to penetrate, and the slip factor is treated internally as +1. The surface is treated as adiabatic. Common uses of the Type 20 cell are:

- a free liquid surface with no heat transfer
- the center phantom cells in cylindrical coordinates.

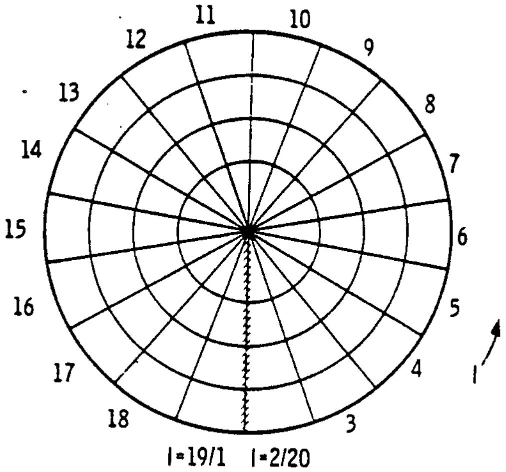


	1	2	3	4	5	6	7	8	9	10
13	50	40	40	40	40	40	40	50	50	50
12	20	0/10	0/10	0/10	0/10	0/10	0/10	70	70	60
11	20	0/10	0	0	0	0	0/10	70	70	60
10	20	0/10	0	0	0	0	0/10	70	70	60
9	20	0/10	0	0	0	0	0/10	70	70	60
8	20	0/10	0	0	0	0	0/10	70	70	60
7	20	0/10	0	0	0	0	0/10	70	70	60
6	20	0/10	0	0	0	0	0/10	70	70	60
5	20	0/10	0	0	0	0	0/10	70	70	60
4	20	0/10	0	0	0	0	0/10	70	70	60
3	20	0/10	0	0	0	0	0/10	70	70	60
2	20	0/10	0/10	0/10	0/10	0/10	0/10	70	70	60
1	20	30	30	30	30	30	30	50	50	50

FIGURE 3.3. Typical Cell Type Layout

TYPE 25: Type 25 cells are used to specify reflected boundary conditions such as those required for 360° cylindrical simulations and other cyclic boundaries. Figures 3.4 and 3.5 illustrate the use of Type 25 cells in cylindrical geometry. Cells J = 2 to J = 5, K = 1 to K = 1 (two-dimensional, and I = 1 to I = 1 are Type 25. Then JM = 0, KM = 0, and IM = 19. Likewise, for the opposite Type 25 boundary, J = 2 to J = 5, K = 1 to K = 1, and I = 20 to I = 20. Then JM = 0, KM = 0, and IM = 2. This input will cause values in the I = 19 tier to be loaded to the I = 1 boundary tier, and values in the I = 2 tier to be loaded to the I = 20 tier.

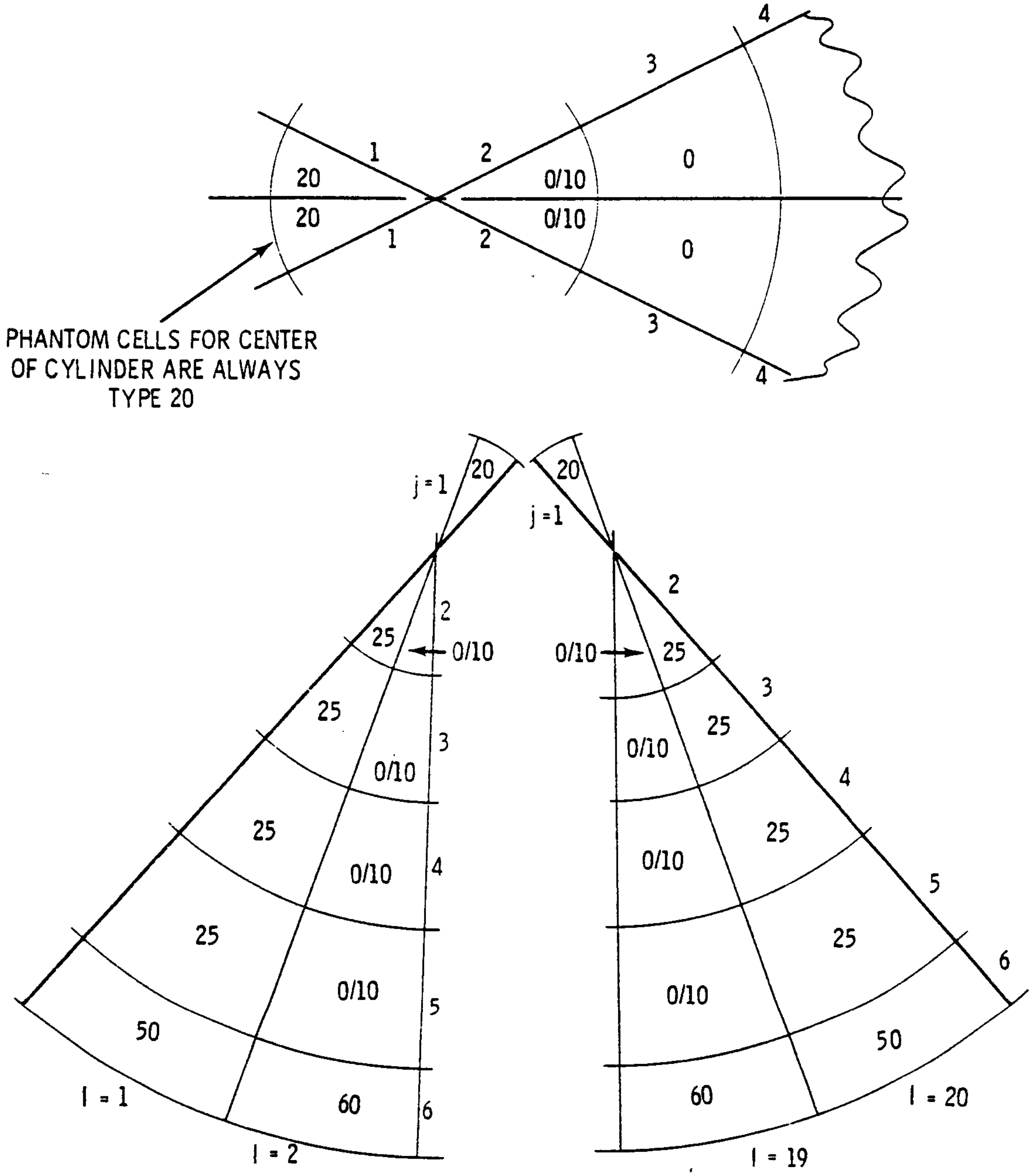
Type 30: Type 30 cells are specified flow boundaries where conditions may be fixed or vary with time. If the velocity or temperature varies with time, a table identifier must be specified and



1) RAY I=20 SET TO VALUES IN RAY I=2

2) RAY I=1 SET TO VALUES IN RAY I=19

FIGURE 3.4. Two-Dimensional Nodalization of a Full-Circular Cylinder



PHANTOM CELLS FOR CYCLIC BOUNDARY
CONDITIONS ARE ALWAYS TYPE 25

FIGURE 3.5. Construction of Cyclic Boundary Conditions

tabular input provided. In Figure 3.2, J = 2 to J = 7, K = 1 to K = 1, and I = 1 to I = 1 would define the Type 30 cells. One point of caution needs consideration. If Type 30 cells are specified on east, north, or far surfaces, the velocity must be initialized on the first interior fluid cell next to the Type 30 cell (Card Group 4). That is, boundary velocity is assigned to the interior cell rather than the Type 30 cell (see Figure 3.6).

TYPE 40: Type 40 cells are outflow/inflow boundary cells where conditions are computed rather than specified. The Type 40 cells, as shown in Figure 3.3, are specified by J = 2 to J = 7, K = 13 to K = 13, and I = 1 to I = 1. Two points of caution are required in using Type 40 cells.

- If the computed inflow/outflow is located on the west, south, or near boundary of the simulated system, an extra row of null cells (Type 50) are needed to accommodate storage location requirements. Implementation of this requirement is illustrated in Figure 3.7 for a south boundary.
- If the energy equation is being solved, it is necessary to specify a boundary table identifier and tabular temperature input to ensure the correct fluid temperature for flow into the system. Although the inflow may be at fixed temperature, TEMPEST still requires at least a 2-point table. In the case of inflow, the boundary table value is used rather than the extrapolated value. Pressures are computed in all Type 40 cells.

TYPE 45: Type 45 cells are constant pressure boundary condition cells. All other aspects are similar to Type 40 cells. Constant pressure boundaries are only available in a version with the compressible module enabled.

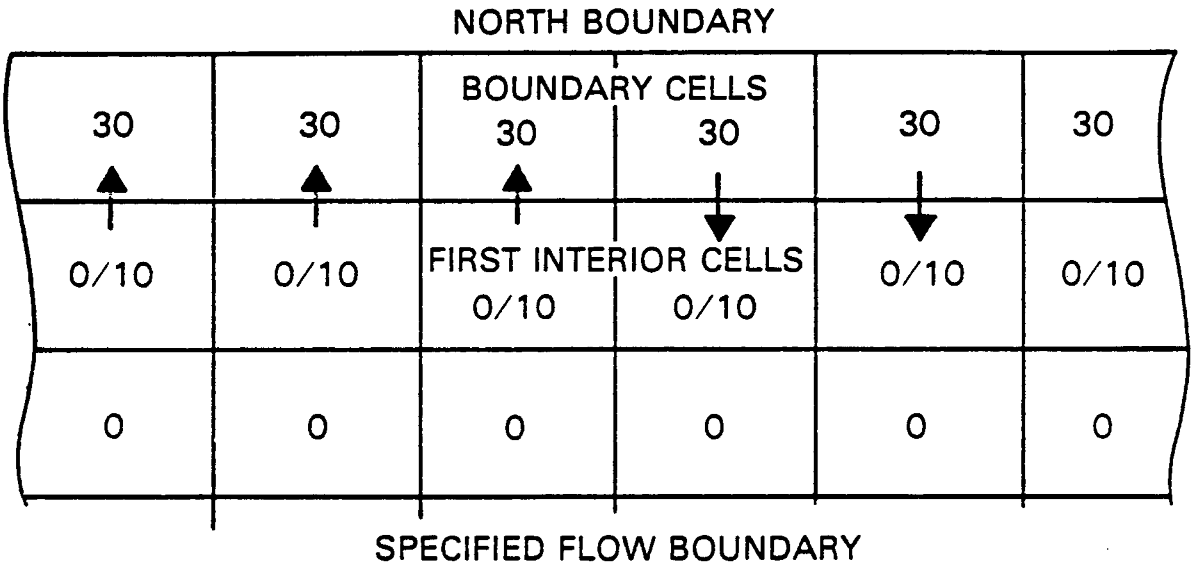


FIGURE 3.6. Cell Layout for Type 30 Cells on a North Boundary

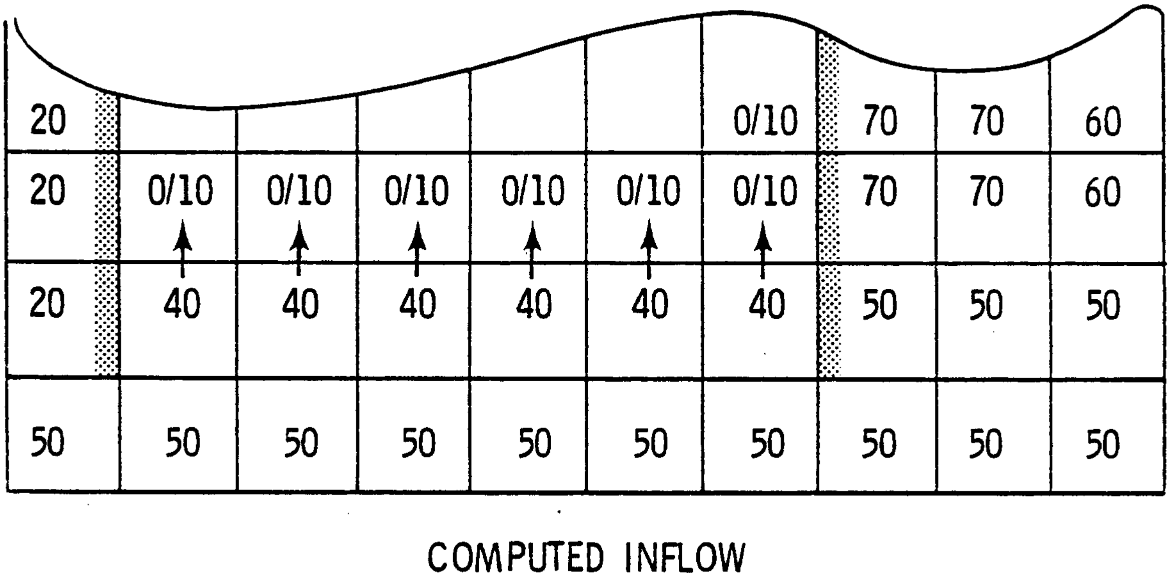


FIGURE 3.7. Cell Layout for Type 40 Inflow/Outflow for a South Boundary

TYPE 50: TEMPEST automatically presets all cell types to 50. These are null cells whose surfaces are considered adiabatic, and the fluid slip condition is determined by the value of SFACT (Card Group 1, MISC, card). The only time that the user would specify Type 50 at input would be for overwriting types read in by a previous card. That is, a fluid region with a null cell blockage in the middle could be specified by typing the entire region with zeros and overwriting as required with Type 50s on a subsequent card(s). This same procedure can be done with all cell types. TEMPEST will internally set the material type of null cells to 51.

TYPE 60: Type 60s are solid material cells with specified temperatures either fixed or time dependent. If the temperatures are time dependent, an appropriate table number must be assigned along with the required tabular input. Type 60 cells are used to set wall temperatures and have an internally set material thermal conductivity of BIGGER (10^{30}). TEMPEST will internally set the material type to 52 (revealed by the material type map). In Figure 3.3, Type 60 cells are specified as J = 10 to J = 10, K = 2 to K = 12, and I = 1 to I = 1.

TYPES 61-64: These cells are solid-material-type cells with a specified temperature. This cell type is exactly the same as Type 60 _except_ that _real_ material properties are used to compute the thermal resistances. Thus, a material type and a corresponding properties card (Type 6, Card Group 4) must be specified.

TYPE 65: Type 65 cells are useful when the velocity field is known and specified by input. The transport solutions are applied; the hydrodynamic solution is not. A time-dependent table may be applied to these cell types to change the velocity as a function of time (computed temperatures will not be overridden by the table). Because transport solutions are applied, specified velocities for Type 65 cells _must_ satisfy continuity.

TYPE 70: Type 70 is a normal solid material heat conduction cell. It is also used as electrically conducting cells. In the Figure 3.3 example, Type 70 cells are J = 8 to J = 9, K = 2 to K = 12, and I = 1 to I = 1.

Notes:

1. Any fluid computational cell that is adjacent to a boundary cell will be set internally to Type 10. Do not set any cell to Type 10 at input.
2. TEMPEST uses phantom cell storage logic for velocities. In three dimensions, the required boundary cell storage locations may conflict at exterior corners and edges. Conflicts in two, as well as three, dimensions can arise if walls have zero- or single-cell thickness. TEMPEST will automatically search out all storage conflicts and set the adjacent cell to Type 11. The only indication that the user will have of this procedure is in observing the cell-type map output, where it will be noted that some of the cells that were specified as Type 0 at input have been changed to Type 11. This observation also applies in Type 10 cells.
3. Each cell must have a type. Any cell that is not typed by input card will be assigned Type 50, the null cell.
4. Overwriting is good practice and, in many cases, can substantially reduce the type card input. However, the user must ensure that the cards are ordered properly if overwriting is used.
5. For full 360° cylindrical simulations, coarse-mesh balancing may not be particularly effective in the R- and X-directions. Balancing may be selectively enabled with the BALR, BALZ, and BALX, options on the CONT, Card, Group 2.
6. The index "start" and "end" of array values may be defaulted if two-dimensional, single-cell thickness simulation is desired (e.g., if K1 = K2 = 1, then K1 and K2 may be defaulted).
7. A node-type output map may be obtained with NTYP, on the DBUG, card (Card Group 1).

3.3.1.2 Materials Types (Field 2)

Material type identifiers are located in Field 2 as noted. TEMPEST will accommodate 50 material types from input. Material Type 51 is set internally for Type 50 cells and has a thermal conductivity equal to SMALLR (10^{-30}). Material Type 52 is also set internally for Type 60 cells having a thermal conductivity of BIGGER (10^{30}). All cell types except Types 20, 50, and 60 thus need a material identification number. Material identification for Type 25 cells may be defaulted. Properties associated with the material identification numbers are specified with Card Type 6, Card Group 4.

Notes:

1. TEMPEST will accommodate several disconnect fluid regions. Disconnected flow regions are separated by solid boundaries that may conduct heat. To permit the coarse-mesh balancing logic to function properly, it is necessary to use a different material type identifier for each region, even though each region may have the same fluid properties.
2. No more than 50 materials may be used.
3. A materials type output map may be obtained by specifying MTYP, on the DBUG Card (Card Group 1).
4. Material types should be sequential integers (e.g., 1, 2, 3, 4, ..., rather than 1, 2, 5, 6, ...).
5. Specification of secondary material number (MT2(N) in Field 2) is significant only for a code version containing a sub-grid flow and thermal model.

3.3.1.3 Boundary Value and Source Term Table Identifiers (Field 3)

Field 3 may contain up to four pieces of information. The table number (Columns 14-15) serves the purpose of being either a boundary value table or a source term table. There is no conflict because if the node type in Field 1 is 30, 40, 45, 60, or 61-64, which are boundary nodes, then the table number will be a boundary table. If the node type is a normal 0 computational cell or a Type 65 fix flow cell, the table number in Field 3 is a source term table.

Boundary table data are input using Card Type 16, Group 4, Option 1, and source term table data are input using Card Type 16, Group 4, Option 2, as discussed in Sections 3.16.1 and 3.16.2, respectively.

For a source term table, additional identifiers are specified in Columns 11, 12, and/or 13. These are MR, MZ, and MX. These momentum source flags may take on the following values:

Column	Flag	Value	Description
11	MR	0	Default. No U-momentum specified.
		1	U-velocity specification east face.
		2	U-velocity specification west face.
		3	U-velocity specification both east and west faces.
12	MZ	>3	Source without momentum (see Note 5).
		0	Default. No V-momentum specified.
		1	V-velocity specification north face.
		2	V-velocity specification south face.
		3	V-velocity specification both north and south faces.
13	MX	0	Default. No W-momentum specified.
		1	W-velocity specification far face.
		2	W-velocity specification near face.
		3	W-velocity specification both far and near faces.

The source option is particularly useful for modeling subgrid-size phenomena such as fans, obstructions, small pipe jet injections, etc.

Notes:

1. Table values will be printed if TTBL, is specified on DBUG, card (Card Group 2).

2. A total maximum of 20 tables may be used including boundary, source, and heat generation (Field 4). Sequential integers should be used (e.g., 1, 2, 3, ..., rather than 1, 2, 5, 6).
3. Type 40 cells that may have inflow must have at least a 2-point time table if transport equations are to be solved (e.g., thermal energy). This is required for TEMPEST to determine temperature of incoming fluid. It does not affect flow velocity or pressure.
4. For source tables, a computational cell must not be overspecified, e.g., momentum specified on all six faces of a three-dimensional cell.
5. Specifying an integer greater than 3 in any of the Columns 11, 12, or 13 indicates that a source is to be applied without momentum. This source may be mass or turbulence, but not heat. Heat source specification on a node-by-node basis is by the heat generation table number in Field 4.
6. Operation of TEMPEST on different computers has shown that certain FORTRAN compilers "blank-fill" and others "zero-fill" trailing blanks in a field. If uncertain, Field 3 should be "zero-filled" (e.g., use 30001 instead of 3bbb1, where b indicates a blank).

3.3.1.4 Heat Generation Table Identifiers (Field 4)

Heat generation table number in this field is used to specify heat generation on a node-by-node basis. Heat generation applies only to normal 0, 65, and 70 computational cells. If table number is input on this card, time-dependent heat generation values in consistent units must be input using Card Type 16, Group 4, Option 2. (Alternately, heat generation table numbers may be input on a material-by-material basis on Card Type 6, Group 4.) For this latter case, initial heat generation values are input using Card Type 9, Group 4, and then transient table factors are input with Card Type 24, Group 4.

These two heat generation input modes allow the user certain flexibility. One difference between the two modes is whether the user wants to input values of heat generation as a function of time or whether the user wants to input initial values and corresponding time-dependent factors. Both methods are self consistent in their end result if only one transient table applies to all heat generation in one material. If two transient tables are required to describe transient conditions in one material, the node-by-node method must be used.

Notes:

1. Table values will be printed if TTBL, is specified on DBUG, card (Card Group 2).
2. A total maximum of 20 tables may be used including boundary and source (Field 3) and heat generation (Field 4). Sequential integers should be used (e.g., 1, 2, 3, 4, ..., rather than 1, 2, 5, 6 ...).
3. A heat generation table number input on this card may or may not be the same as a boundary table number but may not be the same as a source table number. The deciding criteria is if MR=MZ=MX=0 (Field 3) then the table numbers may be the same. To avoid confusion it is recommended that each type of table use a unique table number.
4. Node-by-node heat generation (table) specification requires more table storage array space than material-by-material heat generation (table) specification.

3.3.2 Card Type 2: Cell and Material Types and Boundary Value Table Identification (Single Cell)

Card Type 2 provides single-cell specification of information similar to that on Card Type 1. One limitation is, however, that this card cannot be used for Type 25 cells.

Field	Column	Data	Description
1	1 - 5	NT(N)	Cell type.
	6 - 8	MT2(N)	Secondary material type.
2	9 - 10	MT(N)	Material type.
	11	MR	R-direction momentum source flag.
	12	MZ	Z-direction momentum source flag.
	13	MX	X-direction momentum source flag.
3	14 - 15	NTAB	Boundary value table number for this cell.
4	16 - 20	NTABQ	Heat generation table number for this cell.
5-10	21 - 50	Blank	
11	51 - 55	J	J-index of cell.
12	56 - 60	K	K-index of cell.
13	61 - 65	I	I-index of cell.
14	70	KIND	Always the integer 2.
	73 - 80		Identification if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   30    1    1                                       1    1    2    2  NODETYPE
```

Note:

1. Notes in Section 3.3.1 are applicable.

3.3.3 Card Type 3: Film Coefficient Identification

This card provides for assigning a film coefficient identification number to each solid or fluid cell face as required. Contact coefficients between solid cells are treated with the same logic as film coefficients.

Field	Column	Variable	Description
1	1 - 5	NHC(N)	Film coefficient identifier for Eastside cell N.
2	6 - 10	NHC(N)	Film coefficient identifier for Northside cell N.
3	11 - 15	NHC(N)	Film coefficient identifier for Farside cell N.
4	16 - 20	Blank	
5	21 - 25	J1	J-direction start of array.
6	26 - 30	J2	J-direction end of array.
7	31 - 35	K1	K-direction start of array.
8	36 - 40	K2	K-direction end of array.
9	41 - 45	I1	I-direction start of array.
10	46 - 50	I2	I-direction end of array.
11	51 - 55	Blank	
12	56 - 60	SOR	Surface orientation for heat flux (see note 5).
13	61 - 65	SID	Surface identification number (see note 5).
14	70	KIND	Always the integer 3.
	73 - 80		Identification if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
    1    2    3        39   39    1   10    1    6                   3  HT COEFF
```

Notes:

1. Up to 98 different film/contact coefficient identification numbers may be assigned. This is the number of different coefficients that can be used--not the number of cells. A single identification number may be assigned to many different cell faces. For turbulent flows, identifiers 97 and 98 are set internally and should not be input. Position 99 is a default value and indicates that a coefficient has not been assigned. A map of coefficient identifiers is obtained by selection of FCID, on DBUG, card, Group 2.
2. If a film coefficient is assigned to a cell with a solid/fluid interface, the conduction resistance between the fluid cell center and the solid surface will be set to zero so that the film coefficient constitutes the total thermal resistance. This does not apply to contact coefficients between two solid cells (see Figure 3.8).

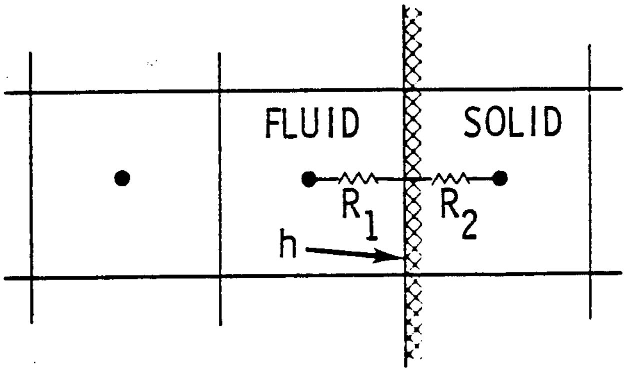


FIGURE 3.8. Heat Transfer Resistances for Fluid/Solid Interface

3. The film/contact coefficient identification numbers are word packed in the NHC(N) array. A computer word may be 002013044, which indicates coefficient identifications of 2, 13, and 44 in the R-, Z-, and X-direction cell faces, respectively. The user need not be concerned about this fact unless internal modifications are to be made regarding I/O and usage of the NHC(N) array. Be cautious about overwriting because identifiers on each R-, Z-, and X-direction cell are set on each card. A coefficient identification number cannot be overwritten unless the value was previously defaulted or set to 0.
4. For additional details see Section 3.4.18 (Card Group 4, Card Type 18).
5. This card may also be used to request output for heat flow through specified surfaces as follows:
   - Default Fields 1, 2, and 3 (if a contact coefficient is not specified).
   - Use Fields 5 through 10 to specify a two-dimensional surface over which the heat flow is to be computed (same as specifying a surface over which a contact coefficient is applied).
   - Use Column 60 to specify the surface orientation:
     1 = Z-X (R is fixed)
     2 = R-X (Z is fixed)
     3 = R-Z (X is fixed)
   - Use Columns 64 and 65 to specify the surface identification number (up to 20 surfaces may be specified). Each two-dimensional surface must have a unique identification number (1 through 20).

EXAMPLE CARD FOR HEAT FLUX OUTPUT:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
                        6    6    2   10    3    7         1    2    3    HTFLUX
```

The above input card instructs TEMPEST to compute the following information for the surface defined by K = 2 to 10 (Z) and I = 3 to 7 (X) at the R position J=6:

- surface area, A_2
- total heat flow, Q_2
- average heat flux, Q_2/A_2

3.3.4 Card Type 4: Flow Drag Coefficient Identification

This card provides for assigning either friction or form drag coefficient identification numbers and slip factors at each fluid cell face.

Field	Column	Variable	Description
	1 - 3	NSR	Slip factor identifier for R-cell face of cell N.
1	4 - 5	NDC(N)	Drag coefficient identifier for cell N, R-direction flow.
	6 - 8	NSZ	Slip factor identifier for Z-cell face of cell N.
2	9 - 10	NDC(N)	Drag coefficient identifier for cell N, Z-direction flow.
	11 - 13	NSX	Slip factor identifier for X-cell face of cell N.
3	14 - 15	NDC(N)	Drag coefficient identifier for cell N, X-direction flow.
4	16 - 20	Blank	
5	21 - 25	J1	J-direction start of array.
6	26 - 30	J2	J-direction end of array.
7	31 - 35	K1	K-direction start of array.
8	36 - 40	K2	K-direction end of array.
9	41 - 45	I1	I-direction start of array.
10	46 - 50	I2	I-direction end of array.
11-13	51 - 65	Blank	
14	70	KIND	Always the integer 4.
	73 - 80		Identification if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
    1   72    3        39   39    1   10    1    6                   4  DR COEFF
```

Notes:

1. Each drag coefficient may contain two items of information as follows:
   - slip factor identification numbers
   - wall drag coefficient identification numbers.
2. Placement of the identifiers in the five column field is as follows:

```
    ↓- Slip Factor Identifier (0-9)
_ _ 3 _ 2
        ↑
        Wall Drag Identifier (0-98)
```

Slip Identifier

The slip identifiers (NSR, NSZ, NSX) are used if slip factors other than the specified or defaulted value of SFACT on the MISC, card (Card Group 1) is desired. If the value is defaulted on this card, the slip factor SFACT will be used. If a value of 1 through 9 is specified on this card, a corresponding slip factor must be supplied in Card Group 4 by Card Type 23 (Section 3.4.23). This option allows the user to specify up to 9 (10, including the default value SFACT) different slip factors on a cell-by-cell basis. The convention to be followed in specifying these slip factors is as follows. For a slip factor to be applied to the R- and X- direction velocities (e.g., a Z-face solid boundary), specify the identifier in Columns 6-8 in Field 2. Similarly, for R and Z directions, use Field 3, and for Z and X directions, use Field 1.

Wall Drag Coefficient Identifiers

Up to 98 different drag coefficients may be assigned in the same way the film/contact coefficient identifiers are assigned. Identification numbers from 1 to 48 are reserved for form drag coefficients, whereas numbers 49 to 98 are reserved for friction drag.

3. Drag coefficient identifiers are word packed in the same way film/contact coefficient identifiers are, thus the same precautions must be observed in overwriting and internal modification.
4. See Section 3.4.17 (Card Group 4, Card Type 17) and Section 3.4.23 (Card Group 4, Card Type 23) for additional details.
5. A map of coefficient identifiers is obtainable by selection of DCID, on DBUG, Card, Group 2.
6. See note 6, Section 3.3.1.3.

3.3.5 Card Type 5: Monitor Cell Specification

TEMPEST allows U, V, W, P, and T to be printed at every time step (or every MSKIP time step as specified on the PRNT, Card, Group 1) for up to 4 cells. An additional 12 cells may be monitored for postprocessing graphics, but they will not be printed on the output file. The indices for the total of 16 monitor cells are specified on this card type.

Field	Column	Variable	Description
1	1 - 5	J1	J-index of first monitored cell on this card.
2	6 - 10	K1	K-index of first monitored cell on this card.
3	11 - 15	I1	I-index of first monitored cell on this card.
4	16 - 20	J2	J-index of second monitored cell on this card.
5	21 - 25	K2	K-index of second monitored cell on this card.
6	26 - 30	I2	I-index of second monitored cell on this card.
7	31 - 35	J3	J-index of third monitored cell on this card.
8	36 - 40	K3	K-index of third monitored cell on this card.
9	41 - 45	I3	I-index of third monitored cell on this card.
10	46 - 50	J4	J-index of fourth monitored cell on this card.
11	51 - 55	K4	K-index of fourth monitored cell on this card.
12	56 - 60	I4	I-index of fourth monitored cell on this card.

Field	Column	Variable	Description
13	61 - 65	ISET	Monitor set number (Default = 1). Maximum is 4.
14	70	KIND	Always the integer 5.
	73 - 80		Identification if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
    3   17    2    4   25    6    1    1    3    3    1    6         5   MONITOR
```

This card must be used with the control parameter MONT, specified in Card Group 2 on the CONT, Card. This card may be omitted if MONT, is not specified.

Notes:

1. The parameter ISET (Field 13) is the monitor set defined on that input card. Four sets of four (16) monitor cells are the maximum number of computational cells that can be monitored during a simulation. Only the set defined by ISET=1 (or default) will be printed on the TEMPEST line printer output. All sets specified will be written to an output file called MONSAV for postprocessing. Time histories of the listed variables for up to 16 cells are thus available for plotting. A table listing the MONSAV identifiers and corresponding computational cell locations is printed near the end of the TEMPEST line printer output. ISET must be a sequential integer in the range $0 \leq ISET \leq 4$. The control option MSAV, must be specified on the CONT, Card (Card Group 2) to create the postprocessing MONSAV file.
2. Additional monitor printing may be selected if desired. These are selected on AOUT, Card (Card Group 2) and include:

Monitor Variables	Required AOUT, Option	Required CONT, Option
Turbulence (TKE, DKE)	TKMN,	TURB,
Species (C)	SPMN,	MASS,
Surface (H)	VSMN,	SURF,
Voltage (EMF)	EFMN,	EMFR,
Current (AMPS)	ECMN,	EMFR,

3. Postprocessing file MONSAV will contain variables monitored by TEMPEST for options enabled. Variables currently monitored and written for postprocessing include:

Variable Number	Array Variable	Description	Monitor Cell Numbers
1	T	Temperature	All
2	U	U-velocity (R-direction)	All
3	V	V-velocity (Z-direction)	All
4	W	W-velocity (X-direction)	All
5	P	Pressure (or pressure difference)	All
6	TKE	Turbulent Kinetic Energy	All
7	DKE	Dissipation of Kinetic Energy	All
8	H	Blank	
9	H	Blank	
10-17	C	Species mass fractions (requires AOUT, option SPMN)	All

Number	Variable	Description	Monitor Cell Number
18-27	C	Species volume fractions (requires AOUT, options SPMN, and VOLF,)	All
28-29	EMF	Electric potential of Fields 1 and 2	All
30-31	QJ	Joulian heat generation for Fields 1 and 2	All
32-34	(local)	Electric current density components	All

3.3.6 Card Type 6: Special Output Array Flags

Field	Column	Variable	Description
1	1 - 5	LSKAN(1)	Time step for first printout.
2	6 - 10	LSKAN(2)	Time step for second printout.
3	11 - 15	LSKAN(3)	Time step for third printout.
4	16 - 20	LSKAN(4)	Time step for fourth printout.
5	21 - 25	LSKAN(5)	Time step for fifth printout.
6	26 - 30	LSKAN(6)	Time step for sixth printout.
7	31 - 35	LSKAN(7)	Time step for seventh printout.
8	36 - 40	LSKAN(8)	Time step for eighth printout.
9	41 - 45	LSKAN(9)	Time step for ninth printout.
10	46 - 50	LSKAN(10)	Time step for tenth printout.
11-13	51 - 65	Blank	
14	70	KIND	Always the integer 6.
	73 - 80		Identification if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
    1    2    3   70   71   72  101  102  161  162                   6     PRINT
```

The LSKAN(L) array allows the user to select up to 10 time steps for special array output printing at unequal intervals. The special arrays contain information that can be very handy for debugging. For instance, a sequence of time steps, 1, 2, 3, 70, 71, 72, 101, 102, 161, 162, might be used to print out the heat transfer connectors, divergence, or densities. The user should consult the AOUT, and DBUG, Card input instructions from Card Group 2 to identify which special arrays are available for output under LSKAN(L) instructions.

Note:

1. Special output printing will occur only only as specified by LSKAN(L) but also in increments of NSOUT (which is specified on the PRNT, Card of Card Group 1). For instance, in the above example, if NSOUT=50, printing would occur at time steps 1, 2, 3, 50, 70, 71, 72, 100, 101, 102, 150, 161, 162, 200, 250, 300, etc. All arrays requested on the AOUT, Card will also be printed.

3.3.7 Card Type 7: Not Used

3.3.8 Card Type 8: Not Used

3.4 CARD GROUP 4: FLOATING POINT INPUT

Card Group 4 provides floating point input for the following information:

- cell spacing and coordinate system location/orientation
- material properties
- field variable boundary values/initialization
- heat generation rates
- time-dependent boundary value tables
- time-dependent source value tables
- drag and heat transfer coefficients
- tabular material property data.

With the exception of certain continuation cards, cards may be arranged in any order within the group. The format for this group is: FORMAT (10F5.0,I5,I2,I3,I3,I2,2A1,I1,I2,A2). While the latter portion of this format looks confusing, it is rather straightforward. As the user becomes familiar with input, he will find that on all but only a few cards the latter portion looks just like (...,3I5,2A1,I3,A2), that is aligned on five column field boundaries through Column 70.

The user may find some difficulty using the F5.0 format to achieve the number of significant figures that might be desired. Generally three significant figures can be achieved (e.g., 1.37×10^{-6} may be input as 137-8) except in the case of negative values. Input requirements beyond three significant figures are not routinely needed for engineering computation in view of data accuracy. If input requiring additional significant figures is needed, the input format will need to be rewritten. Since there is only one read statement for the floating-point input (SUBROUTINE INPUT, Statement Number 200) this can be easily accomplished. A format such as (10F6.0,I3,I2,I2,I2,I2,2A1,I1,I2,A2) would gain one additional significant figure.

The input type key is always located in Field 19 (Columns 69 to 70). Omitting a type key number will cause the remaining data to be ignored, and TEMPEST will begin execution.

Specifying the system of units--as pointed out earlier, TEMPEST is designed to operate in the normal mode using either Engineering or SI units. Card Group 4 input data may be supplied in either system on a card-by-card basis. The system of units for a particular data card may be specified in Columns 71 and 72 (variable name SYS) using the alphanumeric character "SI" for the International System of Metric Units (Systeme International), or "ES" for the Engineering System. SI or ES is to be used if the data on that card has units different from the operating mode. For instance, suppose SISY, is specified on the CONT, Card (Card Group 2) so that TEMPEST will operate in the SI system. Engineering System input data may be supplied by specifying "ES" in Columns 71 and 72. On the other hand, if SISY, has been defaulted, the normal operating mode is the Engineering System, but SI data may be input by specifying "SI" in Columns 71 and 72. <u>All data</u> on a <u>single card</u> must be in the <u>same consistent system</u> of units (see Table 3.1). If SYS is defaulted, the input must be in units consistent with the normal operating mode, as controlled by specifying or defaulting SISY, on the CONT, Card.

On certain cards the data for SYS may be specified as "IN" or "CM" for length units "inches" or "centimeters", respectively. Interpretation of this usage is given by the card description.

3.4.1 Card Type 1: Coordinate Quantities

Field	Column	Variable	Description
1	1 - 5	DRC	Cell width in R-direction (leave blank if variable--Type 3 card must be used).
2	6 - 10	DZC	Cell width in Z-direction (leave blank if variable--Type 4 card must be used).
3	11 - 15	DXC	Cell width in X-direction (leave blank if variable--Type 5 card must be used); use degrees if cylindrical coordinates.
4	16 - 20	RSTART	Distance to start of R-direction cell network.
5	21 - 25	XSTART	Distance or angle to start of X-direction cell network.
6	26 - 30		Blank
7	31 - 35	GRAV	Reference gravitational constant, $\lvert g \rvert$ (default = 32.17 ft/sec^2 or 9.8 m/sec^2) positive value. Direction cosines establish sign.
8	36 - 40	THETAR	Angle θ_R for direction cosine between $\vec{g}$ and R-axis (degrees).
9	41 - 45	THETAZ	Angle θ_Z for direction cosine between $\vec{g}$ and Z-axis (degrees).
10	46 - 50	THETAX	Angle θ_X for direction cosine between $\vec{g}$ and X-axis (degrees).
11-15	51 - 65	Blank	
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 1.
20	71 - 72	SYS	SI, ES, IN, CM, or default.
	73 - 80		Identification if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   1.   5.  180                       90  180   90                   1CM  COORDS
```

Notes:

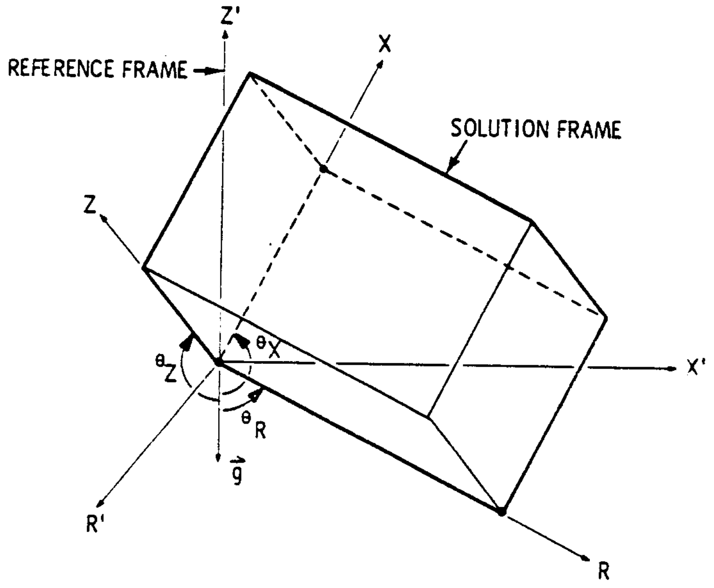
1. RSTART is specified if the user wishes to begin the cylindrical coordinate system at a point other than R = 0 (default). For instance, for simulation of flow in an annular region, RSTART = R_{INSIDE}. Thus the cell network will span only the region of interest and not the entire cylindrical coordinate system.
2. If SYS = IN or CM, then lengths on this card are in inches or centimeters, respectively. Only DRC, DZC, DXC, RSTART, and XSTART are affected, and they will be converted, as appropriate, to the normal operating model.

3.4.1.1 Cartesian Coordinate System and Use of Direction Cosines

A Cartesian solution frame (R,Z,X) whose rotations within the reference frame are defined by the direction angles θ_R, θ_Z, and θ_X is illustrated in Figure 3.9. For this tilted configuration, the solution frame gravitational components are:

$$g_R = |g| \cos \theta_R$$
$$g_Z = |g| \cos \theta_Z$$
$$g_X = |g| \cos \theta_X$$

An example of planar rotation about the X'-axis and R'-axis is shown in Figure 3.10. The input variables THETAR, THETAZ, and THETAX correspond to the illustrated direction angles θ_R, θ_Z, and θ_X in degrees. The default value of $|g|$ is 32.17 ft/sec^2 or 9.8 m/sec^2.

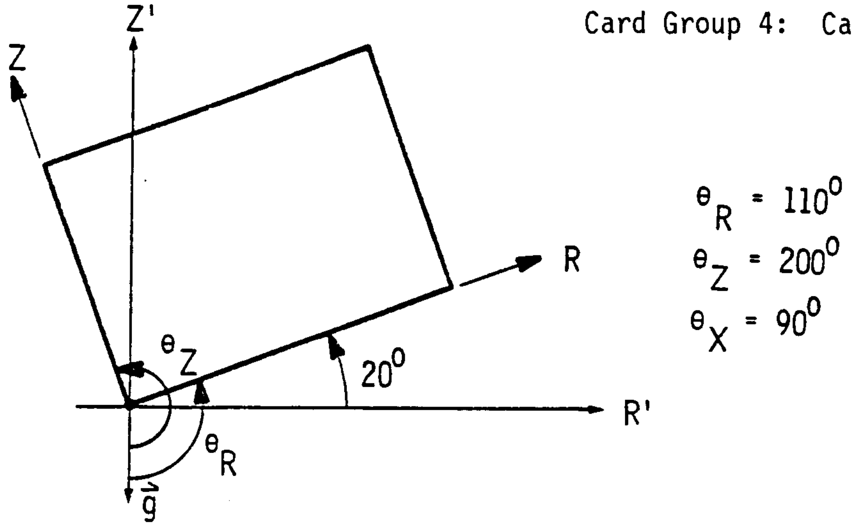


GRAVITATIONAL COMPONENTS: $g_R = |g| \cos(\theta_R)$

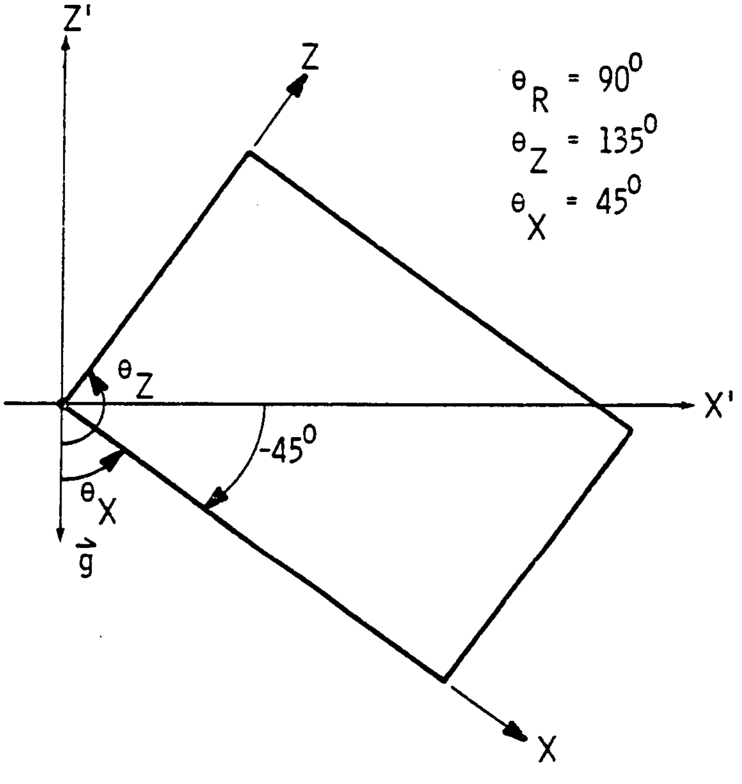
$g_Z = |g| \cos(\theta_Z)$

$g_X = |g| \cos(\theta_X)$

FIGURE 3.9. Tilted Solution Frame in Cartesian Coordinates



A. $+20^0$ ROTATION ABOUT x-AXIS



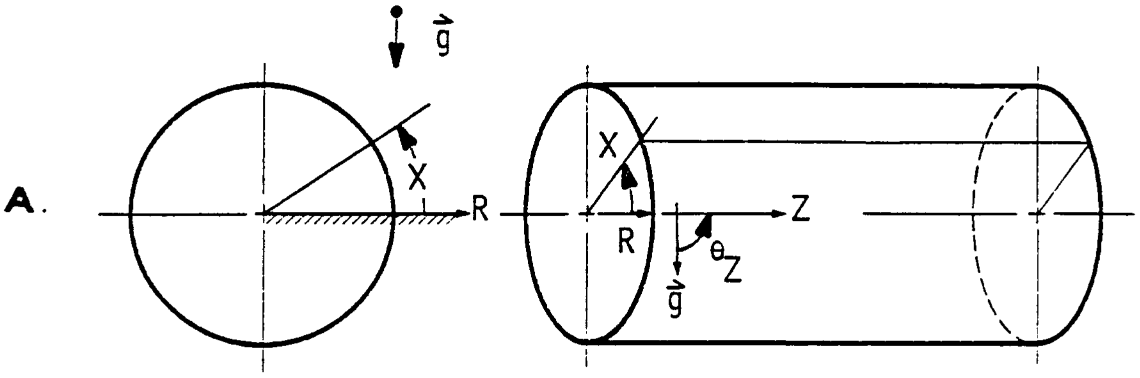
B. -45^0 ROTATION ABOUT R-AXIS

FIGURE 3.10. Planar Rotations in Cartesian Coordinates

3.4.1.2 Cylindrical Coordinate System

Rotations are treated somewhat differently in cylindrical coordinates: the only direction angle employed is θ_Z (THETAZ), which is the angle between the reference frame gravitational vector and the solution frame axial direction as illustrated in Figure 3.11A.

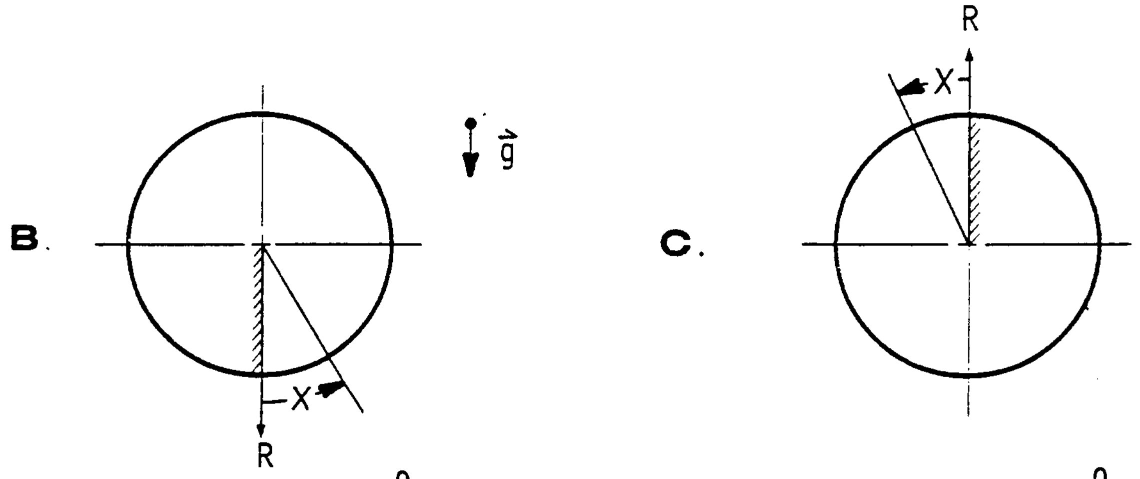
As shown in Figure 3.11A, the base cylindrical coordinate solution frame is a horizontal cylinder with the origin of the azimuthal coordinate, X, on the horizontal plane and with the counterclockwise direction being positive. Figure 3.11B and 3.11C illustrate how different azimuthal starting positions (XSTART) are achieved for modeling circular segments of symmetry. Examples of inclined cylinders are shown in Figure 3.12. The values of THETAR and THETAX are always default values for cylindrical coordinates.



BASE CYLINDRICAL COORDINATE SYSTEM

X_0 = XSTART = 0^0

θ_Z = THETAZ = 90^0



X_0 = XSTART = -90^0

θ_Z = THETAZ = 90^0

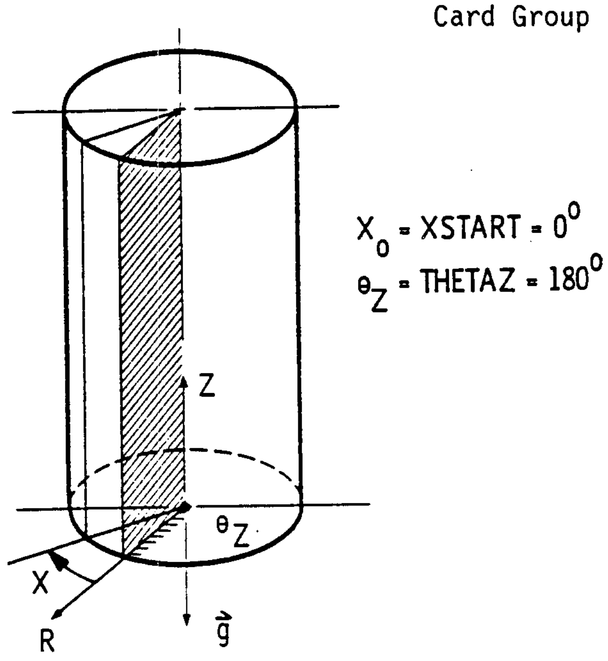
A -90^0 ROTATION OF BASE SYSTEM ABOUT Z-AXIS

X_0 = XSTART = $+90^0$

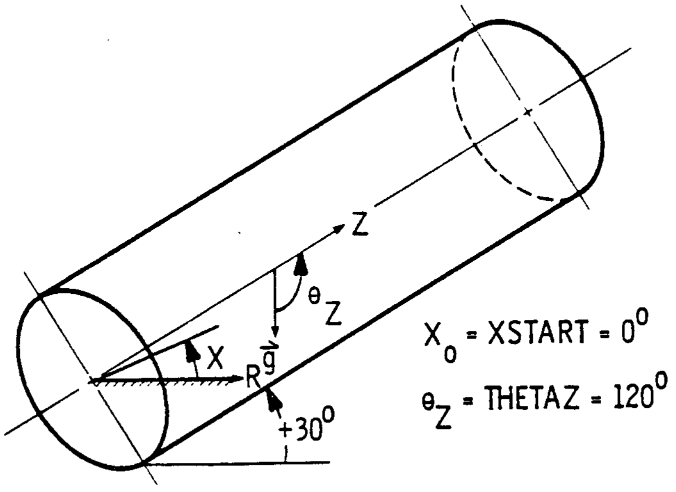
θ_Z = THETAZ = 90^0

A $+90^0$ ROTATION OF BASE SYSTEM ABOUT Z-AXIS

FIGURE 3.11. Base Cylindrical Coordinate System and Rotation About Z-Axis



A VERTICAL CYLINDER



AN INCLINED CYLINDER

FIGURE 3.12. Inclined Cylindrical System

3.4.2 Card Type 2: Not Used

3.4.3 Card Type 3: Variable Cell Width, R-Direction

Cell widths may be specified in one or both of two modes: the Standard Input Mode and the Optional Input Mode.

3.4.3.1 Standard Input Mode

Field	Column	Variable	Description
1	1 - 5	DR(JI)	Width of R-direction cell JI.
2	6 - 10	DR(JI+1)	Width of R-direction cell JI+1.
3	11 - 15	DR(JI+2)	Width of R-direction cell JI+2.
4	16 - 20	DR(JI+3)	Width of R-direction cell JI+3.
5	21 - 25	DR(JI+4)	Width of R-direction cell JI+4.
6	26 - 30	DR(JI+5)	Width of R-direction cell JI+5.
7	31 - 35	DR(JI+6)	Width of R-direction cell JI+6.
8	36 - 40	DR(JI+7)	Width of R-direction cell JI+7.
9	41 - 45	DR(JI+8)	Width of R-direction cell JI+8.
10	46 - 50	DR(JI+9)	Width of R-direction cell JI+9.
11	51 - 55	JI	R-direction cell number referred to in Field 1.
12	56 - 57	Blank	
13	58 - 60	KI	R-direction cell number referred to in Field 10 or field number of last cell.
14-18	61 - 68	Blank	
19	70	TYPE	Always the integer 3.
20	71 - 72	SYS	SI, ES, IN, CM, or default.
	73 - 80		Identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  .01  .02       .03  .04                             1    5         3  R-DIRECT
```

Notes:

1. DR(1) and DR(NR) must always be specified (phantom cells).
2. If Type 40 boundary cells are used, the cell width of the first internal cell must be the same width as the Type 40 cell.
3. If SYS = IN or SYS = CM, then the data on this card are in inches or centimeters, respectively.
4. Any defaulted value for DR(J) will be set to the preceding value, DR(J) ≡ DR(J-1). Thus, it is unnecessary to repeat constant values on the input card.

3.4.3.2 Optional Input Mode

This option is a convenience feature that permits the user to specify cell widths in groups.

Field	Column	Variable	Description
1	1 - 5	N1	Index for start of group.
2	6 - 10	N2	Index for end of group.
3	11 - 15	DR(N)	Constant cell width for preceding group.
4	16 - 20	N4	Index for start of group.
5	21 - 25	N5	Index for end of group.
6	26 - 30	DR(N)	Constant cell width for preceding group.
7	31 - 35	N7	Index for start of group.
8	37 - 40	N8	Index for end of group.
9	41 - 45	DR(N)	Constant cell width for preceding group.
10-14	46 - 63	Blank	
15	64 - 65	II	Always an integer greater than 0.
16-18	66 - 68	Blank	
19	70	TYPE	Always the integer 3.
20	71 - 72	SYS	SI, ES, IN, CM, or default.
	73 - 80		Identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
    1    5  .01    6   10  .03   11   40  .01                   3    3  R-OPTION
```

Input via this option is compatible with use of the standard option. That is, the input may be supplied as a combination of both input options. A similar option is available for Card Types 4 and 5 where DZ(N) and DX(N) may be set in groups.

3.4.4 Card Type 4: Variable Cell Width, Z-Direction

Field	Column	Variable	Description
1	1 - 5	DZ(JI)	Width of Z-direction cell JI.
2	6 - 10	DZ(JI+1)	Width of Z-direction cell JI+1.
3	11 - 15	DZ(JI+2)	Width of Z-direction cell JI+2.
4	16 - 20	DZ(JI+3)	Width of Z-direction cell JI+3.
5	21 - 25	DZ(JI+4)	Width of Z-direction cell JI+4.
6	26 - 30	DZ(JI+5)	Width of Z-direction cell JI+5.
7	31 - 35	DZ(JI+6)	Width of Z-direction cell JI+6.
8	36 - 40	DZ(JI+7)	Width of Z-direction cell JI+7.
9	41 - 45	DZ(JI+8)	Width of Z-direction cell JI+8.
10	46 - 50	DZ(JI+9)	Width of Z-direction cell JI+9.
11	51 - 55	JI	Z-direction cell number referred to in Field 1.
12	56 - 57	Blank	
13	58 - 60	KI	Z-direction cell number referred to in Field 10 or field number of last cell.
14-18	66 - 68	Blank	
18	70	TYPE	Always the integer 4.
20	71 - 72	SYS	SI, ES, IN, CM, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  .01    .02   .5  .25                                  1    5         4  Z-DIRECT
```

Notes:

1. DZ(1) and DZ(NZ) must always be specified (phantom cells).
2. See notes 2, 3, and 4, Section 3.4.3.1 and Section 3.4.3.2.

3.4.5 Card Type 5: Variable Cell Width, X-Direction

Field	Column	Variable	Description
1	1 - 5	DX(JI)	Width of X-direction cell JI.
2	6 - 10	DX(JI+1)	Width of X-direction cell JI+1.
3	11 - 15	DX(JI+2)	Width of X-direction cell JI+2.
4	16 - 20	DX(JI+3)	Width of X-direction cell JI+3.
5	21 - 25	DX(JI+4)	Width of X-direction cell JI+4.
6	26 - 30	DX(JI+5)	Width of X-direction cell JI+5.
7	31 - 35	DX(JI+6)	Width of X-direction cell JI+6.
8	36 - 40	DX(JI+7)	Width of X-direction cell JI+7.
9	41 - 45	DX(JI+8)	Width of X-direction cell JI+8.
10	46 - 50	DX(JI+9)	Width of X-direction cell JI+9.
11	51 - 55	JI	X-direction cell number referred to in Field 1.
12	56 - 57	Blank	
13	58 - 60	KI	X-direction cell number referred to in Field 10 or field number of last cell.
14-18	61 - 68	Blank	
19	70	TYPE	Always the integer 5.
20	71 - 72	SYS	SI, ES, IN, CM, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   10   20         50   20   10                        1    6         5  X-DIRECT
```

Notes:

1. DX(1) and DX(NX) must always be specified (phantom cells.
2. See Notes 2, 3, and 4, Section 3.4.3.1 and Section 3.4.3.2.

3.4.6 Card Type 6: Material Properties

Material properties are input using one or two cards, depending upon modules enabled in TEMPEST and control options selected. The format of the first card is as follows.

Field	Column	Variable	Description
1	1 - 5	PROP(1,II)	Thermal conductivity of material.
2	6 - 10	PROP(2,II)	Density.
3	11 - 15	PROP(3,II)	Specific heat.
4	16 - 20	PROP(4,II)	Dynamic viscosity or emissivity.
5	21 - 25	PROP(5,II)	Brine concentration (in parts per thousand) or gas constant.
6	26 - 30	PROP(6,II)	Reference pressure.
7	31 - 35	PROP(7,II)	Reference temperature.
8	36 - 40	PROP(8,II)	Minimum temperature for properties table.
9	41 - 45	PROP(9,II)	Maximum temperature for properties table.
10	46 - 50	PROP(10,II)	N+1, where N is the number of segments in above temperature range.
	51 - 53	PROP(22,II)	Turbulence constants identifier for Material II.
11	54 - 55	PROP(21,II)	Heat generation table number for Material II.
12	56 - 57	KII	Species number (integer between 1 and 9; for MAST, only).
13	58 - 60	KI	Properties table library index: 0 = constant properties 1 = tabular data input (see Card Type 19 2 and greater--library index number (see Table 3.2).

Field	Column	Variable	Description
15	64 - 65	II	Material number (same as second field on Card Type 1 or 2, Card Group 3).
16	66	KB	Alpha character for properties nature: C = constant, V = variable.
17	67	KP	Alpha character for material state: S = solid, L = liquid, G = gas, M = mixture. If material is a nonconvecting liquid or gas, specify "S".
18	68	LC	Compressibility flag: = 0 for incompressible (default) = 1 for compressible = 2 for thermal expanding.
19	70	TYPE	Always the integer 6.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                100   50  150   11   11    2    1CL  6     PROPS
```

The material properties cards are the most complex cards to construct in the TEMPEST input file because of the code's versatility in treating properties.

PROP(1,II): This is the thermal conductivity of Material II. It is the material reference value and is the value that will be used by TEMPEST if the thermal conductivity is constant for Material II. If the thermal conductivity is to be temperature dependent, PROP(1,II) may be defaulted. If the thermal conductivity is variable, then VKAY, must appear on the CONT, Card (Card Group 2), and a "V" must appear in Column 66 of this card.

PROP(2,II): This is the reference density of Material II and must always be loaded unless PROP(7,II) is specified and a table or library number is available. Density is used by TEMPEST in three possible ways:

1. as a variable in the momentum equation term ρ/ρ_0
2. as a constant ρ_0 (P/ρ_0 and ρ/ρ_0 g in the momentum equations)
3. as a product in the energy equation, ρC.

PROP(2,II) = ρ_0 is always used in the hydrodynamic computation. A different value of ρ_0 will be required for each fluid region (recall that a different material identification number is required for each disconnected fluid region even though the real properties of the fluid may be the same). If the material is a liquid or gas, density is always treated as a temperature-dependent quantity in the term $(\rho/\rho_0)g$ (the driving force for convection). If the ρC product is to be temperature dependent in the energy equation, then VKAY, must be specified on the CONT, Card (Card Group 2), and a "V" must be placed in Column 66 of this card. Use of variable density for thermal convection computations does not, in itself, require "V" in Column 66.

PROP(3,II): This variable is the reference specific heat for Material II. It may be defaulted if specific heat for this material is to be treated as temperature dependent or if PROP(7,II) is specified and a table or library number is available. VKAY, must also be specified if specific heat is variable.

PROP(4,II): This variable is the reference dynamic viscosity for Material II. If dynamic viscosity for this material is to be treated as temperature dependent, PROP(4,II) may be defaulted and a "V" placed in Column 66. Also VVIS, should be specified on the CONT, Card (Card Group 2). Dynamic viscosity is converted to kinematic viscosity internally. For a solid material, PROP(4,II) is specified as emissivity if required for radiation heat transfer.

PROP(5,II): Brine concentration in parts per thousand. Currently only brine concentration corresponding to that of sea water can be used (less than 40 ppt). Depending upon material state, this variable may be a gas constant (for gases and MAST,).

PROP(6,II): Material reference pressure. Use this variable only for a gas or vapor. The default value is 1 atmosphere.

PROP(7,II): Material II reference temperature. The material reference temperature is used to compute reference properties (k, ρ, c, and μ) if a temperature other than zero is used here and a materials properties table or library index is specified. This input should be used whenever the Boussinesq approximation is specified by BESQ, on the CONT, Card (Card Group 2).

PROP(8,II), PROP(9,II), PROP(10,II): To evaluate temperature-dependent density, specific heat, thermal conductivity, and dynamic viscosity, TEMPEST uses direct-entry property tables that are constructed from built-in library functions or tabular data input. Each material that is convecting and/or has variable properties has the appropriate number of direct look-up tables. PROP(8,II), PROP(9,II), and PROP(10,II) specify the minimum temperature, maximum temperature, and number of increments, respectively, for the set of tables for Material II. The number of increments must be large enough to obtain a reasonable piecewise linear fit to the properties data. These values may be defaulted for constant property solid materials (KI=0), in which case PROP(1,II), PROP(2,II), and PROP(3,II) must be specified.

PROP(21,II): This variable is the time-dependent heat generation table identification number. The default value should be used if no heat generation tables are needed. If time-dependent tables are required, the corresponding values for this table are to be specified on Card Type 24 (Card Group 4), Section 3.4.24. (Also see Section 3.3.1.3.)

PROP(22,II): This variable identifies the set of turbulence constants to be used for flow regions with Material II. Defaulted values of the turbulence constants are used for all turbulent regions identified by specification of PROP(22,II), unless new values are input using Card Type 27 (Card Group 4). The same set of constants may be used for separated turbulent regions. A maximum of ten sets of constants may be used. The default value is 0, implying a fluid region with Material II is to be treated as nonturbulent. Thus separated turbulent and nonturbulent flow regions may be treated in a simulation. (Caution: Be aware of "blank" filling versus "zero" filling trailing blanks in Field 11 if PROP(22,II) is specified and PROP(21,II) is defaulted!).

KII: Species number; an integer from 1 to 9. A pair of properties cards is required for each species transport.

KI: This parameter gives instructions on how the properties are to be computed. If KI = 0, then only the constant values specified on this card will be used. If KI = 1, TEMPEST expects tabular properties data to be read in on Card Type 19 (Card Group 4). If KI ≥ 2, then KI corresponds to a material located in the built-in library (e.g., KI = 2 corresponds to water; KI = 4 corresponds to sodium according to Table 3.2).

II: Material identification number corresponding to MT(N) on Card Type 1 or 2 (Card Group 3).

Properties Continuation Card:

A second or continuation card is required if certain control options are (CONT, Card, Card Group 2) selected. These include:

PART,:	solve participating radiation
MAST,:	solve species transport

The properties continuation card must follow directly behind its companion properties card. The data format is as follows:

Field	Column	Variable	Description
1	1 - 5	PROP(36,II)	Reserved for EMFR,.
2	6 - 10	PROP(37,II)	Reserved for EMFR,.
3	11 - 15	PROP(38,II)	Reserved for MAST,.
4	16 - 20	PROP(39,II)	Reserved for MAST,.
5	21 - 25	PROP(40,II)	Reserved for MAST,.
6	26 - 30	PROP(41,II)	Reserved for MAST,.
7	31 - 35	PROP(41,II)	Reserved for PART,.
8	36 - 40	PROP(43,II)	Reserved for PART,.
9	41 - 45	PROP(44,II)	Reserved for PART,.
10	46 - 50	PROP(45,II)	Reserved for future.
12-14	51 - 63	Blank	
15	64 - 65	II	Material number (Must be same as II of just preceding companion card).
16	66	Blank	
17	67	KB	Alphanumeric character "C".
18	68	Blank	
19	69 - 70	TYPE	Always the integer 6.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Identification, if desired.

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  .05  .11                                                     1 C 6    CONTINUE
```

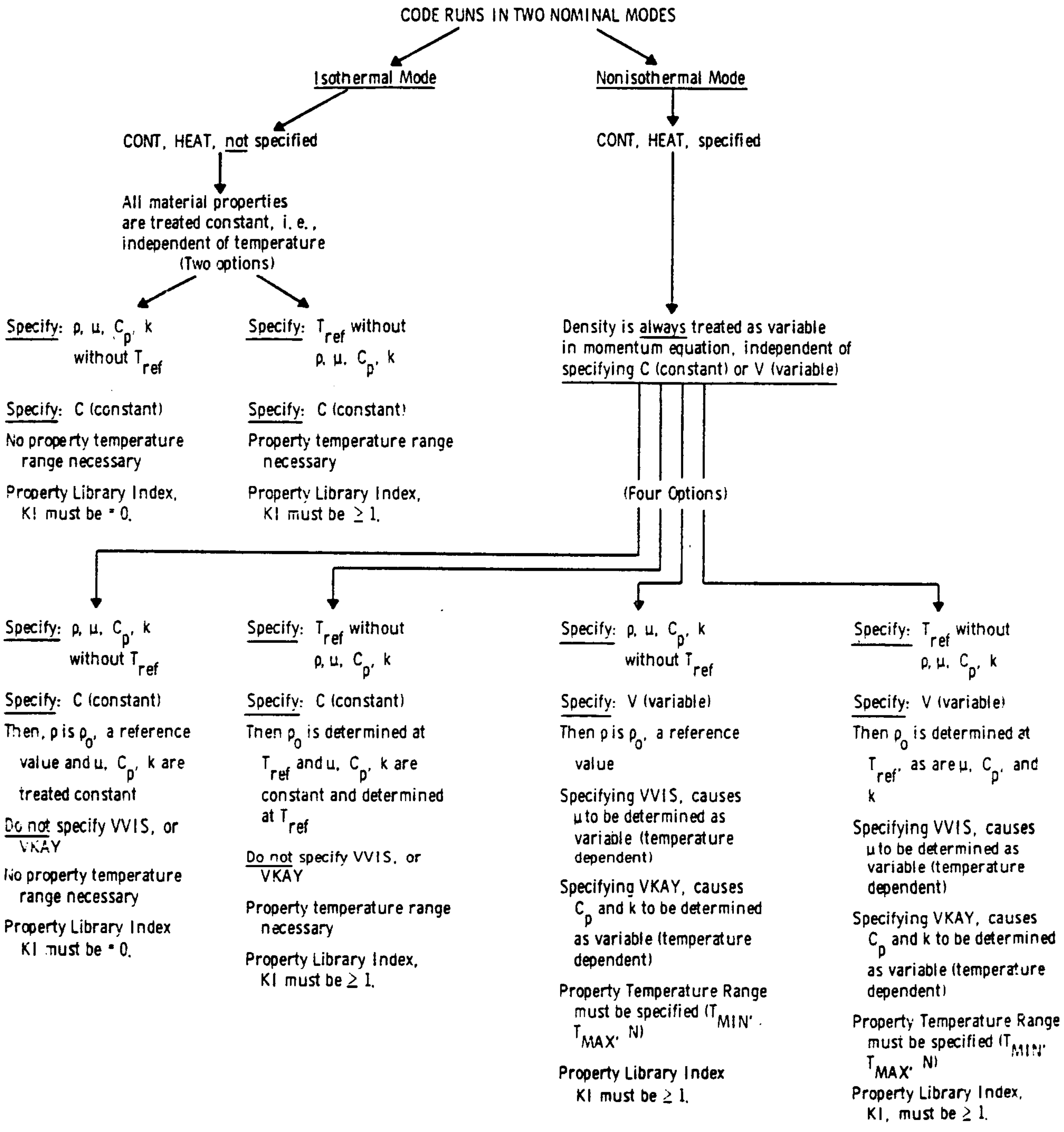
Notes:

1. If the material has constant k, c, and μ, use a "C" in Column 66. If k, c, or μ is variable, use a "V" in Column 66.
2. If the k, c, or μ is variable, the reference values may be defaulted.
3. If the material is nonconvecting (cell Type 61 or greater) and has constant properties ("C" in Column 66), PROP(4,II) through PROP(10,II) may be defaulted.
4. If μ is variable then VVIS, on the CONT, Card (Card Group 2) should be used; if k and c are variable, use VKAY, on the CONT, Card.
5. If PROP(7,II) is specified, and a table or library number is specified, then values for k, ρ, c, and μ may be left blank. Values are computed from the tables at the material reference temperature, PROP(7,II).
6. Density, as used in the momentum equation, is always variable, except for nonconvecting materials. No special designations need to be made. Either "C" or "V" is allowed for convecting fluids.
7. The minimum temperature for the properties table should always be set somewhat lower than expected. Likewise, the maximum temperature should be set higher. If temperatures are computed outside of the temperature range of the table, the simulation will automatically abort.
8. The number of data points in the direct look-up tables depends on the complexity of the data function and the achievement of a reasonable piecewise linear fit to the data. The direct look-up tables constructed by TEMPEST have equal increments. Thus, if density data is to be set up for water that includes good resolution near 4°C, and yet temperatures as high as 50°C are expected, then a large number of increments will be needed. The same number of increments will be used for each property of

a given material. A different material can use a different number of increments. All properties tables will be loaded to the TEXT(N) array. A large number of materials using tables with a large number of increments in each table may require that TEXT(N) be redimensioned. In the current version of TEMPEST, the properties tables will use 4*(I+1)*NTAB where NTAB is the number of materials using direct look-up tables and I is the number of table increments. Note that the current version does not distinguish between those materials needing only one table (ρ) and those needing four tables (ρ, k, c, μ). Four tables are always constructed, even though only one may be used. The number of data points used for tabular input (Card Type 19, Card Group 4) is not related to the number of data points used in the direct look-up tables.

9. The reference pressure PROP(6,II) is not added to the pressure field in this version. It serves the purpose of being an "ambient" reference value. To obtain pressure differences from this reference, control option BESQ, may be selected or output option DELP, may be selected in Card Group 2.
10. If the material properties are constant (i.e., KI = 0) for Material II, then PROP(7,II), PROP(8,II), PROP(9,II), and PROP(10,II) may be left blank.
11. Separated flow regions may be treated individually as turbulent or nonturbulent by specifying or defaulting PROP(22,II), respectively. If the TURB, option on Card Type 1 (Card Group 2) is specified, PROP(22,II) must be specified for each flow region that is to be treated as turbulent. Card Type 27 (Card Group 4) may be used to input new constants.
12. Selection of material state as a mixture (KP=M) implies constituents are to be transported in it. In this case, internal flags are set to indicate properties are variable and that II is the material number of the base fluid of the mixture. Additional properties cards must be supplied for each specie up to and including up to the total (NSP) identified on the MISC, Card, Group 1.

The above notes are generalized in Figure 3.14.



All material properties are treated constant, i.e., independent of temperature (Two options)

Specify: ρ, μ, C_p, k without T_{ref}

Specify: C (constant)

No property temperature range necessary

Property Library Index, KI must be = 0.

Specify: T_{ref} without ρ, μ, C_p, k

Specify: C (constant)

Property temperature range necessary

Property Library Index, KI must be ≥ 1.

Density is always treated as variable in momentum equation, independent of specifying C (constant) or V (variable)

Specify: ρ, μ, C_p, k without T_{ref}

Specify: C (constant)

Then, ρ is ρ_0, a reference value and μ, C_p, k are treated constant

Do not specify VVIS, or VKAY

No property temperature range necessary

Property Library Index KI must be = 0.

Specify: T_{ref} without ρ, μ, C_p, k

Specify: C (constant)

Then ρ_0 is determined at T_{ref} and μ, C_p, k are constant and determined at T_{ref}

Do not specify VVIS, or VKAY

Property temperature range necessary

Property Library Index, KI must be ≥ 1.

Specify: ρ, μ, C_p, k without T_{ref}

Specify: V (variable)

Then ρ is ρ_0, a reference value

Specifying VVIS, causes μ to be determined as variable (temperature dependent)

Specifying VKAY, causes C_p and k to be determined as variable (temperature dependent)

Property Temperature Range must be specified (T_{MIN}, T_{MAX}, N)

Property Library Index KI must be ≥ 1.

Specify: T_{ref} without ρ, μ, C_p, k

Specify: V (variable)

Then ρ_0 is determined at T_{ref}, as are μ, C_p, and k

Specifying VVIS, causes μ to be determined as variable (temperature dependent)

Specifying VKAY, causes C_p and k to be determined as variable (temperature dependent)

Property Temperature Range must be specified (T_{MIN}, T_{MAX}, N)

Property Library Index, KI, must be ≥ 1.

FIGURE 3.14. Materials Type Input Options

TABLE 3.2. Built-in Properties Library (Liquid or Gaseous States)

Number	Material
2	Water
3	Brine (typical of sea water; salinity $\lesssim$ 40 ppt)
4	Sodium
5	Potassium
6	NaK-78
7	Mercury
8	Lead
9	Lithium
10	Glycerin
11	Air
12	Nitrogen
13	Oxygen
14	Carbon dioxide
15	Carbon monoxide
16	Hydrogen
17	Helium
18	Steam
19	Argon

Values generated by the library may be checked before execution by setting NSTEP = 0 and specifying PROP, on the DBUG, Card (Card Group 2). If the user is not satisfied with the values generated, or if library data is not available, tabular properties data may be input using Card Type 19 (Card Group 4). As an alternative, the equations in subroutine LIBRARY may be replaced. Gas/vapor properties are based on low pressure data. Compressible flow of gases is based on the real gas law assumption.

3.4.7 Card Type 7: Velocity Component Input

Card Type 7 allows the user to input an array of velocity components that have the same cellwise value throughout the array. Input of the T, TKE, and DKE data is also allowed.

Field	Column	Variable	Description
1	1 - 5	U	Array R-direction velocity.
2	6 - 10	V	Array Z-direction velocity.
3	11 - 15	W	Array X-direction velocity.
4	16 - 20	T	Array temperature (if default, temperature not set).
5	21 - 25	TKE	Turbulent kinetic energy. Default = 10^{-8}.
6	26 - 30	DKE	Dissipation rate of turbulent kinetic energy. Default = 10^{-10}.
7	31 - 35	Blank	
8	36 - 40	J1	Array start J-index.
9	41 - 45	J2	Array end J-index.
10	46 - 50	K1	Array start K-index.
11	51 - 55	K2	Array end K-index.
12	56 - 57	Blank	
13	58 - 60	I1	Array start I-index.
14	61 - 63	Blank	
15	64 - 65	I2	Array end I-index.
16	66	Blank	
17	67	KP	Alpha character "R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 7.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   10            100  1-3  2-4         1    6    1    1    1    6 R  7  VELOCITY
```

Notes:

1. A single cell entry can be made by setting J1 = J2, K1 = K2, or I1 = I2.
2. Temperature may be input on this card but will not be set if defaulted.
3. If the user is restarting a simulation (READ, on the CONT, Card, Card Group 2), data on this card will be ignored unless an "R" is specified in Column 67. This option allows the user to leave the card file intact without overwriting the restart velocity and temperature fields. If the user wishes to overwrite the restart fields with original or new data, he must place an "R" in Column 67.
4. If the user wishes to restart with different boundary data, it is important to consider the effect of the transient boundary condition tables. As an example, suppose you have run a simulation out to a point in time where a boundary condition table has reduced the boundary temperature to half of the initial value. Upon restart TEMPEST will pick up where it left off in the table but will use the new data as though it were 50% of the initial value. Thus, if the user specifies the new temperature as 1000°F, TEMPEST assumes that 1000°F is half of the initial value (2000°F). Thus, care must be taken to assure that new data on a restart corresponds to the correct transient value according to the boundary value table.
5. In the current version, the initial value of turbulent viscosity, ET, is determined by the input (or defaulted) values of TKE and DKE, as discussed in Section 3.7.

3.4.8 Card Type 8: Velocity Component-Temperature Input (Single Cell)

This card allows the user to input the velocity components, temperature, and heat generation rate for a single cell. Input of the Q, TKE, and DKE data is also allowed.

Field	Column	Variable	Description
1	1 - 5	U	R-direction velocity.
2	6 - 10	V	Z-direction velocity.
3	11 - 15	W	X-direction velocity.
4	16 - 20	T	Temperature (if default, temperature not set).
5	21 - 25	Q	Heat generation (if default, Q not set).
6	26 - 30	TKE	Turbulent kinetic energy. (Default = 10^{-8}.)
7	31 - 35	DKE	Dissipation of turbulent kinetic energy. (Default = 10^{-10}.)
8-10	36 - 50	Blank	
11	51 - 55	J	J-index of cell.
12	56 - 57	Blank	
13	58 - 60	K	K-index of cell.
14	61 - 63	Blank	
15	64 - 65	I	I-index of cell.
16	66	Blank	
17	67	KP	Alpha character R if restart with new data.
18	68	Blank	
19	70	TYPE	Always the integer 8.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   10            100  1+6                             1    1    6 R  8  VELOCITY
```

Notes:

1. Temperature and heat generation (T and Q) will not be set if they are defaulted.
2. The heat generation array is not written to the restart file. If heat generation occurs in a simulation and restarting is to be done, it is recommended that heat generation be input separately using Card Type 9 (Card Group 4).
3. See notes in Section 3.4.7.

3.4.9 Card Type 9: Temperature and Heat Generation Input (Constant Value Matrix)

Card Type 9 allows the user to input an array of temperatures, heat generation rates, turbulent kinetic energies and/or dissipations that have the same cellwise value throughout a region.

Field	Column	Variable	Description
1	1 - 5	T	Array temperature (if default, T not set).
2	6 - 10	Q	Array heat generation (if default, Q not set).
3-4	11 - 20	Blank	
5	21 - 25	TKE	Array turbulent kinetic energy (if default, TKE not set).
6	26 - 30	DKE	Array dissipation (if default, DKE not set).
7	31 - 35	Blank	
8	36 - 40	J1	Array start J-index.
9	41 - 45	J2	Array end J-index.
10	46 - 50	K1	Array start K-index.
11	51 - 55	K2	Array end K-index.
12	56 - 57	Blank	
13	58 - 60	I1	Array start I-index.
14	61 - 63	Blank	
15	64 - 65	I2	Array end I-index.
16	66	Blank	
17	67	KP	Alpha character R if restart with new data.
18	68	Blank	
19	70	TYPE	Always the integer 9.
20	71 - 72	SYS	SI, ES, IN, CM, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
       1+6                             1    6    1    1    1    6 R  9      TEMP
```

Notes:

1. Temperature, heat generation, kinetic energy, and dissipation will not be set if they are defaulted. Heat generation is not written to the restart file. It is recommended that heat generation be input on separate card(s) and that the "R" option (restart with new data) always be used on those cards.
2. See notes in Section 3.4.7.
3. If SYS = IN, Q must be specified in Btu/in.^{3}-hr and T must be in normal units.
4. If SYS = CM, Q must be specified in watts/cm^3 and T must be in normal units.

3.4.10 Card Type 10: Temperature and Heat Generation Input (Single Cell)

This card allows the user to input temperature and heat generation rate for a single cell.

Field	Column	Variable	Description
1	1 - 5	T	Cell temperature (if default, T not set).
2	6 - 10	Q	Cell heat generation (if default, Q not set).
3-10	11 - 50	Blank	
11	51 - 55	JI	J-index of cell.
12	56 - 57	Blank	
13	58 - 60	KI	K-index of cell.
14	61 - 63	Blank	
15	64 - 65	II	I-index of cell.
16	66	Blank	
17	67	KP	Alpha character R if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 10.
20	71 - 72	SYS	SI, ES, IN, CM, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
       1+6                                            1    1    6   10      TEMP
```

Notes:

1. Temperature and heat generation rate will not be set if they are defaulted.
2. See notes in Section 3.4.7 and 3.4.9.

3.4.11 Card Type 11: U-Velocity Distribution Input (One-Dimensional Array)

Card Type 11 allows the user to specify one-dimensional distributions of the variable U.

Field	Column	Variable	Description
1	1 - 5	U(JI)	U-velocity of JI cell.
2	6 - 10	U(JI+1)	U-velocity of JI+1 cell.
3	11 - 15	U(JI+2)	U-velocity of JI+2 cell.
4	16 - 20	U(JI+3)	U-velocity of JI+3 cell.
5	21 - 25	U(JI+4)	U-velocity of JI+4 cell.
6	26 - 30	U(JI+5)	U-velocity of JI+5 cell.
7	31 - 35	U(JI+6)	U-velocity of JI+6 cell.
8	36 - 40	U(JI+7)	U-velocity of JI+7 cell.
9	41 - 45	U(JI+8)	U-velocity of JI+8 cell.
10	46 - 50	U(JI+9)	U-velocity of JI+9 cell.
11	51 - 55	JI	J-index of array start.
12	56 - 57	Blank	
13	58 - 60	KI	K-index of array start.
14	61 - 63	Blank	
15	64 - 65	II	I-index of array start.
16	66	KB	Alphanumeric character, specify: "R" if along R, "Z" if along Z, "X" if along X.
17	67	KP	"R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 11.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

Card Group 4: Card Type 11

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  .10  .15  .2099999                                  1    1   12R  11  U-VELOCI
```

Notes:

1. JI, KI, II is the starting point for information on the card.
2. KB is the coordinate direction that the array runs.
3. If the array does not fill all ten locations on the cards, follow the last value with one field of all 9s (i.e., 99999).

3.4.12 Card Type 12: V-Velocity Distribution Input (One-Dimensional Array)

Card Type 12 allows the user to specify one-dimensional distributions of the variable V.

Field	Column	Variable	Description
1	1 - 5	V(JI)	V-velocity of JI cell.
2	6 - 10	V(JI+1)	V-velocity of JI+1 cell.
3	11 - 15	V(JI+2)	V-velocity of JI+2 cell.
4	16 - 20	V(JI+3)	V-velocity of JI+3 cell.
5	21 - 25	V(JI+4)	V-velocity of JI+4 cell.
6	26 - 30	V(JI+5)	V-velocity of JI+5 cell.
7	31 - 35	V(JI+6)	V-velocity of JI+6 cell.
9	36 - 40	V(JI+7)	V-velocity of JI+7 cell.
10	46 - 50	V(JI+9)	V-velocity of JI+9 cell.
11	51 - 55	JI	J-index start of array.
12	56 - 57	Blank	
13	58 - 60	KI	K-index start of array.
14	61 - 63	Blank	
15	64 - 65	II	I-index start of array.
16	66	KB	Alphanumeric character specify: "R" if along R, "Z" if along Z, "X" if along X.
17	67	KP	"R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 12.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  -.6  3.0   1.99999                                 10    1    6R  12  V-VELOCI
```

Notes:

1. JI, KI, II is the starting point for information on the card.
2. KB is the coordinate direction that the array runs.
3. If the array does not fill all ten locations on the cards, follow the last value with one field of all 9s (i.e., 99999).

3.4.13 Card Type 13: W-Velocity Distribution Input (One-Dimensional Array)

Card Type 13 allows the user to specify one-dimensional distributions of the variable W.

Field	Column	Variable	Description
1	1 - 5	W(JI)	W-velocity of JI cell.
2	6 - 10	W(JI+1)	W-velocity of JI+1 cell.
3	11 - 15	W(JI+2)	W-velocity of JI+2 cell.
4	16 - 20	W(JI+3)	W-velocity of JI+3 cell.
5	21 - 25	W(JI+4)	W-velocity of JI+4 cell.
6	26 - 30	W(JI+5)	W-velocity of JI+5 cell.
7	31 - 35	W(JI+6)	W-velocity of JI+6 cell.
8	36 - 40	W(JI+7)	W-velocity of JI+7 cell.
9	41 - 45	W(JI+8)	W-velocity of JI+8 cell.
10	46 - 50	W(JI+9)	W-velocity of JI+9 cell.
11	51 - 55	JI	J-index start of array.
12	56 - 57	Blank	
13	58 - 60	KI	K-index start of array.
14	61 - 63	Blank	
15	64 - 65	II	I-index start of array.
16	66	KB	Alphanumeric character specify: "R" if along R, "Z" if along Z, "X" if along X.
17	67	KP	"R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 13.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   .7   2.   1.   6.99999                             3    3    3R  13  W-VELOCI
```

Notes:

1. JI, KI, II is the starting point for information on the card.
2. KB is the coordinate direction that the array runs.
3. If the array does not fill all ten locations on the cards, follow the last value with one field of all 9s (i.e., 99999).

3.4.14 Card Type 14: Temperature Distribution Input (One-Dimensional Array)

Card Type 14 allows the user to specify one-dimensional distributions of the variable T.

Field	Column	Variable	Description
1	1 - 5	TEMP(JI)	Temperature of cell JI.
2	6 - 10	TEMP(JI+1)	Temperature of cell JI+1.
3	11 - 15	TEMP(JI+2)	Temperature of cell JI+2.
4	16 - 20	TEMP(JI+3)	Temperature of cell JI+3.
5	21 - 25	TEMP(JI+4)	Temperature of cell JI+4.
6	26 - 30	TEMP(JI+5)	Temperature of cell JI+5.
7	31 - 35	TEMP(JI+6)	Temperature of cell JI+6.
8	36 - 40	TEMP(JI+7)	Temperature of cell JI+7.
9	41 - 45	TEMP(JI+8)	Temperature of cell JI+8.
10	46 - 50	TEMP(JI+9)	Temperature of cell JI+9.
11	51 - 55	JI	J-index start of array.
12	56 - 57	Blank	
13	58 - 60	KI	K-index start of array.
14	61 - 63	Blank	
15	64 - 65	II	I-index start of array.
16	66	KB	Alphanumeric character specify: "R" if along R, "Z" if along Z, "X" if along X.
17	67	KP	"R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 14.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  100   90   5599999                                  1    1   12R  14    TEMPER
```

Notes:

1. JI, KI, II is the starting point for information on the card.
2. KB is the coordinate direction that the array runs.
3. If the array does not fill all ten locations on the cards, follow the last value with one field of all 9s (i.e., 99999).

3.4.15 Card Type 15: Heat Generation Distribution Input (One-Dimensional Array)

Card Type 15 allows the user to specify one-dimensional distributions of the variable Q.

Field	Column	Variable	Description
1	1 - 5	Q(JI)	Heat generation of cell JI.
2	6 - 10	Q(JI+1)	Heat generation of cell JI+1.
3	11 - 15	Q(JI+2)	Heat generation of cell JI+2.
4	16 - 20	Q(JI+3)	Heat generation of cell JI+3.
5	21 - 25	Q(JI+4)	Heat generation of cell JI+4.
6	26 - 30	Q(JI+5)	Heat generation of cell JI+5.
7	31 - 35	Q(JI+6)	Heat generation of cell JI+6.
8	36 - 40	Q(JI+7)	Heat generation of cell JI+7.
9	41 - 45	Q(JI+8)	Heat generation of cell JI+8.
10	46 - 50	Q(JI+9)	Heat generation of cell JI+9.
11	51 - 55	JI	J-index start of array.
12	56 - 57	Blank	
13	58 - 60	KI	K-index start of array.
14	61 - 63	Blank	
15	64 - 65	II	I-index start of array.
16	66	KB	Alphanumeric character specify: "R" if along R, "Z" if along Z, "X" if along X.
17	67	KP	"R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 15.
20	71 - 72	SYS	SI, ES, IN, CM, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  1+6  1+799999                                       3    3    3X  15   Q GENER
```

Notes:

1. JI, KI, II is the starting point for information on the card.
2. KB is the coordinate direction that the array runs.
3. If the array does not fill all ten locations on the cards, follow the last value with one field of all 9s (i.e., 99999).
4. The heat generation array is not written to the restart file. "R" restart with new data should always be used if heat generation is present subsequent to a restart.
5. See notes in Section 3.4.9 for explanation of IN or CM use.

3.4.16 Card Type 16: Time-Dependent Boundary, Source Term and Electrode Tables

This card serves several purposes. It is used to prescribe time-dependent boundary data for velocity and temperature, time-dependent momentum, volume (mass), heat, and turbulence sources, and time-dependent heat generation when input on a node-by-node basis. There are three options for data on these cards. Determining which option to use is based on information supplied on Card Types 1 and 2 in Card Group 3.

Option 1 is used for defining tables which apply to:

- Boundary cells (types 30, 40, 60, and 61-64) for which NTAB is specified on Card Types 1 and 2 in Card Group 3.
- Node-by-node heat generation in computational cells (types 0, 10, 11, 65, and 70) for which NTABQ is specified on Card Types 1, 2, and 8 in Card Group 3.

Option 2 is used for defining tables which apply to:

- Source cells (types 0, 10, 11, and 65) for which flags MR, MZ, and MX are specified on Card Types 1 and 2 in Card Group 3.

Option 3 is used for defining tables which apply to:

- Electrode cells (type 70) which are identified with Card Type 8, Group 3.

When constituent transport is being modeled and constituent boundary and/or source term tables are required, they are input using a continuation card to the appropriate Card Type 16 option. The continuation card must directly follow the companion time point card.

3.4.16.1 Option 1: Boundary Factors and/or Heat Generation

Data for this option are input as:

Field	Column	Variable	Description
1	1 - 5	t	Time, compatible units
2	6 - 10	TFAC	Temperature factor for time in Field 1.
3	11 - 15	UFAC	U-velocity factor for time in Field 1.
4	16 - 20	VFAC	V-velocity factor for time in Field 1.
5	21 - 25	WFAC	W-velocity factor for time in Field 1.
6-8	26 - 40	Blank	
9	41 - 45	Q	Heat generation rate (Btu/ft^3-hr or J/m^3-hr) for time in Field 1.
10	46 - 50	Blank	
11	51 - 55	JI	Cyclic table flag.
12-14	56 - 63	Blank	
15	64 - 65	II	Boundary value or heat generation table number (Card Type 1 or 2, Card Group 3).
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 16.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

Continuation Card (for Option 1)

Use only if species boundary conditions are required.

Field	Column	Variable	Description
1	1 - 5	t	Time (same as on first card; not required but useful for identification purposes).
2	6 - 10	C_1	Mass fraction for constituent number 1.
3	11 - 15	C_2	Mass fraction for constituent number 2.
4	16 - 20	C_3	Mass fraction for constituent number 3.
5	21 - 25	C_4	Mass fraction for constituent number 4.
6	26 - 30	C_5	Mass fraction for constituent number 5.
7	31 - 35	C_6	Mass fraction for constituent number 6.
8	36 - 40	C_7	Mass fraction for constituent number 7.
9	41 - 45	C_8	Mass fraction for constituent number 8.
10	46 - 50	C_9	Mass fraction for constituent number 9.
11	51 - 55	Blank	
12	56 - 57	Blank	
13	58 - 60	KI	Power of ten scale factor applied to all mass fractions on this card. Default = 0, i.e., ($10^0 = 1$).
14	61 - 63	Blank	
15	64 - 65	II	Boundary value table number.

Field	Column	Variable	Description
16	66	KB	Always alpha variable "C" for continuation card.
17	67	Blank	
18	68	Blank	
19	69-70	TYPE	Always the integer 16.
20	71 - 72		SI, ES, or Default.
	73 - 80		Card identification, if desired.

EXAMPLE CARDS:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   43 1.19    .4                                                 1   16  BOUN TAB
```

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
      .030  .20                                           -2    1C  16  CONTINUE
```

Notes on Option 1:

1. A data point consists of several pieces of information (t, TFAC, VFAC, etc.) as a boundary value table. Each card will accommodate data for only one time point. Cards may be arranged in any order except that a continuation card must directly follow its companion time point card.
2. A data point consists of two pieces of information (t,Q) for a heat generation table. Note that if no source term flags are set, the same table number may be used for defining both boundary cell factors and node-by-node heat generation rates because they apply to different cell types. If used this way, all data (t,UFAC,VFAC,WFAC, and Q) must be completely specified at each time point.
3. The point t = 0 must be included. It need not be the first input value. It is recommended that the last point be a large time (e.g., $t = 10^{10}$.)
4. The time points may be arranged in any order within Card Group 4. TEMPEST internally sorts the tabular data, arranging it in time-ascending order within the proper table. Thus the data for any table can be expanded by adding additional points for intermediate values of time.
5. On any restart, TEMPEST will search through the time-dependent tables to obtain boundary values at the restart time. Thus if a table is expanded

for a restart with additional time points in the vicinity of the restart time, the boundary value table may give a slightly different interpolated value than that computed from the previous table.

6. The table values for temperature and velocity must be "factors". This approach was taken to reduce the amount of velocity information that would otherwise be required. These factors are fractions of the initial value. For instance, suppose initial values at t = 0 are U_O = 10 ft/sec, V_O = 5 ft/sec, W_O = 6 ft/sec, and T_O = 563°F. If at 43 sec data gives U = 4 ft/sec, V = 5 ft/sec, W = 3 ft/sec, and T = 670°F, the input data would consist of at least the two points:

t = 0		t = 43.0
TFAC = 1.	and	TFAC = 1.19
UFAC = 1.		UFAC = 0.4
VFAC = 1.		VFAC = 1.0
WFAC = 1.		WFAC = 0.5

7. If a table is to be used at any time during the transient, the table must be set up at the beginning of the transient. That is, you cannot start a simulation that uses no table and later restart with a table. Thus, if conditions are constant during the initial part of the transient, set the table to reflect this condition.
8. Heat generation values (not factors) must be input when using this card. The intent of this heat generation input option is to provide the user with the ability to specify heat generation tables on a node-by-node basis for simulations which include differing heat generation transients in a given material region. The alternate method of defining heat generation factors is available with Card Type 24 for application on a material-by-material basis. Because of tabular table storage limitations, this latter method is recommended.
9. Mass fractions are specified as a fraction between 0 and 1.0. When a boundary table is specified, each constituent mass fraction must be specified even if the mass fraction is a constant for the inflow direction. Mass fractions are specified in ascending order beginning in

Field 2 of the continuation card. A continuation card is defined by specifying a C in Column 66.

10. Boundary tables may be cyclic. Specifying JI = 5, for example, would indicate that five time point cards are to be used to form one cycle. The sixth time point in the table is then set equal to the first, etc.

3.4.16.2 Option 2: Time-Dependent Source Term Tables

Data on this card apply to cell types 0 and 65 (also internally set cell type 10 and 11). Velocities specified on this card are set in the simulation corresponding to MR, MZ, and/or MX flags specified on Card Types 1 and 2, Card Group 3.

Field	Column	Variable	Description
1	1 - 5	t	Time, compatible units.
2	6 - 10	U(N)	R-direction velocity, east cell face.
3	11 - 15	U(J-1)	R-direction velocity, west cell face.
4	16 - 20	V(N)	Z-direction velocity, north cell face.
5	21 - 25	V(K-1)	Z-direction velocity, south cell face.
6	26 - 30	W(N)	X-direction velocity, far cell face.
7	31 - 35	W(I-1)	X-direction velocity, near cell face.
8	36 - 40	E(N)	Cell volume divergence, L^3/L^3-t.
9	41 - 45	Q(N)	Cell energy inflow, Btu/ft^3 or Joule/m^3.
10	46 - 50	PK(N)	Turbulent kinetic energy production, L^2/t^3.
11	51 - 55	JI	Cyclic table flag.
12-13	56 - 60	Blank	
14	61 - 63	Blank	
15	64 - 65	II	Source term table number.
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 16.
20	71 - 72		SI, ES, CM, IN or default.
	73 - 80		Card identification.

Continuation Card (for Option 2)

Used only if species generation is required.

Field	Column	Variable	Description
1	1 - 5	t	Time (same as on first card; not required but may be useful for identification).
2	6 - 10	C_1	Mass generation rate for constituent number 1.
3	11 - 15	C_2	Mass generation rate for constituent number 2.
4	16 - 20	C_3	Mass generation rate for constituent number 3.
5	21 - 25	C_4	Mass generation rate for constituent number 4.
6	26 - 30	C_5	Mass generation rate for constituent number 5.
7	31 - 35	C_6	Mass generation rate for constituent number 6.
8	36 - 40	C_7	Mass generation rate for constituent number 7.
9	41 - 45	C_8	Mass generation rate for constituent number 8.
10	46 - 50	C_9	Mass generation rate for constituent number 9.
11	51 - 55	Blank	
12	56 - 57	Blank	
13	58 - 60	KI	Power of 10 scale factor applied to all mass generation rates on this card. Default = 0, i.e., ($10^0 = 1$).
14	61 - 63	Blank	
15	64 - 65	II	Source term table number.

Field	Column	Variable	Description
16	66	KP	Always the alpha variable "C" for continuation.
17-18	67-68	Blank	
19	69-70	TYPE	Always the integer 16.
20	71 - 72		SI, ES, or default.
	73 - 80		Card identification, if desired.

Notes on Option 2:

1. A data point contains several pieces of information depending upon MR, MZ, and/or MX flags set. Each card will accommodate only one time point, including the continuation card, if required.
2. TEMPEST will accommodate 20 tables. Table values are loaded to the array TEXT(N) and may have any length provided the total program requirements do not exceed the dimensions of TEXT (MAXTXT). Each table must have at least two points. The storage requirement for all tables may be computed as follows:

$$\text{MAXTXT} \geq (\text{NSP} + \text{NSRC} + 5) \sum_{k=1}^{\text{NTAB}} P_k$$

   where NTAB is the total number of tables and P_k is the number of time points in the k^{th} table. NSRC will be either 0 or 7, depending upon whether the tables are Option 1 (boundary or heat generation) or Option 2 (source type), respectively. NSP is the number of species.
3. The point t = 0 must be included. It need not be the first input value.
4. The time point cards may be arranged in any order within Card Group 4. TEMPEST internally sorts the tabular data, arranging it in time-ascending order within the proper table. Thus, the data for any table can be expanded by adding additional points for intermediate values of time.

5. On any restart, TEMPEST will search through the time-dependent tables to obtain boundary values at the restart time. Thus, if a table is expanded for a restart with additional time points in the vicinity of the restart time, the boundary value table may give a slightly different interpolated value than computed from the previous table.
6. Time must be consistent with the value of "TYMUNT" on the TIME, Card (Card Group 1). That is, if TYMUNT = MINUT, then the time units for each data are minutes.
7. For Type 65 cells, only the velocity can be specified as a function of time (e.g., volume divergence, energy inflow, and turbulence production are superfluous). For Type 65 cells, continuity must be satisfied at all times in all cells, however.
8. Volume generation E(N) follows the sign convention of the vector dot product ($\vec{v} \bullet \vec{n}$). Thus flow <u>into</u> the system is negative (-E(N), and flow <u>out</u> of the system is positive (+E(N)).
9. For flow into the system set by the volume source -E(N), an energy source must also be specified if heat transport is to be simulated. The energy source is

   $$Q(N) = \rho C_p T$$

   where ρ, C_p, and T are density, specific heat, and temperature of the inflow. Temperature is referenced to 0 in degrees F or C. Units of the energy source are Btu/ft^3 or Joules/m^3. An energy source for outflow need not be specified.
10. Little guidance is available for specifying turbulence production source. Units for turbulence production source are ft^2/s^3 or m^2/s^3.
11. Mass generation rates are in units of lbm/ft^3 sec or kg/m^3 sec.
12. Source tables may be cyclic. Specifying JI = 5, for example, indicates that five time points are to be used to form one period of a cyclic table.

3.4.16.3 Option 3: Not Used

3.4.17 Card Type 17: Drag Coefficients

This card is used to specify form or friction drag coefficients and velocity exponents corresponding to the identification number assigned by Card Type 4 (Card Group 3).

Field	Column	Variable	Description
1	1 - 5	HDC(JI)	Drag coefficient JI.
2	6 - 10	DEX(JI)	Drag exponent JI.
3	11 - 15	HDCJI+1)	Drag coefficient JI+1.
4	16 - 20	DEX(JI+1)	Drag exponent JI+1.
5	21 - 25	HDC(JI+2)	Drag coefficient JI+2.
6	26 - 30	DEX(JI+2)	Drag exponent JI+2.
7	31 - 35	HDC(JI+3)	Drag coefficient JI+3.
8	36 - 40	DEX(JI+3)	Drag exponent JI+3.
9	41 - 45	HDC(JI+4)	Drag coefficient JI+4.
10	46 - 50	DEX(JI+4)	Drag exponent JI+4.
11	51 - 55	JI	Drag coefficient identifier referred to in Field 1.
12	56 - 57	Blank	
13	58 - 60	KI	Drag coefficient number referred to in Field 9 (or number of last input value).
14	61 - 63	Blank	
15	64 - 65	Blank	
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 17.
20	71 - 72	Blank	
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
 .017    2  1.2  1.8                                  1    2        17  DR COEFF
```

Notes:

1. The identification numbers specified by Card Type 4 (Card Group 3) must correspond to the indices JI, JI+1, JI+2,..., etc. That is, if JI (Field 11) = 1, then HDC(JI+3) and DEX(JI+3) are HDC(4) and DEX(4) where 4 refers to the identifier 4 assigned by Card Type 4 (Card Group 3).
2. Drag coefficients and exponents may have identification numbers from 1 to 98, with numbers 1 to 48 reserved for form drag relationships and numbers 49 to 98 reserved for friction drag relationships. The form and friction drag relationships used by TEMPEST are defined as follows:

   Form drag, f_d: (i = 1 to 48)

   $$\Delta P = K_i \left(\frac{\rho}{2g}\right) V^{N_i}$$

   where K_i and N_i are given by HDC(I) and DEX(I).

   Friction drag, f_f: (i = 49 to 98)

   $$\Delta P = \left(\frac{F}{D}\right)_i \left(L \frac{\rho}{2g}\right) V^{N_i}$$

   where $(F/D)_i$ and N_i are, again, specified by HDC(I) and DEX(I).
3. The value of DEX(I) should always be ≥ 1.0. It need not be an integer.
4. Friction drag currently has a simple, nongeneral form, as indicated by Figure 3.15. That is, only a single cell side is considered to have drag and only a single velocity component is considered (rather than $\vec{u}$ and $\vec{v}$, for instance). Friction drag formulations will be improved in future code modifications.

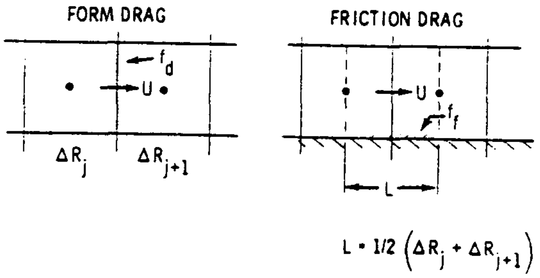


FIGURE 3.15. Location of Drag Coefficients

5. The units of the drag coefficients must be in the units of the operational mode (consistent with SISY,).
6. If a large drag coefficient is used to "shut off" flow, set $N_j = 1.0$ for best results.

3.4.17.1 Zero-Thickness Wall

Zero-thickness walls may be used in TEMPEST through the use of "special" drag coefficients.

Case 1. Impermeable Wall

Set HDC(I) = -9999.

This value of HDC(I) is used only as an internal flag that directs TEMPEST to set appropriate boundary condition bookkeeping. Cells that are adjacent to the wall are tagged Type 11, which will be revealed in the cell type map (the TYPE 11 cells are not set by the user but are internally computed). Slip factors are set as in the case of normal solid walls, and a drag identification number must be set by Card Type 4, Card Group 3.

Case 2. Semipermeable Wall

Set HDC(I) = -HDC(I).

Here the negative sign is used only as a flag that directs TEMPEST to set up tangential boundary conditions similar to a solid wall. HDC(I) is the value K_i discussed previously. The option was devised for those situations where flow penetrates a wall but otherwise behaves more like a solid barrier than, say, a screen. Slip factors may be set as in Case 1. Adjacent cells are set internally as in Case 1.

In both cases, the user can expect TEMPEST to iterate longer in the continuity/pressure solution.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
 9999   2. -.05   2.  .06  1.5                        1    3        17  DR(OPTL)
```

3.4.18 Card Type 18: Heat Transfer Film Coefficient

This card is used to specify film/contact coefficient values corresponding to the identification numbers assigned by Card Type 3 (Card Group 3). Gap radiation and boundary radiation heat transfer are also keyed with this card. Two options for data definition are available.

Film/Contact Coefficient (Option 1)

For contact film/contact coefficient definition, the following card format is used.

Field	Column	Variable	Description
1	1 - 5	HFC(JI)	Film coefficient JI.
2	6 - 10	HEX(JI)	Film exponent JI (see notes).
3	11 - 15	HFC(JI+1)	Film coefficient JI+1.
4	16 - 20	HEX(JI+1)	Film exponent JI+1.
5	21 - 25	HFC(JI+2)	Film coefficient JI+2.
6	26 - 30	HEX(JI+2)	Film exponent JI+2.
7	31 - 35	HFC(JI+3)	Film coefficient JI+3.
8	36 - 40	HEX(JI+3)	Film exponent JI+3.
9	41 - 45	HFC(JI+4)	Film coefficient JI+4.
10	46 - 50	HEX(JI+4)	Film exponent JI+4.
11	51 - 55	JI	Film coefficient identifier referred to in Field 1.
12	56 - 57	Blank	
13	58 - 60	KI	Film coefficient identifier referred to in Field 9 (or number of last input value).
14	61 - 63	Blank	
15	64 - 65	Blank	
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 18.

20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  .12      17.1                                  1    2             18  HT COEFF
```

Notes (Option 1):

1. A total of 98 (96 in turbulent flow) different film coefficients may be accommodated with the input. The identification numbers specified by Card Type 3 (Card Group 3) must correspond to the indices JI, JI+1, JI+2, etc. That is, if JI (Field 11) = 1, then HFC(JI+3) and HEX(JI+3) are HFC(4) and HEX(4) where 4 refers to the identifier 4 (variable HNC(N)) assigned by Card Type 3 (Card Group 3).
2. As explained in Section 3.3.3, if a film coefficient is specified at a fluid-solid interface, the fluid conduction resistance between the field cell center and the solid surface is set to zero. In this way, the thermal resistance is controlled completely by the value of the film coefficient. This logic does not apply to solid-to-solid heat conduction cells having a contact resistance or to fluid cells where a film coefficient is not specified.
3. This input option currently only allows constant film coefficients. Thus, the exponent input (HEX(I)) is superfluous and is to be defaulted. Input has been constructed to accommodate future development of film coefficient models such as gap radiation allowed with Option 2.
4. A value of HFC(I) = 0 [set internally to SMALL, (which is equal to 10^{-15})] effects an adiabatic surface. Recall, however, that Cell Types 20 and 50 are internally structured to effect an adiabatic wall, so that a zero film coefficient is not required for these surfaces and should not be used.

5. The TEMPEST turbulence model will compute a local turbulent film coefficient based on a "law-of-the-wall" temperature profile model by default. This default mode may be overridden on a cell-by-cell basis by specifying film coefficients on this card.

Gap and Boundary Radiation (Option 2)

For specification of radiation and/or temperature-difference-dependent convection coefficients, Card Type 18 input is as follows:

Field	Column	Variable	Description
1	1 - 5	HFC(II)	Film coefficient II.
2	6 - 10	HEX(II)	Film exponent II.
3	11 - 15	EMS(II)	Emissivity of adjacent boundary sink. Default = 1.0.
4-12	16 - 60	Blank	
14	61 - 63	Blank	
15	64 - 65	II	Film coefficient identification number.
16	66	KB	Always the alpha character "R".
17-18	67 - 68	Blank	
19	69 - 70	TYPE	Always the integer 18.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   .1  .25   1.                                                 2R  18  HT COEFF
```

The above example card indicates that there is a natural convection heat transfer coefficient specified having the form $h_c = 0.1\ \Delta T^{0.25}$ and that the emissivity of the sink is 1.0, giving $F_{j-b} = \epsilon j$.

Notes:

1. The film coefficient in Field 1 and exponent in Field 2 have the following relationships:

   $$h_c = C \Delta T^N$$

   where C is placed in Field 1
   N is placed in Field 2
   If Field 2 is blank or 0, then $h_c = C$ (constant).

2. Film coefficients are specified on the east, north, and far sides of a computational cell. The emissivity (ϵ_1) of this cell is specified on the properties card (PROP(5,II)). If the adjacent radiation surface is the surface of a computational cell, the emissivity (ϵ_2) is also obtained from the material type input. If the adjacent cell is a fluid or noncomputational boundary cell (Type 0 through 65), emissivity (ϵ_2) is not available from the materials type input card and a value must be supplied in Field 3 of Card Type 18. The radiation sink temperature is that of the adjacent boundary cell.

3. If both radiation and convection are present, the overall film coefficient is

$$h = h_r + h_c = \frac{\sigma(T_S^{\ 4} - T_b^{\ 4})}{(\frac{1}{\epsilon_j} + \frac{1}{\epsilon_b} - 1)(T_j - T_b)} + C|T_S - T_b|^N$$

4. Only one set of values can be placed on a card.

3.4.19 Card Type 19: Tabular Property Data

Tabular property data may be supplied by this card type. Each card can accommodate only one temperature point and must be followed directly by a continuation card if control options EMFR, PART, and/or MAST, are selected (CONT, Card, Card Group 2) and relevant properties are required.

Field	Column	Variable	Description
1	1 - 5	$TEMP_1$	Temperature corresponding to property values on this and continuation card.
2	6 - 10	k_1	Thermal conductivity.
3	11 - 15	ρ_1	Density.
4	16 - 20	c_1	Specific heat.
5	21 - 25	μ_1 or ϵ_1	Dynamic viscosity or emissivity.
6	26 - 30	R_1 or S_1	Gas constant or salinity.
7-13	31 - 60	Blank	
14	61 - 63	Blank	
15	64 - 65	II	Material number.
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 19.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

Tabular Properties Continuation Card

Properties required by selection of control options EMFR, PART, and/or MAST, are input on this continuation card.

Field	Column	Variable	Description
1	1 - 5	PROP(36,II)	Reserved for EMFR,.
2	6 - 10	PROP(37,II)	Reserved for EMFR,.
3	11 - 15	PROP(38,II)	Reserved for MAST,.
4	16 - 20	PROP(39,II)	Reserved for MAST,.
5	21 - 25	PROP(40,II)	Reserved for MAST,.
6	26 - 30	PROP(41,II)	Reserved for MAST,.
7	31 - 35	PROP(42,II)	Reserved for PART,.
8	36 - 40	PROP(43,II)	Reserved for PART,.
9	41 - 45	PROP(44,II)	Reserved for PART,.
10	46 - 50	PROP(45,II)	Future.
11-13	51 - 60	Blank	
14	61 - 63	Blank	
15	64 - 65	II	Material type.
16	66	KB	"C" for identifying continuation.
17	67	KP	"P" for identifying properties.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 19.
20	71 - 72	SYS	
	73 - 80		Card identification, if desired.

EXAMPLE CARDS:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   90   8. 980. 132.  1-4                                       1   19ES  TBPROP
```

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  .03   .2                                                      1CP 19  CONTINUE
```

Notes:

1. Tabular input is to be used when the Properties Table Index KI = 1 in Field 13 of Card Type 6 (Card Group 4). The material number on this card and Card Type 6 (Card Group 4) must be the same.
2. Temperature points for any material can be entered in any order. Data on any one card must be for the same material as indicated by Field 15. Data may be entered with unequal temperature intervals.
3. If property values are defaulted, the corresponding value on Card Type 6 will be used (i.e., if k_1 is left blank, the thermal conductivity specified on Card Type 6 for the same material will be used). Thus, if a default value appears on this data card, Card Type 6 must precede Card Type 19 for the same material.
4. Ensure that data is available to at least cover the temperature range specified on Card Type 6 for the same material (except as indicated below).
5. If only one temperature point is read in, the table will be constant. If two temperature points are read in, the distribution of property values will be linear. In this case, the value 2 should be used on Card Type 6, Field 10 (more may be used but are unnecessary).

6. The tables input here are not the same tables used during the problem simulation. These data will be used to construct the direct entry table used by TEMPEST during the simulation.
7. Interpolation is linear. Thus, the user should supply those points that will give an adequate piecewise linear interpolation of the data.
8. The QS(N) array is used for internal table manipulation and must have dimensions larger than 2*M where

$$M = 15 \sum_{k=1}^{NTABS} P_k$$

and P_k is the number of time points in the kth table. If the QS(N) array size (3 times PARAMETER MAXSZE) is not large enough to accommodate the required table manipulation, an error message will be printed. Generally this problem is not likely to arise. For instance, a simulation dimensioned for MAXSZE = 1000 would accommodate:

$$\frac{3000-1}{2} \bullet \frac{1}{5} = 299 \text{ table temperature points}$$

if no continuation data is required. If all continuation data is required, this would allow 99 table time points. Very small field variable array dimensions or a large table requirement may require redimensioning of the QS(N) array.

3.4.20 Card Type 20: Tabular Printer Output Time Table

This card provides the user with the option of specifying the simulation times for which printer output is desired. The input parameter TBPRT (PRNT, Card Group 1) is used to initialize PTIME(N) according to PTIME(N + 1) = TBPRT + PTIME(N). Input on this card may be used to override or to supplement the PTIME(N) initialization and must be in time units compatible with TYMUNT on the TIME, Card (Card Group 1).

Field	Column	Variable	Description
1	1 - 5	PTIME(JI)	Print time JI, compatible units.
2	6 - 10	PTIME(JI+1)	Print time JI+1, compatible units.
3	11 - 15	PTIME(JI+2)	Print time JI+2, compatible units.
4	16 - 20	PTIME(JI+3)	Print time JI+3, compatible units.
5	21 - 25	PTIME(JI+4)	Print time JI+4, compatible units.
6	26 - 30	PTIME(JI+5)	Print time JI+5, compatible units.
7	31 - 35	PTIME(JI+6)	Print time JI+6, compatible units.
8	36 - 40	PTIME(JI+7)	Print time JI+7, compatible units.
9	41 - 45	PTIME(JI+8)	Print time JI+8, compatible units.
10	46 - 50	PTIME(JI+9)	Print time JI+9, compatible units.
11	51 - 55	JI	Print time index referred to in Field 1.
12	56 - 57	Blank	
13	58 - 60	KI	Print time index referred to in Field 10 or last field.
14-15	61 - 65	Blank	
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 20.
20	71 - 72	Blank	Always default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

```
                                   Columns

         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   11   12                                           33   34        20  PRNTTIME
```

Notes:

1. Current dimensions are set to PTIME(NPFT). Dimension may be changed in COMDECK FACTS: PARAMETER (NPFT = 100).
2. As an example, suppose TBPRT is set to 10 sec, creating a PTIME array of: 10,20,30,40...90,100,110,120...sec for printout. If the user sets PTIME(33) = 11 and PTIME(34) = 12, printing will occur at: 10,11,12,20,30,40...sec. Values on this card may be in any order. The PTIME array is ordered after insertion. Thus inserting them higher in the array will preserve the lower times, and vice versa. On restart the PTIME(N) array is initialized beginning with the first multiple of TBPRT greater than the restart time.

3.4.21 Card Type 21: Tabular Tape/File Output Time Table

This card provides the user with the option of specifying the simulation times for which tape/file output is desired. The input parameter TBTD (POST, Card Group 1) is used to initialize FTIME(N) according to FTIME(N+1) = TBPD + FTIME(N). Thus, input on this card may be used to override or to supplement the initialization and must be in the units compatible with TYMUNT, on the TIME, Card (Card Group 1).

Field	Column	Variable	Description
1	1 - 5	FTIME(JI)	File time JI, compatible units.
2	6 - 10	FTIME(JI+1)	File time JI+1, compatible units.
3	11 - 15	FTIME(JI+2)	File time JI+2, compatible units.
4	16 - 20	FTIME(JI+3)	File time JI+3, compatible units.
5	21 - 25	FTIME(JI+4)	File time JI+4, compatible units.
6	25 - 30	FTIME(JI+5)	File time JI+5, compatible units.
7	31 - 35	FTIME(JI+6)	File time JI+6, compatible units.
8	36 - 40	FTIME(JI+7)	File time JI+7, compatible units.
9	41 - 45	FTIME(JI+8)	File time JI+8, compatible units.
10	46 - 50	FTIME(JI+9)	File time JI+9, compatible units.
11	51 - 55	JI	File time index referred to in Field 1.
12	56 - 57	Blank	
13	58 - 60	KI	File time index referred to in Field 10 or last value.
14-15	61 - 65	Blank	
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 21.
20	71 - 72	Blank	Always default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   11   12                                           33   34        21  FILETIME
```

Notes:

Notes for Card Type 20 apply.

3.4.22 Card Type 22: Tabular Postprocessing Output Time Table

This card provides the user with the option of specifying the simulation times for which postprocessing output is desired. The input parameter TPODST (on the TPOST, Card, Card Group 1) is used to initialize PPTIME(N) according to PPTIME(N+1) = TPOST + PPTIME(N). Thus, input on this card may be used to override or to supplement the initialization and must be in the units compatible with TYMUNT, on the TIME, Card (Card Group 1).

Field	Column	Variable	Description
1	1 - 5	PPTIME(JI)	File time JI, compatible units.
2	6 - 10	PPTIME(JI+1)	File time JI+1, compatible units.
3	11 - 15	PPTIME(JI+2)	File time JI+2, compatible units.
4	16 - 20	PPTIME(JI+3)	File time JI+3, compatible units.
5	21 - 25	PPTIME(JI+4)	File time JI+4, compatible units.
6	25 - 30	PPTIME(JI+5)	File time JI+5, compatible units.
7	31 - 35	PPTIME(JI+6)	File time JI+6, compatible units.
8	36 - 40	PPTIME(JI+7)	File time JI+7, compatible units.
9	41 - 45	PPTIME(JI+8)	File time JI+8, compatible units.
10	46 - 50	PPTIME(JI+9)	File time JI+9, compatible units.
11	51 - 55	JI	File time index referred to in Field 1.
12	56 - 57	Blank	
13	58 - 60	KI	File time index referred to in Field 10 or last value.
14-15	61 - 65	Blank	
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 22.
20	71 - 72	Blank	Always default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   11   12                                           33   34        22  POSTTIME
```

Notes:

Notes for Card Type 20 apply.

3.4.23 Card Type 23: Slip Factors

This card is to be used where a wall slip factor is needed different from the default value SFACT specified on the MISC, Card (Card Group 1).

Field	Column	Variable	Description
1	1 - 5	DATA(1)	Value of slip factor number 1.
2	6 - 10	DATA(2)	Value of slip factor number 2.
3	11 - 15	DATA(3)	Value of slip factor number 3.
4	16 - 20	DATA(4)	Value of slip factor number 4.
5	21 - 25	DATA(5)	Value of slip factor number 5.
6	26 - 30	DATA(6)	Value of slip factor number 6.
7	31 - 35	DATA(7)	Value of slip factor number 7.
8	36 - 40	DATA(8)	Value of slip factor number 8.
9	41 - 45	DATA(9)	Value of slip factor number 9.
10-18	46 - 68	Blank	
19	69 - 70	TYPE	Always the integer 23.
20	71 - 72		Always default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
                                     -.5                            23  SLIPFACT
```

Notes:

1. Slip factors may be any numerical value but are usually $-1 \leq c_f \leq 1$.
2. A value must be provided for each identifier specified by Card Type 4 (Card Group 3).
3. Only nine different values may be used.
4. Do not use this card for surfaces bounding turbulent regions (superfluous).

3.4.24 Card Type 24: Time-Dependent Heat Generation Tables

Field	Column	Variable	Description
1	1 - 5	t_1	Time, compatible time units.
2	6 - 10	Q_1	Heat generation factor for time in Field 1.
3	11 - 15	t_2	Time, compatible time units.
4	16 - 20	Q_2	Heat generation factor for time in Field 3.
5	21 - 25	t_3	Time, compatible time units.
6	26 - 30	Q_3	Heat generation factor for time in Field 5.
7	31 - 35	t_4	Time, compatible time units.
8	36 - 40	Q_4	Heat generation factor for time in Field 7.
9	41 - 45	t_5	Time, compatible time units.
10	46 - 50	Q_5	Heat generation factor for time in Field 9.
11	51 - 55	JI	Cyclic table flag (Default = 0).
12	56 - 57	Blank	
13	58 - 60	KI	Number of time points on this card.
14	61 - 63	Blank	
15	64 - 65	II	Table number.
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 24.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
    0   1.   50   .7   30   .9                             3    1   24  GENTABLE
```

Notes:

1. A data point consists of two pieces of information: 1) time, and 2) heat generation factor. Each card will accommodate five data points.
2. TEMPEST will accommodate up to 20 tables. Table values will be loaded to the TEXT(N) array, and tables may have any length, provided the overall program storage requirements for TEXT(N) are not exceeded.
3. Each table must have at least two data points. One data point must be at time t = 0. It is recommended that the last point be a large time (e.g., $t = 10^{10}$) unless the data are cyclic.
4. Time must be consistent with the value of "TYMUNT" on the TIME, Card (Card Group 1). That is, if TYMUNT = HOURS, then the time units for these data are hours.
5. The data may be supplied in any time or table order within Card Group 4. Data are sorted and arranged internally.
6. Heat generation table number II corresponds to PROP(21,II) input on Card Type 6, Group 4. These tables thus apply on a material-by-material basis and are the recommended method of transient heat generation input. The alternate node-by-node method is available using Card Types 1 or 2, Card Group 3, and corresponding Card Type 16, Card Group 4, Option 1.
7. Heat generation tables may be cyclic. Specifying JI = 5, for example, indicates that five time points form one period of a cyclic table.

3.4.25 Card Type 25: Not Used

3.4.26 Card Type 26: Not Used

3.4.27 Card Type 27: Turbulence Model Constants

Card Type 27 allows the user of input turbulent model constants.

Field	Column	Variable	Description
1	1 - 5	TCON(1,LL)	σ_T: Turbulent (thermal) Prandtl number. Default = 0.9.
2	6 - 10	TCON(2,LL)	C_μ: Effective turbulent viscosity constant. Default = 0.9.
3	11 - 15	TCON(3,LL)	σ_k: Turbulent diffusion constant. Default = 1.0.
4	16 - 20	TCON(4,LL)	$C_{\epsilon 1}$: Dissipation (shear) production constant. Default = 1.44.
5	21 - 25	TCON(5,LL)	$C_{\epsilon 2}$: Dissipation (sink) constant. Default = 1.92.
6	26 - 30	TCON(6,LL)	$C_{\epsilon 3}$: Dissipation (buoyant) production constant. Default = 1.44.
7	31 - 35	TCON(7,LL)	σ_ϵ: Dissipation diffusion constant. Default = 1.3.
8	36 - 40	TCON(8,LL)	σ_m: Turbulent Schmidt number. Default = 0.77.
9	40 - 45	TCON(9,LL)	$\sigma_{T,0}$: Turbulent (thermal) Prandtl number for wall heat transfer model applied to low Prandtl number fluids. Default = 0.9.
10	46 - 50	TCON(10,LL)	Molecular diffusion coefficient. Default = 0.001.
11-14	51 - 63	Blank	
15	64 - 65	LL	Turbulent region identifier.
16-18	66 - 68	Blank	
19	69 - 70	TYPE	Always the integer 27.
20	71 - 72	Blank	
	73 - 80		Card identification, if desired.

Card Group 4: Card Type 27

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   .8                      1.2                                  1   27  TURBCONS
```

Notes:

1. LL must correspond to a turbulent constants identifier (PROP(22,II) on Card Type 6, Card Group 4).
2. Turbulent flow regions for which an identifier (PROP(22,II) on Card Type 6, Card Group 4) is specified will use defaulted turbulence model constants unless Card Type 27 is used.
3. Default values are those suggested by Jones and Launder (1973).
4. A maximum of ten different sets of constants may be used (i.e., LL $\leq$ 10).

3.4.28 Card Type 28: TKE-Distribution Input (One-Dimensional Array)

Card Type 28 allows the user to input one-dimensional distributions of the variable TKE (turbulent kinetic energy).

Field	Column	Variable	Description
1	1 - 5	TKE(JI)	Turbulent Kinetic Energy of JI cell.
2	6 - 10	TKE(JI+1)	Turbulent Kinetic Energy of JI+1 cell.
3	11 - 15	TKE(JI+2)	Turbulent Kinetic Energy of JI+2 cell.
4	16 - 20	TKE(JI+3)	Turbulent Kinetic Energy of JI+3 cell.
5	21 - 25	TKE(JI+4)	Turbulent Kinetic Energy of JI+4 cell.
6	26 - 30	TKE(JI+5)	Turbulent Kinetic Energy of JI+5 cell.
7	31 - 35	TKE(JI+6)	Turbulent Kinetic Energy of JI+6 cell.
8	36 - 40	TKE(JI+7)	Turbulent Kinetic Energy of JI+7 cell.
9	41 - 45	TKE(JI+8)	Turbulent Kinetic Energy of JI+8 cell.
10	46 - 50	TKE(JI+9)	Turbulent Kinetic Energy of JI+9 cell.
11	51 - 55	JI	J-index of array start.
13	58 - 60	KI	K-index of array start.
15	64 - 65	II	I-index of array start.
16	66	KP	Alphanumeric character; specific "R" if along R, "Z" if along Z, "X" if along X.
17	67	KP	"R" if restart with new data.
18	68	Blank	

19	69 - 70	TYPE	Always the integer 28.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  1-3 15-4 12-499999                                  1    1    1RR 28   TURB KE
```

Notes:

1. Notes in Section 3.4.11 (Card Type 11, Card Group 4) apply.

3.4.29 Card Type 29: DKE-Distribution Input (One-Dimensional Array)

Card Type 29 allows the user to input one-dimensional distributions of the variable DKE (dissipation rate of turbulent kinetic energy).

Field	Column	Variable	Description
1	1 - 5	DKE(JI)	Dissipation rate of JI cell.
2	6 - 10	DKE(JI+1)	Dissipation rate of JI+1 cell.
3	11 - 15	DKE(JI+2)	Dissipation rate of JI+2 cell.
4	16 - 20	DKE(JI+3)	Dissipation rate of JI+3 cell.
5	21 - 25	DKE(JI+4)	Dissipation rate of JI+4 cell.
6	26 - 30	DKE(JI+5)	Dissipation rate of JI+5 cell.
7	31 - 35	DKE(JI+6)	Dissipation rate of JI+6 cell.
8	36 - 40	DKE(JI+7)	Dissipation rate of JI+7 cell.
9	41 - 45	DKE(JI+8)	Dissipation rate of JI+8 cell.
10	46 - 50	DKE(JI+9)	Dissipation rate of JI+9 cell.
11	51 - 55	JI	J-index of array start.
13	58 - 60	KI	K-index of array start.
15	64 - 65	II	I-index of array start.
16	66	KB	Alphanumeric character; specify "R" if along R, "Z" if along Z, "X" if along X.
17	67	KP	"R" if restart with new data
18	68	Blank	
19	69 - 70	TYPE	Always the integer 29.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
  1-4 25-5 13-499999                                  1    1    1RR 30  TURB DKE
```

Notes:

1. Notes in Section 3.4.11 (Card Type 11, Card group 4) apply.

3.4.30 Card Type 30: Not Used

3.4.31 Card Type 31: Concentration Input (One-Dimensional Array)

Card Type 31 allows the user to input one-dimensional distributions of the concentration for each species.

Field	Column	Variable	Description
1	1 - 5	$C_I(JI)$	Mass fraction of JI cell.
2	6 - 10	$C_I(JI+1)$	Mass fraction of JI+1 cell.
3	11 - 15	$C_I(JI+2)$	Mass fraction of JI+2 cell.
4	16 - 20	$C_I(JI+3)$	Mass fraction of JI+3 cell.
5	21 - 25	$C_I(JI+4)$	Mass fraction of JI+4 cell.
6	26 - 30	$C_I(JI+5)$	Mass fraction of JI+5 cell.
7	31 - 35	$C_I(JI+6)$	Mass fraction of JI+6 cell.
8	36 - 40	$C_I(JI+7)$	Mass fraction of JI+7 cell.
9	41 - 45	$C_I(JI+8)$	Mass fraction of JI+8 cell.
10	46 - 50	$C_I(JI+9)$	Mass fraction of JI+9 cell.
11	51 - 55	JI	J-index of array start.
13	58 - 60	KI	K-index of array start.
15	64 - 65	II	I-index of array start.
16	66	KB	Alphanumeric character; specify "R" if along R, "Z" if along Z, "X" if along X.
17	67	KP	"R" if restart with new data.
18	68	I	Species number (integer from 1 to 9)
19	69 - 70	TYPE	Always the integer 31.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   .8   .6   .199999                                  1    1    1RR 29    E-VISC
```

Note:

1. Notes in Section 3.4.11 (Card Type 11, Card Group 4) apply.

3.4.32 Card Type 32: Not Used

3.4.33 Card Type 33: Component Mass Fraction (constant array value)

Card Type 33 allows the user to specify constant array distributions of the component mass fraction C_i.

Field	Column	Variable	Description
1	1 - 5	C_{L1}	Component C_{L1} mass fraction.
2	6 - 10	L1	Component number, L1.
3	11 - 15	C_{L2}	Component C_{L2} mass fraction.
4	16 - 20	L2	Component number, L2.
5	21 - 25	C_{L3}	Component C_{L3} mass fraction.
6	26 - 30	L3	Component number, L3.
7	31 - 35	Blank	
8	36 - 40	J1	Array start J-index.
9	41 - 45	J2	Array end J-index.
10	46 - 50	K1	Array start K-index.
11	51 - 55	K2	Array end K-index.
13	58 - 60	I1	Array start I-index
15	64 - 65	I2	Array end I-index.
16	66	Blank	
17	67	KP	Alpha character "R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 33.
20	71 - 72	Blank	
	73 - 80		Card identification, if desired.

Note:

1. Up to three cards may be required to specify all C_i.

3.4.34 Card Type 34: Not Used

3.4.35 Card Type 35: Setting Velocity and Viscosity Constants

A settling velocity may be specified for each transported constituent. This capability has been included for future considerations and has not been fully enabled. Currently, settling is only considered in the direction of the gravity vector when aligned parallel with the Z-coordinate direction. Only a fixed value for such constituents is allowed.

Field	Column	Variable	Description
1	1 - 5	VS(1), VC(1)	Settling velocity component 1, Constant 1.
2	6 - 10	VS(2), VC(2)	Settling velocity component 2, Constant 2.
3	11 - 15	VS(3), VC(3)	Settling velocity component 3, Constant 3.
4	16 - 20	VS(4), VC(4)	Settling velocity component 4, Constant 4.
5	21 - 25	VS(5), VC(5)	Settling velocity component 5, Constant 5.
6	26 - 30	VS(6), VC(6)	Settling velocity component 6, Constant 6.
7	31 - 35	VS(7), VC(7)	Settling velocity component 7, Constant 7.
8	36 - 40	VS(8), VC(8)	Settling velocity component 8, Constant 8.
9	41 - 45	VS(9), VC(9)	Settling velocity component 9, Constant 9.
10-15	46 - 65	Blank	
16	66	KB	Alphanumeric character (blank or "C").
17-18	67 - 68	Blank	
19	69 - 70	TYPE	Always the integer 35.
	73 - 80		Card identification, if desired.

Note:

1. A "blank" input for KB inputs data to the VS array (settling velocity). A "C" input for KB inputs data to the VC array (viscosity constants). These latter are used in a module-specific concentration-dependent viscosity model. In the absence of this module, availability of the VC array provides the user with a convenient method of inputting constants or other data of his own without the need to modify or add another card type.

3.4.36 Card Type 36: Volume and Surface Area Input

Card Type 36 allows the user to input an array of cell volume and surface area factors for use with the porosity module.

Field	Column	Variable	Description
1	1 - 5	VF(N)	Array cell volume fraction.
2	6 - 10	AR(N)	Array R-direction cell face area.
3	11 - 15	AZ(N)	Array Z-direction cell face area.
4	16 - 20	AX(N)	Array X-direction cell face area.
5-7	21 - 35	Blank	
8	36 - 40	J1	Array start J-index.
9	41 - 45	J2	Array end J-index.
10	46 - 50	K1	Array start K-index.
11	51 - 55	K2	Array end K-index.
13	58 - 60	I1	Array start I-index.
15	64 - 65	I2	Array end I-index.
16	66	Blank	
17	67	KP	Alpha character "R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 7.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   .5   .5   .5   .5                   1    6    1    1    1    6   36    VOLUME
```

3.4.37 Card Type 37: Volume and Surface Area Input (Single Cell)

This card allows the user to input the velocity components, temperature, and heat generation rate for a single cell. Input of the Q, TKE, and DKE data is also allowed.

Field	Column	Variable	Description
1	1 - 5	VF(N)	Cell volume fraction.
2	6 - 10	AR(N)	R-direction cell face area.
3	11 - 15	AZ(N)	Z-direction cell face area.
4	16 - 20	AX(N)	X-direction cell face area.
5	41 - 50	Blank	
11	51 - 55	J	J-index of cell.
13	58 - 60	K	K-index of cell.
15	64 - 65	I	I-index of cell.
16	66	Blank	
17	67	KP	Alpha character "R" if restart with new data.
18	68	Blank	
19	69 - 70	TYPE	Always the integer 37.
20	71 - 72	SYS	SI, ES, or default.
	73 - 80		Card identification, if desired.

EXAMPLE CARD:

Columns

```
         1         2         3         4         5         6         7         8
12345678901234567890123456789012345678901234567890123456789012345678901234567890
   10            100  1+6                             1    1    6 R  8  VELOCITY
```

4.0 INSTALLATION, REDIMENSIONING, AND UTILITY FILES

Installation, to some degree, is site dependent. TEMPEST, Version N, Mod 31, has been installed and executed on several machines including:

- CRAY-1S, 1A, and X-MP (both CTSS and UNICOS operating systems)
- IBM-3090
- DEC VAX 11/780, MICROVAX
- APOLLO DN3000, DN660
- SUN III and SUN IV
- APPLE MacIntosh II

In the process, the code has become very clean in terms of compiler specifics and FORTRAN programming. Thus installation should be pretty clean. This section describes normal installation procedures, code redimensioning, and utility files used during execution.

4.1 INSTALLATION

TEMPEST is distributed on magnetic media containing sufficient files to install the code and execute test problems. Post-processing codes are also provided. The base code source is ASCII card image file in UPDATE creation format. The basic format of the file is:

```
* COMDECK FACTS
     (parameter definitions)
* COMDECK COMLST
     (common blocks)
* COMDECK NCOM
     (common blocks)
* COMDECK VTYPE
     (declarations)
* COMDECK VERSE
     (version common block)
* DECK VERSER
     (version BLOCK DATA)
* DECK TEMPEST
     (main Program)
* DECK subroutine
     •
     •
     •
```

For sites that have the UPDATE utility (or equivalent HISTORIAN or WITNESS utilities), installation requires that an UPDATE creation be done using the card deck as input. Although somewhat site dependent, the UPDATE creation command would be like:

```
UPDATE I=cards,N=NEWPL,C=COMPILE,F
```

The compile file can then be used as input to a FORTRAN compiler and subsequently loaded.

However, prior to performing the creation run, two things must be done. With an editor, the card deck file must be edited to the target machine. For CRAY machines, the four characters CRAY in columns 1 - 4 must be replaced throughout the file with four blanks in columns 1 - 4. This will enable certain CRAY specific optimization. For other target machines, the four characters CSCL in columns 1 - 4 must be replaced with four blanks in columns 1 - 4. Note: without doing one or the other of these edits, the code will compile and execute, but not correctly!

Two other edits of the card deck must be done. First is in subroutine OPNFIL, the other is in subroutine DATTIM. In subroutine OPNFIL, there are two sets of commented OPEN statements. One is identified by "COPEN-STANDARD" and the other is "CAPOLLOATPNL". The first is a set of ASCII standard file opens that have been found to work on many (but not all) machines. The second is specific to APOLLO computers. Enable one set or the other by removing the appropriate comment string.

Timing calls are all done to subroutine DATTIM. Thus, for a particular target machine, the subroutine DATTIM must be appropriately edited. Currently in place are commented-out blocks of coding for date, time, and CPU timing calls for CRAY, IBM, APOLLO, VAX, and Mac II machines. The installer will have to enable the appropriate block of coding (or write his own) for the target machine. Every site and machine are a little different.

Once installed, provided test problem inputs can be executed and compared to provided test problem outputs. This should be done to ensure that the code is executing properly at the target site.

More extensive notes on target machines specifics and editing OPNFIL and DATTIM routines are included as comments in the source code of the main program. Those comments are reproduced on the subsequent pages.

```
c***********************************************************************
c**                                                                   **
c**            code version and update information                    **
c**         ------------------------------------------                **
c**                                                                   **
c**                      code version n31                             **
c**                                                                   **
c**        creation run    - mod 0   -    jun        1988             **
c**                                                                   **
c**                         fortran 77                                **
c**                                                                   **
c***********************************************************************
c**                                                                   **
c**        n o t e s   f o r   c o d e   c o n v e r s i o n          **
c**                                                                   **
c**    the tempest    code card deck image is designed so that        **
c**    conversion to various computer architectures can be            **
c**    implemented through edit commands.  this is accomplished       **
c**    by activating certain lines of coding by deleting 'comment'    **
c**    characters in the appropriate columns.                         **
c**                                                                   **
c**   there are three edit actions that must be taken:                **
c**                                                                   **
c**        1. activate vector or scalar coding lines or calls         **
c**           (will require one or two edit sweeps)                   **
c**                                                                   **
c**        2. activate apropriate file open commands                  **
c**           (will require one edit sweep)                           **
c**                                                                   **
c**        3. activate proper system timer routines                   **
c**           (will require one edit sweep)                           **
c**            note: you may have to write your own routine           **
c**                  and add it to the existing options.              **
c**                  see: subroutine 'dattim'                         **
c**                                                                   **
c**       a. types of systems are:                                    **
c**                                                                   **
c**          i. vector machines                                       **
c**              1. cray (all)                                        **
c**              2. ibm (vf)                                          **
c**              3. other vector machines both 32 and 64 bit word     **
c**                                                                   **
c**         ii. scalar machines                                       **
c**              1. 32 bit word length                                **
c**              2. 64 bit word length                                **
c**                                                                   **
c**       b. edit commands (see note below for definition)            **
c**           i. cray                                                 **
c**               1. rpl,*,1,4/cray/bbbb                              **
c**                                                                   **
c**          ii. ibm with vector facility                             **
c**               1. rpl,*,1,4/cscl/bbbb                              **
c**                                                                   **
c**                                                                   **
c**                                                                   **
c**         iii. other vector - 64 or 32 bit word length              **
c**               1. rpl,*,1,4/cscl/bbbb                              **
c**                                                                   **
c**          iv. scalar - 64 or 32 bit word length                    **
```

```
c**             1. rpl,*,1,4/cscl/bbbb                                **
c**                                                                   **
c**                                                                   **
c**   notes:                                                          **
c**     0) blanket double precision: implicit real*8 (a-h,o-z)        **
c**        can be eliminated by commenting this line in               **
c**        comdeck 'facts'                                            **
c**                                                                   **
c**     1) rpl,*,1,4/xxxx/bbbb means search entire card deck          **
c**        image for the string xxxx in columns 1 through 4 and       **
c**        replace it with 4 blank spaces (bbbb).                     **
c**                                                                   **
c**     2) there are also other system dependent changes which have   **
c**        to be made.  these are date/time/cpu calls and file open   **
c**        calls.  these are located in routines dattim and opnfil,   **
c**        respectively.  these  routine must be examined to ensure   **
c**        system compatibility.                                      **
c**                                                                   **
c**        activation of the proper timing routines:                  **
c**              (use indicated edit commands)                        **
c**             1. cray       (lanl)                                  **
c**                  rpl,10/cri-atlanl/                              **
c**             2. dec vax    (pnl/bnw)                               **
c**                  rpl,9/cvaxatpnl/                                 **
c**             3. apollo     (pnl/bnw)                               **
c**                  rpl,12/capolloatpnl/                             **
c**             4. ibm-3090                                           **
c**                  rpl,9/cibm-3090/                                 **
c**             5. cray       (unicos)                                **
c**                  rpl,10/cri-unicos/                               **
c**             6. mac-II                                             **
c**                  rpl,5/cmac2/                                     **
c**             7. sun 4                                              **
c**                  rpl,10/csun4atpnl/                               **
c**                                                                   **
c**                                                                   **
c**        activation of the proper file open commands:               **
c**              (use indicated edit commands)                        **
c**                                                                   **
c**             1. ansi standard                                      **
c**                  rpl,14/copen-standard/                           **
c**                                                                   **
c**             2. exceptions                                         **
c**                a. apollo (pnl/bnw)                                **
c**                   rpl,12/capolloatpnl/                            **
c**                                                                   **
c**
```

4.2 UTILITY FILES

Several files are utilized during execution of TEMPEST and several may be created upon normal termination of execution. The files required or created depend upon control options selected by input. Each file utilized or created by TEMPEST is listed below along with a description of how it is utilized or created. How these files are assigned or opened may be computer system dependent. Logical unit numbers are defined in subroutine SETUP if they need to be changed for a particular site.

Filename	Unit	Description
INPUT	lun(5)	The file INPUT is required to execute TEMPEST. TEMPEST reads the execution, control, and simulation data from this file.
OUTPUT	lun(6)	The file OUTPUT is the normal printed output.
OUTAPE	lun(8)	The file OUTAPE contains restart data. The file OUTAPE should be saved by the user at the end of normal termination if a restart is to be done. Restart data is written during execution and at the end of normal termination if the user selects the SAVE, option (CONT, card, Card Group 2). Time increments at which restart data are written are controlled by the REST, card (Card Group 1) and Card Type 20 (Card Group 4). (Refer to Sections 3.1.4, 3.2.1, 3.4.20.)
INTAPE	lun(7)	The file INTAPE contains the data required for restart. Previous data written to the file OUTAPE must be attached or assigned with the file name INTAPE to restart. To restart and read from the INTAPE file, the READ, option (CONT, card, Group 2). The file number at which restart commences is controlled with the REST, card (Card Group 1). (Refer to Sections 3.1.4, 3.2.1.)
REPOST	lun(2)	The file REPOST contains postprocessing (graphics) data. The REPOST file should be saved by the user if postprocessing is to be done. Data is written during execution and

		at the end of normal termination if the user selects the PSAV, option (CONT, card, Card Group 2). Time increments at which postprocessing data are written are controlled with the POST, Card (Card Group 1) and Card Type 22 (Card Group 4). Variable arrays written to the REPOST file are controlled with the PLOT, card (Card Group 2). (Refer to Sections 3.1.8, 3.2.1, 3.2.4, 3.4.22.)
INPOST	lun(1)	The file INPOST contains postprocessing (graphics) data written to the file REPOST during execution of a previous job. The file INPOST must be assigned or attached to the current execution if the user selects the PRED, option (Card Group 2). Data on the file INPOST which is to be written to a new REPOST file created during the current job is controlled with the POST, card (Card Group 1). (Refer to Sections 3.1.8, 3.2.1.)
MONSAV	lun(3)	The file MONSAV contains monitor cell transient time history data. The user should store the MONSAV file if postprocessing of the data is to be done. (Currently TEMPEST Version N does not read previously generated MONSAV files on restart.) The file MONSAV is created by selection of the MSAV, option on the (CONT, card (Card Group 2). The number of cells monitored is the same as the total number of cells specified on Card Type 5 (Card Group 3). The number of time steps between monitor data is controlled with the MSKIP variable on the PRNT, card (Card Group 1). (Refer to Sections 3.1.3, 3.2.1, and 3.3.5.)

In addition to the above files, TEMPEST uses scratch files during execution, depending upon the control options selected. Because they are scratch I/O files, they need not be saved or stored after normal termination.

There are no graphics capabilities built directly into TEMPEST. Graphics are done using data from postprocessing files REPOST and MONSAV and a postprocessing program. This approach provides greater flexibility to the user in preparation of graphical results, but does require that the user specify what information (variables) to be output to the postprocessing files. A little thought is sometimes necessary.

4.3 REDIMENSIONING

The TEMPEST code can be redimensioned using any of several procedures. All dimensioning is done through PARAMETER statements, thus the procedures include:

1. before an UPDATE creation run, edit the PARAMETER statements in COMDECK FACTS
2. after a creation run, perform an UPDATE correction run and replace the PARAMETER statements appropriately
3. edit the COMPILE file (this is not recommended because PARAMETER statements exist in nearly all subroutines).

In this version of TEMPEST, there are only five PARAMETER statements that should have to be changed. These are:

Parameter	Default	Comment
MAXSZE	2500	All main arrays. Needs to be changed if total number of cells NR*NZ*NX is greater than default.
LSIZE	102	Cell spacing arrays. Needs to be changed only if NR+NZ+NX is greater than default.
MAXTXT	4000	Length of TEXT array. Needs to be changed only if TEXT storage is exceeded.

Parameter	Default	Comment
MAXSET	10000	Length of INDEX array. Needs to be changed only if INDEX storage is exceeded.
MAXCNT	1*MAXSZE	Length of concentration of species array. This should be set to the number of species times MAXSZE.

Array requirements for a particular problem may be determined specifying DBUG,SIZE in Group 2. Abort error messages are also printed to OUTPUT if arrays are exceeded. Note: There are rare situations for a particular problem where the TEXT array and the INDEX array limits are exceeded prior to checking. This can lead to erroneous and oftentimes confusing output. Thus, specifying DBUG,SIZE is a good suggestion.

More complete comments on redimensioning are included in the program. They are reproduced on pages hereafter.

```
c**                                                                   **
c**   as noted in the discussion above                                **
c**   the required dimension (parameters) sizes may be obtained by    **
c**   specifing  'size,' on the dbug, input card.  if dimensions are  **
c**   too small, the program must be recompiled.  setting these       **
c**   dimensions somewhat larger than necessary will eliminate  the   **
c**   need for recompile  for other problems of about the same size   **
c**   or smaller.                                                     **
c**                                                                   **
c**   other dimensional considerations to accomodate input.           **
c**                                                                   **
c**   ptime(npft) = print time array                                  **
c**   ftime(npft) = file  time array                                  **
c**   pptime(npft)= post process time array                           **
c**                                                                   **
c**   ptime, pptime and ftime dimensions must be at least as large    **
c**   as the number of specified times that output is requested.      **
c**   the parameter npft is found in the comdeck ' facts '            **
c**                                                                   **
c**   note that nox(lsize) is located in to common block /itg/        **
c**                                                                   **
c**                                                                   **
c***********************************************************************
c**                                                                   **
c**                 n o t e s   o n   c o n v e r s i o n             **
c**                          f a c t o r s                            **
c**                                                                   **
c**   si and engineering system conversion factor are contained in    **
c**   the array dkind(i,n) which converts input to normal mode        **
c**                                                                   **
c**   dkind(i,1)   is standard for both si and engineering            **
c**   dkind(i,2)   converts engineering to si                         **
c**   dkind(i,3)   converts si to engineering  .                      **
c**                                                                   **
c**   input conversion factors                                        **
c**                                                                   **
c**   dkind(i,n)                 engineering       si                 **
c**     i=1       length         feet            metre                **
c**     i=1       velocity       feet/sec        metre/sec            **
c**     i=1       acc. gravity   feet/sec**2     metre/sec**2         **
c**     i=2       temperature    deg f           deg c                **
c**     i=3       therm cond     btu/ft-f-hr     watt/metre-k         **
c**     i=4       density        lbm/ft**3       kg/metre**3          **
c**     i=5       sp. heat       btu/lbm-f       joule/kg-k           **
c**     i=6       kin viscosity  ft**2/sec       metre**2/sec         **
c**     i=7       film coef.     btu/ft**2-hr-f  watt/metre**2-k      **
c**     i=8       heat gen       btu/ft**3-hr    watt/metre**3        **
c**     i=9       pressure       lbf/in**2       pascal               **
c**     i=10      dyn viscosity  lbm/sec-ft      pascal-sec           **
c**     i=11      gas constant   ft-lb/lbm r     joule/kg-k           **
c**     i=12      absolute temp  deg r           deg k                **
c**     i=13      energy/vol     btu/ft3         joule/mt3            **
c**                                                                   **
c**   dkind(i,n)    engr(n=1)   si(n=1)      n=2            n=3       **
c**     i=1    l,v,g     1         1         .3048       3.28084      **
c**     i=2    t         1         1        2            3            **
c**     i=3    k       1/3600      1        1.7307       1.605e-4     **
c**     i=4    rho       1         1       16.01845       .062428     **
c**     i=5    c         1         1     4186.8          2.3885e-4    **
c**     i=6    nu        1         1         .092903    10.7639       **
```

```
c**     i=7    h       1/3600      1        5.678262     4.891944e-5  **
c**     i=8    q       1/3600      1       10.34971      2.683917e-5  **
c**     i=9    p        144        1     6894.8           .020885     **
c**     i=10   mu        1         1        1.48803       .671971     **
c**     i=11   r         1         1        5.38149       .185822     **
c**     i=12   tabs      1         1         5/9         1.8          **
c**     i=13   e         1         1    37250.0          1./37250.    **
c**                                                                   **
c**                                                                   **
c**   if sisy, is specified on cont, card dkind(i,1) is set to si     **
c**   factors(all 1's for standard si input)                          **
c**   if sisy, is defaulted dkind(i,1) is set to engineering factors  **
c**                                                                   **
c***********************************************************************
```

```
c***********************************************************************
c**                                                                   **
c**                  n o t e s   f o r   c h a n g i n g              **
c**                        d i m e n s i o n s                        **
c**                                                                   **
c**   changing dimensions to accommodate a different                  **
c**   problem size normally requires only changing the parameter      **
c**   specifications in the comdeck named ' facts '.  other           **
c**   dimensions such as those found in common blocks /lcf/,          **
c**   /scf/,/alf/, and those not in comdecks should not be            **
c**   changed without detailed knowledge of the coding                **
c**   structure.  additionally, these dimensions will only need       **
c**   to be changed if required by internal coding changes.           **
c**                                                                   **
c**   dimensional requirements (dimension parameters) can be found    **
c**   by specifying ' size, ' on the input record named 'dbug, '      **
c**   in card group 2.  if the arrays are too small, the ' size, '    **
c**   option is automatically activated to print instructions for     **
c**   redimensioning.                                                 **
c**                                                                   **
c**   the following table indicates how array sizes are to be matched **
c**                    dimensions (parameters)                        **
c**       maxsze          3*maxsze     lsize            maxtxt  maxset   **
c**       ------          --------     -----  -----    ------  ------   **
c**                                                                   **
c**                                                                   **
c**   base arrays                                                     **
c** /lci/                                                             **
c**       nt,mt,nhc,ndc                                 text    index    **
c** /lcm/                                                             **
c**       beta,q,d,et     qs,qqs                                      **
c**       p,h,rho,tke,    stx,fdc                                     **
c**       dke,pk,cv,cf                                                **
c**       t,e,sp,emu                                                  **
c** /cct/                                                             **
c**       st(n,3,3),                                                  **
c**       ut(n,3),af(n,3)                                             **
c**                                                                   **
c** /dtl/                                                             **
c**                                    x,xc,r,rc,                     **
c**                                    dx,dx0,bn                      **
c**                                    am,ac,ap                       **
c**                                                                   **
c**   species transport                                               **
c** /mta/                                                             **
c**       c(maxcnt)                                                   **
c**                                                                   **
c**   if additional modules are incorporated, then others arrays are  **
c**   affected:                                                       **
c**   compressible flow (not active in this mod)                      **
c** /cmp/                                                             **
c**       rup(n,3),rold,                                              **
c**       vko,vkn                                                     **
c**                                                                   **
c**   implicit momentum (not active in this mod)                      **
c** /imp/                                                             **
c**       afx(n,3),smi(n,3)                                           **
c**       scm(n,3),sut(n,3)                                           **
c**                                                                   **
c**   electric field (not active in this mod)                         **
```

```
c** /emf/                                                             **
c**      emf(maxemf)                                                  **
c**        qj(maxemf)                                                 **
c**                                                                   **
c**                                                                   **
c**   minimum array sizes (parameters) are as follows-                **
c**                                                                   **
c**   maxsze   = nr*nz*nx                                             **
c**   lsize    = nr+nz+nx                                             **
c**                                                                   **
c**   maxcnt   = nsp*maxsze (or 1, if nsp = 0)                        **
c**   maxarr   = 3*maxsze                                             **
c**   maxtxt   = problem dependent                                    **
c**   maxset   = problem dependent                                    **
c**                                                                   **
c**   maxcmp   = 1 (not active)                                       **
c**   maximp   = 1 (not active)                                       **
c**   maxemf   = 1 (not active)                                       **
c**                                                                   **
c**   npft     = 100 (for ptime, ftime, and pptime arrays - see below)**
c**                                                                   **
c**   where  nr,nz and nx are the number of computational cell        **
c**   in the r,z and x directions, respectively.                      **
c**                                                                   **
c**   notes on equivalences:                                          **
c**                                                                   **
c**   st(maxzse,3,3)                                                  **
c**   st(n,1,1)  =  st1(n,1)  =  qs(n)                                **
c**   st(n,2,1)  =  st1(n,2)  =  qs(n + kq)                           **
c**   st(n,3,1)  =  st1(n,3)  =  qs(n + iq)                           **
c**   st(n,1,2)  =  st2(n,1)  =  fdc(n)                               **
c**   st(n,2,2)  =  st2(n,2)  =  fdc(n + kq)                          **
c**   st(n,3,2)  =  st2(n,3)  =  fdc(n + iq)                          **
c**   st(n,1,3)  =  st3(n,1)  =  stx(n)                               **
c**   st(n,2,3)  =  st3(n,2)  =  stx(n + kq)                          **
c**   st(n,3,3)  =  st3(n,3)  =  stx(n + iq)                          **
c**                                                                   **
c**   ut(maxsze,3)                                                    **
c**   ut(n,1)    =  u(n)                                              **
c**   ut(n,2)    =  v(n)                                              **
c**   ut(n,3)    =  w(n)                                              **
c**                                                                   **
c**   af(maxsze,3)                                                    **
c**   af(n,1)    =  qqs(n)                                            **
c**   af(n,2)    =  qqs(n + kq)                                       **
c**   af(n,3)    =  qqs(n + iq)                                       **
c**                                                                   **
c**   where kq and iq are offsets:                                    **
c**   kq  = maxsze                                                    **
c**   iq  = 2*maxsze                                                  **
c**                                                                   **
c**   commentary:                                                     **
c**                                                                   **
c**   one approach for setting the problem dependent dimensions       **
c**   is to make them 'big enough'. another approach is to run the    **
c**   problem with estimated dimensions and then recompile with       **
c**   dimensional information obtained from the debug option ' size '.**
c**   if the dimensions are too small, the code will abort with a     **
c**   normal termination. output information will give the correct    **
c**   dimensions (parameter sizes).                                   **
```

5.0 A COMPUTATIONAL EXAMPLE

In this section a sample problem is developed to demonstrate TEMPEST input instructions and to illustrate typical line printer output. The sample problem was developed to illustrate how TEMPEST input is set up to model various system complexities and thus does not represent a modeled real system. Additionally, the sample problem demonstrates a number of the TEMPEST modeling features.

5.1 SAMPLE PROBLEM DESCRIPTION

The sample problem physical configuration and computational cell structure is shown in Figure 5.1. The problem has two-dimensional cylindrical geometry and is oriented with gravity acting downward parallel to the cylinder axis. Three materials are represented as follows:

1. a region filled with air that develops laminar natural circulations as the transient proceeds
2. an annular region filled with water in turbulent forced flow
3. a solid region with a time-dependent heat generation rate.

All regions are in thermal communication. The forced flow region 2 has a constant inflow/outflow, a constant boundary temperature along the outer periphery, and is insulated at the top and bottom. Region 1 has a time-dependent boundary temperature at the periphery and is insulated at the top. Region 1 contains an adiabatic blockage near the top and three zero-thickness horizontal plates. Region 1 and 2 are separated along their common vertical boundary by a zero-thickness plate.

At time $t = 0$, the system is initialized to 50°C throughout with no flow. At time $t = 0+$, the region 2 inflow at 20°C is impulsively started, heat generation in the solid region 3 is started (5×10^6 W/M^3), and the region 1 boundary temperature begins to fall at a 10°C/sec rate. Particular features of the resulting flow field are the baffle plates impeding natural circulation in region 1 and development of a stratified layer in the turbulent flow in region 2.

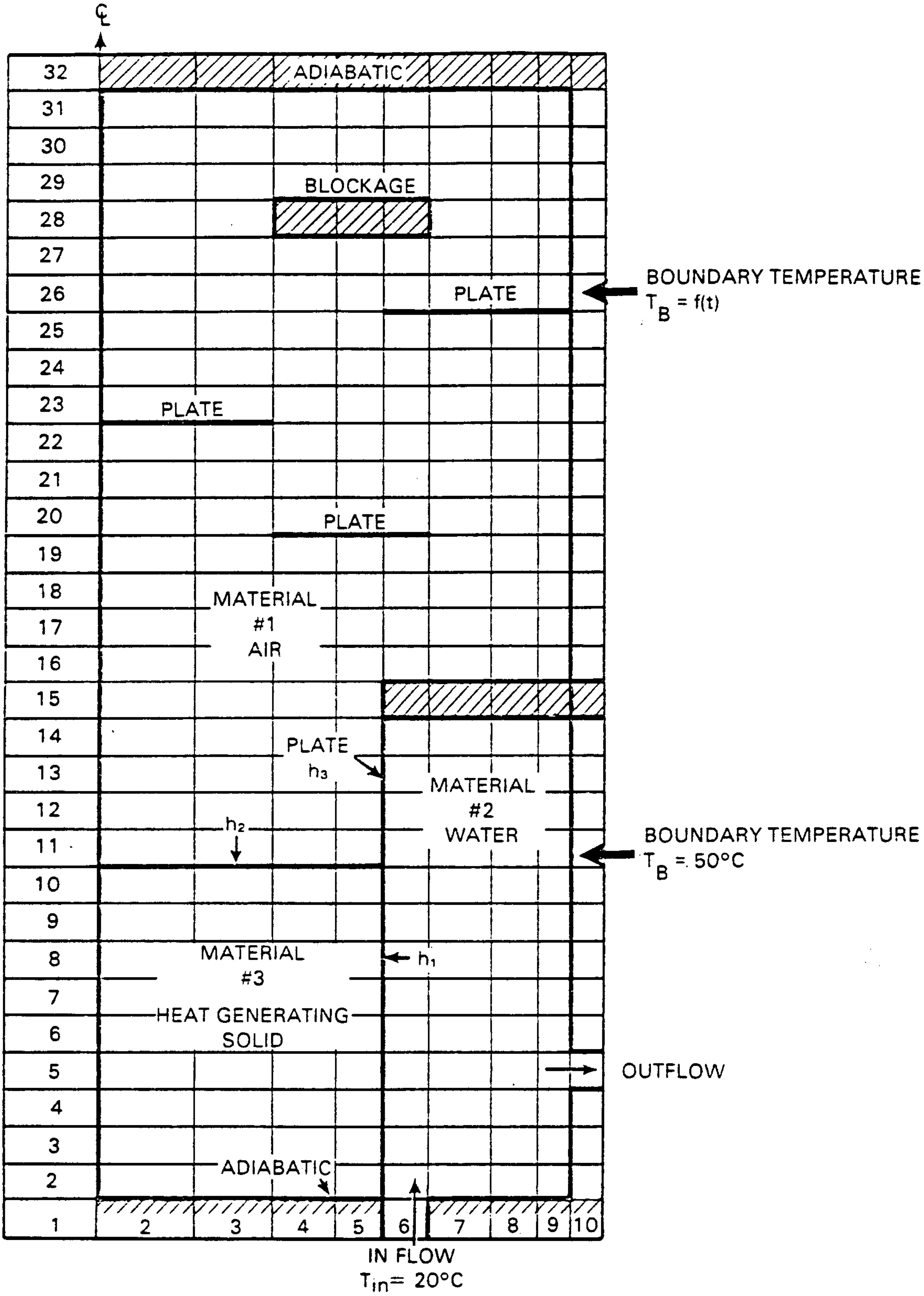


FIGURE 5.1. Sample Problem Physical Configuration and Computational Cell Structure

As show in Figure 5.1, the computational cell structure consists of 10 cells in the adial direction (8 computational, 2 boundary) and 32 cells in the vertical irection (30 computational, 2 boundary). Because this problem is two-dimen ional, boundary cells are not needed along the circumferential faces. The mputational cell spacing in the vertical direction is constant. Computationa cell spacing in the radial direction is variable with the larger radial spaci being near the centerline.

5.2 INPUT D CRIPTION

The TEM ST input file for the sample problem is located at the end of this section It is printed as a foldout for user convenience.

A brief iscussion of each card follows.

Cards a identified in this discussion by number listed in the right hand column the input listing. These card numbers are not part of the input record but rather are used for discussion only. The first card is the title card a , as discussed in Section 4.0, the problem description title may be placed an here within columns 2 through 80. Cards numbered 2 through 6 are identifi in the input instructions as group 1. The first four characters are alphanum ic keys followed by a separator. Although this separator may be any chara er including a space, it is suggested that a comma always be used for con stency.

Card nu er 2 is the SIZE card indicating that the computational grid system has 1 cells in the radial (R) direction, and 32 in the vertical (Z) direction. nce the sample problem is two dimensional, the circumferential direction (X is defaulted (columns 16 through 20). Card number 3 is the TIME card and ind ates that the simulated time is to be 5 sec with an initial time step of 0.01 ec. The initial time step size could have been defaulted without a problem in tartup but may be needed for other simulations. The input time units of sec ds are the default time units. In this case the arrays specified by AOUT, car number 8, will be printed every 2.5 sec of simulated time. Monitor outp will be printed every five time steps (column 45). All other printing par eters on the PRNT card are defaulted. Pressure/continuity iteration parameters are given on the PRES card (card number 5). Values in columns 10 and 15 are default values; these fields could have been left blank. The 0 in column 10 will default the maximum number of pressure iterations at each time step to 20. The 1 in column 15 is the minimum number of pressure iterations to be taken at each time step and is the default value. The iteration acceleration factor is 1.5, and the potential function error criterion is 10^{-8}. Card number 6 is the postprocessing dump file control card, which, in this case, specifies that postprocessing records will be created every 2.5 sec of simulation time. The records will be written to a file called REPOST. Card number 7 is blank, which signals the end of card group 1 input. Cards in group 1 may be arranged in any order; SIZE, TIME, and PRNT cards are required while all others may be omitted if default parameters are suitable.

Card group 2 includes cards numbered 8 through 13. These cards are used to specify printer output, program control, debug output, and postprocessing output. The AOUT card (card number 8) specifies that Z-direction velocity, V; R-direction velocity, U; temperature, T; pressure difference, $P-P_0$; divergence, D; and turbulent kinetic energy, TKE, arrays will be printed at times indicated on the PRNT card. Program control options are specified by cards numbered 9 and 10. These parameters, in the order of their occurrence, are:

MONT - monitor output
HEAT - energy transport solution
PACE - automatic time stepping
FORM - array format is F10.2 (for U, V, and T)
DTIM - running time monitor
SISY - the normal operating mode for this run uses the SI system of units
CYLN - cylindrical coordinate
TURB - turbulence model (k-ϵ) is to be used.

Card number 11 specifies program debug output as follows:

PROP - print results of the direct lookup properties tables

SIZE - printout array dimension and array pointer

DATA - echo the input file

NTYP - print out the computational cell (node) type map

MTYP - print out the materials type map

TTBL - print out the time-dependent boundary value and heat generation tables.

Additional program control parameters are listed on card number 12 as follows:

SAVE - create a restart file
PSAV - create a postprocessing plot file
MSAV - create a monitor plot file.

These parameters could have been included on cards numbered 9 or 10.

The PLOT card indicates that R-direction velocity, U; Z-direction velocity, V; and temperature, T; are to written to the postprocessing file REPOST. Card number 14 is blank and signals the end of group 2 input. Cards in group 2 may be arranged in any order.

Card group 3 is the integer input and includes cards numbered 15 through 33. This input is used to specify the system computational cell types, material types, time-dependent boundary value table identifiers, drag and heat transfer coefficients, and monitor cell locations. Each card has optional identification located in columns 73 through 80. As indicated by this identifier, cards numbered 15 through 24 contain cell (or node) type specification and material types. The user should keep in mind that all cells are initialized to type 50, which is the null cell.

On card number 15, the centerline column of phantom cells (J = 1) is set to type 20. Boundary temperature cells are set by cards numbered 16 and 17. Note that a boundary value table is specified on card number 17 indicating that a time varying boundary condition is to be applied to cells J = 10 and K = 16 through 31. Material types are not needed for type 60 cells nor for type 20 cells. Card number 18 defines the inflow cells (type 30) and card number 19 defines the computed inflow/outflow (type 40) cells. Regular type 0 cells are assigned by cards numbered 20 and 21. Note that two different regions are defined by the two different material types (1 and 2). Also note that a portion of the region defined by material type 1 is overwritten by the definition of the material type 2 region. Further, the K = 15 level of material 2 is overwritten by card number 23 to place a row of null cells (type 50) between these two regions. Card number 22 defines a solid material heat conduction region by using type 70 cells (material number 3). Cards numbered 23 (discussed above) and 24 overwrite previously defined cell types with null cells. Card number 24 is used to place an adiabatic blockage at level K = 28.

Zero-thickness plate or wall identifiers are specified by cards numbered 25 through 28. Card number 28 completes the separation of material 1 and 2 with a zero-thickness wall at J = 5. Cell face heat transfer coefficient identification numbers are assigned by cards numbered 29 through 31. Card number 31 also sets up flags to monitor heat flow through the zero-thick wall separating regions 1 and 2. Cards numbered 32 and 33 define eight computational cells to be monitored at every MSKIP (card number 4) time steps. Note that results at those cells identified on card number 32 will be on the printed output (because column 65 is defaulted), whereas results at those cells identified on both cards will be written to the MONSAV file for postprocessing.

Card number 34 is blank, which signals the end of Card Group 3 integer input. Card number 35 starts the floating point input be specifying cell width and coordinate information in the Engineering System (ES). ΔR (Field 1) is defaulted, indicating that variable cell spacing is to be used in the radial direction. Field 3 sets ΔX to 360° (2π). The variable ΔRs are specified on card number 36. Note that values are in centimeters (CM). Properties for the three materials are specified by cards numbered 37 through 39. Card number 37 gives information for air (library number 11) where k, ρ_0, C, and μ are specified. A variable density direct entry table is to be set up extending from -40 to 110°C with 101 points. This table is used to compute buoyancy effect. Material type 2 (card number 38) is water (library number 2). In this case the reference properties (k, ρ_0, C, and μ) are defaulted because a reference temperature (50°C) is specified in column 35 that signals TEMPEST to compute the reference values at 50°C using the built-in library. The direct entry table for density will extend from 10 to 110°C using 51 points. The 1 placed in column 53 indicates that turbulence modeling is to be applied to the region defined by material 2. Material 3 (card number 39) defines the solid region with constant properties (library number 0). Note that property values on this card are in the Engineering System (ES), and that there is a heat generation table assigned in column 55.

Card number 40 defines the type 30 cell inflow velocity and temperature, which are 0.5 m/sec and 20°C, respectively. Cards numbered 41 through 43 specify the system boundary and initial temperature, which are all set to 50°C. Additionally, card number 43 assigns an initial heat generation rate of 0.5 x 10^7 W/m^3 to the solid region previously defined as material type 3. The time-dependent temperature boundary condition table is defined by cards numbered 44 through 46 at times 0, 0.5, and 100 sec. This table corresponds to the identifier specified on card number 17. The corresponding temperature factors are 1.0, 0.5, and 0.5, which indicate that the boundary is initially at 50°C (card number 41), drops to 25°C (0.5 * 50°C) at 5 sec, and remains constant at this value to 100 sec. Card number 47 defines the Q-factor table. The factors are multipliers for the initial heat generation rate specified on card number 43. These table values indicate that the heat generation is constant (0.5 x 10^7 W/m^3) from t = 0 to t = 5 sec, increases to 1.0 x 10^7 W/m^3 at t = 10 sec, and remains constant at this value out to 100 sec. The value 4 in column 60 indicates that there are four time table points specified on this card.

Card number 48 defines the drag coefficient corresponding to identifiers specified on cards numbered 25 through 28. In this case all drag coefficients are zero-thickness walls (-9999). The film coefficients corresponding to identifier specified on cards numbered 29 through 31 are given on card number 49. Card number 50 is a blank card that signals the end of the floating point data and all input for this file.

5.3 SAMPLE PROBLEM OUTPUT DESCRIPTION

The line printer output for the sample problem described in Section 5.1 is listed and described in this section. Each page of the output is given a separate page number for reference in the following discussion. This reference page number is not a part of the TEMPEST line printer output.

The first page of the TEMPEST output is the banner page and simulation title. The banner displays the code version and modification identification that produced the simulation. The banner page can be suppressed by placing a "1" in column 1 of the first input record (title card). If the banner is suppressed, the title will still appear on page 1 along with the simulation date and time. Page 2 prints the control option lists called for by input. Page 3 displays an echo of the input file, which is activated by specifying "DATA" on the DBUG card. If an error is detected on reading the input, such as an out-of-range array, an error message will be printed immediately following the record containing the error. If an input record error is detected, TEMPEST should read the remainder of the file, and terminate the run with a message indicating that input errors have been found.

Output on pages 4 and 5 was activated by requesting "PROP" on the DBUG card option list. The built-in library key is printed followed by a checkout table for each material having variable properties. Page 6 prints out a list of input parameters that the user specified, or that were defaulted. Note that this simulation is to be terminated at a given simulation time (TSTOP = 5.000E+00 SECONDS), which defaults NSTEPS to a large value. Therefore, the value of NSTEPS is displayed as variable.

Output on pages 6 and 7 was activated by requesting "SIZE" on the DBUG card option list. Information valuable to the user is given at the bottom of page 7 under the heading "SUMMARY OF PROBLEM DEPENDENT ARRAY SIZE REQUIREMENTS". This output tells the user what array dimensions are required for the current simulation. If these requirements are exceeded, an error message will be printed on a later page that indicates which arrays have been exceeded followed by termination of the simulation. Thus, the user may need to redimension the major TEMPEST arrays based on the information listed in this summary. The summaries listed for the INDEX and TEXT array pointers and lengths are valuable only for code modification.

A materials properties summary is given on page 7 along with the volume and heat generation summary for each material. These are property reference values. Certain information for constant material properties may be unused and superfluous, such as the value -17.778 listed for the minimum table value under material number 3. Other information may be of value only for code modification.

The simulated system coordinate information is given on page 8. Cell types are given on page 9. Note that cells adjacent to boundaries (type 10) or cells that have boundary condition conflicts (type 11) have replaced the zeros specified on the input records. The system material type map is printed on page 10. Note that material type 51 is automatically set for node type 20 and 50 cells and material type 52 is set for node type 60 cells. The node type map output was activated by specifying "NTYP" on the DBUG card, and the material type map was activated by specifying "MTYP" on the same card. A listing of the time-dependent tables is printed on page 11, which was activated by specifying "TTBL" on the DBUG card.

Page 11 ends the TEMPEST output related to the simulation setup. There are a number of other setup output options that are not exercised in this sample problem, as well as error messages if TEMPEST detects setup errors. The remaining output gives results computed during the problem execution and consists of both monitor and array output. The monitor output gives a running account of the code's computational performance and selected array values as specified on card number 32 of the input file.

Page 12 begins monitor output for certain convergence information and execution time data. This output was activated by specifying "DTIM" on the program control option card. The listed information is printed at "constant integer intervals" of the time steps as determined by the input parameter "MSKIP" located on card number 4. For the current case MSKIP = 5 is indicated. The information listed gives the number of iterations required to meet the continuity error criterion, in addition to subroutine timing. If a steady-state thermal solution is being computed, the number of energy equation iterations are given along with the heat balance error. The monitor information is terminated at time step 150 (page 12) because array printing was requested at 2.5 sec, which occurs at time step 152.

Pages 15 through 18 contain the arrays requested for printing (see AOUT card) at t = 2.5 sec. These are flow divergence, velocity components U and V, pressure, temperature, and turbulent kinetic energy.

Although this output is self-explanatory, a few points need to be noted. First, velocities will be printed for the boundaries and the values correspond to the slip or no-slip conditions. Thus, the user should not be alarmed regarding velocities positioned in solid cells next to a fluid region. For instance, the velocity 0.0115 located at J = 8 and K = 1 (page 14) is the correct no-slip condition for the fluid velocity -0.0115 located at J = 8 and K = 2. If, however, the fluid cell is a node type 11 where the boundary condition is in conflict with a neighboring fluid cell, the value printed may not be the boundary value for the corresponding fluid cell. For instance, a one-cell-thick plate is located at the K = 28 level in region 1 (see node type map). Radial velocities above and below the plate need boundary conditions at level K = 28, but there is only one level of storage locations available. Referring again to the cell type map, the position J = 5, K = 27 (5,27) shows a type 10 cell that is a normal boundary cell. However, right above this position at K = 29 the boundary cell type is 11, indicating that there is no location to store the boundary velocity since the required location (5,28) is already occupied by the boundary velocity required by cell (5,27). It thus has a boundary value conflict with cell (5,27). In this case the velocity printed at location (5,28) is the boundary value for cell (5,27) having a value of -0.0014 rather than +0.0106 (fluid velocity component for cell (5,29) is -0.0105). The correct no-slip boundary velocity for cell (5,29) is applied using conflict boundary logic in the code; it is not included in the printed output array.

The second item to note deals with values of turbulent kinetic energy (also dissipation) printout as shown on pages 5.21 and 5.28. The only turbulent region in this simulation is region 2. All other values are defaulted to 10^{-30}.

Pages 5.22 and 5.29 gives a surface heat flux summary as requested on input card number 31. A heat balance summary is given also but has little meaning for a transient simulation. Additional information on page 5.22 indicates that postprocessing file number 1 has been created at time step number 152 or 2.5 seconds into the transient.

After the arrays have been dumped, the monitor output continues on page 5.22. Note that the execution time summary terminates at time step 250 and the array monitor values begin to be printed starting from time step 5 continuing through page 5.23 for the first 250 time steps.(a) Execution time monitoring begins again on page 5.24 at time step 255.

The simulation continues through 354 time steps, where the simulated time reaches 5.000 sec and the second array dump time is reached (input card number 4 instructed TEMPEST to print arrays every 2.500 sec of simulation time). Also TSTOP was set to 5.000 sec so that the total simulation time has been achieved. Page 5.25 shows the flow divergence array printout. TEMPEST always prints out the last monitored values for the execution time, which, in this case, was interrupted by the flow divergence printout. As shown on page 5.26, one monitored time plane is printed. (Note that this interruption will occur whenever the flow divergence is called for). Next, the monitored array point data that has accumulated in the monitor buffer is printed, starting on page 5.26 and ending on page 5.26. The arrays for velocity components, pressure, temperature, and turbulent kinetic energy are then printed on pages 5.26 through 5.28. A heat flux and heat balance summary are again printed on page 33. As stated previously, the heat balance will have usefulness only as the simulation approaches steady state.

A postprocessing and restart file dump summary is listed on page 5.29. As indicated, a restart file has been created at time step 354 and post-processing file dump number 2 occurred at the same time step. The time-history data records written to the MONSAV file are also noted. Recall that array data points were printed only for four monitored locations (see input card number 32). These are the monitor locations 1, 2, 3, and 4 noted on page 5.29. However, for additional monitor points were requested as indicated by input card number 33. These points are noted as 5 through 8 on page 5.29.

(a) Monitored output for temperature, velocity components, pressure, and turbulent parameters is loaded to a programmed buffer array that has storage space for 50 time planes. This monitored data will be printed only when this buffer is full or the simulation terminates. Once the 50 time planes are printed, the buffer will begin to refill with new time planes loaded at every MSKIP time steps.

Thus, only four locations can be printed but four additional points were written to the postprocessing file for plotting (up to 16 total points could have been loaded to the postprocessing file for future plotting).

Page 5.29 gives a computation time summary and is useful for determining the CPU time required for various phases of the computation. Both total and normalized execution time are given. As indicated, this simulation, which required solution to the momentum, continuity, energy, and turbulence equations, proceeded at a computational speed of about 0.1 milliseconds/time step cell. This calculation was performed on a CRAY-XMP.

```
                                                                                                                       page 1

                                                               xxxx
                                                               xxxx
                                                          xxxxxxxxxxxxxxx
                                                     xxxxx               xxxxx
                                                 xxxx                         xxxx
                                            xxxxx   xx                     xxx    xxxxx
                                         xxx          xxxxxxxxxxxxxxxxxxxxx            xxxx
                                     xxxx                                                 xxxx
                                  xxx                                                       xxxx
            ttttttttttttttttttttt                                                             xxxx
         xx ttttttttttttttttttttt                                                                xxxx
       xx   ttttttttttttttttttttt                                                                  xxx
     xx     ttttttttttttttttttttt                                                                    xxxx
    xx      ttttttttttttttttttttt                                                                      xxxx
   xx               ttttt                                                                                  xxx           xxx
  x       x         ttttt                                                                                     ttt      xx  x
  x      x          ttttt                                                                                    tttt     x    x
 x       x          ttttt                                                                                ttttttttttt       x
 x       x          ttttt                                                                                ttttttttttt       x
 x       x          ttttt                                                                                    tttt         xx
 x       x          ttttt         eeeeeee      mmmm mmm  mmmm   pppp  pppp        eeeeeee       sssssss      tttt   x    x
 x       x          ttttt        eeee    e     mmmmmmmmmmmmmmm  pppppp   pp      eeee    e     ssss    s     tttt  x    x
 x       x          ttttt       eeee     ee    mmmmm mmm   mmm  ppppp    ppp    eeee    ee    ssss           tttt  x    x
 x       x          ttttt      eeeeeeeeeeee    mmmm  mmm   mmm  pppp     ppp   eeeeeeeeeeee   sssssss        tttt       x
 x        x         ttttt      eeeee           mmmm  mmm   mmm  pppp     ppp   eeeee            ssssssss     tttt       x
 x        x         ttttt       eeee     ee    mmmm  mmm   mmm  ppppp    ppp    eeee    ee          ssss     tttt  tt   x
  x       x         ttttt        eeeeeeeeee    mmmm  mmm   mmm  pppppp   pp      eeeeeeeeee   s     ssss     ttttttt    x
  x        x        ttttt          eeeeee      mmmm  mmm   mmm  pppp  pppp         eeeeee      sssssss        ttttt     x
   x        xx                                                  pppp                                            x       x
    x         xx    x                                           pppp                                            x       x
     xx         xx   x                                          pppp                                           x        x
       xx         xx  x                      BASE               pppp   Version: N31      Mod: 0.0             x        x
         xx         xxx                                         pppp       Jun  1988     Jun  1988          x         x
          xx            x                                       pppp                                      xx        x
            xxx          x                                                                               x          x
               xxxx       x                                                                            xx          x
                   xxxxx   xx                 Developed for  U.S. Department of Energy                x           x
                        xxxxxxxx                                                                    xx         xx
                                xx               by:  Battelle                                    xx          xx
                                   xx                 Pacific Northwest Laboratory             xxxxxxxxxxxxxxxx
                                    xxx               P.O. Box 999                          xxx
                                       xxx            Richland, Washington  99352       xxxx
                                          xxxxx                                    xxxxx
                                               xxx          contact:             xx
                                                 xx   D.S. Trent  (509)375-2105  xx
                                                xx    L.L. Eyler  (509)375-3740   xx
                                              xxxxx   M.J. Budden (509)375-3766  xxxxx
                                            xxxxxxxxxx                        xxxxxxxxxx
                                         xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

*     user sample problem : 2-d flow in a multicompartment enclosure                date 07/12/88       time 00:20:53
```

```
                                                                                                                  page 2
option lists called for this run



output option list
            velr,
            velz,
            temp,
            tkin,
            divg,
            delp,


control option list
            cyln,
            heat,
            turb,
            save,
            mont,
            pace,
            sisy,
            dtim,
            form,
            psav,
            msav,


plotting option list
            velr,
            velz,
            temp,


debug option list
            prop,
            size,
            mtyp,
            ttbl,
            ntyp,
            data,
```

```
                                                                                                                      page 3

                     * * *   i n p u t   c a r d   i m a g e s   * * *

column  1   5    1    1    2    2    3    3    4    4    5    5    6    6    7    7    8            card
                 0    5    0    5    0    5    0    5    0    5    0    5    0    5    0             no.

        *     user sample problem : 2-d flow in a multicompartment enclosure                          1
        size,   10   32                                                                               2
        time,  .01         5                                                                          3
        prnt,  2.5                                  5                                                 4
        pres,    0    1  1.5  1-8                                                                     5
        post,  2.5                                                                                    6
                                                                                                      7
        aout,velz,velr,temp,delp,divg,tkin,                                                           8
        cont,mont,heat,pace,form,dtim,sisy,                                                           9
        cont,cyln,turb,                                                                              10
        dbug,prop,size,data,ntyp,mtyp,ttbl,                                                          11
        cont,save,psav,msav,                                                                         12
        plot,temp,velr,velz,                                                                         13
                                                                                                     14
           20    0              1    1    2   31                             1   nod-typ             15
           60    0             10   10    2   31                             1   nod-typ             16
           60    0    1        10   10   16   31                             1   nod-typ             17
           30    2              6    6    1    1                             1   nod-typ             18
           40    2             10   10    5    5                             1   nod-typ             19
            0    1              2    9    2   31                             1   nod-typ             20
            0    2              6    9    2   15                             1   nod-typ             21
           70    3              2    5    2   10                             1   nod-typ             22
           50    0              6    9   15   15                             1   nod-typ             23
           50    0              4    6   28   28                             1   nod-typ             24
                 1              4    6   19   19                             4     plate             25
                 1              2    3   22   22                             4     plate             26
                 1              6    9   25   25                             4     plate             27
            1                   5    5   11   14                             4     plate             28
                 1              2    5   10   10                             3    film-c             29
            2                   5    5    2   10                             3    film-c             30
            3                   5    5   11   14                   1    1    3    film-c             31
            4   14    1    9   14    1    2    5    1    9    5    1         5   monitor             32
            2   23    1    9   23    1    5   18    1    5   31    1    2    5   monitor             33
                                                                                                     34
             .0492  360                       90  180   90                   1es  coords             35
          .60  .60  .50  .40  .30  .30  .40  .30  .20  .20    1   10         3cm delta-r             36
        .02821.0411105.213-7     101+3       -40  110  101        11    1cg  6   mat-air             37
                                 101+3   50   10  110   51  100    2    2cl  6   mat-h20             38
          24. 500.  .11                                       1    0    3cs  6es m-solid             39
                .5        20                   6    6    1    1              7     b-velo             40
           50                                 10   10    2   31              9     b-temp             41
           50                                  2    9    2   31              9     init-t             42
           50 .5+7                             2    5    2   10              9     init-t             43
            0    1  0.0  1.0  0.0                                       1   16   t-table             44
            5   .5  0.0  1.0  0.0                                       1   16   t-table             45
          100   .5  0.0  1.0  0.0                                       1   16   t-table             46
            0  1.0    5  1.0   10  2.0  100  2.0                   4    1   24   q-table             47
        -9999    2                                            1    1        17  pl-coeff             48
           .5       2.5       .75                             1    3        18   f-coeff             49
                                                                         enddata             50
```

```
                                                                                                                   page 4

fluid properties table checkout


library no. key - - -   (s) = solid, (l) = liquid, (g) = gaseous, perfect gas

tabular input    = 1
                       air          (g)= 11
     water    (l)= 2   nitrogen     (g)= 12
     brine    (l)= 3   oxygen       (g)= 13
     sodium   (l)= 4   car. dioxide (g)= 14
     potassium(l)= 5   car. monoxide(g)= 15
     nak-78   (l)= 6   hydrogen     (g)= 16
     mercury  (l)= 7   helium       (g)= 17
     lead     (l)= 8   steam        (g)= 18
     lithium  (l)= 9   argon        (g)= 19
     glycerin (l)= 10


material no.    1
table no.       1
library no.    11

     temp      therm cond     density         sp heat       viscosity     emissivity      enthalpy
    deg. c      w/m-k          kg/m3          j/kg-k         pa-sec                         j/kg


   -40.000   2.033725E-02   1.508428E+00   1.006717E+03   1.490142E-05   0.000000E+00   0.000000E+00
   -30.000   2.109097E-02   1.446403E+00   1.006470E+03   1.538728E-05   0.000000E+00   0.000000E+00
   -20.000   2.184101E-02   1.389266E+00   1.006324E+03   1.586898E-05   0.000000E+00   0.000000E+00
   -10.000   2.258736E-02   1.336462E+00   1.006278E+03   1.634655E-05   0.000000E+00   0.000000E+00
     0.000   2.332999E-02   1.287543E+00   1.006332E+03   1.681999E-05   0.000000E+00   0.000000E+00
    10.000   2.406894E-02   1.242070E+00   1.006483E+03   1.728935E-05   0.000000E+00   0.000000E+00
    20.000   2.480419E-02   1.199693E+00   1.006729E+03   1.775467E-05   0.000000E+00   0.000000E+00
    30.000   2.553573E-02   1.160125E+00   1.007070E+03   1.821595E-05   0.000000E+00   0.000000E+00
    40.000   2.626358E-02   1.123077E+00   1.007504E+03   1.867324E-05   0.000000E+00   0.000000E+00
    50.000   2.698775E-02   1.088318E+00   1.008028E+03   1.912657E-05   0.000000E+00   0.000000E+00
    60.000   2.770820E-02   1.055655E+00   1.008641E+03   1.957594E-05   0.000000E+00   0.000000E+00
    70.000   2.842496E-02   1.024891E+00   1.009342E+03   2.002142E-05   0.000000E+00   0.000000E+00
    80.000   2.913803E-02   9.958656E-01   1.010129E+03   2.046303E-05   0.000000E+00   0.000000E+00
    90.000   2.984739E-02   9.684463E-01   1.011000E+03   2.090077E-05   0.000000E+00   0.000000E+00
   100.000   3.055305E-02   9.424928E-01   1.011954E+03   2.133470E-05   0.000000E+00   0.000000E+00
   110.000   3.125504E-02   9.178910E-01   1.012989E+03   2.176485E-05   0.000000E+00   0.000000E+00
```

```
                                                                                                          page 5
material no.    2
table no.       2
library no.     2

     temp       therm cond      density         sp heat       viscosity     emissivity      enthalpy
    deg. c       w/m-k           kg/m3          j/kg-k         pa-sec                          j/kg

    10.000   5.773806E-01   9.997271E+02   4.175823E+03   1.299537E-03   0.000000E+00   0.000000E+00
    15.000   5.863690E-01   9.991205E+02   4.170276E+03   1.136552E-03   0.000000E+00   0.000000E+00
    20.000   5.949765E-01   9.982303E+02   4.165914E+03   1.001749E-03   0.000000E+00   0.000000E+00
    25.000   6.031713E-01   9.970661E+02   4.162757E+03   8.907992E-04   0.000000E+00   0.000000E+00
    30.000   6.109850E-01   9.956732E+02   4.160639E+03   7.972324E-04   0.000000E+00   0.000000E+00
    35.000   6.183861E-01   9.940538E+02   4.159569E+03   7.187238E-04   0.000000E+00   0.000000E+00
    40.000   6.254062E-01   9.922412E+02   4.159393E+03   6.514279E-04   0.000000E+00   0.000000E+00
    45.000   6.320136E-01   9.902335E+02   4.160107E+03   5.940376E-04   0.000000E+00   0.000000E+00
    50.000   6.382400E-01   9.880566E+02   4.161569E+03   5.441600E-04   0.000000E+00   0.000000E+00
    55.000   6.440536E-01   9.857061E+02   4.163765E+03   5.010317E-04   0.000000E+00   0.000000E+00
    60.000   6.494863E-01   9.832031E+02   4.166564E+03   4.631034E-04   0.000000E+00   0.000000E+00
    65.000   6.545063E-01   9.805419E+02   4.169938E+03   4.299151E-04   0.000000E+00   0.000000E+00
    70.000   6.591453E-01   9.777402E+02   4.173770E+03   4.004291E-04   0.000000E+00   0.000000E+00
    75.000   6.633716E-01   9.747914E+02   4.178020E+03   3.743605E-04   0.000000E+00   0.000000E+00
    80.000   6.672169E-01   9.717110E+02   4.182582E+03   3.509933E-04   0.000000E+00   0.000000E+00
    85.000   6.706495E-01   9.684919E+02   4.187405E+03   3.301475E-04   0.000000E+00   0.000000E+00
    90.000   6.737012E-01   9.651478E+02   4.192395E+03   3.113157E-04   0.000000E+00   0.000000E+00
    95.000   6.763401E-01   9.616714E+02   4.197488E+03   2.943824E-04   0.000000E+00   0.000000E+00
   100.000   6.785980E-01   9.580753E+02   4.202603E+03   2.789795E-04   0.000000E+00   0.000000E+00
   105.000   6.804432E-01   9.543516E+02   4.207664E+03   2.650320E-04   0.000000E+00   0.000000E+00
   110.000   6.819074E-01   9.505123E+02   4.212601E+03   2.522675E-04   0.000000E+00   0.000000E+00
```

```
                                                                                                          page 6

p a r a m e t e r   l i s t   f o r   c a s e                                  07/12/88             00:20:53

number of time steps            , nsteps  - - -         (variable)
total number of fluid cells     , nfluid  - - -  197
total number of solid cells     , nsolid  - - -   36
total number of compt cells     , ntotal  - - -  233
total number of constituents    , nsp - - - - -    0
number of cells in r-direction, nr  - - - - -   10
number of cells in z-direction, nz  - - - - -   32
number of cells in x-direction, nx  - - - - -    1
width  of cells in r-direction, dr  - - - - -    0.00000 metres (variable)
width  of cells in z-direction, dz  - - - - -    0.01500 metres
width  of cells in x-direction, dx  - - - - - 360.00000 degrees
start of r-direction noding     , rstart  - - -    0.00000 metres
start of x-direction noding     , xstart  - - -    0.00000 degrees
simulation time limit(opt'l)    , tstop - - - - 5.000E+00 seconds
gravitational comp r-direction, gr  - - - - -    0.00000 m/sec2
gravitational comp z-direction, gz  - - - - -   -9.80000 m/sec2
gravitational comp x-direction, gx  - - - - -    0.00000 m/sec2
direction angle, r-axis         , thetar  - - -  90.00000 degrees
direction angle, z-axis         , thetaz  - - - 180.00000 degrees
direction angle, x-axis         , thetax  - - -  90.00000 degrees
slip condition                  , sfact - - - -  -1.0000
pressure acceleration factor    , pac - - - - -   1.500
continuity error criterion      , smax  - - - -   1.000E-08
maximum number pressure iters   , itmax - - - -  20
crank-nichlsn implicit factor   , frnk  - - - -   0.60
time adder                      , tadd  - - - - 0.0000E+00 seconds
thermal time step limiter       , limp  - - - -   5.000
implicit time step limitation   , dtimax  - - - 1.0000E+15 seconds


     automatic time step selection is used
     initial time step,        dt = 1.0000E-02 seconds
     fract of max time step, cmax =   0.99


                     summary of problem dependent array size requirements

     parameter name      current setting      req'd for current run       arrays affected

       maxsze                  2500                    320                 field and utility arrays
       maxset                 10000                   1833                 index array
       maxtxt                  4000                   1233                 text array
       lsize                    102                     43                 dx,x,etc..... grid arrays

     if parameter change is required, see comdeck 'facts' for parameter list
```

```
                                                                                          page 7
       summary of text array requirements

                      index pointer    length
       lent(  1) =           1            15  boundary value table
       lent(  2) =          16             8  heat generation table
       lent(  3) =          24           612  properties table
       lent(  4) =         636           312  properties table
       lent(  5) =         948            65  normal slip factors
       lent(  6) =        1013           198  conflict slip factors
       lent(  7) =        1211             6  boundary values

   materials property summary - - - pge 1


 prop(l,mat)                 mat = material no.    mat =  1  mat =  2  mat =  3

 l=1  thermal conductivity  - - - - - w/m-k      2.820E-02 6.382E-01 4.154E+01
 l=2  density - - - - - - - - - - - - kg/m3      1.041E+00 9.881E+02 8.009E+03
 l=3  specific heat - - - - - - - - - j/kg-k     1.105E+03 4.162E+03 4.605E+02
 l=4  dyn viscosity - - - - - - - - - pa-sec     2.130E-05 5.442E-04 0.000E+00
 l=5  gas const, emiss or salinity- - j/kg-k      287.1848    0.0000    0.0000
 l=6  reference pressure- - - - - - - pascals    1.010E+05 1.010E+05 0.000E+00
 l=7  reference temperature - - - - - deg. c         0.000    50.000     0.000
 l=8  properties table min. temp  - - deg. c       -40.000    10.000   -17.778
 l=9  properties table max. temp  - - deg. c       110.000   110.000   -17.778
 l=10 mole weight or dens ratio - - -               28.950     0.000     0.000
 l=11 properties library index  - - -                 11.        2.        0.
 l=12 material state - - - - - - - -                   gas    liquid     solid
 l=15 material property behavior  - -             constant  constant  constant
 l=16 pressure multiplier - - - - - - kg/m3      1.041E+00 9.881E+02 0.000E+00
 l=21 time-dep. heat gen table no - -                   0.        0.        1.
 l=24 properties table segments - - -                 101.       51.        0.
 l=29 compressibility - - - - - - - -               incomp    incomp    incomp

      volume - - - - - - - - - - - - - cu mtrs   7.397E-04 3.528E-04 1.374E-04
      total heat generation- - - - - watts       0.000E+00 0.000E+00 6.869E+02
      average heat generation  - - - w/m3        0.000E+00 0.000E+00 5.000E+06
```

```
                                                                                          page 8

                                                   system coordinates

                      r-direction                           z-direction                                 x-direction
                        metres                                metres                                      degrees

 cell no        r(j)       rc(j)      dr(j)          z(k)       zc(k)      dz(k)            x(i)       xc(i)      dx(i)
    1         0.0000    -0.0030     0.0060         0.0000    -0.0075     0.0150        360.0000   180.0000   360.0000
    2         0.0060     0.0030     0.0060         0.0150     0.0075     0.0150
    3         0.0110     0.0085     0.0050         0.0300     0.0225     0.0150
    4         0.0150     0.0130     0.0040         0.0450     0.0375     0.0150
    5         0.0180     0.0165     0.0030         0.0600     0.0525     0.0150
    6         0.0210     0.0195     0.0030         0.0750     0.0675     0.0150
    7         0.0250     0.0230     0.0040         0.0900     0.0825     0.0150
    8         0.0280     0.0265     0.0030         0.1050     0.0975     0.0150
    9         0.0300     0.0290     0.0020         0.1200     0.1125     0.0150
   10         0.0320     0.0310     0.0020         0.1350     0.1275     0.0150
   11                                              0.1500     0.1425     0.0150
   12                                              0.1650     0.1575     0.0150
   13                                              0.1800     0.1725     0.0150
   14                                              0.1950     0.1875     0.0150
   15                                              0.2099     0.2024     0.0150
   16                                              0.2249     0.2174     0.0150
   17                                              0.2399     0.2324     0.0150
   18                                              0.2549     0.2474     0.0150
   19                                              0.2699     0.2624     0.0150
   20                                              0.2849     0.2774     0.0150
   21                                              0.2999     0.2924     0.0150
   22                                              0.3149     0.3074     0.0150
   23                                              0.3299     0.3224     0.0150
   24                                              0.3449     0.3374     0.0150
   25                                              0.3599     0.3524     0.0150
   26                                              0.3749     0.3674     0.0150
   27                                              0.3899     0.3824     0.0150
   28                                              0.4049     0.3974     0.0150
   29                                              0.4199     0.4124     0.0150
   30                                              0.4349     0.4274     0.0150
   31                                              0.4499     0.4424     0.0150
   32                                              0.4649     0.4574     0.0150
```

```
                                                                              page 9
     system cell types                             f r a m e    i =   1

j =            1  2  3  4  5  6  7  8  9 10
k =   32      50 50 50 50 50 50 50 50 50 50
k =   31      20 10 10 10 10 10 10 10 10 60
k =   30      20 10  0  0  0  0  0  0 10 60
k =   29      20 10  0 11 11 11  0  0 10 60
k =   28      20 10 10 50 50 50 10  0 10 60
k =   27      20 10  0 10 10 10  0  0 10 60
k =   26      20 10  0  0  0 11 11 11 11 60
k =   25      20 10  0  0  0 11 11 11 11 60
k =   24      20 10  0  0  0  0  0  0 10 60
k =   23      20 11 11  0  0  0  0  0 10 60
k =   22      20 11 11  0  0  0  0  0 10 60
k =   21      20 10  0  0  0  0  0  0 10 60
k =   20      20 10  0 11 11 11  0  0 10 60
k =   19      20 10  0 11 11 11  0  0 10 60
k =   18      20 10  0  0  0  0  0  0 10 60
k =   17      20 10  0  0  0  0  0  0 10 60
k =   16      20 10  0  0  0 11 11 11 11 60
k =   15      20 10  0  0 10 50 50 50 50 60
k =   14      20 10  0  0 11 11 10 10 10 60
k =   13      20 10  0  0 11 11  0  0 10 60
k =   12      20 10  0  0 11 11  0  0 10 60
k =   11      20 10 10 10 11 11  0  0 10 60
k =   10      20 70 70 70 70 10  0  0 10 60
k =    9      20 70 70 70 70 10  0  0 10 60
k =    8      20 70 70 70 70 10  0  0 10 60
k =    7      20 70 70 70 70 10  0  0 10 60
k =    6      20 70 70 70 70 10  0  0 10 60
k =    5      20 70 70 70 70 10  0  0 10 40
k =    4      20 70 70 70 70 10  0  0 10 60
k =    3      20 70 70 70 70 10  0  0 10 60
k =    2      20 70 70 70 70 10 10 10 10 60
k =    1      50 50 50 50 50 30 50 50 50 50
```

```
                                                                              page 10
     system material type identifier map           f r a m e    i =   1

j =            1  2  3  4  5  6  7  8  9 10
k =   32      51 51 51 51 51 51 51 51 51 51
k =   31      51  1  1  1  1  1  1  1  1 52
k =   30      51  1  1  1  1  1  1  1  1 52
k =   29      51  1  1  1  1  1  1  1  1 52
k =   28      51  1  1 51 51 51  1  1  1 52
k =   27      51  1  1  1  1  1  1  1  1 52
k =   26      51  1  1  1  1  1  1  1  1 52
k =   25      51  1  1  1  1  1  1  1  1 52
k =   24      51  1  1  1  1  1  1  1  1 52
k =   23      51  1  1  1  1  1  1  1  1 52
k =   22      51  1  1  1  1  1  1  1  1 52
k =   21      51  1  1  1  1  1  1  1  1 52
k =   20      51  1  1  1  1  1  1  1  1 52
k =   19      51  1  1  1  1  1  1  1  1 52
k =   18      51  1  1  1  1  1  1  1  1 52
k =   17      51  1  1  1  1  1  1  1  1 52
k =   16      51  1  1  1  1  1  1  1  1 52
k =   15      51  1  1  1  1 51 51 51 51 52
k =   14      51  1  1  1  1  2  2  2  2 52
k =   13      51  1  1  1  1  2  2  2  2 52
k =   12      51  1  1  1  1  2  2  2  2 52
k =   11      51  1  1  1  1  2  2  2  2 52
k =   10      51  3  3  3  3  2  2  2  2 52
k =    9      51  3  3  3  3  2  2  2  2 52
k =    8      51  3  3  3  3  2  2  2  2 52
k =    7      51  3  3  3  3  2  2  2  2 52
k =    6      51  3  3  3  3  2  2  2  2 52
k =    5      51  3  3  3  3  2  2  2  2  2
k =    4      51  3  3  3  3  2  2  2  2 52
k =    3      51  3  3  3  3  2  2  2  2 52
k =    2      51  3  3  3  3  2  2  2  2 52
k =    1      51 51 51 51 51  2 51 51 51 51
```

```
                                                                                                    page 11

        list of time dependent boundary or source term tables
                 number of tables found =    1

                 table(  1)        time points =    3

point     time          temp        u-veloc     v-veloc     w-veloc
  no.   seconds        factor       factor      factor      factor

  1  0.000E+00    1.000E+00   0.000E+00   1.000E+00   0.000E+00
  2  5.000E+00    5.000E-01   0.000E+00   1.000E+00   0.000E+00
  3  1.000E+02    5.000E-01   0.000E+00   1.000E+00   0.000E+00


        list of time-dependent heat generation tables
                 number of tables found =    1

                 table(  2)        time points =    4

                 point          time,          q
                  no.          seconds       factor

                   1            0.0000        1.0000
                   2            5.0000        1.0000
                   3           10.0000        2.0000
                   4          100.0000        2.0000
```

```
                                                                                                    page 12
        monitor output - - pressure/continuity iteration and execution time data

            note - cpu execution time is in milliseconds/time step-cell (unless otherwise noted)
                   pressure/continuity error criteria =  1.000E-08

time   sim        time        number   cont/   sol cpu solution  tilde    cont/     thermal   thermal   turb      variable  ss heat
step   time,      step,     pres/temp  pres     accum   total   momenta   press     phase,    connect   phase     viscosity bal err.
no      seconds   seconds    iters     error   minutes  no i/o  (moment)  (patter)  (condif)  (semble)  (kemod)   (visset)   watts
  5  1.2799E-01 2.9375E-02   9/  0 3.342E-09   0.003   0.143   0.0453    0.0526    0.0092    0.0100    0.0161    0.0053  0.000E+00
 10  2.6892E-01 2.6777E-02   8/  0 9.628E-09   0.006   0.133   0.0450    0.0482    0.0056    0.0100    0.0136    0.0050  0.000E+00
 15  3.9295E-01 2.3903E-02   6/  0 6.723E-09   0.008   0.126   0.0451    0.0394    0.0056    0.0100    0.0136    0.0050  0.000E+00
 20  5.0987E-01 2.3023E-02   6/  0 1.225E-09   0.010   0.126   0.0452    0.0394    0.0056    0.0101    0.0136    0.0050  0.000E+00
 25  6.2236E-01 2.2156E-02   5/  0 4.674E-09   0.013   0.118   0.0452    0.0305    0.0056    0.0101    0.0136    0.0050  0.000E+00
 30  7.3064E-01 2.1323E-02   3/  0 7.480E-09   0.015   0.111   0.0452    0.0217    0.0056    0.0101    0.0136    0.0050  0.000E+00
 35  8.3473E-01 2.0477E-02   5/  0 3.063E-09   0.017   0.119   0.0453    0.0308    0.0056    0.0101    0.0136    0.0050  0.000E+00
 40  9.3450E-01 1.9601E-02   4/  0 8.760E-09   0.020   0.116   0.0464    0.0261    0.0056    0.0101    0.0136    0.0051  0.000E+00
 45  1.0299E+00 1.8728E-02   3/  0 8.122E-09   0.022   0.111   0.0453    0.0217    0.0056    0.0101    0.0136    0.0050  0.000E+00
 50  1.1203E+00 1.7637E-02   3/  0 5.042E-09   0.024   0.111   0.0453    0.0217    0.0056    0.0101    0.0136    0.0050  0.000E+00
 55  1.2056E+00 1.6684E-02   5/  0 3.171E-09   0.026   0.119   0.0453    0.0306    0.0056    0.0101    0.0136    0.0050  0.000E+00
 60  1.2862E+00 1.5763E-02   3/  0 7.735E-09   0.029   0.111   0.0454    0.0217    0.0056    0.0101    0.0136    0.0050  0.000E+00
 65  1.3627E+00 1.5101E-02   2/  0 8.417E-09   0.031   0.107   0.0454    0.0172    0.0056    0.0101    0.0136    0.0050  0.000E+00
 70  1.4361E+00 1.4411E-02   4/  0 5.015E-09   0.033   0.115   0.0454    0.0261    0.0056    0.0101    0.0136    0.0050  0.000E+00
 75  1.5065E+00 1.3896E-02   2/  0 7.364E-09   0.035   0.111   0.0454    0.0173    0.0092    0.0101    0.0136    0.0050  0.000E+00
 80  1.5748E+00 1.3533E-02   3/  0 4.129E-09   0.037   0.115   0.0455    0.0217    0.0092    0.0101    0.0136    0.0050  0.000E+00
 85  1.6417E+00 1.3281E-02   2/  0 5.609E-09   0.040   0.111   0.0454    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
 90  1.7076E+00 1.3110E-02   2/  0 5.785E-09   0.042   0.111   0.0454    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
 95  1.7728E+00 1.2998E-02   2/  0 6.297E-09   0.044   0.111   0.0454    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
100  1.8375E+00 1.2926E-02   1/  0 3.433E-09   0.046   0.107   0.0454    0.0128    0.0092    0.0101    0.0136    0.0050  0.000E+00
105  1.9020E+00 1.2880E-02   2/  0 4.911E-09   0.048   0.111   0.0455    0.0172    0.0092    0.0101    0.0136    0.0051  0.000E+00
110  1.9663E+00 1.2848E-02   2/  0 4.392E-09   0.050   0.111   0.0454    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
115  2.0305E+00 1.2826E-02   2/  0 4.856E-09   0.053   0.111   0.0455    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
120  2.0946E+00 1.2818E-02   1/  0 7.984E-09   0.055   0.107   0.0454    0.0128    0.0092    0.0101    0.0136    0.0050  0.000E+00
125  2.1587E+00 1.2812E-02   2/  0 5.255E-09   0.057   0.111   0.0454    0.0173    0.0092    0.0101    0.0136    0.0050  0.000E+00
130  2.2227E+00 1.2805E-02   2/  0 5.705E-09   0.059   0.111   0.0454    0.0173    0.0092    0.0102    0.0136    0.0050  0.000E+00
135  2.2867E+00 1.2796E-02   2/  0 2.039E-09   0.061   0.111   0.0454    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
140  2.3506E+00 1.2785E-02   6/  0 7.591E-10   0.063   0.130   0.0454    0.0394    0.0092    0.0101    0.0136    0.0050  0.000E+00
145  2.4145E+00 1.2765E-02   6/  0 7.000E-10   0.066   0.130   0.0454    0.0394    0.0092    0.0101    0.0136    0.0050  0.000E+00
150  2.4783E+00 1.2730E-02   6/  0 7.609E-10   0.068   0.130   0.0454    0.0394    0.0092    0.0101    0.0136    0.0050  0.000E+00
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                                                                                                              page 13

     flow divergence- - - - - - - - - - divg  m3/m3-s     f r a m e  i =     1    date 07/12/88     hour 00:21:12
         xcoord =      3.1416 radians                    time step         152    time =  2.5000E+00 seconds
         r-z coordinates are in metres

               j =          1          2          3          4          5          6          7          8          9         10
          rcoord =    -0.0030     0.0030     0.0085     0.0130     0.0165     0.0195     0.0230     0.0265     0.0290     0.0310
          zcoord
k= 32 z=     0.457  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
k= 31 z=     0.442  0.000E+00 -1.626E-07  9.184E-07  3.327E-07 -2.154E-07 -3.271E-07 -2.786E-07  9.317E-08  8.563E-08  0.000E+00
k= 30 z=     0.427  0.000E+00 -1.777E-07 -2.802E-07 -5.299E-07 -6.464E-07  1.067E-07  3.588E-07  3.109E-07 -1.681E-07  0.000E+00
k= 29 z=     0.412  0.000E+00 -5.274E-07 -1.282E-08  5.613E-08  5.133E-07  4.875E-07  9.725E-08 -1.251E-06  3.890E-07  0.000E+00
k= 28 z=     0.397  0.000E+00  9.207E-07 -3.983E-08  0.000E+00  0.000E+00  0.000E+00 -6.643E-07  8.741E-07 -9.831E-08  0.000E+00
k= 27 z=     0.382  0.000E+00 -7.735E-07 -2.586E-07 -1.206E-07  4.137E-07 -6.494E-07  2.331E-07  3.935E-07 -1.591E-07  0.000E+00
k= 26 z=     0.367  0.000E+00 -4.569E-07 -2.055E-07 -1.052E-07  1.689E-07 -4.698E-07  1.162E-06 -1.288E-06  2.160E-07  0.000E+00
k= 25 z=     0.352  0.000E+00  9.351E-07  8.199E-07  7.801E-07 -1.689E-07 -5.804E-07 -5.211E-07 -9.267E-07  6.084E-07  0.000E+00
k= 24 z=     0.337  0.000E+00 -1.532E-07  3.405E-07 -4.123E-08 -3.380E-07  2.463E-07  1.108E-07  1.107E-06 -6.134E-07  0.000E+00
k= 23 z=     0.322  0.000E+00 -3.941E-07  1.400E-07 -6.356E-07 -4.763E-08  2.492E-07  2.636E-07  2.275E-07 -2.005E-07  0.000E+00
k= 22 z=     0.307  0.000E+00 -1.566E-07  5.897E-07  3.815E-08  8.489E-07 -3.589E-07 -2.724E-07 -6.290E-07  3.630E-07  0.000E+00
k= 21 z=     0.292  0.000E+00  3.735E-07 -4.562E-07 -3.646E-07  3.797E-07 -1.708E-06  4.860E-07  1.204E-06 -3.909E-07  0.000E+00
k= 20 z=     0.277  0.000E+00 -2.462E-06 -1.501E-07  4.582E-07  1.179E-06 -4.446E-07  2.344E-06 -3.041E-06  3.242E-07  0.000E+00
k= 19 z=     0.262  0.000E+00  7.111E-07 -1.165E-06  9.612E-08 -1.118E-06  1.611E-06  1.954E-07 -4.870E-07 -5.690E-08  0.000E+00
k= 18 z=     0.247  0.000E+00  1.042E-06  3.826E-07 -4.241E-07 -6.517E-07  5.189E-07 -2.108E-06  2.818E-06 -3.723E-07  0.000E+00
k= 17 z=     0.232  0.000E+00 -2.637E-07 -8.908E-08  1.249E-07 -5.728E-08  6.524E-07 -3.072E-07 -3.034E-07  1.380E-07  0.000E+00
k= 16 z=     0.217  0.000E+00 -2.717E-07 -1.259E-07 -2.820E-07 -2.278E-07  7.703E-07 -9.400E-07  1.136E-06 -1.593E-07  0.000E+00
k= 15 z=     0.202  0.000E+00  4.053E-07 -3.983E-07  6.043E-07 -1.968E-07  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
k= 14 z=     0.187  0.000E+00  4.548E-07 -2.939E-07  1.547E-08 -1.599E-09 -6.602E-07  3.655E-07  2.185E-07 -1.663E-07  0.000E+00
k= 13 z=     0.172  0.000E+00  4.579E-08 -2.602E-07  3.379E-07 -4.855E-08  1.882E-07  6.687E-08 -3.890E-07  6.288E-08  0.000E+00
k= 12 z=     0.157  0.000E+00  2.672E-08  5.231E-08 -8.593E-08 -1.685E-10 -1.536E-07 -6.320E-07  1.100E-06 -1.633E-07  0.000E+00
k= 11 z=     0.142  0.000E+00  8.186E-08  1.127E-07 -1.173E-07 -3.161E-09 -3.064E-07 -3.214E-08  3.125E-07 -8.613E-08  0.000E+00
k= 10 z=     0.127  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -1.979E-07  7.488E-08  3.144E-08 -5.521E-08  0.000E+00
k=  9 z=     0.112  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -1.152E-07 -9.693E-08  2.840E-07 -5.903E-08  0.000E+00
k=  8 z=     0.097  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.966E-07 -1.179E-07 -3.914E-08  4.384E-08  0.000E+00
k=  7 z=     0.082  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -3.011E-07 -2.158E-09  2.836E-09  2.509E-08  0.000E+00
k=  6 z=     0.067  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -4.619E-06  3.983E-06 -1.008E-07 -6.344E-07  0.000E+00
k=  5 z=     0.052  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  6.496E-06 -3.555E-07 -3.776E-06  1.627E-06  0.000E+00
k=  4 z=     0.037  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  2.078E-05 -9.701E-06 -8.081E-06  4.274E-06  0.000E+00
k=  3 z=     0.022  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  5.344E-08 -2.289E-05  3.051E-05 -4.380E-06  0.000E+00
k=  2 z=     0.007  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -2.340E-05  3.076E-05 -1.813E-05 -4.799E-07  0.000E+00
k=  1 z=    -0.007  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
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                                                                                                              page 14

     r-direction velocity component - - - u   m/sec       f r a m e  i =     1    date 07/12/88     hour 00:21:12
         xcoord =      3.1416 radians                    time step         152    time =  2.5000E+00 seconds
         r-z coordinates are in metres

               j =          1          2          3          4          5          6          7          8          9         10
          rcoord =     0.0000     0.0060     0.0110     0.0150     0.0180     0.0210     0.0250     0.0280     0.0300     0.0320
          zcoord
k= 32 z=     0.457     0.0000    -0.0133    -0.0201    -0.0221    -0.0218    -0.0195    -0.0123    -0.0040     0.0000     0.0000
k= 31 z=     0.442     0.0000     0.0133     0.0201     0.0221     0.0218     0.0195     0.0123     0.0040     0.0000     0.0000
k= 30 z=     0.427     0.0000     0.0046     0.0069     0.0060     0.0045     0.0026     0.0006    -0.0003     0.0000     0.0000
k= 29 z=     0.412     0.0000     0.0001    -0.0013    -0.0092    -0.0105    -0.0086    -0.0039    -0.0011     0.0000     0.0000
k= 28 z=     0.397     0.0000    -0.0008     0.0000     0.0012    -0.0014     0.0000     0.0001     0.0001     0.0000     0.0000
k= 27 z=     0.382     0.0000    -0.0069    -0.0098    -0.0012     0.0014     0.0014    -0.0002    -0.0001     0.0000     0.0000
k= 26 z=     0.367     0.0000    -0.0062    -0.0111    -0.0150    -0.0171    -0.0148    -0.0089    -0.0026     0.0000     0.0000
k= 25 z=     0.352     0.0000     0.0016     0.0058     0.0121     0.0164     0.0160     0.0108     0.0037     0.0000     0.0000
k= 24 z=     0.337     0.0000    -0.0010    -0.0006     0.0025     0.0043     0.0045     0.0023     0.0002     0.0000     0.0000
k= 23 z=     0.322     0.0000    -0.0048    -0.0100    -0.0059    -0.0035    -0.0014     0.0001     0.0000     0.0000     0.0000
k= 22 z=     0.307     0.0000     0.0158     0.0255     0.0187     0.0133     0.0083     0.0029     0.0006     0.0000     0.0000
k= 21 z=     0.292     0.0000     0.0033     0.0043     0.0007    -0.0021    -0.0038    -0.0027    -0.0009     0.0000     0.0000
k= 20 z=     0.277     0.0000    -0.0015    -0.0037    -0.0114    -0.0124    -0.0098    -0.0040    -0.0009     0.0000     0.0000
k= 19 z=     0.262     0.0000    -0.0036    -0.0041     0.0058     0.0090     0.0088     0.0044     0.0013     0.0000     0.0000
k= 18 z=     0.247     0.0000    -0.0001     0.0003     0.0008     0.0006    -0.0002    -0.0008    -0.0004     0.0000     0.0000
k= 17 z=     0.232     0.0000    -0.0029    -0.0052    -0.0068    -0.0074    -0.0070    -0.0041    -0.0011     0.0000     0.0000
k= 16 z=     0.217     0.0000    -0.0086    -0.0149    -0.0181    -0.0181    -0.0152    -0.0089    -0.0024     0.0000     0.0000
k= 15 z=     0.202     0.0000    -0.0019    -0.0017    -0.0007     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
k= 14 z=     0.187     0.0000    -0.0004    -0.0005    -0.0002     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
k= 13 z=     0.172     0.0000     0.0000     0.0000     0.0000     0.0000    -0.0001    -0.0001     0.0000     0.0000     0.0000
k= 12 z=     0.157     0.0000     0.0003     0.0004     0.0003     0.0000    -0.0006    -0.0009    -0.0005     0.0000     0.0000
k= 11 z=     0.142     0.0000    -0.0003    -0.0005    -0.0003     0.0000     0.0029     0.0021     0.0005     0.0000     0.0000
k= 10 z=     0.127     0.0000     0.0003     0.0005     0.0003     0.0000     0.0031     0.0028     0.0012     0.0000     0.0000
k=  9 z=     0.112     0.0000     0.0000     0.0000     0.0000     0.0000     0.0020     0.0022     0.0012     0.0000     0.0000
k=  8 z=     0.097     0.0000     0.0000     0.0000     0.0000     0.0000     0.0031     0.0027     0.0015     0.0000     0.0000
k=  7 z=     0.082     0.0000     0.0000     0.0000     0.0000     0.0000     0.0065     0.0056     0.0028     0.0000     0.0000
k=  6 z=     0.067     0.0000     0.0000     0.0000     0.0000     0.0000     0.0117     0.0096     0.0030     0.0000    -0.0610
k=  5 z=     0.052     0.0000     0.0000     0.0000     0.0000     0.0000     0.0227     0.0446     0.0587     0.0650     0.0610
k=  4 z=     0.037     0.0000     0.0000     0.0000     0.0000     0.0000     0.0150     0.0140     0.0079     0.0000    -0.0610
k=  3 z=     0.022     0.0000     0.0000     0.0000     0.0000     0.0000     0.0161     0.0135     0.0049     0.0000     0.0000
k=  2 z=     0.007     0.0000     0.0000     0.0000     0.0000     0.0000     0.0106    -0.0178    -0.0115     0.0000     0.0000
k=  1 z=    -0.007     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0178     0.0115     0.0000     0.0000
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                                                                                                                   page 15

     z-direction velocity component - - - v   m/sec         f r a m e  i =      1     date 07/12/88       hour 00:21:12
        xcoord =        3.1416 radians                      time step         152     time =  2.5000E+00 seconds
        r-z coordinates are in metres

             j =          1          2          3          4          5          6          7          8          9         10
        rcoord =    -0.0030     0.0030     0.0085     0.0130     0.0165     0.0195     0.0230     0.0265     0.0290     0.0310
        zcoord
k= 32 z=    0.465    0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
k= 31 z=    0.450    0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
k= 30 z=    0.435    0.0664     0.0664     0.0498     0.0318     0.0183     0.0045    -0.0166    -0.0366    -0.0292     0.0292
k= 29 z=    0.420    0.0894     0.0894     0.0669     0.0358     0.0155    -0.0023    -0.0231    -0.0412    -0.0268     0.0268
k= 28 z=    0.405    0.0900     0.0900     0.0617     0.0000     0.0000     0.0000    -0.0096    -0.0287    -0.0186     0.0186
k= 27 z=    0.390    0.0862     0.0862     0.0633     0.0000     0.0000     0.0000    -0.0090    -0.0288    -0.0194     0.0194
k= 26 z=    0.375    0.0518     0.0518     0.0396     0.0259     0.0134     0.0008    -0.0144    -0.0285    -0.0186     0.0186
k= 25 z=    0.360    0.0206     0.0206     0.0099    -0.0039    -0.0118     0.0000     0.0000     0.0000     0.0000     0.0000
k= 24 z=    0.345    0.0289     0.0289     0.0291     0.0299     0.0224     0.0104    -0.0106    -0.0316    -0.0265     0.0265
k= 23 z=    0.330    0.0240     0.0240     0.0288     0.0424     0.0348     0.0148    -0.0168    -0.0411    -0.0282     0.0282
k= 22 z=    0.315    0.0000     0.0000     0.0000     0.0487     0.0424     0.0234    -0.0114    -0.0418    -0.0279     0.0279
k= 21 z=    0.300    0.0789     0.0789     0.0655     0.0486     0.0300     0.0066    -0.0280    -0.0524    -0.0321     0.0321
k= 20 z=    0.285    0.0954     0.0954     0.0753     0.0378     0.0157    -0.0044    -0.0259    -0.0444    -0.0256     0.0256
k= 19 z=    0.270    0.0877     0.0877     0.0642     0.0000     0.0000     0.0000    -0.0086    -0.0301    -0.0194     0.0194
k= 18 z=    0.255    0.0697     0.0697     0.0558     0.0380     0.0228     0.0058    -0.0208    -0.0438    -0.0288     0.0288
k= 17 z=    0.240    0.0694     0.0694     0.0571     0.0407     0.0222     0.0019    -0.0233    -0.0425    -0.0256     0.0256
k= 16 z=    0.225    0.0549     0.0549     0.0430     0.0279     0.0124    -0.0014    -0.0160    -0.0291    -0.0174     0.0000
k= 15 z=    0.210    0.0118     0.0118     0.0035    -0.0031    -0.0041     0.0000     0.0000     0.0000     0.0000     0.0000
k= 14 z=    0.195    0.0025     0.0025     0.0010    -0.0007    -0.0010     0.0000     0.0000     0.0000     0.0000     0.0000
k= 13 z=    0.180    0.0003     0.0003     0.0001    -0.0001    -0.0001     0.0000     0.0000     0.0000     0.0000     0.0000
k= 12 z=    0.165    0.0003     0.0003     0.0002    -0.0001    -0.0002    -0.0007     0.0000     0.0003     0.0004    -0.0004
k= 11 z=    0.150    0.0017     0.0017     0.0013    -0.0002    -0.0015    -0.0039    -0.0019     0.0022     0.0038    -0.0038
k= 10 z=    0.135    0.0000     0.0000     0.0000     0.0000     0.0000     0.0120    -0.0033    -0.0048    -0.0002     0.0002
k=  9 z=    0.120    0.0000     0.0000     0.0000     0.0000    -0.0286     0.0286    -0.0023    -0.0118    -0.0090     0.0090
k=  8 z=    0.105    0.0000     0.0000     0.0000     0.0000    -0.0392     0.0392    -0.0003    -0.0156    -0.0178     0.0178
k=  7 z=    0.090    0.0000     0.0000     0.0000     0.0000    -0.0557     0.0557     0.0001    -0.0203    -0.0286     0.0286
k=  6 z=    0.075    0.0000     0.0000     0.0000     0.0000    -0.0907     0.0907     0.0005    -0.0319    -0.0486     0.0486
k=  5 z=    0.060    0.0000     0.0000     0.0000     0.0000    -0.1538     0.1538    -0.0006    -0.0611    -0.0704     0.0000
k=  4 z=    0.045    0.0000     0.0000     0.0000     0.0000    -0.2758     0.2758     0.1035     0.0389     0.0087     0.0000
k=  3 z=    0.030    0.0000     0.0000     0.0000     0.0000    -0.3567     0.3567     0.1089     0.0147    -0.0483     0.0483
k=  2 z=    0.015    0.0000     0.0000     0.0000     0.0000    -0.4431     0.4431     0.1088    -0.0232    -0.0835     0.0835
k=  1 z=    0.000    0.0000     0.0000     0.0000     0.0000    -0.5000     0.5000     0.0000     0.0000     0.0000     0.0000
```

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                                                                                                                   page 16

     pressure field (p-pref)  - - - - delta-p pascals       f r a m e  i =      1     date 07/12/88       hour 00:21:12
        xcoord =        3.1416 radians                      time step         152     time =  2.5000E+00 seconds
        r-z coordinates are in metres

             j =          1           2           3           4           5           6           7           8           9          10
        rcoord =    -0.0030      0.0030      0.0085      0.0130      0.0165      0.0195      0.0230      0.0265      0.0290      0.0310
        zcoord
k= 32 z=    0.457  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
k= 31 z=    0.442  0.000E+00   8.768E-04   5.557E-04   1.927E-04  -2.929E-05  -1.366E-04  -1.623E-04  -1.217E-04  -5.191E-05   0.000E+00
k= 30 z=    0.427  0.000E+00   1.603E-01   1.601E-01   1.600E-01   1.599E-01   1.599E-01   1.599E-01   1.600E-01   1.601E-01   0.000E+00
k= 29 z=    0.412  0.000E+00   3.217E-01   3.216E-01   3.216E-01   3.216E-01   3.217E-01   3.218E-01   3.218E-01   3.218E-01   0.000E+00
k= 28 z=    0.397  0.000E+00   4.835E-01   4.834E-01   0.000E+00   0.000E+00   0.000E+00   4.851E-01   4.851E-01   4.851E-01   0.000E+00
k= 27 z=    0.382  0.000E+00   6.479E-01   6.479E-01   6.480E-01   6.480E-01   6.479E-01   6.479E-01   6.479E-01   6.479E-01   0.000E+00
k= 26 z=    0.367  0.000E+00   8.106E-01   8.106E-01   8.106E-01   8.106E-01   8.107E-01   8.109E-01   8.110E-01   8.110E-01   0.000E+00
k= 25 z=    0.352  0.000E+00   9.713E-01   9.713E-01   9.712E-01   9.710E-01   9.708E-01   9.708E-01   9.708E-01   9.708E-01   0.000E+00
k= 24 z=    0.337  0.000E+00   1.132E+00   1.132E+00   1.131E+00   1.131E+00   1.131E+00   1.131E+00   1.131E+00   1.131E+00   0.000E+00
k= 23 z=    0.322  0.000E+00   1.292E+00   1.292E+00   1.292E+00   1.293E+00   1.293E+00   1.293E+00   1.293E+00   1.293E+00   0.000E+00
k= 22 z=    0.307  0.000E+00   1.456E+00   1.455E+00   1.454E+00   1.454E+00   1.454E+00   1.454E+00   1.454E+00   1.454E+00   0.000E+00
k= 21 z=    0.292  0.000E+00   1.616E+00   1.615E+00   1.615E+00   1.615E+00   1.615E+00   1.615E+00   1.615E+00   1.615E+00   0.000E+00
k= 20 z=    0.277  0.000E+00   1.778E+00   1.778E+00   1.778E+00   1.778E+00   1.778E+00   1.778E+00   1.778E+00   1.778E+00   0.000E+00
k= 19 z=    0.262  0.000E+00   1.941E+00   1.941E+00   1.941E+00   1.941E+00   1.941E+00   1.941E+00   1.941E+00   1.941E+00   0.000E+00
k= 18 z=    0.247  0.000E+00   2.102E+00   2.102E+00   2.102E+00   2.102E+00   2.102E+00   2.102E+00   2.102E+00   2.102E+00   0.000E+00
k= 17 z=    0.232  0.000E+00   2.265E+00   2.265E+00   2.264E+00   2.264E+00   2.264E+00   2.264E+00   2.264E+00   2.264E+00   0.000E+00
k= 16 z=    0.217  0.000E+00   2.428E+00   2.428E+00   2.428E+00   2.428E+00   2.428E+00   2.428E+00   2.428E+00   2.428E+00   0.000E+00
k= 15 z=    0.202  0.000E+00   2.589E+00   2.589E+00   2.589E+00   2.589E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
k= 14 z=    0.187  0.000E+00   2.749E+00   2.749E+00   2.749E+00   2.749E+00   1.162E+00   1.162E+00   1.162E+00   1.162E+00   0.000E+00
k= 13 z=    0.172  0.000E+00   2.909E+00   2.909E+00   2.909E+00   2.909E+00   1.464E+02   1.464E+02   1.464E+02   1.464E+02   0.000E+00
k= 12 z=    0.157  0.000E+00   3.069E+00   3.069E+00   3.069E+00   3.069E+00   2.916E+02   2.916E+02   2.916E+02   2.916E+02   0.000E+00
k= 11 z=    0.142  0.000E+00   3.229E+00   3.229E+00   3.229E+00   3.229E+00   4.370E+02   4.370E+02   4.370E+02   4.370E+02   0.000E+00
k= 10 z=    0.127  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   5.827E+02   5.827E+02   5.827E+02   5.827E+02   0.000E+00
k=  9 z=    0.112  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   7.285E+02   7.285E+02   7.285E+02   7.286E+02   0.000E+00
k=  8 z=    0.097  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   8.744E+02   8.744E+02   8.744E+02   8.744E+02   0.000E+00
k=  7 z=    0.082  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.020E+03   1.020E+03   1.020E+03   1.020E+03   0.000E+00
k=  6 z=    0.067  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.163E+03   1.163E+03   1.163E+03   1.164E+03   0.000E+00
k=  5 z=    0.052  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.294E+03   1.295E+03   1.293E+03   1.291E+03   1.290E+03
k=  4 z=    0.037  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.429E+03   1.430E+03   1.429E+03   1.430E+03   0.000E+00
k=  3 z=    0.022  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.564E+03   1.563E+03   1.562E+03   1.563E+03   0.000E+00
k=  2 z=    0.007  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   1.703E+03   1.701E+03   1.701E+03   1.701E+03   0.000E+00
k=  1 z=   -0.007  0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00   0.000E+00
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                                                                                                              page 17

     temperature field                 - - - t   deg. c        f r a m e  i =     1     date 07/12/88       hour 00:21:12
          xcoord =      3.1416 radians                          time step        152     time =  2.5000E+00 seconds
          r-z coordinates are in metres

             j =           1           2           3           4           5           6           7           8           9          10
        rcoord =     -0.0030      0.0030      0.0085      0.0130      0.0165      0.0195      0.0230      0.0265      0.0290      0.0310
        zcoord
k= 32 z=   0.457        0.00        0.00        0.00        0.00        0.00        0.00        0.00        0.00        0.00        0.00
k= 31 z=   0.442       49.70       49.70       49.60       49.46       49.35       49.13       48.29       45.53       40.44       37.50
k= 30 z=   0.427       49.50       49.50       49.25       48.76       48.42       47.99       46.75       43.63       39.51       37.50
k= 29 z=   0.412       49.28       49.28       48.92       47.67       46.67       45.87       44.89       42.38       39.12       37.50
k= 28 z=   0.397       49.03       49.03       48.76        0.00        0.00        0.00       44.17       41.91       38.98       37.50
k= 27 z=   0.382       48.70       48.70       48.09       47.68       47.37       46.89       45.25       42.12       39.02       37.50
k= 26 z=   0.367       48.57       48.57       47.37       45.98       44.97       44.19       43.28       41.33       38.83       37.50
k= 25 z=   0.352       49.76       49.76       49.57       49.17       48.73       48.51       47.68       45.00       40.23       37.50
k= 24 z=   0.337       49.70       49.70       49.49       49.15       48.67       48.01       46.70       43.66       39.51       37.50
k= 23 z=   0.322       49.56       49.56       49.30       49.00       48.41       47.52       45.89       42.81       39.22       37.50
k= 22 z=   0.307       49.69       49.69       49.48       49.19       48.82       48.21       46.52       43.04       39.30       37.50
k= 21 z=   0.292       49.54       49.54       49.14       48.41       47.66       46.74       45.30       42.38       39.11       37.50
k= 20 z=   0.277       49.39       49.39       48.85       47.36       46.32       45.48       44.39       41.93       38.98       37.50
k= 19 z=   0.262       49.23       49.23       48.97       48.77       48.52       48.02       46.49       43.12       39.38       37.50
k= 18 z=   0.247       48.87       48.87       48.42       48.06       47.76       47.24       45.73       42.58       39.16       37.50
k= 17 z=   0.232       48.37       48.37       47.59       46.91       46.33       45.66       44.52       41.99       39.00       37.50
k= 16 z=   0.217       47.90       47.90       46.65       45.46       44.56       43.81       42.96       41.17       38.78       37.50
k= 15 z=   0.202       49.82       49.82       49.67       49.37       49.20        0.00        0.00        0.00        0.00       50.00
k= 14 z=   0.187       49.99       49.99       49.98       49.97       49.96       50.00       50.00       50.00       50.00       50.00
k= 13 z=   0.172       50.00       50.00       50.00       50.00       50.00       50.00       50.00       50.00       50.00       50.00
k= 12 z=   0.157       50.01       50.01       50.00       49.97       49.93       49.46       49.98       49.95       49.99       50.00
k= 11 z=   0.142       50.09       50.09       49.98       49.62       48.92       32.92       42.56       47.73       49.69       50.00
k= 10 z=   0.127        0.00       53.39       53.39       53.39       53.38       25.25       33.05       40.45       45.75       50.00
k=  9 z=   0.112        0.00       53.39       53.39       53.39       53.38       24.08       29.13       36.19       42.49       50.00
k=  8 z=   0.097        0.00       53.39       53.39       53.39       53.38       23.38       29.08       32.65       39.34       50.00
k=  7 z=   0.082        0.00       53.39       53.39       53.38       53.38       22.28       27.19       29.24       35.43       50.00
k=  6 z=   0.067        0.00       53.39       53.39       53.38       53.38       21.37       24.92       26.34       32.44       50.00
k=  5 z=   0.052        0.00       53.39       53.39       53.38       53.38       20.82       22.69       23.72       24.56       24.56
k=  4 z=   0.037        0.00       53.39       53.39       53.38       53.38       20.60       22.69       23.09       24.75       50.00
k=  3 z=   0.022        0.00       53.39       53.39       53.38       53.38       20.39       23.24       23.59       25.42       50.00
k=  2 z=   0.007        0.00       53.39       53.39       53.38       53.38       20.14       24.46       26.37       26.76       50.00
k=  1 z=  -0.007        0.00        0.00        0.00        0.00        0.00       20.00        0.00        0.00        0.00        0.00
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                                                                                                              page 18

     turbulent kinetic energy - - - - - - tke m2/sec2        f r a m e  i =     1     date 07/12/88       hour 00:21:12
          xcoord =      3.1416 radians                          time step        152     time =  2.5000E+00 seconds
          r-z coordinates are in metres

             j =           1           2           3           4           5           6           7           8           9          10
        rcoord =     -0.0030      0.0030      0.0085      0.0130      0.0165      0.0195      0.0230      0.0265      0.0290      0.0310
        zcoord
k= 32 z=   0.457   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 31 z=   0.442   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 30 z=   0.427   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 29 z=   0.412   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 28 z=   0.397   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 27 z=   0.382   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 26 z=   0.367   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 25 z=   0.352   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 24 z=   0.337   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 23 z=   0.322   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 22 z=   0.307   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 21 z=   0.292   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 20 z=   0.277   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 19 z=   0.262   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 18 z=   0.247   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 17 z=   0.232   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 16 z=   0.217   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 15 z=   0.202   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
k= 14 z=   0.187   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   4.047E-11   1.012E-10   8.659E-11   2.420E-11   1.000E-30
k= 13 z=   0.172   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   4.088E-09   4.296E-10   5.353E-10   3.571E-09   1.000E-30
k= 12 z=   0.157   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.946E-06   1.462E-07   1.908E-07   4.405E-07   1.000E-30
k= 11 z=   0.142   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   4.947E-05   1.779E-05   6.544E-06   3.145E-06   1.000E-30
k= 10 z=   0.127   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   5.529E-05   6.913E-05   3.213E-05   4.031E-05   1.000E-30
k=  9 z=   0.112   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   8.874E-05   2.114E-04   9.054E-05   1.028E-04   1.000E-30
k=  8 z=   0.097   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.478E-04   6.383E-04   3.939E-04   1.257E-04   1.000E-30
k=  7 z=   0.082   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   2.795E-04   1.509E-03   1.307E-03   2.173E-04   1.000E-30
k=  6 z=   0.067   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   5.875E-04   5.938E-03   4.172E-03   4.334E-04   1.000E-30
k=  5 z=   0.052   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.087E-03   8.530E-03   6.856E-03   5.730E-03   5.730E-03
k=  4 z=   0.037   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.641E-03   1.011E-02   7.708E-03   7.834E-04   1.000E-30
k=  3 z=   0.022   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   2.111E-03   1.335E-02   1.366E-02   1.002E-03   1.000E-30
k=  2 z=   0.007   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.928E-03   7.511E-04   4.087E-04   2.698E-04   1.000E-30
k=  1 z=  -0.007   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-10   1.000E-30   1.000E-30   1.000E-30   1.000E-30
```

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                                                                                              page 19

                                  surface heat flux summary

   surface      j   j       k   k       i   i       qsum         area         avg q/a      avg temp     avg h(not in)
   number      beg end     beg end     beg end      watts        metre**2     watt/m2      deg. c         j/kg

     1          5   5       11  14      1   1      2.090E-02    6.784E-03    3.080E+00    4.970E+01    0.000E+00


                                  system heat balance summary

   qpos  =  1.978E+04 watts     (thermal energy flow out ofsystem)
   qneg  = -1.581E+04 watts     (thermal energy flow into system  )
   qgen  =  6.869E+02 watts     (total heat generation in system  )

   qnet  =  3.283E+03 watts     (system heat balance error        )
   qevol =  2.670E+06 w/m3      (heat balance error per unit vol  )
   qratio=  1.660E-01           (heat balance error - - - fraction of total heat transport)


      n o t e ! !

      advective heat flux and heat balance summaries are
      accurate only for constant specific heat and then
      only the differences are accurate.
      an enthalpy balance will be provided in a later mod.



post processing file created at- -


time step   =   152
time        = 2.5000E+00 seconds
file number =     1
```

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                                                                                              page 20
      monitor output - - pressure/continuity iteration and execution time data

         note - cpu execution time is in milliseconds/time step-cell (unless otherwise noted)
                pressure/continuity error criteria =  1.000E-08

 time    sim         time       number    cont/  sol cpu solution  tilde     cont/     thermal   thermal   turb      variable  ss heat
 step   time,        step,    pres/temp   pres    accum   total   momenta   press     phase,    connect   phase     viscosity bal err.
  no     seconds     seconds    iters     error  minutes  no i/o  (moment)  (patter)  (condif)  (semble)  (kemod)   (visset)   watts
155   2.5381E+00 1.2690E-02   6/   0 7.430E-10   0.071  0.130    0.0454    0.0394    0.0092    0.0101    0.0136    0.0050  0.000E+00
160   2.6014E+00 1.2650E-02   6/   0 7.299E-10   0.073  0.130    0.0454    0.0394    0.0092    0.0101    0.0136    0.0050  0.000E+00
165   2.6646E+00 1.2611E-02   1/   0 9.450E-09   0.075  0.108    0.0454    0.0128    0.0097    0.0101    0.0136    0.0050  0.000E+00
170   2.7275E+00 1.2571E-02   2/   0 7.290E-09   0.078  0.111    0.0454    0.0174    0.0092    0.0101    0.0136    0.0050  0.000E+00
175   2.7903E+00 1.2538E-02   2/   0 6.155E-09   0.080  0.111    0.0454    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
180   2.8528E+00 1.2504E-02   2/   0 5.805E-09   0.082  0.111    0.0454    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
185   2.9153E+00 1.2473E-02   1/   0 5.034E-09   0.084  0.107    0.0454    0.0128    0.0092    0.0101    0.0136    0.0050  0.000E+00
190   2.9776E+00 1.2450E-02   2/   0 2.448E-09   0.086  0.111    0.0454    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
195   3.0398E+00 1.2432E-02   2/   0 5.054E-09   0.088  0.111    0.0454    0.0173    0.0092    0.0101    0.0136    0.0050  0.000E+00
200   3.1019E+00 1.2419E-02   1/   0 5.947E-09   0.090  0.107    0.0454    0.0128    0.0092    0.0101    0.0136    0.0050  0.000E+00
205   3.1639E+00 1.2408E-02   1/   0 6.186E-09   0.093  0.107    0.0453    0.0128    0.0092    0.0101    0.0136    0.0050  0.000E+00
210   3.2259E+00 1.2400E-02   2/   0 2.088E-09   0.095  0.111    0.0454    0.0173    0.0092    0.0102    0.0136    0.0051  0.000E+00
215   3.2879E+00 1.2394E-02   2/   0 9.431E-10   0.097  0.111    0.0453    0.0172    0.0092    0.0101    0.0136    0.0050  0.000E+00
220   3.3499E+00 1.2388E-02   2/   0 7.869E-09   0.099  0.111    0.0453    0.0173    0.0092    0.0102    0.0136    0.0050  0.000E+00
225   3.4118E+00 1.2383E-02   1/   0 6.725E-09   0.101  0.107    0.0454    0.0128    0.0092    0.0102    0.0136    0.0050  0.000E+00
230   3.4737E+00 1.2379E-02   2/   0 1.873E-09   0.103  0.111    0.0453    0.0172    0.0092    0.0102    0.0136    0.0050  0.000E+00
235   3.5356E+00 1.2376E-02   1/   0 9.919E-09   0.105  0.107    0.0453    0.0128    0.0092    0.0102    0.0136    0.0050  0.000E+00
240   3.5975E+00 1.2373E-02   2/   0 1.716E-09   0.108  0.111    0.0454    0.0172    0.0092    0.0102    0.0136    0.0051  0.000E+00
245   3.6593E+00 1.2370E-02   2/   0 7.515E-09   0.110  0.111    0.0453    0.0172    0.0092    0.0102    0.0136    0.0050  0.000E+00
250   3.7212E+00 1.2367E-02   2/   0 7.012E-09   0.112  0.111    0.0453    0.0173    0.0092    0.0102    0.0136    0.0050  0.000E+00
```

```
       monitor output     temperature - - -  deg. c

 time           sim                       cell                 cell                 cell                 cell
 step          time,                ( 4, 14,   1)        ( 9, 14,   1)        ( 2,  5,   1)        ( 9,  5,   1)
  no.         seconds                      t                    t                    t                    t

   5        1.2799E-01               50.000               50.000               50.173               49.838
  10        2.6892E-01               50.000               50.000               50.365               44.948
  15        3.9295E-01               50.000               50.000               50.533               39.632
  20        5.0987E-01               50.000               50.000               50.691               36.806
  25        6.2236E-01               50.000               50.000               50.844               35.309
  30        7.3064E-01               50.000               50.000               50.990               34.321
  35        8.3473E-01               50.000               50.000               51.131               33.562
  40        9.3450E-01               50.000               50.000               51.267               32.988
  45        1.0299E+00               50.000               50.000               51.396               32.493
  50        1.1203E+00               50.000               50.000               51.519               31.989
  55        1.2056E+00               50.000               50.000               51.634               31.447
  60        1.2862E+00               50.000               50.000               51.743               30.872
  65        1.3627E+00               50.000               50.000               51.847               30.294
  70        1.4361E+00               50.000               50.000               51.947               29.736
  75        1.5065E+00               49.999               50.000               52.042               29.261
  80        1.5748E+00               49.999               50.000               52.135               28.794
  85        1.6417E+00               49.999               50.000               52.225               28.355
  90        1.7076E+00               49.998               50.000               52.314               27.945
  95        1.7728E+00               49.998               50.000               52.403               27.562
 100        1.8375E+00               49.997               50.000               52.491               27.203
 105        1.9020E+00               49.996               50.000               52.578               26.867
 110        1.9663E+00               49.995               50.000               52.665               26.551
 115        2.0305E+00               49.993               50.000               52.752               26.255
 120        2.0946E+00               49.992               50.000               52.839               25.978
 125        2.1587E+00               49.989               50.000               52.926               25.717
 130        2.2227E+00               49.987               50.000               53.012               25.472
 135        2.2867E+00               49.984               50.000               53.099               25.242
 140        2.3506E+00               49.980               50.000               53.186               25.027
 145        2.4145E+00               49.975               50.000               53.272               24.822
 150        2.4783E+00               49.970               50.000               53.359               24.626
 155        2.5381E+00               49.965               50.000               53.440               24.449
 160        2.6014E+00               49.958               50.000               53.526               24.273
 165        2.6646E+00               49.951               50.000               53.611               24.105
 170        2.7275E+00               49.942               50.000               53.696               23.946
 175        2.7903E+00               49.932               50.000               53.781               23.795
 180        2.8528E+00               49.922               50.000               53.866               23.652
 185        2.9153E+00               49.910               50.000               53.951               23.516
 190        2.9776E+00               49.896               50.000               54.035               23.389
 195        3.0398E+00               49.882               50.000               54.119               23.270
 200        3.1019E+00               49.865               50.000               54.203               23.157
 205        3.1639E+00               49.847               50.000               54.287               23.051
 210        3.2259E+00               49.827               50.000               54.371               22.951
 215        3.2879E+00               49.806               50.000               54.455               22.857
 220        3.3499E+00               49.782               50.000               54.539               22.769
 225        3.4118E+00               49.755               50.000               54.623               22.686
 230        3.4737E+00               49.727               50.000               54.707               22.608
 235        3.5356E+00               49.696               50.000               54.791               22.535
 240        3.5975E+00               49.662               50.000               54.875               22.466
 245        3.6593E+00               49.624               50.000               54.958               22.401
 250        3.7212E+00               49.584               50.000               55.042               22.341
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        monitor output     u and v velocities - -  m/sec

time     sim                cell                          cell                          cell                          cell
step    time,          (  4, 14,   1)                (  9, 14,   1)                (  2,  5,   1)                (  9,  5,   1)
no.    seconds          u             v               u             v               u             v               u             v

  5  1.2799E-01  -5.8436E-08  -1.1113E-07   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.4369E-02
 10  2.6892E-01  -3.4315E-07  -7.8365E-07   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.8092E-02
 15  3.9295E-01  -7.8990E-07  -2.0448E-06   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.2413E-01
 20  5.0987E-01  -1.3928E-06  -3.9170E-06   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.3708E-01
 25  6.2236E-01  -2.1786E-06  -6.4514E-06   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.4438E-01
 30  7.3064E-01  -3.1813E-06  -9.6965E-06   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.4895E-01
 35  8.3473E-01  -4.4610E-06  -1.3749E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.5210E-01
 40  9.3450E-01  -6.0742E-06  -1.8728E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.5441E-01
 45  1.0299E+00  -8.0844E-06  -2.4797E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5016E-02  -1.5274E-01
 50  1.1203E+00  -1.0535E-05  -3.2079E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.4673E-01
 55  1.2056E+00  -1.3457E-05  -4.0691E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.3761E-01
 60  1.2862E+00  -1.6872E-05  -5.0781E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.2739E-01
 65  1.3627E+00  -2.0802E-05  -6.2451E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.1766E-01
 70  1.4361E+00  -2.5277E-05  -7.5920E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.0922E-01
 75  1.5065E+00  -3.0318E-05  -9.1323E-05   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -1.0231E-01
 80  1.5748E+00  -3.5912E-05  -1.0881E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -9.6597E-02
 85  1.6417E+00  -4.2141E-05  -1.2875E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -9.1930E-02
 90  1.7076E+00  -4.9015E-05  -1.5139E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -8.8140E-02
 95  1.7728E+00  -5.6559E-05  -1.7699E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -8.5069E-02
100  1.8375E+00  -6.4787E-05  -2.0585E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -8.2564E-02
105  1.9020E+00  -7.3708E-05  -2.3828E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -8.0491E-02
110  1.9663E+00  -8.3317E-05  -2.7452E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.8746E-02
115  2.0305E+00  -9.3618E-05  -3.1481E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.7261E-02
120  2.0946E+00  -1.0467E-04  -3.5943E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.5999E-02
125  2.1587E+00  -1.1641E-04  -4.0840E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.4904E-02
130  2.2227E+00  -1.2883E-04  -4.6186E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.3942E-02
135  2.2867E+00  -1.4202E-04  -5.2006E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.3093E-02
140  2.3506E+00  -1.5592E-04  -5.8281E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.2337E-02
145  2.4145E+00  -1.7052E-04  -6.4997E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.1542E-02
150  2.4783E+00  -1.8580E-04  -7.2144E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -7.0677E-02
155  2.5381E+00  -2.0081E-04  -7.9262E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.9874E-02
160  2.6014E+00  -2.1740E-04  -8.7223E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.9006E-02
165  2.6646E+00  -2.3467E-04  -9.5600E-04   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.8180E-02
170  2.7275E+00  -2.5263E-04  -1.0439E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.7351E-02
175  2.7903E+00  -2.7128E-04  -1.1360E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.6536E-02
180  2.8528E+00  -2.9063E-04  -1.2322E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.5733E-02
185  2.9153E+00  -3.1065E-04  -1.3326E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.5010E-02
190  2.9776E+00  -3.3140E-04  -1.4373E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.4378E-02
195  3.0398E+00  -3.5298E-04  -1.5462E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.3831E-02
200  3.1019E+00  -3.7540E-04  -1.6597E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.3356E-02
205  3.1639E+00  -3.9861E-04  -1.7783E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.2945E-02
210  3.2259E+00  -4.2263E-04  -1.9024E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.2587E-02
215  3.2879E+00  -4.4746E-04  -2.0322E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.2274E-02
220  3.3499E+00  -4.7311E-04  -2.1677E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.2002E-02
225  3.4118E+00  -4.9964E-04  -2.3094E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.1764E-02
230  3.4737E+00  -5.2705E-04  -2.4573E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.1557E-02
235  3.5356E+00  -5.5535E-04  -2.6118E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.1376E-02
240  3.5975E+00  -5.8454E-04  -2.7731E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.1217E-02
245  3.6593E+00  -6.1468E-04  -2.9412E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.1078E-02
250  3.7212E+00  -6.4596E-04  -3.1162E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0957E-02
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                                                                                                                              page 23
       monitor output     w-velocity - - -  m/sec   and pressure - - -   pascals

 time      sim                    cell                          cell                          cell                          cell
 step     time,             (  4, 14,   1)                (  9, 14,   1)                (  2,   5,   1)                (  9,   5,   1)
 no.     seconds              w            p                w            p                w            p                w            p

   5   1.2799E-01   0.0000E+00   2.7192E+00   0.0000E+00   1.2648E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.3002E+03
  10   2.6892E-01   0.0000E+00   2.7198E+00   0.0000E+00   8.1286E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2907E+03
  15   3.9295E-01   0.0000E+00   2.7204E+00   0.0000E+00   1.1437E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2818E+03
  20   5.0987E-01   0.0000E+00   2.7211E+00   0.0000E+00   1.2157E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2783E+03
  25   6.2236E-01   0.0000E+00   2.7218E+00   0.0000E+00   1.2634E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2760E+03
  30   7.3064E-01   0.0000E+00   2.7226E+00   0.0000E+00   1.2972E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2741E+03
  35   8.3473E-01   0.0000E+00   2.7235E+00   0.0000E+00   1.3245E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2722E+03
  40   9.3450E-01   0.0000E+00   2.7243E+00   0.0000E+00   1.3559E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2703E+03
  45   1.0299E+00   0.0000E+00   2.7252E+00   0.0000E+00   1.3789E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2702E+03
  50   1.1203E+00   0.0000E+00   2.7261E+00   0.0000E+00   1.3880E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2715E+03
  55   1.2056E+00   0.0000E+00   2.7270E+00   0.0000E+00   1.3873E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2735E+03
  60   1.2862E+00   0.0000E+00   2.7280E+00   0.0000E+00   1.3832E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2758E+03
  65   1.3627E+00   0.0000E+00   2.7289E+00   0.0000E+00   1.3674E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2780E+03
  70   1.4361E+00   0.0000E+00   2.7298E+00   0.0000E+00   1.3441E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2798E+03
  75   1.5065E+00   0.0000E+00   2.7307E+00   0.0000E+00   1.3190E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2814E+03
  80   1.5748E+00   0.0000E+00   2.7316E+00   0.0000E+00   1.2942E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2828E+03
  85   1.6417E+00   0.0000E+00   2.7326E+00   0.0000E+00   1.2705E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2840E+03
  90   1.7076E+00   0.0000E+00   2.7335E+00   0.0000E+00   1.2487E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2851E+03
  95   1.7728E+00   0.0000E+00   2.7345E+00   0.0000E+00   1.2290E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2860E+03
 100   1.8375E+00   0.0000E+00   2.7356E+00   0.0000E+00   1.2118E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2868E+03
 105   1.9020E+00   0.0000E+00   2.7367E+00   0.0000E+00   1.1969E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2875E+03
 110   1.9663E+00   0.0000E+00   2.7378E+00   0.0000E+00   1.1844E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2881E+03
 115   2.0305E+00   0.0000E+00   2.7390E+00   0.0000E+00   1.1767E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2886E+03
 120   2.0946E+00   0.0000E+00   2.7402E+00   0.0000E+00   1.1732E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2891E+03
 125   2.1587E+00   0.0000E+00   2.7414E+00   0.0000E+00   1.1707E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2896E+03
 130   2.2227E+00   0.0000E+00   2.7427E+00   0.0000E+00   1.1691E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2900E+03
 135   2.2867E+00   0.0000E+00   2.7441E+00   0.0000E+00   1.1680E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2904E+03
 140   2.3506E+00   0.0000E+00   2.7455E+00   0.0000E+00   1.1675E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2907E+03
 145   2.4145E+00   0.0000E+00   2.7469E+00   0.0000E+00   1.1659E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2910E+03
 150   2.4783E+00   0.0000E+00   2.7483E+00   0.0000E+00   1.1643E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2913E+03
 155   2.5381E+00   0.0000E+00   2.7497E+00   0.0000E+00   1.1606E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2916E+03
 160   2.6014E+00   0.0000E+00   2.7513E+00   0.0000E+00   1.1567E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2919E+03
 165   2.6646E+00   0.0000E+00   2.7528E+00   0.0000E+00   1.1509E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2921E+03
 170   2.7275E+00   0.0000E+00   2.7544E+00   0.0000E+00   1.1441E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2924E+03
 175   2.7903E+00   0.0000E+00   2.7560E+00   0.0000E+00   1.1360E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2926E+03
 180   2.8528E+00   0.0000E+00   2.7576E+00   0.0000E+00   1.1272E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2928E+03
 185   2.9153E+00   0.0000E+00   2.7592E+00   0.0000E+00   1.1182E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2930E+03
 190   2.9776E+00   0.0000E+00   2.7609E+00   0.0000E+00   1.1094E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2932E+03
 195   3.0398E+00   0.0000E+00   2.7626E+00   0.0000E+00   1.1006E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2934E+03
 200   3.1019E+00   0.0000E+00   2.7643E+00   0.0000E+00   1.0921E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2935E+03
 205   3.1639E+00   0.0000E+00   2.7660E+00   0.0000E+00   1.0839E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2936E+03
 210   3.2259E+00   0.0000E+00   2.7678E+00   0.0000E+00   1.0759E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2937E+03
 215   3.2879E+00   0.0000E+00   2.7695E+00   0.0000E+00   1.0682E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2938E+03
 220   3.3499E+00   0.0000E+00   2.7713E+00   0.0000E+00   1.0608E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2939E+03
 225   3.4118E+00   0.0000E+00   2.7732E+00   0.0000E+00   1.0536E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2940E+03
 230   3.4737E+00   0.0000E+00   2.7750E+00   0.0000E+00   1.0466E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2941E+03
 235   3.5356E+00   0.0000E+00   2.7769E+00   0.0000E+00   1.0399E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2941E+03
 240   3.5975E+00   0.0000E+00   2.7788E+00   0.0000E+00   1.0333E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2942E+03
 245   3.6593E+00   0.0000E+00   2.7807E+00   0.0000E+00   1.0269E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2942E+03
 250   3.7212E+00   0.0000E+00   2.7826E+00   0.0000E+00   1.0206E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2943E+03
```

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                                                                                                                              page 24
       monitor output - - pressure/continuity iteration and execution time data

            note - cpu execution time is in milliseconds/time step-cell (unless otherwise noted)
                   pressure/continuity error criteria =  1.000E-08

 time    sim        time      number    cont/   sol cpu solution  tilde     cont/     thermal   thermal   turb      variable  ss heat
 step   time,      step,    pres/temp  pres     accum    total   momenta   press     phase,    connect   phase     viscosity bal err.
 no      seconds    seconds    iters    error   minutes  no i/o  (moment)  (patter)  (condif)  (semble)  (kemod)   (visset)   watts
255   3.7830E+00 1.2365E-02   2/  0 4.648E-09   0.114  0.111   0.0453    0.0172    0.0092    0.0102    0.0136    0.0050   0.000E+00
260   3.8448E+00 1.2363E-02   2/  0 4.611E-09   0.116  0.111   0.0453    0.0172    0.0092    0.0102    0.0136    0.0050   0.000E+00
265   3.9066E+00 1.2361E-02   1/  0 7.067E-09   0.118  0.107   0.0453    0.0129    0.0092    0.0102    0.0136    0.0050   0.000E+00
270   3.9684E+00 1.2359E-02   2/  0 4.158E-09   0.120  0.111   0.0454    0.0173    0.0092    0.0102    0.0136    0.0051   0.000E+00
275   4.0302E+00 1.2357E-02   1/  0 7.001E-09   0.122  0.107   0.0453    0.0128    0.0092    0.0102    0.0136    0.0050   0.000E+00
280   4.0920E+00 1.2355E-02   2/  0 3.839E-09   0.125  0.111   0.0453    0.0173    0.0092    0.0102    0.0136    0.0050   0.000E+00
285   4.1537E+00 1.2354E-02   1/  0 9.907E-09   0.127  0.109   0.0453    0.0128    0.0092    0.0102    0.0151    0.0050   0.000E+00
290   4.2155E+00 1.2352E-02   2/  0 4.410E-09   0.129  0.111   0.0454    0.0173    0.0092    0.0102    0.0136    0.0050   0.000E+00
295   4.2773E+00 1.2351E-02   2/  0 4.789E-09   0.131  0.111   0.0453    0.0172    0.0092    0.0102    0.0136    0.0050   0.000E+00
300   4.3390E+00 1.2350E-02   2/  0 4.160E-09   0.133  0.111   0.0453    0.0172    0.0092    0.0102    0.0137    0.0050   0.000E+00
305   4.4008E+00 1.2348E-02   2/  0 4.450E-09   0.135  0.111   0.0453    0.0173    0.0092    0.0102    0.0136    0.0050   0.000E+00
310   4.4625E+00 1.2347E-02   1/  0 9.860E-09   0.137  0.107   0.0453    0.0128    0.0092    0.0102    0.0136    0.0050   0.000E+00
315   4.5242E+00 1.2346E-02   2/  0 4.302E-09   0.139  0.111   0.0453    0.0173    0.0092    0.0102    0.0136    0.0050   0.000E+00
320   4.5860E+00 1.2345E-02   2/  0 3.777E-09   0.142  0.111   0.0453    0.0172    0.0092    0.0102    0.0136    0.0050   0.000E+00
325   4.6477E+00 1.2344E-02   2/  0 4.381E-09   0.144  0.111   0.0453    0.0172    0.0092    0.0102    0.0136    0.0050   0.000E+00
330   4.7094E+00 1.2344E-02   2/  0 3.955E-09   0.146  0.111   0.0453    0.0172    0.0092    0.0102    0.0136    0.0050   0.000E+00
335   4.7711E+00 1.2343E-02   2/  0 4.537E-09   0.148  0.111   0.0453    0.0173    0.0092    0.0102    0.0136    0.0050   0.000E+00
340   4.8328E+00 1.2342E-02   2/  0 3.988E-09   0.150  0.112   0.0453    0.0172    0.0092    0.0102    0.0144    0.0050   0.000E+00
345   4.8945E+00 1.2341E-02   2/  0 5.603E-09   0.152  0.111   0.0453    0.0172    0.0092    0.0102    0.0136    0.0050   0.000E+00
350   4.9562E+00 1.2341E-02   2/  0 4.183E-09   0.154  0.111   0.0453    0.0172    0.0092    0.0102    0.0136    0.0050   0.000E+00
```

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                                                                                                                  page 25

  flow divergence- - - - - - - - - - divg  m3/m3-s        f r a m e  i =      1    date 07/12/88       hour 00:21:35
     xcoord =      3.1416 radians                         time step         354    time =  5.0000E+00 seconds
     r-z coordinates are in metres

            j =          1          2          3          4          5          6          7          8          9         10
     rcoord =      -0.0030     0.0030     0.0085     0.0130     0.0165     0.0195     0.0230     0.0265     0.0290     0.0310
     zcoord
k= 32 z=   0.457  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
k= 31 z=   0.442  0.000E+00 -1.090E-05 -5.806E-06 -9.713E-06 -1.413E-05 -1.988E-06  1.601E-05  8.507E-06 -7.529E-06  0.000E+00
k= 30 z=   0.427  0.000E+00  9.238E-06  8.575E-06  2.535E-06 -5.458E-06  1.317E-06  6.704E-06  3.499E-06 -5.947E-06  0.000E+00
k= 29 z=   0.412  0.000E+00 -9.732E-06 -2.041E-06 -5.203E-06  2.146E-06  1.412E-06 -1.982E-06 -1.241E-05  8.133E-06  0.000E+00
k= 28 z=   0.397  0.000E+00  1.770E-05  1.005E-06  0.000E+00  0.000E+00  0.000E+00  2.589E-06 -8.898E-06  2.216E-06  0.000E+00
k= 27 z=   0.382  0.000E+00  1.263E-05  3.861E-06  1.257E-05 -9.878E-06 -5.885E-06 -9.909E-06  1.798E-06  3.593E-06  0.000E+00
k= 26 z=   0.367  0.000E+00 -1.205E-05 -5.417E-06 -3.639E-06  6.622E-06  1.013E-05  2.165E-06  8.962E-06 -6.764E-06  0.000E+00
k= 25 z=   0.352  0.000E+00  3.177E-05  5.700E-06 -4.444E-06  8.081E-07 -1.024E-05 -8.580E-06 -3.174E-07  5.388E-06  0.000E+00
k= 24 z=   0.337  0.000E+00 -1.611E-05  3.509E-06 -5.140E-07 -1.093E-05 -8.288E-07  1.374E-05  1.588E-05 -1.179E-05  0.000E+00
k= 23 z=   0.322  0.000E+00 -5.034E-05 -1.458E-05 -3.215E-06  1.639E-05  7.237E-06  1.316E-05 -1.427E-05  1.063E-06  0.000E+00
k= 22 z=   0.307  0.000E+00 -5.267E-05 -6.625E-06  6.169E-06  1.068E-05 -8.528E-07 -1.119E-05 -2.325E-05  1.673E-05  0.000E+00
k= 21 z=   0.292  0.000E+00  4.331E-05  2.671E-05  1.176E-05 -1.747E-05 -3.672E-06 -1.266E-06  1.681E-05 -1.097E-05  0.000E+00
k= 20 z=   0.277  0.000E+00  3.215E-06 -1.048E-06 -1.070E-05 -7.682E-06 -5.330E-06  2.521E-06  1.526E-06  2.443E-06  0.000E+00
k= 19 z=   0.262  0.000E+00 -4.244E-06 -7.131E-06 -1.347E-06  1.230E-05  1.155E-05 -1.799E-06  7.014E-06 -5.583E-06  0.000E+00
k= 18 z=   0.247  0.000E+00 -8.654E-06  1.423E-06  5.935E-06  4.246E-06  5.490E-06 -4.347E-06 -8.196E-06  4.020E-06  0.000E+00
k= 17 z=   0.232  0.000E+00  1.478E-05  2.494E-06 -4.924E-07 -9.883E-06 -5.059E-06 -8.137E-06 -4.634E-06  7.694E-06  0.000E+00
k= 16 z=   0.217  0.000E+00 -1.044E-05 -2.075E-05 -6.478E-06  4.638E-06  1.158E-05  7.794E-06  1.116E-05 -1.020E-05  0.000E+00
k= 15 z=   0.202  0.000E+00  3.204E-05 -1.117E-05  9.818E-06 -4.895E-06  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
k= 14 z=   0.187  0.000E+00 -2.654E-06  9.551E-06 -5.417E-06  2.832E-06 -6.607E-07  4.516E-07  2.663E-08 -8.475E-08  0.000E+00
k= 13 z=   0.172  0.000E+00 -2.504E-06 -5.715E-06 -1.238E-05  7.419E-06 -8.697E-07  5.097E-07  1.910E-07 -1.762E-07  0.000E+00
k= 12 z=   0.157  0.000E+00  7.919E-07  9.470E-10  3.572E-07 -1.818E-07 -4.294E-07  5.976E-07  3.873E-07 -4.413E-07  0.000E+00
k= 11 z=   0.142  0.000E+00 -1.715E-06  1.361E-06  1.358E-06 -4.080E-07  1.136E-06 -1.704E-06 -5.661E-08  2.268E-07  0.000E+00
k= 10 z=   0.127  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  3.004E-06 -1.776E-06  2.323E-07  8.024E-08  0.000E+00
k=  9 z=   0.112  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  2.125E-06 -4.172E-07 -7.391E-07  4.785E-07  0.000E+00
k=  8 z=   0.097  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  4.391E-06 -2.248E-06 -2.706E-06  2.040E-06  0.000E+00
k=  7 z=   0.082  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  6.522E-06 -3.187E-06 -1.120E-06  1.133E-06  0.000E+00
k=  6 z=   0.067  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -7.612E-06  3.499E-06  8.792E-07 -8.475E-07  0.000E+00
k=  5 z=   0.052  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -2.949E-06  7.852E-07  8.659E-08 -4.338E-07  0.000E+00
k=  4 z=   0.037  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -1.662E-07  1.314E-06  2.230E-06 -1.740E-06  0.000E+00
k=  3 z=   0.022  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -4.323E-06  1.689E-06 -2.256E-07  6.605E-08  0.000E+00
k=  2 z=   0.007  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00 -1.831E-07  3.595E-07  7.207E-09 -1.637E-07  0.000E+00
k=  1 z=  -0.007  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
```

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                                                                                                                  page 26
       monitor output - - pressure/continuity iteration and execution time data

          note - cpu execution time is in milliseconds/time step-cell (unless otherwise noted)
                 pressure/continuity error criteria =  1.000E-08

  time   sim       time      number    cont/   sol cpu solution  tilde    cont/     thermal   thermal  turb     variable  ss heat
  step  time,      step,    pres/temp  pres    accum    total   momenta   press     phase,    connect  phase    viscosity bal err.
   no    seconds   seconds   iters     error  minutes  no i/o  (moment)  (patter)  (condif)  (semble)  (kemod)   (visset)  watts
  354  5.0000E+00 6.7339E-03   2/  0 6.387E-09   0.156  0.193    0.0453    0.0172    0.0108    0.0102    0.0136    0.0050  0.000E+00

       monitor output     temperature - - -  deg. c

  time          sim                   cell                 cell                 cell                 cell
  step         time,              ( 4, 14,  1)         ( 9, 14,  1)         ( 2,  5,  1)         ( 9,  5,  1)
   no.         seconds                  t                    t                    t                    t

  255        3.7830E+00             49.540               50.000               55.126               22.284
  260        3.8448E+00             49.493               50.000               55.210               22.231
  265        3.9066E+00             49.442               50.000               55.293               22.181
  270        3.9684E+00             49.386               50.000               55.377               22.135
  275        4.0302E+00             49.326               50.000               55.461               22.091
  280        4.0920E+00             49.261               50.000               55.544               22.049
  285        4.1537E+00             49.192               50.000               55.628               22.010
  290        4.2155E+00             49.116               50.000               55.711               21.974
  295        4.2773E+00             49.035               49.999               55.795               21.939
  300        4.3390E+00             48.948               49.999               55.879               21.907
  305        4.4008E+00             48.855               49.999               55.962               21.876
  310        4.4625E+00             48.755               49.999               56.046               21.847
  315        4.5242E+00             48.648               49.999               56.129               21.820
  320        4.5860E+00             48.533               49.999               56.213               21.794
  325        4.6477E+00             48.411               49.999               56.297               21.770
  330        4.7094E+00             48.280               49.999               56.380               21.747
  335        4.7711E+00             48.141               49.999               56.464               21.725
  340        4.8328E+00             47.992               49.999               56.547               21.704
  345        4.8945E+00             47.835               49.999               56.631               21.685
  354        5.0000E+00             47.543               49.999               56.774               21.654
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                                                                                                  page 27
       monitor output      u and v velocities - -  m/sec


 time      sim                  cell                          cell                          cell                          cell
 step     time,          (  4, 14,   1)                (  9, 14,   1)                (  2,   5,   1)                (  9,   5,   1)
 no.     seconds          u                 v            u                 v            u                 v            u                 v

255    3.7830E+00  -6.7829E-04  -3.2990E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0850E-02
260    3.8448E+00  -7.1165E-04  -3.4903E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0757E-02
265    3.9066E+00  -7.4604E-04  -3.6906E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0674E-02
270    3.9684E+00  -7.8148E-04  -3.9000E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0602E-02
275    4.0302E+00  -8.1801E-04  -4.1189E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0538E-02
280    4.0920E+00  -8.5564E-04  -4.3473E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0482E-02
285    4.1537E+00  -8.9446E-04  -4.5854E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0433E-02
290    4.2155E+00  -9.3461E-04  -4.8331E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0389E-02
295    4.2773E+00  -9.7602E-04  -5.0915E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0349E-02
300    4.3390E+00  -1.0186E-03  -5.3614E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0315E-02
305    4.4008E+00  -1.0623E-03  -5.6427E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0283E-02
310    4.4625E+00  -1.1071E-03  -5.9354E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0255E-02
315    4.5242E+00  -1.1530E-03  -6.2396E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0230E-02
320    4.5860E+00  -1.2003E-03  -6.5551E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0208E-02
325    4.6477E+00  -1.2489E-03  -6.8820E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0188E-02
330    4.7094E+00  -1.2987E-03  -7.2222E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0169E-02
335    4.7711E+00  -1.3495E-03  -7.5756E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0153E-02
340    4.8328E+00  -1.4013E-03  -7.9422E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0138E-02
345    4.8945E+00  -1.4543E-03  -8.3213E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0124E-02
354    5.0000E+00  -1.5476E-03  -8.9978E-03   0.0000E+00   0.0000E+00   0.0000E+00   0.0000E+00   6.5017E-02  -6.0104E-02

       monitor output      w-velocity - - -  m/sec    and pressure - - -   pascals


 time      sim                  cell                          cell                          cell                          cell
 step     time,          (  4, 14,   1)                (  9, 14,   1)                (  2,   5,   1)                (  9,   5,   1)
 no.     seconds          w                 p            w                 p            w                 p            w                 p

255    3.7830E+00   0.0000E+00   2.7846E+00   0.0000E+00   1.0145E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2943E+03
260    3.8448E+00   0.0000E+00   2.7866E+00   0.0000E+00   1.0085E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2943E+03
265    3.9066E+00   0.0000E+00   2.7886E+00   0.0000E+00   1.0025E+00   0.0000E+00   0.0000E+00   0.0000E+00   1.2944E+03
270    3.9684E+00   0.0000E+00   2.7906E+00   0.0000E+00   9.9668E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2944E+03
275    4.0302E+00   0.0000E+00   2.7927E+00   0.0000E+00   9.9088E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2944E+03
280    4.0920E+00   0.0000E+00   2.7947E+00   0.0000E+00   9.8513E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2945E+03
285    4.1537E+00   0.0000E+00   2.7968E+00   0.0000E+00   9.7943E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2945E+03
290    4.2155E+00   0.0000E+00   2.7990E+00   0.0000E+00   9.7377E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2945E+03
295    4.2773E+00   0.0000E+00   2.8011E+00   0.0000E+00   9.6815E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2945E+03
300    4.3390E+00   0.0000E+00   2.8033E+00   0.0000E+00   9.6255E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2945E+03
305    4.4008E+00   0.0000E+00   2.8054E+00   0.0000E+00   9.5698E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2945E+03
310    4.4625E+00   0.0000E+00   2.8076E+00   0.0000E+00   9.5143E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
315    4.5242E+00   0.0000E+00   2.8098E+00   0.0000E+00   9.4590E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
320    4.5860E+00   0.0000E+00   2.8121E+00   0.0000E+00   9.4038E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
325    4.6477E+00   0.0000E+00   2.8143E+00   0.0000E+00   9.3487E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
330    4.7094E+00   0.0000E+00   2.8166E+00   0.0000E+00   9.2938E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
335    4.7711E+00   0.0000E+00   2.8189E+00   0.0000E+00   9.2390E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
340    4.8328E+00   0.0000E+00   2.8212E+00   0.0000E+00   9.1843E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
345    4.8945E+00   0.0000E+00   2.8235E+00   0.0000E+00   9.1297E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
354    5.0000E+00   0.0000E+00   2.8278E+00   0.0000E+00   9.0224E-01   0.0000E+00   0.0000E+00   0.0000E+00   1.2946E+03
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                                                                                                  page 28

   r-direction velocity component - - - u   m/sec           f r a m e  i =    1     date 07/12/88      hour 00:21:36
      xcoord =         3.1416 radians                        time step       354    time =  5.0000E+00 seconds
      r-z coordinates are in metres

             j =        1          2          3          4          5          6          7          8          9         10
      rcoord =      0.0000     0.0060     0.0110     0.0150     0.0180     0.0210     0.0250     0.0280     0.0300     0.0320
      zcoord
k= 32 z=   0.457    0.0000    -0.0211    -0.0295    -0.0312    -0.0302    -0.0267    -0.0172    -0.0060     0.0000     0.0000
k= 31 z=   0.442    0.0000     0.0211     0.0295     0.0312     0.0302     0.0267     0.0172     0.0060     0.0000     0.0000
k= 30 z=   0.427    0.0000     0.0053     0.0073     0.0056     0.0039     0.0022     0.0007    -0.0005     0.0000     0.0000
k= 29 z=   0.412    0.0000    -0.0003    -0.0020    -0.0113    -0.0128    -0.0108    -0.0050    -0.0016     0.0000     0.0000
k= 28 z=   0.397    0.0000    -0.0012     0.0000     0.0013    -0.0013     0.0000    -0.0004    -0.0002     0.0000     0.0000
k= 27 z=   0.382    0.0000    -0.0075    -0.0112    -0.0013     0.0013     0.0008    -0.0011    -0.0004     0.0000     0.0000
k= 26 z=   0.367    0.0000    -0.0070    -0.0125    -0.0193    -0.0225    -0.0190    -0.0113    -0.0033     0.0000     0.0000
k= 25 z=   0.352    0.0000    -0.0014     0.0036     0.0135     0.0201     0.0199     0.0143     0.0053     0.0000     0.0000
k= 24 z=   0.337    0.0000    -0.0027    -0.0026     0.0017     0.0048     0.0060     0.0036     0.0005     0.0000     0.0000
k= 23 z=   0.322    0.0000    -0.0063    -0.0120    -0.0074    -0.0050    -0.0027     0.0002    -0.0001     0.0000     0.0000
k= 22 z=   0.307    0.0000     0.0234     0.0356     0.0281     0.0212     0.0139     0.0045     0.0008     0.0000     0.0000
k= 21 z=   0.292    0.0000     0.0035     0.0035    -0.0017    -0.0052    -0.0072    -0.0048    -0.0017     0.0000     0.0000
k= 20 z=   0.277    0.0000    -0.0028    -0.0062    -0.0149    -0.0158    -0.0127    -0.0049    -0.0011     0.0000     0.0000
k= 19 z=   0.262    0.0000    -0.0034    -0.0040     0.0071     0.0108     0.0109     0.0051     0.0016     0.0000     0.0000
k= 18 z=   0.247    0.0000    -0.0002     0.0002     0.0008     0.0002    -0.0011    -0.0018    -0.0008     0.0000     0.0000
k= 17 z=   0.232    0.0000    -0.0037    -0.0065    -0.0084    -0.0093    -0.0089    -0.0055    -0.0016     0.0000     0.0000
k= 16 z=   0.217    0.0000    -0.0085    -0.0159    -0.0213    -0.0219    -0.0182    -0.0108    -0.0030     0.0000     0.0000
k= 15 z=   0.202    0.0000    -0.0029    -0.0011    -0.0002     0.0000     0.0000    -0.0001     0.0000     0.0000     0.0000
k= 14 z=   0.187    0.0000    -0.0036    -0.0040    -0.0015     0.0000     0.0000     0.0001     0.0000     0.0000     0.0000
k= 13 z=   0.172    0.0000    -0.0013    -0.0013    -0.0005     0.0000     0.0002     0.0003     0.0001     0.0000     0.0000
k= 12 z=   0.157    0.0000     0.0001     0.0000     0.0000     0.0000    -0.0007    -0.0010    -0.0004     0.0000     0.0000
k= 11 z=   0.142    0.0000    -0.0006    -0.0004    -0.0001     0.0000    -0.0005    -0.0012    -0.0007     0.0000     0.0000
k= 10 z=   0.127    0.0000     0.0006     0.0004     0.0001     0.0000     0.0001     0.0002    -0.0003     0.0000     0.0000
k=  9 z=   0.112    0.0000     0.0000     0.0000     0.0000     0.0000     0.0024     0.0023     0.0012     0.0000     0.0000
k=  8 z=   0.097    0.0000     0.0000     0.0000     0.0000     0.0000     0.0036     0.0034     0.0018     0.0000     0.0000
k=  7 z=   0.082    0.0000     0.0000     0.0000     0.0000     0.0000     0.0061     0.0052     0.0025     0.0000     0.0000
k=  6 z=   0.067    0.0000     0.0000     0.0000     0.0000     0.0000     0.0132     0.0109     0.0040     0.0000    -0.0610
k=  5 z=   0.052    0.0000     0.0000     0.0000     0.0000     0.0000     0.0247     0.0463     0.0593     0.0650     0.0610
k=  4 z=   0.037    0.0000     0.0000     0.0000     0.0000     0.0000     0.0154     0.0142     0.0079     0.0000    -0.0610
k=  3 z=   0.022    0.0000     0.0000     0.0000     0.0000     0.0000     0.0169     0.0146     0.0056     0.0000     0.0000
k=  2 z=   0.007    0.0000     0.0000     0.0000     0.0000     0.0000     0.0114    -0.0173    -0.0115     0.0000     0.0000
k=  1 z=  -0.007    0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0173     0.0115     0.0000     0.0000
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                                                                                                                    page 29

    z-direction velocity component - - - v   m/sec         f r a m e  i =      1      date 07/12/88       hour 00:21:36
         xcoord =       3.1416 radians                     time step          354      time =  5.0000E+00 seconds
         r-z coordinates are in metres

              j =         1          2          3          4          5          6          7          8          9         10
         rcoord =    -0.0030     0.0030     0.0085     0.0130     0.0165     0.0195     0.0230     0.0265     0.0290     0.0310
         zcoord
 k= 32 z=   0.465     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
 k= 31 z=   0.450     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000     0.0000
 k= 30 z=   0.435     0.1054     0.1054     0.0698     0.0414     0.0227     0.0048    -0.0217    -0.0491    -0.0436     0.0436
 k= 29 z=   0.420     0.1317     0.1317     0.0872     0.0424     0.0186    -0.0014    -0.0265    -0.0550    -0.0398     0.0398
 k= 28 z=   0.405     0.1302     0.1302     0.0799     0.0000     0.0000     0.0000    -0.0103    -0.0399    -0.0279     0.0279
 k= 27 z=   0.390     0.1240     0.1240     0.0825     0.0000     0.0000     0.0000    -0.0119    -0.0389    -0.0268     0.0268
 k= 26 z=   0.375     0.0866     0.0866     0.0548     0.0300     0.0129    -0.0019    -0.0189    -0.0360    -0.0236     0.0236
 k= 25 z=   0.360     0.0518     0.0518     0.0210    -0.0137    -0.0224     0.0000     0.0000     0.0000     0.0000     0.0000
 k= 24 z=   0.345     0.0447     0.0447     0.0380     0.0331     0.0261     0.0144    -0.0101    -0.0394    -0.0383     0.0383
 k= 23 z=   0.330     0.0314     0.0314     0.0334     0.0486     0.0448     0.0247    -0.0159    -0.0538    -0.0420     0.0420
 k= 22 z=   0.315     0.0000     0.0000     0.0000     0.0546     0.0512     0.0332    -0.0057    -0.0551    -0.0417     0.0417
 k= 21 z=   0.300     0.1171     0.1171     0.0887     0.0633     0.0392     0.0099    -0.0350    -0.0721    -0.0472     0.0472
 k= 20 z=   0.285     0.1344     0.1344     0.0950     0.0449     0.0184    -0.0048    -0.0300    -0.0583    -0.0349     0.0349
 k= 19 z=   0.270     0.1205     0.1205     0.0769     0.0000     0.0000     0.0000    -0.0065    -0.0409    -0.0272     0.0272
 k= 18 z=   0.255     0.1037     0.1037     0.0686     0.0431     0.0270     0.0090    -0.0231    -0.0567    -0.0387     0.0387
 k= 17 z=   0.240     0.1024     0.1024     0.0697     0.0458     0.0248     0.0020    -0.0265    -0.0527    -0.0329     0.0329
 k= 16 z=   0.225     0.0840     0.0840     0.0525     0.0299     0.0122    -0.0028    -0.0185    -0.0351    -0.0214     0.0000
 k= 15 z=   0.210     0.0416     0.0416     0.0087    -0.0117    -0.0104     0.0000     0.0000     0.0000     0.0000     0.0000
 k= 14 z=   0.195     0.0271     0.0271     0.0107    -0.0090    -0.0096     0.0000     0.0000     0.0000     0.0000     0.0000
 k= 13 z=   0.180     0.0090     0.0090     0.0030    -0.0031    -0.0026     0.0002     0.0001     0.0000    -0.0003     0.0003
 k= 12 z=   0.165     0.0024     0.0024     0.0006    -0.0008    -0.0005     0.0014     0.0007    -0.0012    -0.0008     0.0008
 k= 11 z=   0.150     0.0028     0.0028     0.0005    -0.0009    -0.0005    -0.0025    -0.0010     0.0013     0.0023    -0.0023
 k= 10 z=   0.135     0.0000     0.0000     0.0000     0.0000     0.0000    -0.0054    -0.0042     0.0034     0.0075    -0.0075
 k=  9 z=   0.120     0.0000     0.0000     0.0000     0.0000     0.0048    -0.0048    -0.0037     0.0010     0.0094    -0.0094
 k=  8 z=   0.105     0.0000     0.0000     0.0000     0.0000    -0.0081     0.0081    -0.0023    -0.0036     0.0005    -0.0005
 k=  7 z=   0.090     0.0000     0.0000     0.0000     0.0000    -0.0276     0.0276    -0.0009    -0.0101    -0.0126     0.0126
 k=  6 z=   0.075     0.0000     0.0000     0.0000     0.0000    -0.0607     0.0607    -0.0006    -0.0214    -0.0309     0.0309
 k=  5 z=   0.060     0.0000     0.0000     0.0000     0.0000    -0.1318     0.1318    -0.0015    -0.0514    -0.0601     0.0000
 k=  4 z=   0.045     0.0000     0.0000     0.0000     0.0000    -0.2645     0.2645     0.1028     0.0435     0.0149     0.0000
 k=  3 z=   0.030     0.0000     0.0000     0.0000     0.0000    -0.3476     0.3476     0.1079     0.0181    -0.0423     0.0423
 k=  2 z=   0.015     0.0000     0.0000     0.0000     0.0000    -0.4387     0.4387     0.1096    -0.0212    -0.0829     0.0829
 k=  1 z=   0.000     0.0000     0.0000     0.0000     0.0000    -0.5000     0.5000     0.0000     0.0000     0.0000     0.0000
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                                                                                                                    page 30

    pressure field (p-pref)  - - - - delta-p pascals       f r a m e  i =      1      date 07/12/88       hour 00:21:36
         xcoord =       3.1416 radians                     time step          354      time =  5.0000E+00 seconds
         r-z coordinates are in metres

              j =         1          2          3          4          5          6          7          8          9         10
         rcoord =    -0.0030     0.0030     0.0085     0.0130     0.0165     0.0195     0.0230     0.0265     0.0290     0.0310
         zcoord
 k= 32 z=   0.457  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 k= 31 z=   0.442  0.000E+00  1.563E-03  8.525E-04  2.188E-04 -9.095E-05 -1.904E-04 -1.434E-04 -1.617E-05  1.143E-04  0.000E+00
 k= 30 z=   0.427  0.000E+00  1.634E-01  1.631E-01  1.629E-01  1.628E-01  1.628E-01  1.628E-01  1.630E-01  1.630E-01  0.000E+00
 k= 29 z=   0.412  0.000E+00  3.290E-01  3.289E-01  3.288E-01  3.288E-01  3.289E-01  3.290E-01  3.291E-01  3.291E-01  0.000E+00
 k= 28 z=   0.397  0.000E+00  4.956E-01  4.954E-01  0.000E+00  0.000E+00  0.000E+00  4.977E-01  4.976E-01  4.976E-01  0.000E+00
 k= 27 z=   0.382  0.000E+00  6.662E-01  6.662E-01  6.663E-01  6.662E-01  6.661E-01  6.661E-01  6.661E-01  6.661E-01  0.000E+00
 k= 26 z=   0.367  0.000E+00  8.350E-01  8.350E-01  8.349E-01  8.348E-01  8.350E-01  8.352E-01  8.354E-01  8.354E-01  0.000E+00
 k= 25 z=   0.352  0.000E+00  1.000E+00  1.000E+00  1.000E+00  9.997E-01  9.993E-01  9.993E-01  9.993E-01  9.994E-01  0.000E+00
 k= 24 z=   0.337  0.000E+00  1.164E+00  1.164E+00  1.163E+00  1.163E+00  1.163E+00  1.163E+00  1.163E+00  1.163E+00  0.000E+00
 k= 23 z=   0.322  0.000E+00  1.327E+00  1.327E+00  1.328E+00  1.328E+00  1.328E+00  1.328E+00  1.328E+00  1.328E+00  0.000E+00
 k= 22 z=   0.307  0.000E+00  1.496E+00  1.495E+00  1.494E+00  1.494E+00  1.494E+00  1.494E+00  1.494E+00  1.494E+00  0.000E+00
 k= 21 z=   0.292  0.000E+00  1.660E+00  1.659E+00  1.659E+00  1.659E+00  1.659E+00  1.659E+00  1.659E+00  1.659E+00  0.000E+00
 k= 20 z=   0.277  0.000E+00  1.828E+00  1.827E+00  1.827E+00  1.827E+00  1.827E+00  1.828E+00  1.828E+00  1.828E+00  0.000E+00
 k= 19 z=   0.262  0.000E+00  1.996E+00  1.996E+00  1.997E+00  1.996E+00  1.996E+00  1.996E+00  1.996E+00  1.996E+00  0.000E+00
 k= 18 z=   0.247  0.000E+00  2.163E+00  2.163E+00  2.162E+00  2.162E+00  2.162E+00  2.162E+00  2.162E+00  2.162E+00  0.000E+00
 k= 17 z=   0.232  0.000E+00  2.331E+00  2.331E+00  2.331E+00  2.330E+00  2.330E+00  2.331E+00  2.331E+00  2.331E+00  0.000E+00
 k= 16 z=   0.217  0.000E+00  2.500E+00  2.500E+00  2.500E+00  2.500E+00  2.500E+00  2.500E+00  2.501E+00  2.501E+00  0.000E+00
 k= 15 z=   0.202  0.000E+00  2.666E+00  2.666E+00  2.666E+00  2.666E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
 k= 14 z=   0.187  0.000E+00  2.828E+00  2.828E+00  2.828E+00  2.828E+00  9.029E-01  9.027E-01  9.024E-01  9.022E-01  0.000E+00
 k= 13 z=   0.172  0.000E+00  2.988E+00  2.988E+00  2.988E+00  2.988E+00  1.461E+02  1.461E+02  1.461E+02  1.461E+02  0.000E+00
 k= 12 z=   0.157  0.000E+00  3.148E+00  3.148E+00  3.148E+00  3.148E+00  2.914E+02  2.914E+02  2.914E+02  2.914E+02  0.000E+00
 k= 11 z=   0.142  0.000E+00  3.308E+00  3.308E+00  3.308E+00  3.308E+00  4.369E+02  4.369E+02  4.369E+02  4.369E+02  0.000E+00
 k= 10 z=   0.127  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  5.827E+02  5.827E+02  5.827E+02  5.827E+02  0.000E+00
 k=  9 z=   0.112  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  7.289E+02  7.289E+02  7.289E+02  7.289E+02  0.000E+00
 k=  8 z=   0.097  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  8.752E+02  8.752E+02  8.752E+02  8.752E+02  0.000E+00
 k=  7 z=   0.082  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.021E+03  1.021E+03  1.021E+03  1.021E+03  0.000E+00
 k=  6 z=   0.067  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.165E+03  1.166E+03  1.165E+03  1.166E+03  0.000E+00
 k=  5 z=   0.052  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.297E+03  1.298E+03  1.296E+03  1.295E+03  1.293E+03
 k=  4 z=   0.037  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.433E+03  1.433E+03  1.433E+03  1.433E+03  0.000E+00
 k=  3 z=   0.022  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.567E+03  1.566E+03  1.565E+03  1.566E+03  0.000E+00
 k=  2 z=   0.007  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  1.705E+03  1.703E+03  1.703E+03  1.703E+03  0.000E+00
 k=  1 z=  -0.007  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00
```

```
                                                                                                              page 31

    temperature field                 - - - t   deg. c         f r a m e  i =     1     date 07/12/88      hour 00:21:36
        xcoord =        3.1416 radians                         time step        354     time =  5.0000E+00 seconds
        r-z coordinates are in metres

              j =         1           2           3           4           5           6           7           8           9          10
        rcoord =    -0.0030      0.0030      0.0085      0.0130      0.0165      0.0195      0.0230      0.0265      0.0290      0.0310
        zcoord
 k= 32 z=   0.457      0.00        0.00        0.00        0.00        0.00        0.00        0.00        0.00        0.00        0.00
 k= 31 z=   0.442     42.04       42.04       41.82       41.95       42.16       42.36       42.00       38.69       30.38       25.00
 k= 30 z=   0.427     41.55       41.55       40.82       40.81       41.01       41.16       40.06       35.49       28.45       25.00
 k= 29 z=   0.412     41.22       41.22       39.97       39.31       38.41       37.62       36.60       32.96       27.57       25.00
 k= 28 z=   0.397     40.98       40.98       39.29        0.00        0.00        0.00       34.44       31.43       27.08       25.00
 k= 27 z=   0.382     40.86       40.86       38.34       37.27       37.11       36.66       34.53       30.84       26.88       25.00
 k= 26 z=   0.367     41.82       41.82       38.00       34.72       33.47       32.70       31.78       29.56       26.57       25.00
 k= 25 z=   0.352     44.68       44.68       43.71       41.83       40.96       41.21       40.68       37.28       29.71       25.00
 k= 24 z=   0.337     44.12       44.12       43.24       42.31       41.83       41.33       39.94       35.43       28.41       25.00
 k= 23 z=   0.322     43.24       43.24       42.15       41.14       40.66       40.00       38.35       33.78       27.77       25.00
 k= 22 z=   0.307     40.97       40.97       40.54       40.25       40.11       40.01       38.82       33.94       27.82       25.00
 k= 21 z=   0.292     40.52       40.52       39.63       38.76       38.10       37.40       36.23       32.40       27.37       25.00
 k= 20 z=   0.277     40.23       40.23       39.01       37.35       36.32       35.51       34.45       31.27       27.03       25.00
 k= 19 z=   0.262     40.13       40.13       39.00       38.98       39.12       38.95       37.45       32.79       27.57       25.00
 k= 18 z=   0.247     40.05       40.05       37.96       37.47       37.53       37.33       35.80       31.80       27.18       25.00
 k= 17 z=   0.232     40.05       40.05       36.95       35.78       35.30       34.73       33.67       30.68       26.86       25.00
 k= 16 z=   0.217     41.01       41.01       36.26       33.89       32.83       32.07       31.24       29.28       26.48       25.00
 k= 15 z=   0.202     47.25       47.25       45.40       42.28       41.62        0.00        0.00        0.00        0.00       50.00
 k= 14 z=   0.187     49.08       49.08       48.49       47.54       47.36       50.00       50.00       50.00       50.00       50.00
 k= 13 z=   0.172     49.86       49.86       49.80       49.68       49.67       49.99       49.98       49.95       49.74       50.00
 k= 12 z=   0.157     49.80       49.80       49.79       49.77       49.74       49.35       48.60       46.92       46.21       50.00
 k= 11 z=   0.142     49.62       49.62       49.54       49.51       49.56       45.30       43.68       41.27       40.80       50.00
 k= 10 z=   0.127      0.00       56.78       56.77       56.77       56.77       38.24       37.13       35.52       36.48       50.00
 k=  9 z=   0.112      0.00       56.77       56.77       56.77       56.76       27.13       29.17       30.29       32.98       50.00
 k=  8 z=   0.097      0.00       56.77       56.77       56.77       56.76       22.09       25.07       26.88       29.63       50.00
 k=  7 z=   0.082      0.00       56.77       56.77       56.77       56.76       21.04       23.11       23.96       27.01       50.00
 k=  6 z=   0.067      0.00       56.77       56.77       56.77       56.76       20.54       21.90       22.32       25.13       50.00
 k=  5 z=   0.052      0.00       56.77       56.77       56.77       56.76       20.32       21.00       21.35       21.65       21.65
 k=  4 z=   0.037      0.00       56.77       56.77       56.77       56.76       20.25       21.09       21.27       22.63       50.00
 k=  3 z=   0.022      0.00       56.77       56.77       56.76       56.76       20.17       21.38       21.54       23.06       50.00
 k=  2 z=   0.007      0.00       56.77       56.77       56.76       56.76       20.06       22.02       23.22       23.88       50.00
 k=  1 z=  -0.007      0.00        0.00        0.00        0.00        0.00       20.00        0.00        0.00        0.00        0.00
```

```
                                                                                                              page 32

    turbulent kinetic energy - - - - - - tke m2/sec2           f r a m e  i =     1     date 07/12/88      hour 00:21:36
        xcoord =        3.1416 radians                         time step        354     time =  5.0000E+00 seconds
        r-z coordinates are in metres

              j =         1           2           3           4           5           6           7           8           9          10
        rcoord =    -0.0030      0.0030      0.0085      0.0130      0.0165      0.0195      0.0230      0.0265      0.0290      0.0310
        zcoord
 k= 32 z=   0.457  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 31 z=   0.442  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 30 z=   0.427  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 29 z=   0.412  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 28 z=   0.397  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 27 z=   0.382  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 26 z=   0.367  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 25 z=   0.352  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 24 z=   0.337  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 23 z=   0.322  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 22 z=   0.307  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 21 z=   0.292  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 20 z=   0.277  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 19 z=   0.262  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 18 z=   0.247  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 17 z=   0.232  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 16 z=   0.217  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 15 z=   0.202  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30
 k= 14 z=   0.187  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.515E-09   9.673E-10   1.640E-09   4.307E-09   1.000E-30
 k= 13 z=   0.172  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   2.092E-07   1.311E-07   3.606E-07   1.045E-06   1.000E-30
 k= 12 z=   0.157  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   5.035E-06   3.437E-06   5.728E-06   1.465E-05   1.000E-30
 k= 11 z=   0.142  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.595E-05   4.831E-06   9.661E-06   3.517E-05   1.000E-30
 k= 10 z=   0.127  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   2.118E-05   7.552E-06   1.379E-05   3.981E-05   1.000E-30
 k=  9 z=   0.112  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   3.842E-05   2.145E-05   1.998E-05   2.395E-05   1.000E-30
 k=  8 z=   0.097  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   7.186E-05   1.729E-04   1.292E-04   9.894E-05   1.000E-30
 k=  7 z=   0.082  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   2.150E-04   1.582E-03   1.230E-03   1.864E-04   1.000E-30
 k=  6 z=   0.067  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   5.807E-04   8.800E-03   6.799E-03   5.970E-04   1.000E-30
 k=  5 z=   0.052  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.003E-03   7.683E-03   6.749E-03   5.730E-03   5.730E-03
 k=  4 z=   0.037  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.587E-03   1.013E-02   7.976E-03   8.000E-04   1.000E-30
 k=  3 z=   0.022  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   2.085E-03   1.415E-02   1.491E-02   1.100E-03   1.000E-30
 k=  2 z=   0.007  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.912E-03   7.480E-04   4.107E-04   2.809E-04   1.000E-30
 k=  1 z=  -0.007  1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-30   1.000E-10   1.000E-30   1.000E-30   1.000E-30   1.000E-30
```

```
                              surface heat flux summary

 surface    j    j       k    k      i    i      qsum          area          avg q/a       avg temp      avg h(not in)
 number    beg  end     beg  end    beg  end     watts         metre**2      watt/m2       deg. c          j/kg

    1       5    5       11   14     1    1      2.165E-03     6.784E-03     3.191E-01     4.908E+01     0.000E+00

                              system heat balance summary

 qpos   =  1.746E+04 watts     (thermal energy flow out ofsystem)
 qneg   = -1.602E+04 watts     (thermal energy flow into system  )
 qgen   =  6.869E+02 watts     (total heat generation in system  )

 qnet   =  7.504E+02 watts     (system heat balance error         )
 qevol  =  6.102E+05 w/m3      (heat balance error per unit vol  )
 qratio=  4.299E-02            (heat balance error - - - fraction of total heat transport)

     n o t e ! !

     advective heat flux and heat balance summaries are
     accurate only for constant specific heat and then
     only the differences are accurate.
     an enthalpy balance will be provided in a later mod.

restart file created at - -


time step    =   354
time         = 5.0000E+00 seconds
file number  =     1

 full hydrothermal


post processing file created at- -


time step    =   354
time         = 5.0000E+00 seconds
file number  =     2
simulation terminated because of sim time limit

    post-processing time-history data written to monsav file

         monitor        cell       indices
         location       no.        j     k     i
            1           134        4    14     1
            2           139        9    14     1
            3            42        2     5     1
            4            49        9     5     1
            5           222        2    23     1
            6           229        9    23     1
            7           175        5    18     1

            8           305        5    31     1
```

```
e x e c u t i o n   t i m e   s u m m a r y

total execution time                   =   10.236 seconds

    set-up and initial debug time      =    0.307 seconds

    output,plotting and monitor time   =    1.460 seconds

    solution computation time          =    9.387 seconds
        computational speed            =    0.114 milli-seconds per time step-cell

    the following summary does not include set up and initial debug time


                                             total computational     computational speed,
                                                time, seconds       millisec's/time step-cell
overall solution - - - - - - - - - - - - - - -     9.9204                   0.1203
overall solution excludes print,plot + monitor-    9.3874                   0.1138
tilde momentum solution - - - - - - - - - - - -    3.2658                   0.0468
pressure solution - - - - - - - - - - - - - - -    1.4480                   0.0208
thermal  solution - - - - - - - - - - - - - - -    0.7015                   0.0085
thermal conductance update  - - - - - - - - - -    0.8370                   0.0101
turbulence solution - - - - - - - - - - - - - -    1.1271                   0.0162
turbulent kinetic energy production - - - - - -    0.7943                   0.0114
viscosity update  - - - - - - - - - - - - - - -    0.3506                   0.0050
boundary condition update - - - - - - - - - - -    1.0523                   0.0128
printer output  - - - - - - - - - - - - - - - -    0.2204                   0.0027
monitoring time - - - - - - - - - - - - - - - -    0.1877                   0.0023
```

5.4 GRAPHICS

As noted in discussing TEMPEST input and output in the previous sections, files were created for postprocessing graphics. A variety of plotting options are available using a computer code named POSTER, developed specifically to process TEMPEST output for graphical display. POSTER provides contour, line, and time-history plots of the scalar field variables and velocities. Additionally, vector plotting capability is provided to display direction and magnitudes of the velocity field.

Figure 5.2 gives plot examples. These include material boundary/grid lines, temperature contours, velocity vectors, and a combination of all three. This plot was created using the sample problem postprocessing dump file at 2.5 sec. Graphical representation of the isotherms illustrates major features of the simulation results. The isotherm values are at 2°C increments starting at 22°C. Region 2 reveals a stratified layer slightly above mid-height and distortion of the isotherms in region 1 illustrates the presence of the plate blockages. No isotherms are shown in region 3 (except at the boundaries) because of the short duration of the simulation.

The POSTER contouring routine does not recognize discontinuities at material boundaries nor the presence of the plate blockages. The contours are constructed using continuous functions between computational cell centers. An example of this behavior are the contours in the vicinity of the boundary separating regions 2 and 3. Physically, the indicated radial temperature gradient would be much steeper and occur within a narrow region along the boundary. The film coefficient would have a major influence on the shape of this gradient.

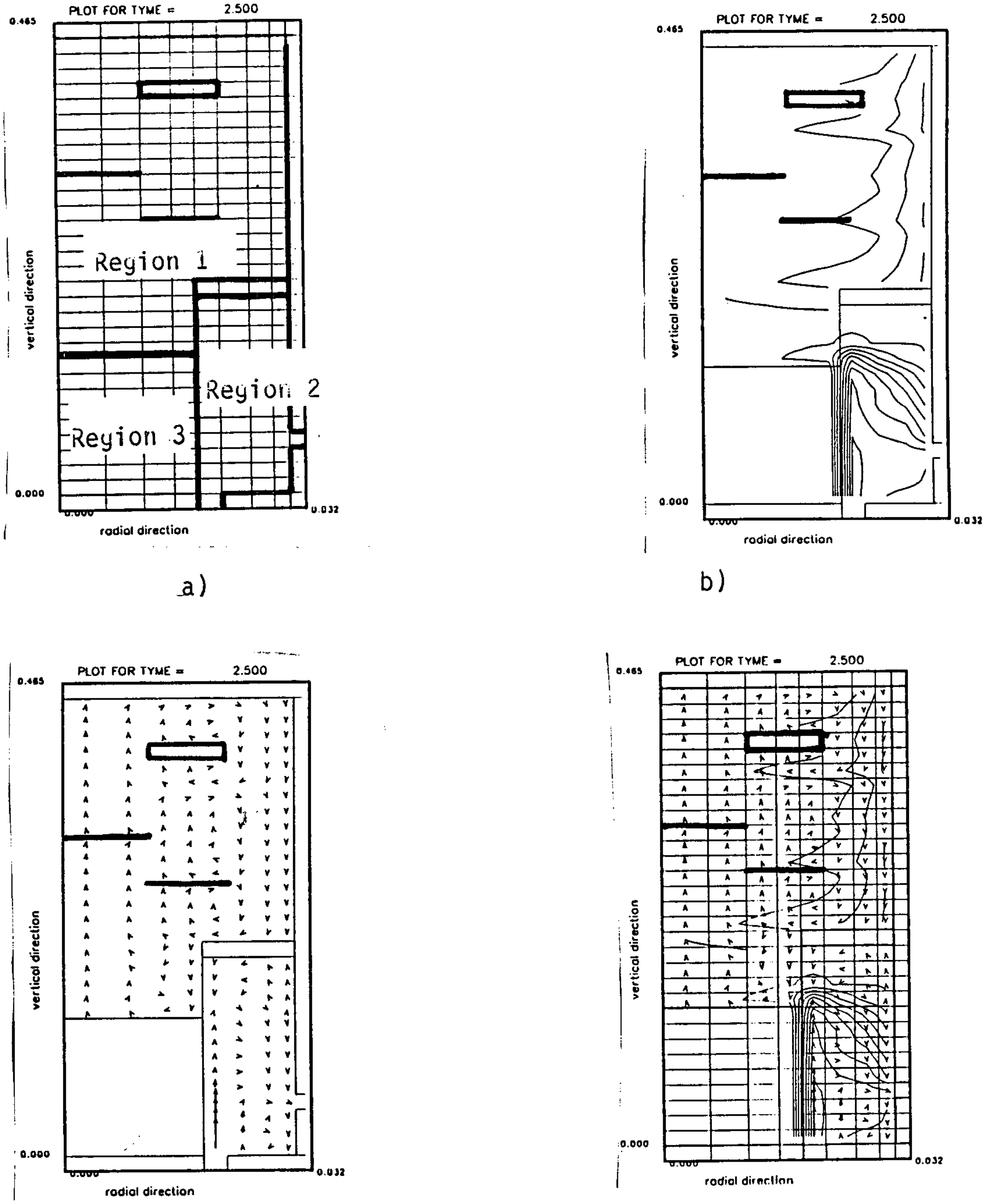

FIGURE 5.2. Sample Problem Isotherm and Vector Plots for t = 2.5 Sec

6.0 REFERENCES

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