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TRAC-BD1 TURBINE MODEL

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INTERIM REPORT

ABSTRACT

A steam turbine model has been developed for use in the TRAC-BD1 computer code. This model is designed for modeling boiling water reactor main steam turbines and for smaller turbines such as those driving feedwater pumps in a nuclear reactor. The model includes a calculation of turbine rotor dynamics as well as turbine fluid conditions. An optional moisture separator feature is also included. A simulation of a hypothetical generator load rejection scenario has been used to verify reasonable behavior of the new turbine model.

FIN No. A6052
Code Development and Improvements

SUMMARY

A steam turbine model has been developed and successfully implemented into the TRAC-BD1 code. Though this model is simplified in several areas, the degree of detail included in the model is consistent with the degree of detail found in the remainder of TRAC-BD1. The turbine model was used to execute several test cases, in which steady state conservation of mass and energy were shown to be satisfied, and reasonable transient behavior was observed. The new model has satisfactorily demonstrated its ability to model boiling water reactor turbine behavior.

CONTENTS

FIGURES

TRAC-BD1 TURBINE MODEL

1. INTRODUCTION

The turbine model will provide a basic capability in the TRAC-BD1 code for modeling BWR main steam turbines and for modeling smaller turbines such as those used for driving feedwater pumps. The turbine model combined with a model for feedwater heaters will comprise the TRAC-BD1 balance-of-plant package. This package will permit modeling of turbine and feedwater loop behavior in a wide variety of operational and anticipated transient scenarios. The turbine model is essentially thermodynamic in nature, requiring primarily such input data as steady state flow rates, pressures and temperatures, and requiring a minimum of turbine geometric data. It is judged that such a model will be convenient for the user, and will have a degree of accuracy consistent with the overall purposes of the TRAC-BD1 code.

2. MODEL DETAILS

The turbine model will be implemented into a new TRAC component type, the TURB component. The TURB component will share the data base for the TEE component, but differs from the TEE component in several respects. The most important of these is the use of a simplified, fully explicit thermal hydraulic solution in the TURB component. This explicit solution is performed only once each time step, and replaces the normal TEE thermal hydraulic solution performed in the OUTER phase of the TRAC computational cycle.

The TURB component contains two fluid cells in the configuration shown in Figure 1. Ideally, a complete turbine would be modeled by connecting a number of TURB components in series, so that each stage of the turbine would be modeled by a separate TURB component. In practice, however, such a modeling method would be excessively expensive since a main steam turbine may contain more than 20 impulse and reaction stages. Hence, in normal use turbine stages must be lumped together into a smaller number of groups, with a TURB component to represent each group

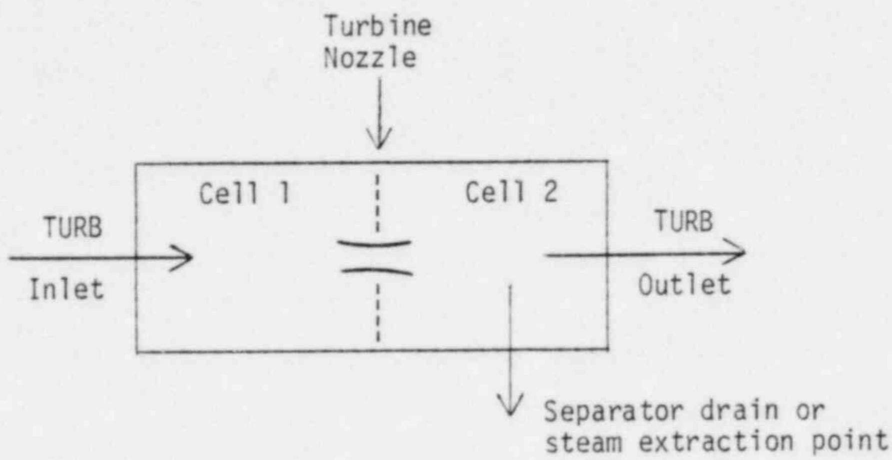

Figure 1. Configuration of TURB component.

of stages. The lumping will probably be dictated by the location of desired steam extraction points or separator drains along the turbine. Hence, if three extraction points are required, a minimum of three TURB components must be used to model the turbine. The TURB component includes the following features for modeling turbine behavior:

1. An isentropic flow equation is used to determine turbine nozzle velocity

2. A term is included in the fluid energy equation to account for energy removal from the fluid stream by the turbine blade assembly

3. An optional steam/water separator is available to remove liquid from the main turbine flow stream and divert it to the side arm drain of the turbine

4. A model is included to simulate the dynamics of the turbine rotor assembly. This calculation tracks the turbine rotor speed, which is required for calculation of turbine efficiency and for detection of turbine overspeed conditions.

The remainder of this section is devoted to a detailed description of the turbine model features listed above.

2.1 Fluid Mass and Enthalpy Equations

The following equations for mixture mass and enthalpy continuity are used for calculating fluid conditions within the two cells of each TURB component:

$$\frac{\partial \rho}{\partial t} - \nabla \cdot \rho v = 0 \tag{1}$$

$$\frac{\partial(\rho h)}{\partial t} - \nabla \cdot (\rho h v) = - \dot{h}'''_{rotor}, \tag{2}$$

where

ρ = mixture density

v = mixture velocity

h = mixture specific enthalpy (J/kg)

$\dot{h}'''_{rotor}$ = volumetric heat removal rate from the fluid by turbine rotor blades.

An expression for v is required to close this set of equations. The method of determining mixture velocity differs for the various cell faces in the TURB, but it is generally valid that $v = v\ (P)$ for all of the various formulations. Since the various expressions for v contain no explicit dependence on time or time derivatives, it is seen that the flow equations are being performed in the quasi-steady-state approximation.

Equations (1) and (2) may be cast in integral form by use of Stokes Theorem,

$$\iiint \frac{\partial \rho}{\partial t}\, dV = \iint \rho v\ dA, \tag{3}$$

$$\iiint \frac{\partial (\rho h)}{\partial t}\, dV = \iint \rho h v\ dA - \iiint \dot{h}'''_{rotor} dV \tag{4}$$

Expressing Equations (3) and (4) in terms of TURB cell variables we obtain the following expressions for cell densities and enthalpies:

$$\rho_j^{n+1} V_j = \rho_j^n V_j + A_j \rho_{j-1}^n v_j^n \Delta t - A_{j+1} \rho_j^n v_{j+1}^n \Delta t - \Delta m_{side} \tag{5}$$

$$h_j^{n+1} \rho_j^{n+1} V_j = h_j^n \rho_j^n V_j + A_j h_{j-1}^n \rho_{j-1}^n v_j^n \Delta t - A_{j+1} h_j^n \rho_j^n v_{j+1}^n \Delta t$$

$$- \rho_1^n v_2^n A_2 h_{rotor} \Delta t - \Delta H_{side} \tag{6}$$

where

j = cell index

V = cell volume

A = cell face flow area

m_{side} = mass transported through the turbine side arm (kg)

H_{side} = enthalpy transported through the turbine side arm (J)

h_{rotor} = specific enthalpy removal by the rotor (J/kg).

The side arm transport qualities are given by

$$\Delta m_{side} = 0 \quad \text{if} \quad j = 1$$

$$= A_{side}\, \rho_j^n\, v_{side}^n\ t \quad \text{if} \quad j = 2\text{, and}$$

$$\Delta H_{side} = 0 \quad \text{if} \quad j = 1$$

$$= A_{side}\, \rho_j^n\, h_j^n\, v_{side}\, \Delta t \quad \text{if} \quad j = 2.$$

A_{side} and v_{side} are the side arm flow area and mixture velocity, respectively. The rotor enthalpy removal is zero for cell 1, and the value of h_{rotor} for use in cell 2 will be discussed later in this report. The mixture qualities used in Equations (5) and (6) have the following definitions:

$$\rho = \rho_\ell\,(1-\alpha) + \rho_v \alpha \text{ , and}$$

$$\rho h = e_\ell \rho_\ell\,(1-\alpha) + e_v \rho_v \alpha + P \text{ , where}$$

ℓ and v are liquid and vapor indices, e is specific internal energy (J/kg), and P is the pressure (Pa).

2.2 Turbine Velocity Equations

As mentioned previously, different velocity formulations are used at different locations in the TURB component. This section is devoted to a description of these various formulations.

2.2.1 Turbine Inlet Velocity

The turbine inlet velocity is not explicitly calculated in the TURB component. The inlet velocity is set equal to the outlet mixture velocity of the upstream component connected to the TURB. Thus, the upstream component is treated as a velocity boundary condition by the TURB.

2.2.2 Turbine Outlet Velocity

The turbine outlet velocity is calculated using a simple form loss flow equation,

$$v_{out} = \left[\frac{2\Delta P}{K_{ex}\ \rho_2}\right]^{1/2},$$

where

$$\Delta P = P_2 - P_{down},$$

P_{down} is the pressure in the downstream component, and K_{ex} is the exit loss coefficient. A fixed value of 0.5 is used for K_{ex}. This value provides a small pressure drop between the outlet shell of one turbine section and the inlet steam chest of the next section.

2.2.3 Turbine Side Arm Velocity

The user may specify through an input flag whether the TURB side arm is to be used as a steam extraction point or as a moisture separator drain. If steam extraction is specified, then the side arm velocity is calculated in the same manner as for the turbine outlet. In this case, however, a user-supplied loss coefficient SALOSK is used for the calculation, or,

$$v_{side} = \left[\frac{2\Delta P}{SALOSK \cdot \rho_2}\right]^{1/2}$$

If a separator drain is specified, then the side arm flow is assumed to be all liquid, with its velocity defined such that all of the liquid contained in cell 2 at the end of time step n is drained through the side arm during time step n+1. Thus,

$$v_{side} = SEPEF\ (1-\alpha_2)\ v_2/A_{side}\ \Delta t.$$

SEPEF is a user-supplied separator efficiency which would be 1.0 for perfect separation.

2.2.4 Turbine Nozzle Velocity

The nozzle mass flow rate in the TURB component is calculated using the isentropic ideal gas flow equation,

$$\dot{m}_{TURB} = A_{NOZ}\left[\frac{2\gamma}{\gamma-1}\, P\rho\left(r^{2/\gamma} - r^{(\gamma+1)/\gamma}\right)\right]^{1/2}, \tag{7}$$

where

A_{NOZ} = nozzle flow area

γ = isentropic ratio (C_p/C_v)

r = nozzle pressure ratio (downstream pressure/upstream pressure)

P = upstream pressure

ρ = upstream mixture density.

Derivations of this equation are given by Salisbury,[1] and Kearton.[2]

Equation (7) is derived for ideal gases, but may be used generally for nonideal gases provided that the value of γ used in the equation is correct for the region under consideration. In the present model, γ is calculated using current values of C_p and C_v obtained from the existing TRAC water properties routines THERMO and FPROP.

Since several turbine stages will normally be combined or lumped into a single TURB component, the nozzle flow equation must be used in a manner consistent with the degree of lumping desired by the user. Thus, the nozzle flow equation must be applied to a single equivalent nozzle having the approximate flow characteristics of the total group of stages being lumped into the single TURB component. The adjustment for turbine stage lumping will be achieved as follows:

Consider N impulse or reaction stages being lumped into a single TURB component. The pressure ratios for each of these stages will be assumed to be equal, or

$$r_1 = r_2 = r_3 = \cdots = r_N, \tag{8}$$

where r_j is the ratio of downstream to upstream pressure for stage j. The overall pressure ratio for the combined stages (ratio of first stage inlet pressure to Nth stage outlet pressure) is given by

$$R = r_1 \, r_2 \, r_3 \cdots r_N. \tag{9}$$

From Equations (8) and (9) we get

$$R = r_1^{\,N} \text{ or,}$$

$$r_1 = R^{1/N}. \tag{10}$$

Assuming the absence of steam bleeds or condensate drains between the first and last lumped stages, we have in steady state

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_N \ ,$$

where $\dot{m}_j$ is the mass flow rate in the j^{th} stage. Thus, the characteristics of the first stage (j=1) in the lumped group of stages will be assumed to determine the mass flow rate in all of the stages or in the lumped TURB component. With this assumption we have

$$\dot{m}_{LUMP} = \dot{m}_1 = A_{NOZ} \left[\frac{2\gamma}{\gamma-1} \rho_1 P_1 \left(r_1^{2/\gamma} - r_1^{\frac{\gamma+1}{\gamma}}\right)\right]^{1/2} \tag{11}$$

where $r_1 = R^{1/N}$.

TURB inlet (cell 1) properties will be used for variables γ, ρ_1, and P_1. The ratio of inlet (cell 1) to outlet (cell 2) pressure in the TURB will be used for R, and N will be user-specified for each TURB component. Since the pressure ratio dependence in Equation (11) is valid only for values of r_1 greater than the critical pressure ratio r_{crit}, r_1 must be restricted to values greater than r_{crit}. Thus, for pressure ratios less than r_{crit}, the mass flow rate will no longer depend on r_1, but will instead depend only on upstream properties (P_1, ρ_1 and γ), as would be expected for choked flow in the nozzle. The critical pressure ratio is given by

$$r_{crit} = \left(\frac{2}{\gamma+1}\right)^{\gamma(\gamma-1)}$$

This equation is obtained by finding the value of r for which the mass flow rate given by Equation (7) is a maximum. Equation (11) is then used to obtain the mixture velocity in the nozzle according to

$$v_{NOZ} = \frac{\dot{m}_{LUMP}}{\rho_L \; A_{NOZ}}, \quad \text{or}$$

$$v_{NOZ} = \left[\frac{2\gamma}{\gamma-1} \frac{P_1}{\rho_1} \left(r_1^{2/\gamma} - r_1^{(\gamma+1)/\gamma}\right)\right]^{1/2} \tag{12}$$

Though the nozzle flow area doesn't appear in Equation (12), it is still used for calculating the transfer of mass and enthalpy between turbine cells.

The nozzle flow area is determined by one of two different methods. If the user inputs a nonzero flow area for the interface between TURB cells 1 and 2, the user-supplied value will be used for A_{NOZ}. If a value of 0.0 is input for this flow area, the value for this flow area will be calculated at initialization using the following equations:

$$\dot{m}_{LUMPi} = \dot{m}_R = A_{NOZ} \left[\frac{2\gamma_i}{\gamma_i - 1} \rho_{1i} \, P_{1i} \left(r_{1i}^{2/\gamma_i} - r_{1i}^{\frac{\gamma_i+1}{\gamma_i}} \right) \right]^{1/2}$$

or

$$A_{NOZ} = \dot{m}_R \left[\frac{2\gamma_i}{\gamma_i - 1} \rho_{1i} \, P_{1i} \left(r_{1i}^{2/\gamma_i} - r_{1i}^{\frac{\gamma_i+1}{\gamma_i}} \right) \right]^{-1/2}$$

where $\dot{m}_R$ is the user-supplied rated turbine mass flow rate, and the subscript i indicates initial values.

2.2.5 Velocity Smoothing

To enhance code stability, changes in the various cell face velocities (with the exception of the separator drain velocity) are smoothed by applying old time weighting to the new velocity values. The formulation

$$v^{n+1} = 0.9 \, v^n + 0.1 \, v_{calc}$$

is used for this smoothing, where v_{calc} is the calculated new velocity before smoothing is applied. This weighting has the effect of smoothing abrupt velocity changes over a time interval of approximately 10 time steps. While this might interfere with the accurate analysis of rapid transient behavior, the method is entirely consistent with the quasi-steady-state assumptions inherent in the turbine hydraulic model.

2.2.6 Reverse Velocities

Velocities in the turbine exit and side arm are not allowed to become negative. If a negative pressure gradient occurs across these junctions, the velocity value is set to 0.0.

2.3 Turbine Energy Equation

The bulk of the pressure drop and enthalpy drop in an impulse turbine stage occurs across the fixed turbine nozzle. The enthalpy drop across the nozzle is accompanied by a corresponding increase in fluid kinetic energy in accordance with the adiabatic conservation of total energy

$$H_1 + K_1 = H_2 + K_2,$$

where H and K are fluid enthalpy and kinetic energy, and where subscripts 1 and 2 refer to properties immediately upstream and downstream of the nozzle. Assuming that the upstream kinetic energy K_1 is negligible, we obtain

$$K_2 = H_1 - H_2 = \Delta H_{nozzle}$$

for the kinetic energy of the emerging fluid before it impinges on the rotor blades. The assumption of negligible inlet kinetic energy is justified in view of the low steam line velocity at the inlet to the turbine first stage and the low "leaving velocities" from each succeeding stage (see Reference 2, pp 6-7). Assuming that the turbine blades remove a fraction η of the nozzle exit kinetic energy from the fluid stream, we have for the energy addition to the rotor

$$\Delta E_{rotor} = \eta K_2 = \eta \Delta H_{nozzle}. \tag{13}$$

Equation (13) also gives the energy removal from the fluid stream since the fraction $1-\eta$ of the available kinetic energy that is not converted to rotor energy remains in the fluid stream, the majority being reconverted to internal energy by irreversible loss processes.

In a reaction turbine stage, the pressure drops are distributed more uniformly throughout the blade assemblies. The thermodynamic analysis is more complex for such an assembly than for an impulse stage, but it is assumed that the overall energy conversion process is similar for both types of stages and that the impulse stage analysis is adequate for modeling of both stage types.

The overall thermodynamic process for the nozzle-blade system may also be viewed on an enthalpy-entropy plane as shown in Figure 2.

An ideal reversible turbine stage would follow the expansion path from point 1 to point 2. For an actual irreversible turbine, however, the expansion path will go from point 1 to point 2´, yielding an actual enthalpy decrease less than the ideal enthalpy decrease. The absence of reversibility is accounted for by various loss mechanisms including leaving loss, rotation loss, leakage loss, and moisture loss.

The turbine efficiency will be defined as

$$\eta = \frac{h_1 - h_{2'}}{h_1 - h_2} .$$

For an ideal isentropic expansion (1 2), the specific enthalpy decrease is given by

$$\Delta h_{ideal} = \int_1^2 \nu \, dP \qquad (14)$$

where ν is the mixture specific volume. For the discrete nodalization of Figure 1, Equation (14) may be approximated as

$$\Delta h_{ideal} = 0.5 \, (\nu_1 + \nu_2) \, (P_2 - P_1).$$

For an actual expansion with efficiency η, the specific enthalpy removed from the fluid by the turbine rotor is

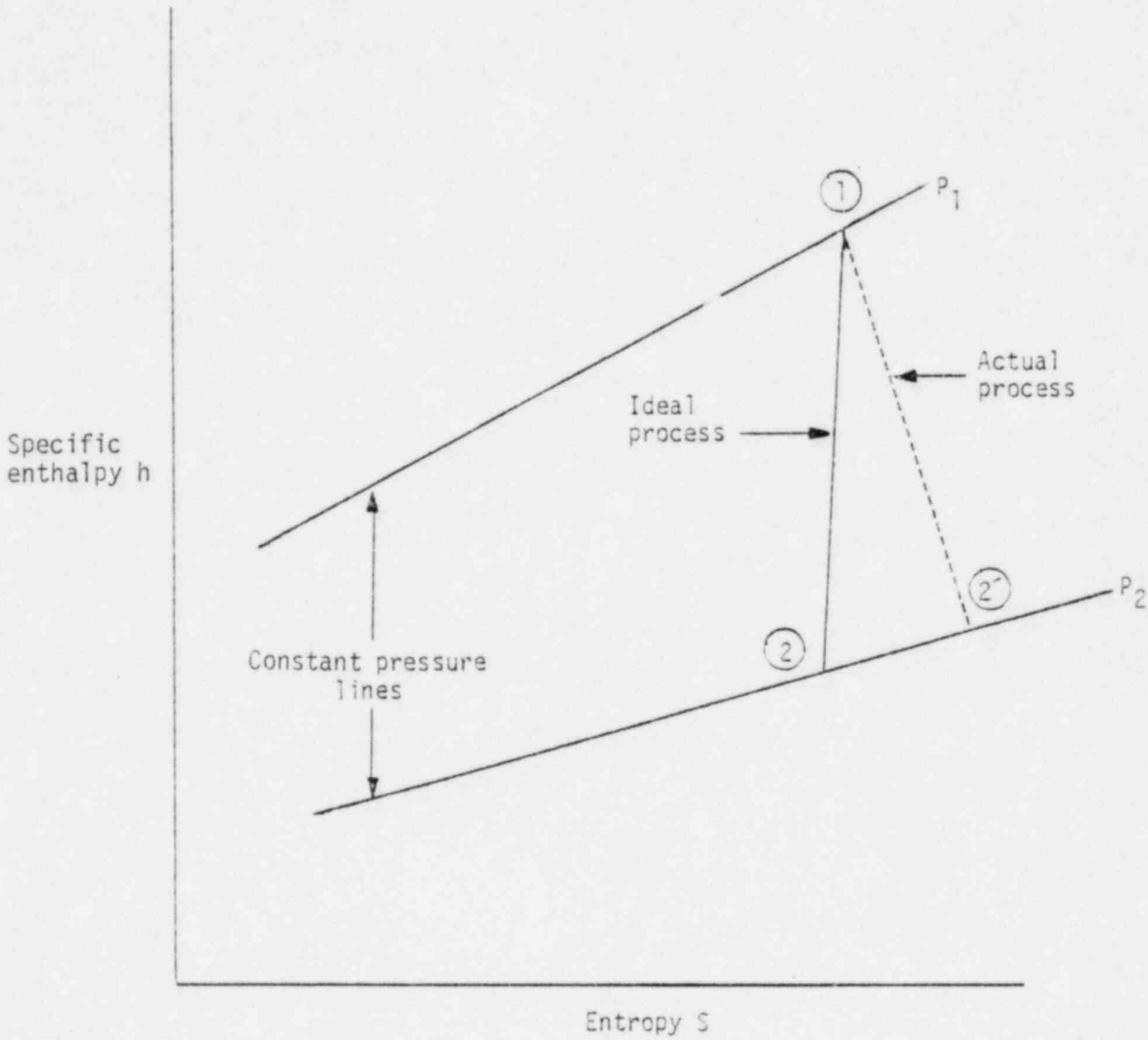

Figure 2. Turbine thermodynamic process path.

$h_{rotor} = \eta\Delta h_{ideal} = 0.5\ \eta(\nu_1 + \nu_2)\ (P_2 - P_1)$. The power removed from the steam and delivered to the turbine rotor is given by

$$\dot{Q}_{rotor} = \dot{m}_2\ h_{rotor} = \rho_1\ v_2\ A_2\ \eta(0.5)\ (\nu_1 = \nu_1)\ (P_2 - P_1), \qquad (15)$$

2.4 Turbine Efficiency

According to Salisbury (see Reference 1, pp 170-172), the stage efficiency of impulse turbines is given to an excellent approximation by

$$\eta = 4\eta_o \left[\frac{V_{blade}}{V_{steam}} - \left(\frac{V_{blade}}{V_{steam}}\right)^2\right] \qquad (16)$$

where

V_{blade} = the turbine blade velocity

V_{steam} = the velocity of steam impinging on the blade

η_o = the maximum efficiency of the stage.

This expression reaches its maximum value of η_o when the ratio of blade speed to steam speed is at its ideal value of 0.5. At this velocity ratio, the "leaving loss" or amount of steam kinetic energy exiting the stage is minimized.

The value of η_o is determined by other loss mechanisms such as friction and leakage, but it will be treated as a user-supplied constant for the purpose of this model.

Equation (15) may be written in terms of quantities readily available in the turbine model if it is assumed that V_{blade} is proportional to the rotor angular velocity, and that V_{steam} is proportional to the nozzle mass flow rate. In this case we obtain

$$\eta = 4\eta_o \left[\frac{c\Omega}{\dot{m}} - \left(\frac{c\Omega}{\dot{m}}\right)^2\right] \tag{17}$$

where Ω is the rotor angular velocity, and $\dot{m}$ is the nozzle mass flow rate. The constant c is obtained by assuming that the ideal velocity ratio (1/2) is obtained at rated conditions, or

$$\frac{c\Omega_R}{\dot{m}_R} = 1/2 \tag{18}$$

where Ω_R and $\dot{m}_R$ are rated conditions.

Equations (16) and (17) are used to obtain the turbine efficiency used in the TRAC turbine model.

2.5 Hydraulic Solution Strategy

The TURB component mass, energy, and velocity equations are solved once each time step in new subroutine TURBHYD. The following computational sequence is used:

(1) The rotor enthalpy removal is calculated using old time fluid properties.

(2) Equations (5) and (6) are evaluated to obtain new time values for mass and enthalpy in TURB cells 1 and 2.

(3) New values for pressure, temperature and vapor fraction in each cell are calculated by new subroutine STATE, which was developed by Dean Taylor for use in the TRAC containment model. STATE is used to invert the TRAC steam properties routine THERMO. Values for cell fluid mass, energy, and volume are input to STATE, and values for pressure, temperature and vapor fraction are returned.

(4) The new pressure and temperature values are used to update other fluid properties in the two TURB cells by use of the existing properties routines THERMO, FPROP, and MIXPRP.

(5) New mixture velocities are calculated at each cell face using new fluid pressures and thermal properties.

(6) Boundary condition arrays are updated to reflect the new velocities and fluid properties.

2.6 Time Step Control

The turbine hydraulic calculation imposes a limit on the maximum problem time step in the form of a volumetric Courant limit

$$\Delta t_{max} = V_{up} / A_j v_j$$

where j is the cell face index   is the upstream (donor cell) volume. This limit is applied   faces 2 and 3 in the main tube and at the side arm cell face.

2.7 Turbine Rotor Model

The turbine rotor model is applied to one or more rotor shaft assemblies, with one or more TURB components connected to each shaft. This model is used in one of two modes of operation:

(1) constant speed before trip occurs

(2) rotor speed calculated from rotor equation of motion after trip occurs.

The first mode of operation is used while the electrical generator is connected to the external power grid, since turbine speed is controlled closely by grid frequency during this period. The second mode of operation is used to simulate turbine behavior after the generator load has been shed and while the turbine is in overspeed or coastdown condition, depending on the steam supply. The second mode of operation calculates turbine speed by integration of the equation

$$I \frac{d\Omega}{dt} = T + T_f + T_b$$

where

I = turbine rotor movement of inertia (including generator armature)

Ω = turbine angular speed (radians/sec)

T = rotor torque supplied by steam flow

T_f = frictional rotor torque (user-supplied constant)

T_b = bearing and windage torque.

The torque supplied by steam is given by

$$T = \Sigma\, Q_{turb}/\Omega \qquad (18)$$

and the bearing and windage torque is given by

$$T_b = C \frac{\Omega|\Omega|}{\Omega^2_R}$$

where C is a user-supplied constant, and Ω_R is the rated turbine speed.

The sum in Equation (18) is performed over all TURB components connected to a given rotor shaft assembly. All of the TURB components comprising a BWR main turbine model would normally be connected to the same turbine shaft, while turbines used to drive feedwater pumps would be connected to separate shafts. Turbine rotor parameters (including trip number) are input separately for each shaft assembly.

3. PROGRAMMING DETAILS

The TURB component will appear to the user as a unique component, but for programming purposes many of the TURB component operations will be performed by existing TEE component subroutines. A new flag, ITURB, has been added to the TEE variable length table to indicate whether or not a TEE component is to be treated as a TURB. If the character string "TURB" is encountered on the card identifier of the component header card, ITURB is set to 1, and the component type is set to "TEEH". Thus, the TURB component will normally be treated as a TEE except for special circumstances when ITURB is used to signal special treatment for the turbine.

3.1 Data Storage

The TURB component will use the same fixed length table, variable length table, and pointer table as the TEE component. The TEE fixed length table and pointer table did not require alteration, while 16 new variables were added to the TEE variable length table to store turbine hydraulic and restart data. A list of these new variables and their definitions is included in Appendix A.

A new common block, TURCOM, has been added to the code to store turbine rotor data since this data is not associated with any single TURB component. This common block contains pointers to the fixed portion of the A array (before the TRIP data) to store dynamics data for NROT turbine rotors. Definitions of these pointers and other variables in TURCOM are also included in Appendix A.

3.2 Input

A new subroutine, FTURB, has been included in the INM2 overlay to read turbine hydraulic data and store it in the appropriate TEE arrays. Turbine rotor dynamic variables will also be read by this subroutine and stored in common block TURCOM or the section of the A array designated by the turbine rotor pointers. Since the data for a given turbine rotor may be input as part of the data set for several different TURB components, only the values from the first TURB encountered will be used. The rotor data for subsequent TURB components connected to a previously defined rotor will be ignored, and an informative message will be printed to remind the user that this data has already been input with a previous component. A description of the input requirements for the TURB component is found in Appendix B.

3.3 Output

The TEE edit subroutine WTEE is modified to include edits of turbine quantities if ITURB = 1. The component heading for the edit will be "TURB" instead of "TEE" and values for turbine rotor speed, torque and power will be added to the edit.

3.4 Graphics

Values for turbine rotor speed and turbine rotor torque are added to the graphics output file. The variable identifiers for these quantities are OMEGATUR and TORQTUR. These quantities are accessed through REFORM by using the component number of any TURB component connected to the desired rotor and by using a level index of 0 and cell index of 1. Since several TURB components may be connected to a single rotor, there may be redundant graphics storage since these quantities are stored for each TURB.

3.5 Control System

Turbine rotor speed and torque are available as inputs to the TRAC-BWR control system model. These quantities are obtained with control system I/Ø identifiers OMEG and TORQ. As in the graphics case, these quantities may be obtained from any TURB component connected to the desired turbine rotor.

3.6 Restart

All extra turbine data required to restart the TURB component is stored in the TEE variable length table which is written to the TRAC restart dump file. This leads to some redundant storage of turbine rotor data since several TURB components may have the same rotor restart data stored in their variable length tables. On restart, data for a given rotor will be taken from the restart file only if it has not already been defined by another component on the input file or restart file. Thus, rotor parameters can be changed on restart by inputting all of the data for a TURB component connected to the given rotor. This is the same as the restart philosophy for all other TRAC components.

3.7 Extract

The EXTRACT subprogram has been extended to create input decks for TURB components, including rotor data.

3.8 New and Altered Subroutines

The turbine model required the addition of four new subroutines and the alteration of 21 existing subroutines. A description of the new and altered subroutines is found in Appendix C.

3.9 Error Checking

Extensive error checking is performed during input processing and execution to ensure that input data is internally consistent and that illegal mathematical operations are not performed during execution. Self-explanatory messages are printed whenever an error condition is detected. All errors detected are flagged as fatal errors with execution continuing until the end of input processing or the current time step.

3.10 Connection to Other Components

Since the TURB component is fully explicit, special care must be taken in coupling it to other TRAC components. The TURB is connected to other components in the same manner as BREAK or FILL components since these two components are also seen as fully explicit boundary conditions by other components. Any component connected to the inlet (cell face 1) of a TURB will see the TURB as if it were a BREAK component or an explicit pressure boundary condition. This is achieved by setting the boundary condition type flags ISLB or ISRB in subroutine TF1DI to 2 for components connected to the TURB inlet. In like manner, components connected to either the TURB exit junction or sidearm junction view the TURB as though it were a FILL component or explicit velocity boundary condition. This is achieved by setting ISLB or ISRB to zero for such components.

4. SAMPLE PROBLEMS

Two sample problems were used to verify the proper operation of the turbine model. The first of these, test case TURB, is a model of a three-section turbine with BREAK components as boundary conditions. The second is a full-scale BWR/4 model connected to the three-section turbine. The second case is not being submitted as a formal sample problem at this time, since it will be augmented with feedwater heaters and pumps at a later time, yielding a complete balance-of-plant sample problem for inclusion in the sample problem set.

4.1 Sample Problem TUR3

Sample problem TUR3 models an isolated turbine with boundary conditions specified by BREAK components as shown in Figure 3. The three TURB components in the model are used to model the high and low pressure sections of a BWR main steam turbine, with an intermediate section to represent the moisture separator. Boundary conditions were chosen to be roughly representative of conditions for a BWR/6 main turbine. A brief transient was run with trips and tables set to simulate a hypothetical generator load rejection incident. During the first 5 sec of transient, the model runs from its unsteady initial state to a well-converged steady state. At 5 sec the turbine trip is activated to simulate a generator load rejection. During the next 3 sec, the turbine rotor accelerates since it has lost its load but is still receiving nearly full power from the turbine steam flow. At 8 sec the inlet BREAK pressure is reduced, simulating a closure of the turbine stop valve due to a turbine overspeed trip.

The central features of this transient can be seen on Figures 4, 5, and 6, which shows turbine rotor speed, turbine rotor power, and high pressure turbine mass flow rate. It is interesting to note the slight decrease in turbine power as the turbine speed increases during the 5 to 8 sec time interval. This power decrease is due to decreasing turbine efficiency as the blade speed to steam speed ratio departs from its ideal value.

This test case was also used to check mass and energy conservation in the TURB component by analysis of the steady state conditions achieved at a problem time of 5 sec. These steady state conditions are shown in Figure 7 for the two TURB components representing the high pressure turbine and the moisture separator. The values of h shown on this figure are mixture specific enthalpies (J/kg) as obtained from an interactive version of the TRAC steam tables. $\dot{Q}_{rotor}$ is the power delivered to the turbine rotor as defined by Equation (15). This quantity is calculated by TRAC and

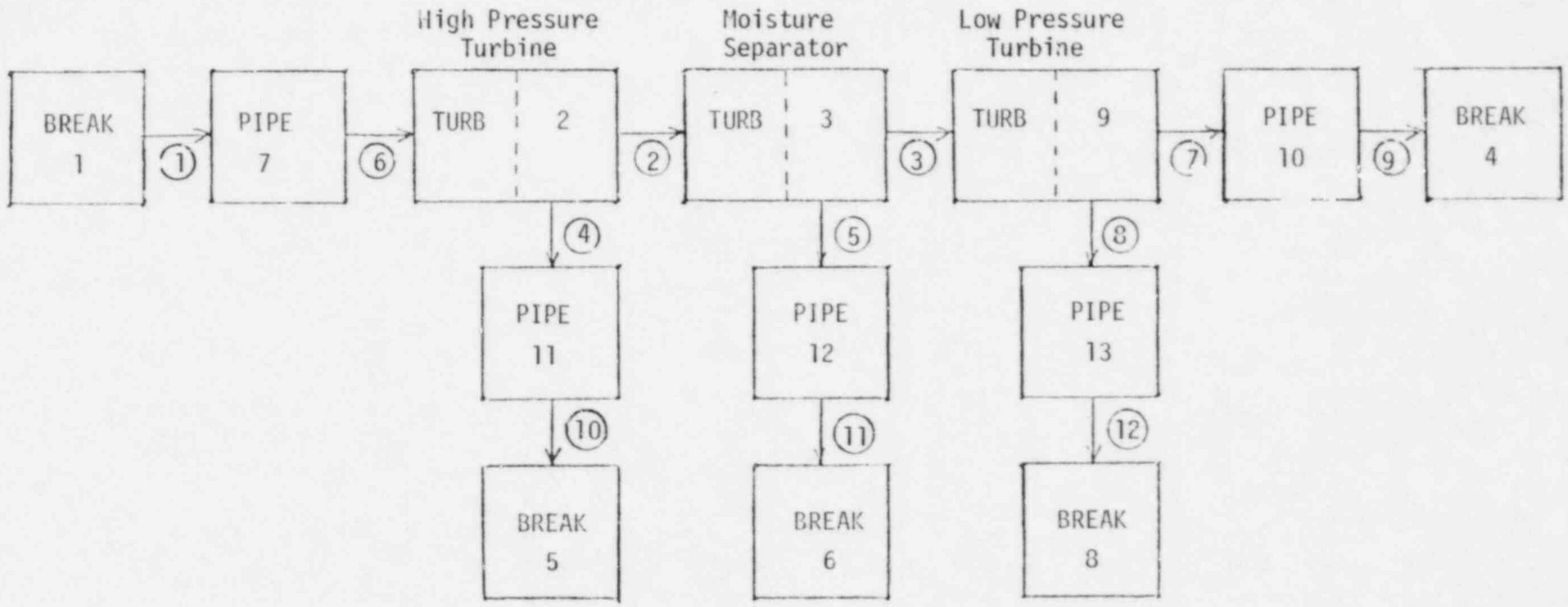

Figure 3. Test case TURB.

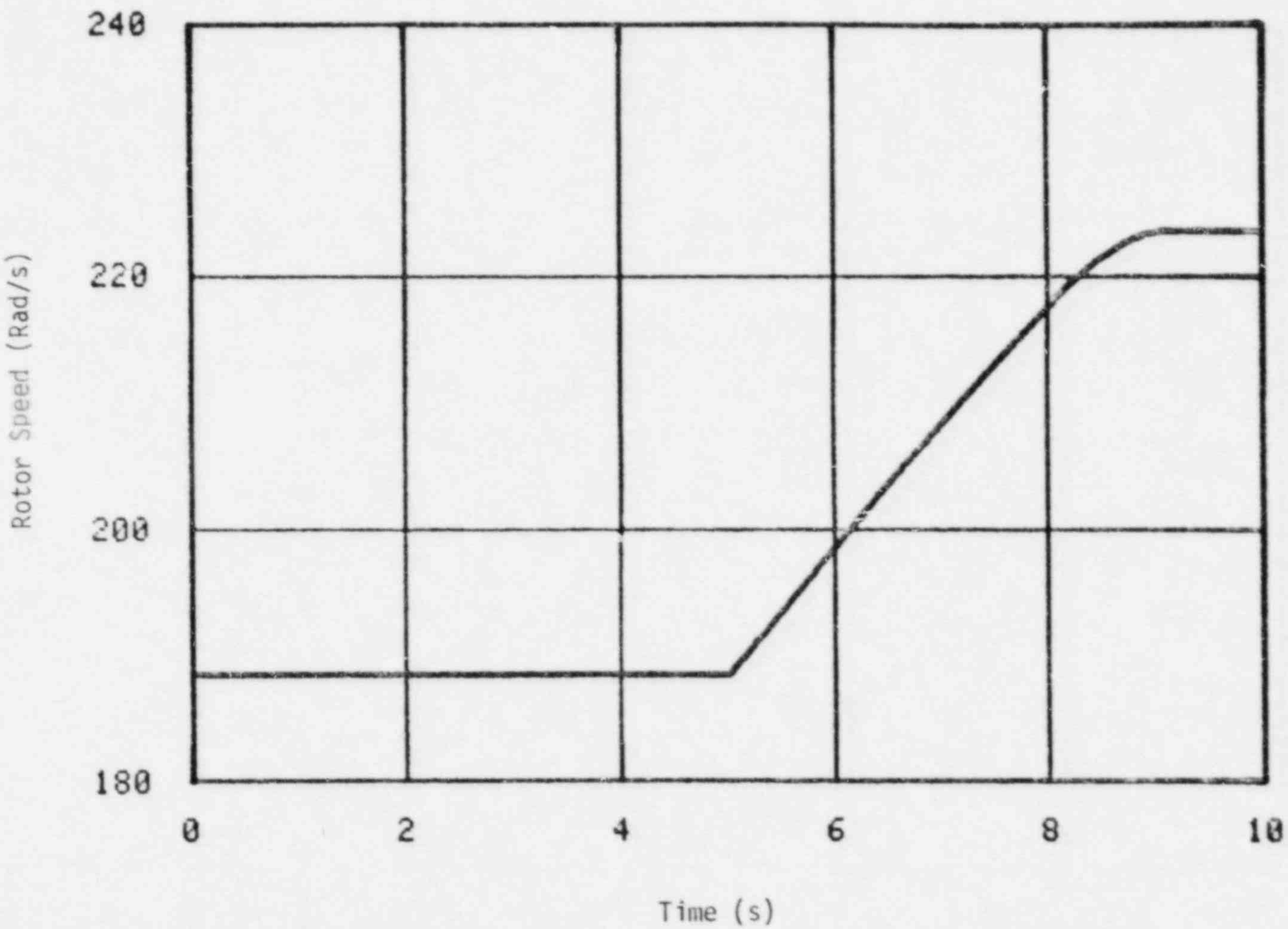

Figure 4. Turbine rotor speed.

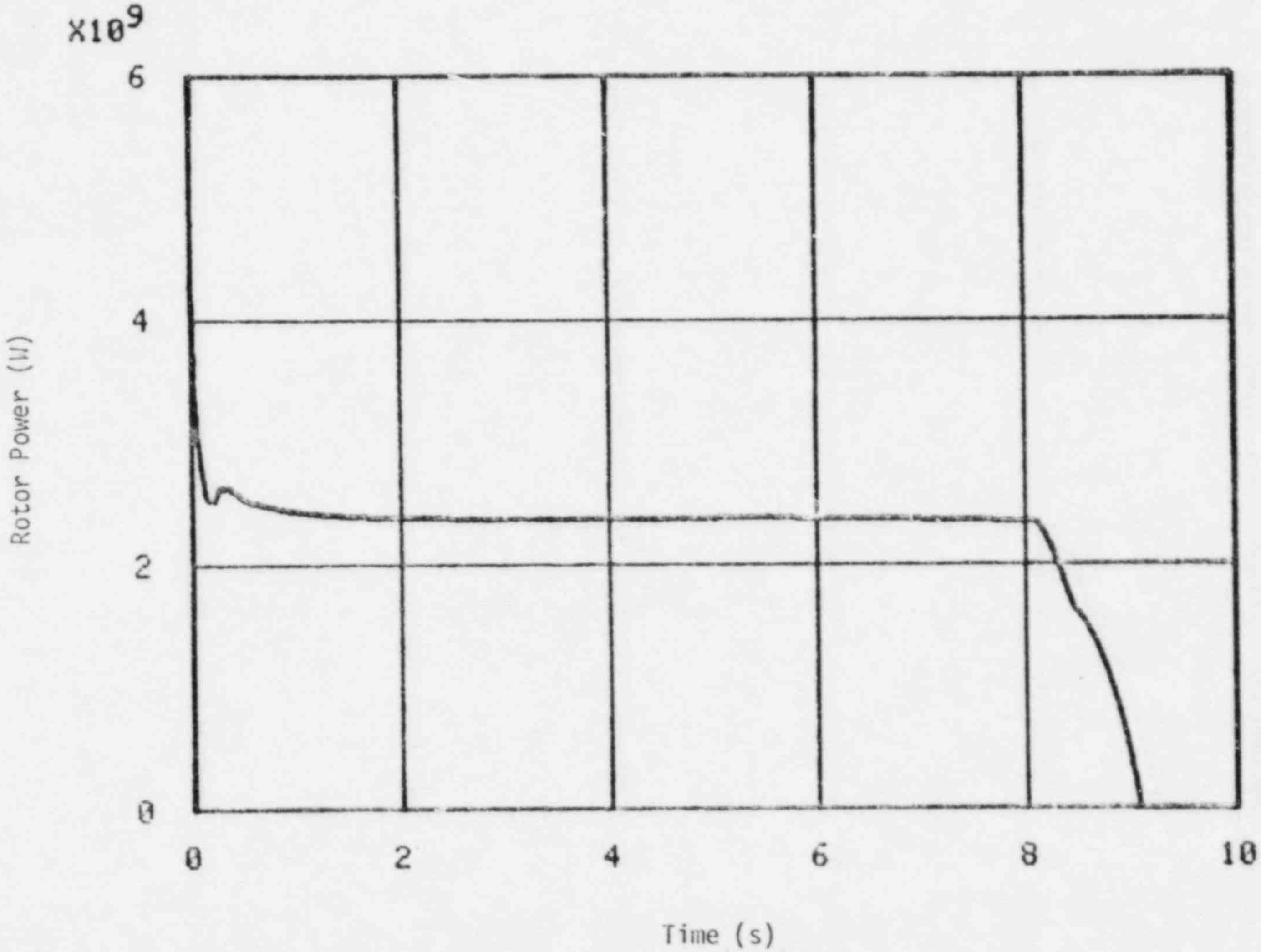

Figure 5. Turbine rotor power.

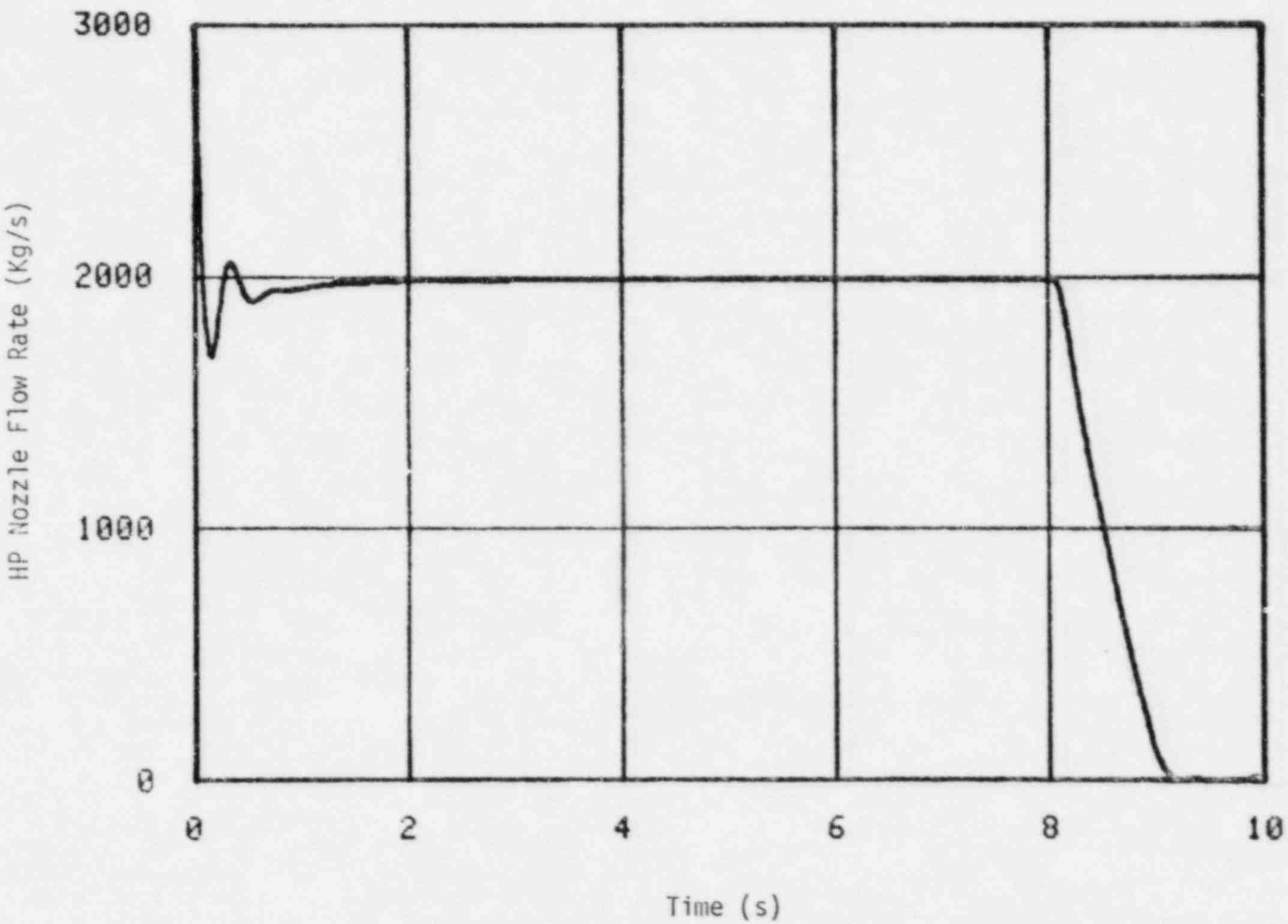

Figure 6. High pressure turbine mass flow rate.

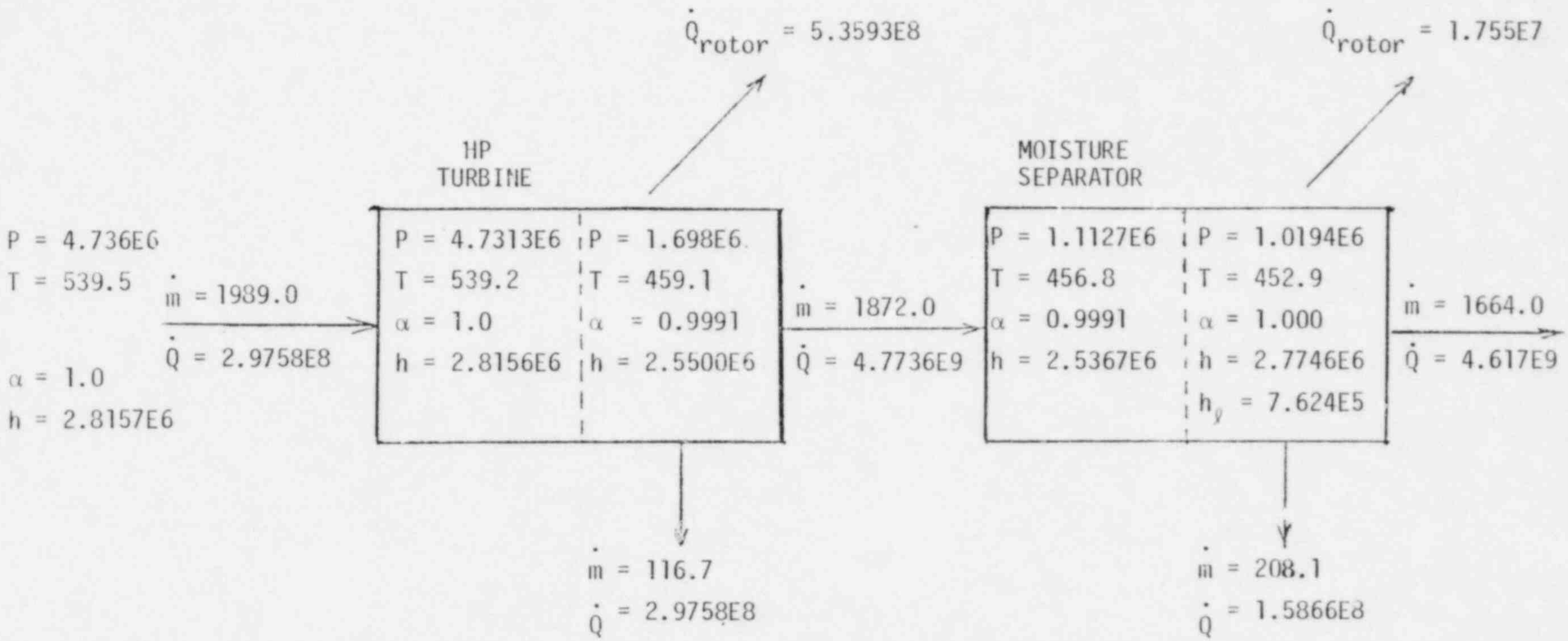

Figure 7. Steady State conditions, test case TUR3.

included in each TURB component major edit. The values for power transmitted in the fluid were obtained from

$$\dot{Q} = h\,\dot{m},$$

except in the case of the separator side arm, where

$$\dot{Q} = \dot{m}\,h_{\ell}.$$

The liquid specific enthalpy is used in this case since the side arm vapor fraction is zero in a separator. The values of $\dot{m}$ shown on Figure 7 are obtained from the printout of inlet and outlet mass flow rates on the TRAC major edit.

For both TURB components, the total mass flow rate in is equal to the total mass flow rate out. This result is accurate to the four significant figures included in the major edit mass flow rate printouts.

The energy balance for each TURB is as follows:

High Pressure Turbine

$$\dot{Q}_{in} = 5.6004E9\ W$$

$$\dot{Q}_{out} = 5.3593E8 + 4.7736E9 + 2.9758E8 = 5.6071E9\ W$$

$$\text{Error} = 100\% \times \frac{\dot{Q}_{out} - \dot{Q}_{in}}{\dot{Q}_{in}} = 0.11\%$$

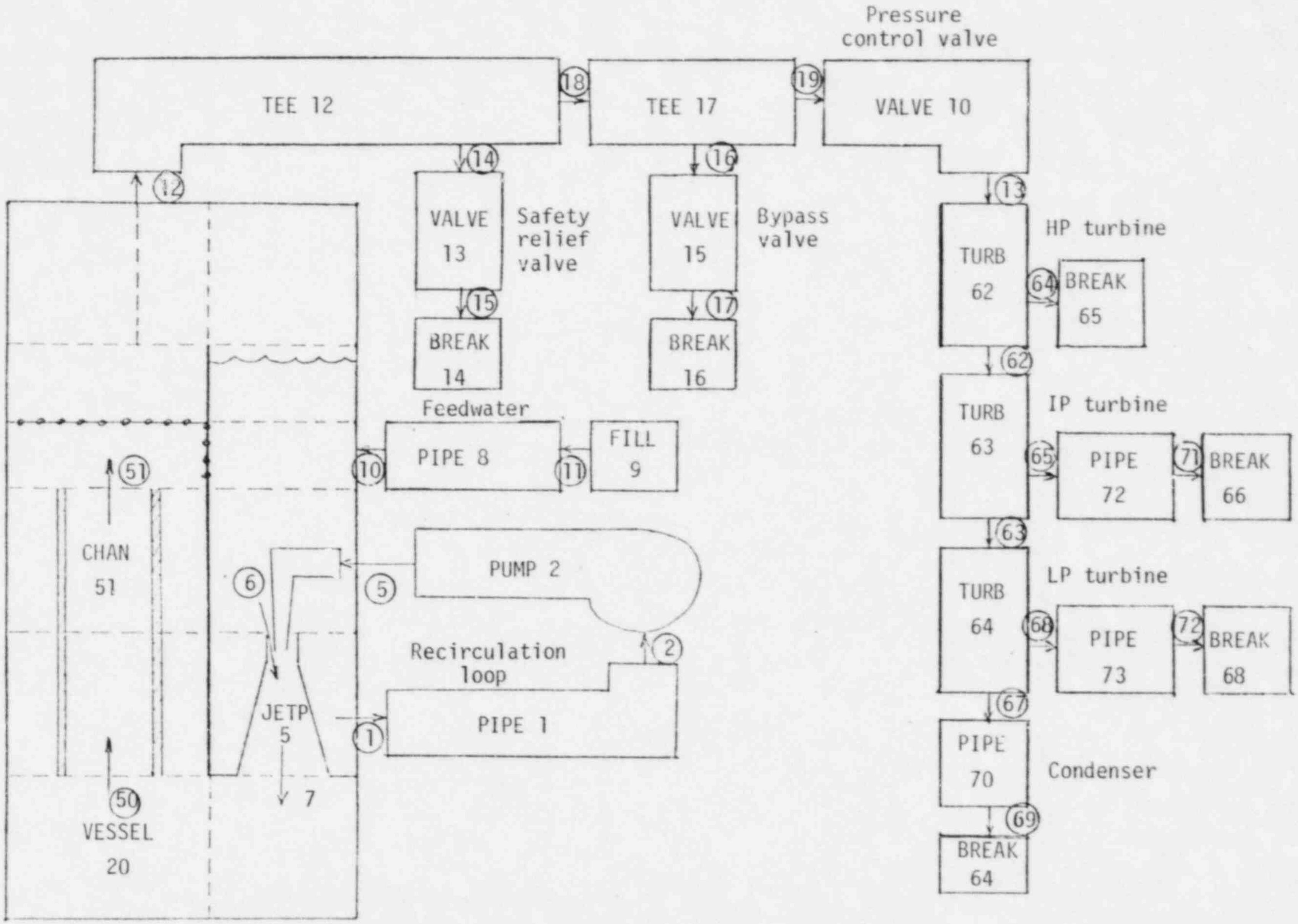

Figure 8. Turbine test case with full-scale BWR/4.

Moisture Separator

$$\dot{Q}_{in} = 4.7736E9 \text{ W}$$

$$\dot{Q}_{out} = 1.755E7 + 4.617E9 + 1.586E8 = 4.7932E9 \text{ W}$$

$$\text{Error} = 100\% \times \frac{\dot{Q}_{out}-\dot{Q}_{in}}{\dot{Q}_{in}} = 0.41\%.$$

The small errors obtained in the energy balances can be accounted for by the fact that vapor fractions are printed out to only four significant figures. Round off error in the printed value of α could account for apparent energy balance errors of as much as 0.6%.

The results of this test case show that the turbine model yields reasonable dynamic response and that steady state conservation of mass and energy are obtained. A microfiche copy of the input and output for this run is included on the back cover of this report.

4.2 Full-Scale BWR/6 Test Case

The second test case was run using a three-section turbine model attached to a complete model of a BWR/4 plant as shown in Figure 8. This case was run to verify the ability of the overall TRAC solution scheme to handle a full plant model with explicit TURB components. The complete model was observed to run smoothly to a converged steady state, indicating that the TURB component doesn't impair overall code operation. Some runs indicated a velocity instability at the interface between the pressure control valve (VALVE 10), and the high pressure turbine (TURB 62). This was due to feedback between the controlled valve area and the explicit pressure boundary condition presented by the TURB. This instability was eliminated by using a longer (and more physically realistic) value for the lag time constant used in the pressure control valve control system.

5. REFERENCES

1. J. K. Salisbury, Steam Turbines and Their Cycles, New York: Robert E. Krieger Publishing Company, 1974, pp 104-105.

2. W. J. Kearton, Steam Turbine Theory and Practice, London: Sir Isaac Pitman and Sons, Ltd., 1958, pp 86-87.

APPENDIX A

LIST OF NEW COMMON BLOCK VARIABLES

APPENDIX A

LIST OF NEW COMMON BLOCK VARIABLES

NAME (DIMENSION)	COMMON BLOCK	COMPONENT	DESCRIPTION
NSTAGE	VLTAB	TEE TURB	NUMBER OF STAGES IN TURB COMPONENT
CTRQBD	VLTAB	TEE TURB	RESTART AND GRAPHIC VALUE OF TURBINE TURBINE BEARING AND WINDAGE TORQUE CONSTANT.
CTRQTB	TURCOM	TURB	BEARING AND WINDAGE TORQUE CONSTANT.
EFISHR	VLTAB	TEE TURB	RATED TURBINE EFFICIENCY.
ITRTRD	VLTAB	TEE TURB	RESTART AND GRAPHIC VALUE OF TURBINE TRIP NUMBER.
ITMSEP	VLTAB	TEE TURB	TURBINE MOISTURE SEPARATOR FLAG.
ITURB	VLTAB	TEE TURB	TURBINE INDICATOR FLAG.
[illegible]CRTR	TURCOM	TURB	TURBINE TRIP NUMBER.
OINERT	VLTAB	TEE TURB	RESTART AND GRAPHIC VALUE OF TURBINE ROTOR MOMENT OF INERTIA.
OMEGT	TURCOM	TURB	TURBINE ROTOR ANGULAR SPEED.
OMEGTD	VLTAB	TEE TURB	RESTART AND GRAPHIC VALUE OF TURBINE ANGULAR SPEED.
OMEGTUR	TURCOM	TURB	RATED ROTOR ANGULAR SPEED.
OMGTRD	VLTAB	TEE TURB	RESTART AND GRAPHIC VALUE OF TURBINE ROTOR RATED SPEED.
POWTCM	VLTAB	TEE TURB	COMPONENT TURBINE ROTOR POWER.
POWTUR	TURCOM	TURB	TOTAL TURBINE ROTOR POWER.
RMDOT	VLTAB	TEE TURB	RATED TURBINE MASS FLOW RATE.
SALOSK	VLTAB	TEE TURB	TURBINE SIDE ARM LOSS COEFFICIENT.

TORQT	TORCOM	TURB	TOTAL ROTOR TORQUE FROM STEAM.
TORQTD	VLTAB	TEE TURB	RESTART AND GRAPHIC VALUE OF TURBINE TORQUE.
TORQTF	TORCOM	TURB	ROTOR FRICTION TORQUE.
TRQTFD	VLTAB	TEE TURB	RESTART AND GRAPHIC VALUE OF TURBINE ROTOR FRICTION TORQUE.
TURBH	HOLL		HOLLERITH REPRESENTATION OF WORD "TURB".
LCTRTB CTRQTB (NROT)	TORCOM	TURB	POINTER TO BEARING AND WINDAGE TORQUE CONSTANT.
LINERT INERT (NROT)	TORCOM	TURB	POINTER TO ROTOR MOMENT OF INERTIA.
LITRTR ITURTR (NROT)	TORCOM	TURB	POINTER TO TURBINE TRIP NUMBER.
LOMEGT OMEGT (NROT)	VLTAB	TEE TURB	POINTER TO TURBINE ROTOR ANGULAR SPEED.
LPOWTR LPOWTUR (NROT)	TORCOM	TURB	POINT TO TOTAL TURBINE ROTOR POWER.
LTORQT TORQT (NROT)	TORCOM	TURB	POINT TO TOTAL ROTOR TORQUE FROM STEAM.
LTRQTF TORQTF (NROT)	TORCOM	TURB	POINT TO ROTOR FRICTION TORQUE.
JROT	VLTAB	TEE TURB	COMPONENT TURBINE ROTOR NUMBER.
NROT	TORCOM	TURB	NUMBER OF TURBINE ROTORS.
LROT	PTRS		POINTER TO TURBINE ROTOR DATA IN IN A ARRAY.
SEPEF	VLTAB	TEE TURB	TURBINE SEPARATOR EFFICIENCY.

APPENDIX B

TURBINE COMPONENT INPUT REQUIREMENTS

APPENDIX B

TURBINE COMPONENT INPUT REQUIREMENTS

Main Control Cards, MAINXX

Word	Variable	Description
W19-I	NROT	Number of turbine rotor assemblies (Default = 0)

Turbine Component (TURB)

TURB Header Card, TURBID000

Word	Variable	Description
W1-I	NUM	Component ID Number (must be unique for each component)
W2-A	CTITLE	User optional description of component. Up to 30 characters may be used. Enclose in quotes.

TURB Primary Tube Parameters Card, TURBID01X

First four words are required.

Word	Variable	Description
W1-I	JUN1	Junction number at TURB inlet
W2-I	JUN2	Junction number at main TURB outlet
W3-R	RMDOT	Turbine rated mass flow rate
W4-R	EFISHR	Turbine rated efficiency
W5-I	NSTAGE	Number of stages in TURB component (Default = 1)

TURB Side Arm Parameters Card, TURBID02X

First four words are required.

Word	Variable	Description
W1-I	JUN3	Junction number at TURB side arm
W2-I	ITSEP	Moisture separator flag 0 = No moisture separator 1 = side arm is moisture separator
W3-R	SAFA	Side arm flow area. Must match flow area value of adjoining component
W4-R	SAVM	Side arm initial mixture velocity
W5-R	SALOSK	Side arm form loss coefficient. Not used if ITSEP = 1 (Default = 1.0)
W6-R	SEPEF	Moisture separator efficiency. Used only if ITSEP = 1. For perfect separation use SEPEF = 1.0 (Default = 1.0)

TURB Rotor Parameters Card, TURBID03X

First four words are required.

Word	Variable	Description
W1-I	JROT	Turbine rotor number. More than one TURB component may use the same rotor number. If several TURB components are connected to the same rotor, the rotor parameters will be taken only from the first TURB encountered which connects to that rotor.
W2-I	ITURTR	Turbine trip number for rotor number JROT. Rotor speed will remain constant until trip has occurred. Rotor speed will be calculated from equation of motion after trip has occurred.
W3-R	OMEGT	Rotor initial angular velocity (rad/s)
W4-R	INERT	Rotor moment of inertia (kg/m^2)
W5-R	OMEGTR	Rated rotor angular velocity (Default = OMEGT)
W6-R	CTRQTB	Rotor bearing and windage torque constant (Default = 0)
W7-R	TORQTR	Rotor frictional torque (n-m) (Default = 0)

TURB Array Cards, TURBID42X-TURBID56X

One set for each of the following variables using load format. Variable FA must match flow area values of adjoining components.

CN	Variable	Dimension	Description
42	VOL	2	Primary tube cell volumes
43	FA	3	Primary tube flow areas
51	ALP	2	Primary tube initial vapor fractions
52	VM	3	Primary tube initial mixture velocities
54	TM	2	Primary tube initial mixture temperatures
56	P	2	Primary tube initial pressures

APPENDIX C

NEW AND MODIFIED SUBROUTINES

APPENDIX C

NEW AND MODIFIED SUBROUTINES

New Subroutines

Name	Overlay	Function of Subroutine
FTURB	INM2	Reads TURB component input data in free format
TRBDYN	TRANS	Performs turbine rotor dynamics calculation
TRBHYD	TRANS	Performs TURB component thermal hydraulic calculation
WETURB	EXTR	Extracts TURB component data from restart dump file and converts it to free format card input data

Modified Subroutines

Name	Overlay	Nature of Modification
BLKDAT	TRAC	Change NPX to 32 and define component type TURBH
J1D	TRANS	Retain component types TURBO and TURBI in 36th word of BD array
PREP	TRANS	Add call to subroutine TRBDYN
ALPHTN	INM2	Add character string TURB for conversion to numeric value
ANTN	INM2	Add character strings VM and TM for conversion to numeric value
FDCOMP	INM2	Set up and add call to subroutine FTURB
TIMO	TRAC	Set up turbine model timers
TEE2	TRANS	Set up and add cell to subroutine TRBHYD
TF1DI	TRANS	Set boundary condition flags for components connecting to TURB, apply damping to outlet velocities connected to TURB
WCOMP	EDIT	Jump around writing of TEE component header
ECOMP	EDIT	Jump around writing of wall data for TURB
WTEE	EDIT	Add editing of turbine rotor data
IGTEE	INIT	Add turbine speed and torque to graphics file

Name	Overlay	Nature of Modification
RDREST	TNM2	Jump around writing of TEE component header
RETEE	INM2	Get TURB component data from restart tape
INM2	INM2	Set pointers for turbine rotor data
FTEE	INM2	Clear turbine parameters
ITEE	INIT	Initialize TURB nozzle area and velocity. Load TURB hydraulic diameters and cell lengths
WETEE	EXTR	Add call to subroutine WETURB
CVDEFS	None	Add new common block variable definitions
SDLIST	None	Add new subroutine definitions