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AN IMPROVED STEAM GENERATOR MODEL FOR THE SASSYS CODE*

by

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Introduction

A new steam generator model has been developed for the SASSYS[1] computer code, which analyzes accident conditions in a liquid metal cooled fast reactor. It has been incorporated into the new SASSYS balance-of-plant model but it can also function on a stand-alone basis. The steam generator can be used in a once-through mode, or a variant of the model can be used as a separate evaporator and a superheater with a recirculation loop. The new model provides for an exact steady-state solution as well as the transient calculation. There was a need for a faster and more flexible model than the old steam generator model. The new model provides for more detail with its multi-node treatment as opposed to the previous model's one node per region approach. Numerical instability problems which were the result of cell-centered spatial differencing, fully explicit time differencing, and the moving boundary treatment of the boiling crisis point in the boiling region have been reduced. This leads to an increase in speed as larger time steps can now be taken. The new model is an improvement in many respects.

General Features of the New Model

On the water side, the steam generator is divided into three regions at most: a subcooled liquid, a saturated boiling and a superheated steam region. A subcooled region is always assumed to exist but the disappearance and reappearance of the other two regions is calculated. Thus a liquid-filled steam generator can be characterized but dry-out can be calculated only to the extent a small liquid region remains. The boundaries of the subcooled region are defined as the inlet of the steam generator and the point where saturated liquid enthalpy is attained or the top of the steam generator. The boiling zone is bounded by the point of saturated liquid enthalpy and the point of saturated vapor enthalpy or the top of the steam generator. The superheated region is, of course, above the point of saturated vapor enthalpy. The subcooled region is treated as incompressible and therefore the inlet flow is constant throughout the subcooled region and provides a lower flow boundary condition for the boiling zone. Saturation conditions and a no slip condition between phases are assumed at all times in the boiling zone. Pressure boundary conditions are provided from an external calculation at the inlet and outlet of the steam generator and an average of this is currently used for calculating properties. The subcooled and superheated regions each have one heat transfer regime and the boiling zone has two regimes separated at the boiling crisis point.

There is no momentum equation used in an integrated fashion to produce nodal velocities. The inlet water flow is assumed to be a driving function of the equation set and only mass and energy conservation equations are used to solve for mass flows, enthalpies, etc. for the compressible regions on the water side. A momentum equation is, however, explicitly coupled to the calculation. It is used to calculate the pressure drop across the steam generator in order to link the steam generator with the balance-of-plant and calculate the liquid mass flow at the steam generator inlet.

Each of the three regions is divided into a fixed number of cells which are thus a constant fraction of the varying region length. The volumetric heat source and the wall temperature are calculated at the cell center. All other parameters are calculated at the cell edge. The heat flux is always explicit in time but other parameters have varying degrees of implicitness in time. Donor-cell differencing is used for numerical stability on both the sodium and water sides. The wall temperature calculation is central differenced, however. The sodium side, always being in the liquid state, is treated as incompressible flow.

General Forms of Conservation Equations

Before the individual solution methods for each water side region and the sodium side can be considered, general forms of the continuity and energy equations must be developed. Equations will be given for one node of the multi-node system of equations. Integration of the continuity equation over the length of one cell from Z_i to Z_{i+1} gives,

$$\int_{Z_i}^{Z_{i+1}} \frac{\partial}{\partial t} \rho dz = - \int_{Z_i}^{Z_{i+1}} \frac{\partial}{\partial z} G dz = -(G_{i+1} - G_i) \tag{1}$$

According to Leibnitz's Theorem,

$$\int_{Z_i}^{Z_{i+1}} \frac{\partial}{\partial t} \rho dz = \frac{d}{dt} \int_{Z_i}^{Z_{i+1}} \rho dz - \rho_{i+1}\dot{Z}_{i+1} + \rho_i \dot{Z}_i \tag{2}$$

Therefore,

$$\frac{d}{dt} \{\bar{\rho}_i \Delta Z_i\} - \rho_{i+1}\dot{Z}_{i+1} + \rho_i \dot{Z}_i = -\Delta G_i \tag{3}$$

In order to write the equation in donor-cell form, let ρ_{i+1} replace the average value over the interval, $\bar{\rho}_i$, and simplify,

$$\dot{\rho}_{i+1}\Delta Z_i - \Delta\rho_i \dot{Z}_i = -\Delta G_i \tag{4}$$

Integration of the enthalpy form of the energy equation (neglecting work terms) from Z_i to Z_{i+1} gives,

$$\int_{Z_i}^{Z_{i+1}} \frac{\partial}{\partial t} (\rho h) dz = - \int_{Z_i}^{Z_{i+1}} \frac{\partial}{\partial z} (Gh) dz + \int_{Z_i}^{Z_{i+1}} Q dz + \int_{Z_i}^{Z_{i+1}} \frac{\partial}{\partial t} P dz \tag{5}$$

Using Leibnitz's Theorem again for the LHS of (5) and the pressure term, and remembering there is no spatial pressure variation, the following results,

$$\frac{d}{dt} \{(\overline{\rho h})_i \Delta Z_i\} - (\rho h)_{i+1}\dot{Z}_{i+1} + (\rho h)_i \dot{Z}_i = -\Delta(Gh)_i + Q_i \Delta Z_i + \dot{P}\Delta Z_i \tag{6}$$

In order to write the equation in donor-cell form let $(\overline{\rho h})_i = (\rho h)_{i+1}$ as in the mass equation and simplify,

$$(\dot{\rho h})_{i+1}\Delta Z_i - \Delta(\rho h)_i \dot{Z}_i = -\Delta(Gh)_i + Q_i \Delta Z_i + \dot{P}\Delta Z_i \tag{7}$$

Subcooled Liquid Region

In the subcooled region, the mass flow is assumed to be uniform throughout the zone due to incompressible flow. Each time step during the transient an updated inlet mass flow is provided to the steam generator from the explicitly-coupled momentum equation. Therefore no continuity equation is required. The coupled set of nodal energy conservation equations are used to determine the length of the zone and the nodal enthalpies simultaneously using the inlet enthalpy and the saturated liquid enthalpy as boundary conditions. Or, alternatively, when liquid fills the steam generator and the zone length is known, the outlet enthalpy is instead determined.

Using equation (7) and setting $\dot{\rho} = 0$ because of the incompressible flow, and recalling that ΔZ_i is invarient within a zone, the following results for node i,

$$\dot{h}_{i+1}\rho_{i+1}\Delta Z - \Delta(\rho h)_i \dot{Z}_i = -\Delta(Gh)_i + Q_i \Delta Z + \dot{P}\Delta Z \tag{8}$$

The following is equation (8) in finite difference form,

$$h_{i+1}^{k+1} \frac{1}{\Delta t} \rho_{i+1}^{k} \frac{1}{n} Z_{SC}^{k} - h_{i+1}^{k} \frac{1}{\Delta t} \rho_{i+1}^{k} \frac{1}{n} \cdot Z_{SC}^{k+1} - \bar{\rho}_i^{k} \left(h_{i+1}^{k} - h_i^{k}\right) \cdot \frac{i-1}{n}$$

$$\cdot \frac{1}{\Delta t} \left(Z_{SC}^{k+1} - Z_{SC}^{k}\right) = - G^{k+1} \cdot \left(h_{i+1}^{k+1} - h_i^{k+1}\right) + Q_i^{k} \frac{1}{n} Z_{SC}^{k+1} + \dot{P} \frac{1}{n} Z_{SC}^{k+1} \tag{9}$$

Rearranging according to coefficients of h_i^{k+1}, h_{i+1}^{k+1} and Z_{SC}^{k+1}, there are n equations of the following form,

$$a_i h_i + b_i h_{i+1} + c_i Z_{SC} = d_i \tag{10}$$

In the case where the liquid region does not reach the top of the steam generator, h_1 and h_{n+1} are known, since they are the inlet enthalpy and h_f. h_2 - h_n and Z_{SC} are unknown and are solved for as follows.

From the first equation of the equation set (10), solve for h_2, then for h_3 from the second equation and so on,

$$h_2 = e_1 + f_1 Z_{SC};\ e_1 = \frac{d_1 - a_1 h_1}{b_1},\ f_1 = -\frac{c_1}{b_1}$$

$$h_3 = e_2 + f_2 Z_{SC};\ e_2 = \frac{d_2 - a_2 e_1}{b_2},\ f_2 = -\frac{c_2 + a_2 f_2}{b_2}$$

$$h_{i+1} = e_i + f_i Z_{SC};\ e_i = \frac{d_i - a_i e_{i-1}}{b_i},\ f_i = -\frac{c_i + a_i f_{i-1}}{b_i} \qquad (11)$$

Finally, in the equation for h_{n+1}, Z_{SC} can be solved for since h_{n+1} is known. Then each of $h_2 - h_n$ can be solved for since they are all functions of only Z_{SC} in the equation set (11).

If the steam generator is filled with liquid, then the outlet enthalpy is unknown and there are n equations with $h_2 - h_{n+1}$ unknowns of the following form which are simply solved from the bottom to the top of the steam generator successively,

$$h_{i+1}^{k+1} = \frac{\frac{1}{\Delta t} h_{i+1}^{k} \rho_{i+1}^{k} \frac{1}{n} Z_{SC} + G^{k+1} h_i^{k+1} + Q_i \frac{1}{n} Z_{SC} + \dot{P} \frac{1}{n} Z_{SC}}{\frac{1}{\Delta t} \rho_{i+1}^{k} \frac{1}{n} Z_{SC} + G^{k+1}} \qquad (12)$$

Boiling Region

In the boiling zone, the fluid is treated as compressible. Simultaneous nodal equations are solved for void fraction, mass flow and region length. Boundary conditions are the saturated liquid enthalpy and subcooled region mass flow at the bottom of the boiling zone and either the saturated vapor enthalpy at the top of the zone or, if there is no superheated vapor zone, the region length is defined and the outlet enthalpy is determined. Only the pressure and the volumetric heat source are treated explicitly in time. The void fraction, the mass flow and the region length are all treated in fully implicit fashion. An iterative method is used to solve for the region length. The current value of the region length is held constant for each pass in the iteration while nodal void fractions and mass flows are calculated from the mass and energy equations. When the uppermost void fraction in the boiling zone is computed at the end of an iteration, its value is compared to 1.0

and the region length is adjusted appropriately and the iterative process continues until convergence. When the boiling zone extends to the top of the steam generator, the same method is used but there is no iteration since the region length is known.

First, the general continuity equation (4) is written in terms of the nodal void fraction, α,

$$(\dot{\alpha}_{i+1}\rho_{fg} + \alpha_{i+1}\dot{\rho}_{fg} + \dot{\rho}_f)\Delta Z - (\alpha_{i+1} - \alpha_i)\rho_{fg}\dot{Z}_i = -\Delta G_i \tag{13}$$

The finite difference form of (13) is,

$$\left[\frac{1}{\Delta t}(\alpha_{i+1}^{k+1} - \alpha_{i+1}^{k})\rho_{fg}^{k} + \alpha_{i+1}^{k+1}\dot{\rho}_{fg}^{k} + \dot{\rho}_f^{k}\right]\frac{1}{n}Z_{TP}^{k+1}$$

$$-(\alpha_{i+1}^{k+1} - \alpha_i^{k+1})\cdot\rho_{fg}^{k}\left[\frac{i-j}{n}\frac{1}{\Delta t}(Z_{TP}^{k+1} - Z_{TP}^{k}) + \dot{Z}_{SC}\right] = -(G_{i+1}^{k+1} - G_i^{k+1}) \tag{14}$$

Arranging according to coefficients of α_{i+1}^{k+1} and G_{i+1}^{k+1}, there results an equation of the following form,

$$\alpha_{i+1}^{k+1}\cdot a + G_{i+1}^{k+1} + c = 0 \tag{15}$$

Writing the general energy equation (7) in terms of α results in the following,

$$[\dot{\alpha}_{i+1}(h\rho)_{fg} + \alpha_{i+1}(\dot{h\rho})_{fg} + (\dot{h\rho})_f]\Delta Z - (\alpha_{i+1} - \alpha_i)(h\rho)_{fg}\dot{Z}_{TP}$$

$$= -\Delta(Gh)_i + Q_i\Delta Z + \dot{P}\Delta Z \tag{16}$$

The finite difference form of (16) is,

$$\left[\frac{1}{\Delta t}\left(\alpha_{i+1}^{k+1} - \alpha_{i+1}^{k}\right)(h\rho)_{fg} + \alpha_{i+1}^{k+1}(\dot{h\rho})_{fg} + (\dot{h\rho})_{f}\right] \frac{1}{n} Z_{TP}^{k+1} - \left(\alpha_{i+1}^{k+1} - \alpha_{i}^{k+1}\right)$$

$$(h\rho)_{fg}\left[\frac{i-j}{n}\frac{1}{\Delta t}\left(Z_{TP}^{k+1} - Z_{TP}^{k}\right) + \dot{Z}_{SC}\right] = -\left[G_{i+1}^{k+1}\left(h_f + \frac{\alpha_{i+1}^{k+1}\rho_g h_{fg}}{\rho_f + \alpha_{i+1}^{k+1}\rho_{fg}}\right) - \right.$$

$$\left. G_{i}^{k+1}\left(h_f + \frac{\alpha_{i}^{k+1}\rho_g h_{fg}}{\rho_f + \alpha_{i}^{k+1}\rho_{fg}}\right)\right] + Q_i^k \frac{1}{n} Z_{TP}^{k+1} + \dot{P}\frac{1}{n} Z_{TP}^{k+1} \qquad (17)$$

If (17) is rearranged according to coefficients of α_{i+1}^{k+1} and G_{i+1}^{k+1}, and a' and c' represent the coefficient of α_{i+1}^{k+1} and the constant term respectively, the following results,

$$\alpha_{i+1}^{k+1}\, a' + G_{i+1}^{k+1}\left[h_f + \frac{\alpha_{i+1}^{k+1}\rho_g h_{fg}}{\rho_f + \alpha_{i+1}^{k+1}\rho_{fg}}\right] + c' = 0 \qquad (18)$$

When the mass equation (15) is substituted into (18), a quadratic in α_{i+1}^{k+1} results,

$$\left(\alpha_{i+1}^{k+1}\right)^2\left[a'\rho_{fg} - ah_f\rho_{fg} - a\rho_g h_{fg}\right] + \alpha_{i+1}^{k+1}\left[a'\rho_f - c\rho_{fg}h_f\right.$$

$$\left. - c\rho_g h_{fg} + c'\rho_{fg} - ah_f\rho_f\right] + \left[c'\rho_f - ch_f\rho_f\right] = 0 \qquad (19)$$

Equation (19) is solved for α_{i+1}^{k+1} and then G_{i+1}^{k+1} is obtained from the continuity equation (15) for each node starting at the bottom of the mesh (i=1)where G_i^{k+1} and α_i^{k+1}(= 0) are known. The solution proceeds upwards until α_{n+1}^{k+1} is calculated and Z_{TP}^{k+1} is adjusted on each iteration until α_{n+1}^{k+1} is sufficiently close to 1.0.

Superheated Vapor Region

A compressible treatment of the vapor is used above the boiling zone and simultaneous nodal mass and energy equations are solved for nodal enthalpies and mass flows since the region length is known, being the remainder of the steam generator length after computing new subcooled and boiling zone lengths. The nodal densities and enthalpies are treated partially explicitly in time. Boundary conditions are the saturated vapor enthalpy and the mass flow at the bottom of the zone. The solution proceeds upwards to the top of the steam generator.

Since there is an expression for ρ as a function of enthalpy and pressure,

$$\dot{\rho} = \frac{\partial \rho}{\partial h}\frac{\partial h}{\partial t} + \frac{\partial \rho}{\partial P}\frac{\partial P}{\partial t} \tag{20}$$

By substituting equation (20) into the mass equation (4), an expression for G_{i+1} as a function of h_{i+1} results,

$$G_{i+1} = G_i - \left[\frac{\partial \rho}{\partial h}\dot{h}_{i+1} + \frac{\partial \rho}{\partial P}\dot{P}\right]\Delta Z + \Delta\rho_i \dot{Z}_i \tag{21}$$

By substituting equation (20) and equation (21) into the general energy equation (7), simplifying, writing in finite difference form and solving for h^{k+1}_{i+1}, the following results,

$$h^{k+1}_{i+1} = \frac{h^{k+1}_i\left(G^{k+1}_i - \rho^{k+1}_i \frac{i-j}{n}\dot{Z}^{k+1}_{SH}\right) + \frac{1}{n} Z^{k+1}_{SH}\left(\frac{1}{\Delta t} h^k_{i+1}\rho^k_{i+1} + Q^k_i + \dot{P}^k\right)}{G^{k+1}_i + \frac{1}{\Delta t}\rho^k_{i+1}\frac{1}{n}Z^{k+1}_{SH} - \rho^k_i \frac{i-j}{n}\dot{Z}_{SH}} \tag{22}$$

The h^{k+1}_{i+1} obtained from equation (22) is substituted into equation (21) to obtain G^{k+1}_{i+1}. The solution then proceeds upwards to the top of the steam generator.

Sodium Side Calculation

Incompressible flow is assumed on the sodium side, so no continuity equation is solved. Also, the pressure term in the energy equation is negligible and is eliminated. Since the sodium flows downward, in order to donor-cell the energy equation, $\overline{(\rho h)}_i = (\rho h)_i$. It is also convenient to assume that G is positive for downward flow which means $-\Delta(Gh)_i = -G(h_i - h_{i+1})$. Thus equation (6) becomes,

$$\dot{(\rho h)}_i \Delta Z - [(\rho h)_{i+1} - (\rho h)_i]\dot{Z}_{i+1} = -G(h_i - h_{i+1}) + Q_i \Delta Z \tag{23}$$

Assume $\dot{\rho} = 0$ because of incompressible flow and rewrite equation (23) in terms of temperature. And in order to make the equation more implicit, set $T_i^{k+1} = T_i^k + \Delta t \dot{T}_i$ and solve for $\dot{T}_i$, noting that the end-of-time step ΔZ's from the water side calculation are used,

$$\dot{T}_i = \frac{(\rho_i \dot{Z}^{k+1} + G) \cdot (T_{i+1}^{k+1} - T_i^k) + \frac{1}{C_{p,i}} Q_i^k \Delta Z^{k+1}}{\rho_i \Delta Z^{k+1} + \rho_i \dot{Z}^{k+1} \Delta t + G \Delta t} \tag{24}$$

Starting at the top of the steam generator, with the new inlet sodium temperatures at the end of the time step, the calculation proceeds downward to the bottom of the mesh.

Wall Temperature Calculation

The heat capacity of the tube wall must be taken into account during the transient. Since there is no convective term in the energy equation, central differencing is used. This means that $\overline{(\rho h)}_i = \frac{1}{2}[(\rho h)_{i+1} + (\rho h)_i]$. Thus equation (6) becomes,

$$\frac{d}{dt}\{\frac{1}{2}[(\rho h)_{i+1} + (\rho h)_i]\Delta Z\} - (\rho h)_{i+1}\dot{Z}_{i+1} + (\rho h)_i \dot{Z}_i = Q_i \Delta Z \tag{25}$$

Writing equation (25) in terms of temperature and noting that C_p and ρ are assumed temperature-independent, the following expression for $\dot{T}$ results,

$$\dot{T}_i = \frac{1}{\rho C_p} Q_i^k + \frac{1}{2}\frac{1}{\Delta Z^{k+1}} \Delta T_i^k (\dot{Z}_{i+1}^{k+1} + \dot{Z}_i^{k+1}) \tag{26}$$

As in the sodium side calculation, updated ΔZ's and $\dot{Z}$'s are used from the water side calculation. It must also be noted that the temperature T_i above is a cell-centered value while the $\dot{Z}$'s are cell-edge values as in the sodium and water equations.

Calculation of Boiling Crisis Point

The point of boiling crisis, or DNB point, in the boiling zone is computed by tracking the continuously varying intersection of two functions which is a point within the node structure. The first function represents the required heat flux for the boiling crisis to occur and the second is the actual local heat flux at the wall surface.

The DNB heat flux correlation[2] is as follows,

$$F_D = 7.84 \cdot 10^8 \left(x \cdot h_{fg} \rho_g / \rho_f \cdot \sqrt{\frac{G}{1355}} \right)^{-0.667} \tag{27}$$

This correlation is evaluated at each cell center in the boiling zone using the local quality. The inlet mass flux G is used instead of the local area mass flux to enhance numerical stability although the original correlation used the local flow.

An expression for the wall surface heat flux is obtained as follows. There is a correlation for the heat transfer coefficient at the tube wall surface but the wall surface temperature is unknown, although the mid-wall temperature and the water temperature at saturation are known. Without going into the details of the correlation, it is known that the heat flux at the wall surface, F_S, is equal to $a \cdot (T_s - T_{sat})^2$, where T_s is the wall surface temperature and a is only a function of pressure. The heat flux between the mid-wall and the wall surface, F_M is $b \cdot (T_M - T_S)$, where b is the inverse of the wall heat resistance and T_M is the mid-wall temperature. When F_S is set equal to F_M, a quadratic in $(T_s - T_{sat})$ results,

$$a \cdot (T_s - T_{sat})^2 + b(T_s - T_{sat}) - b(T_M - T_{sat}) = 0 \tag{28}$$

Thus the wall surface temperature is obtained and then the heat flux at the wall surface, F_S, which is computed at each cell center over the length of the boiling zone. There are thus two functions, F_S and F_D with values at each cell. In order to obtain the intersection of these two functions and thus the point of boiling crisis, a linear approximation is made to each function proceeding two cells at a time along the length of the steam generator until an intersection of the two lines is reached. The intersection point is tracked exactly and the nucleate boiling and film boiling heat transfer coefficients are pro-rated in the cell where the intersection occurs. This method gives a smoothly varying, stable calculation of the DNB point.

Application of the Code

Figures 1-3 show data from a transient resulting from a reactor trip. The primary and secondary sodium pumps, feedwater pumps, and turbines are tripped as a consequence of the reactor trip. The main emphasis, for the current purpose, is to assess the thermal transients that occur in the steam generator as the control system attempts to keep the system in balance. The control rods begin to drop at 15 s. Figure 1 shows the feedwater flow and the outlet steam flow which follows the inlet flow in very stable fashion. Figure 2 shows feedwater and outlet water temperatures and Figure 3 gives the variation of the saturated water and vapor interface locations which result from the changing flow and temperature conditions.

List of Symbols

α	void fraction
ρ	density (kg/M^3)
x	quality
C_p	specific heat (J/kg-K)
F	heat flux (J/M^2-s)
G	mass flux (kg/M^2-s)
h	enthalpy (J/kg)
i	node index
j	lowermost node in a region
k	time step index
n	number of nodes in a region
P	pressure (Pa)
Q	volumetric heat source (J/M^3-s)
t	time (s)
T	temperature (K)
z	spatial variable (M)
Z	spatial location (M)
Z_{SC}	length of subcooled zone (M)
Z_{TP}	length of two phase zone (M)
Z_{SH}	length of superheated zone (M)

Saturation Properties

h_f	saturated liquid enthalpy
h_g	saturated vapor enthalpy
ρ_f	saturated liquid density
ρ_g	saturated vapor density
T_{sat}	saturation temperature

$\rho_{fg} = \rho_g - \rho_f$

$h_{fg} = h_g - h_f$

$h = x h_{fg} + h_f$

$\rho = \alpha\rho_{fg} + \rho_f$

$x = \alpha\rho_g/[\rho_f + \alpha\rho_{fg}]$ (assuming no slip between phases)

$(h\rho)_{fg} = h_g\rho_g - h_f\rho_f$

$(h\rho) = h_f\rho_f + \alpha(h_g\rho_g - h_f\rho_f)$

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STEAM GEN. WATER SIDE FLOWS

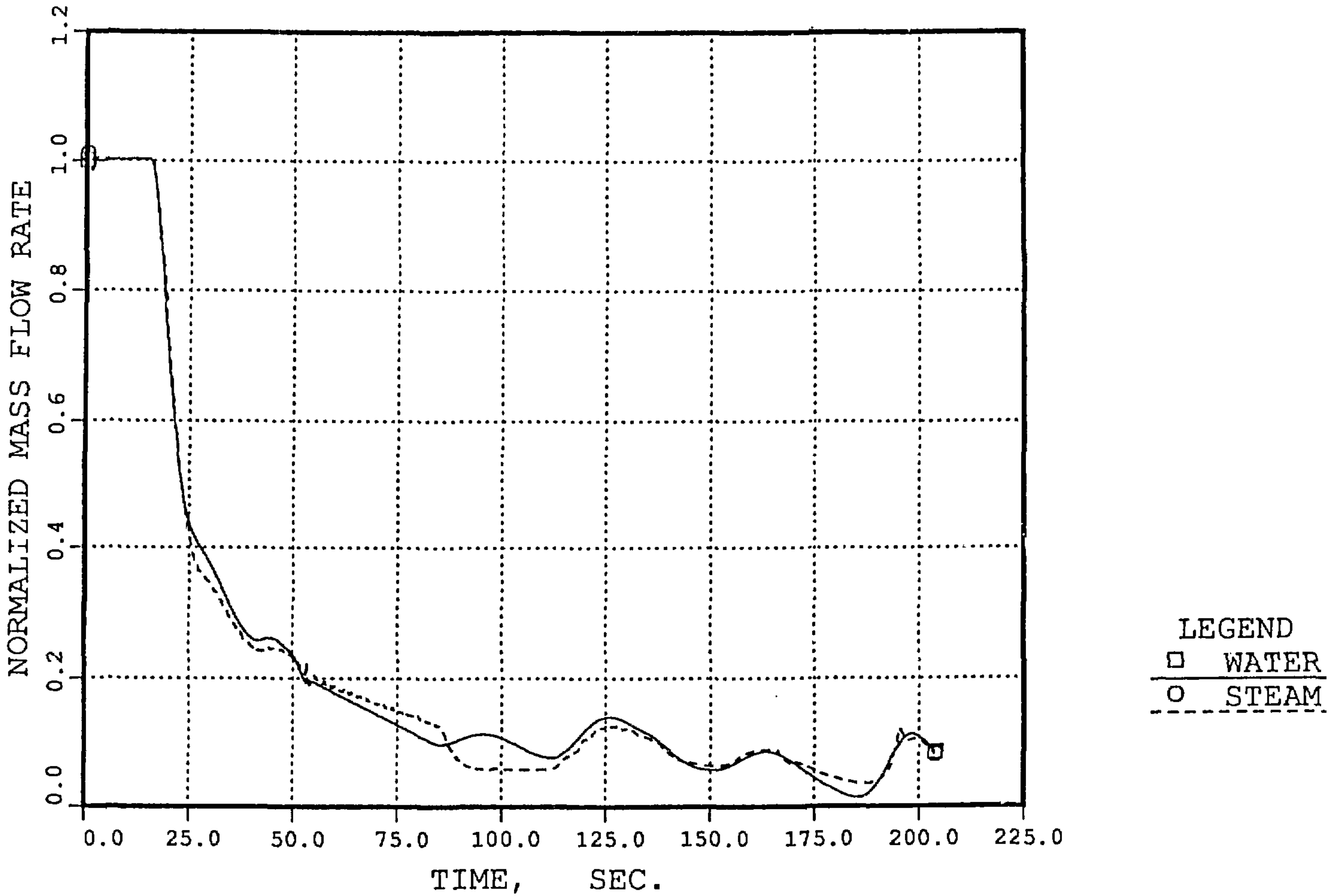


Figure 1

STEAM GEN. WATER TEMPERATURES

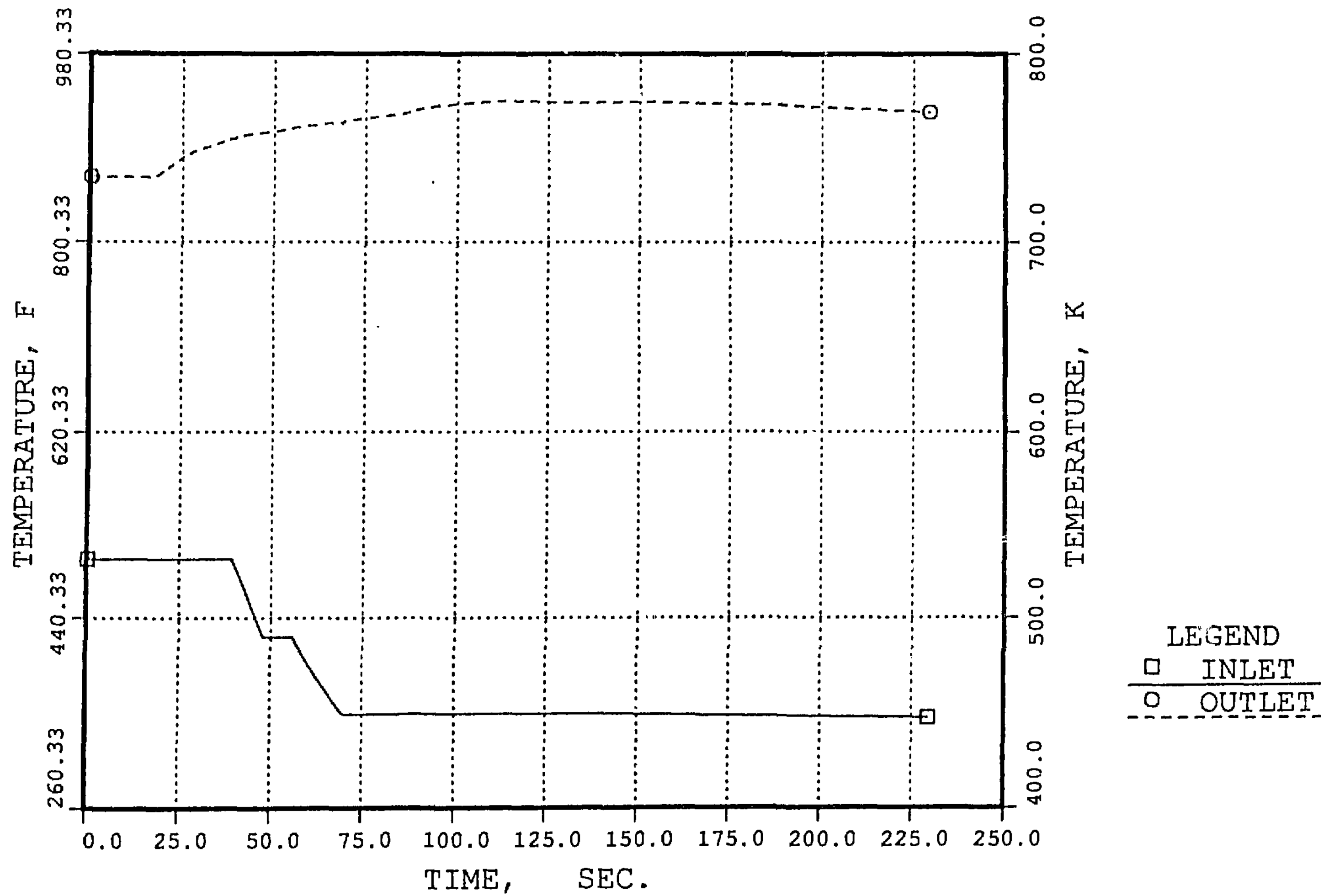
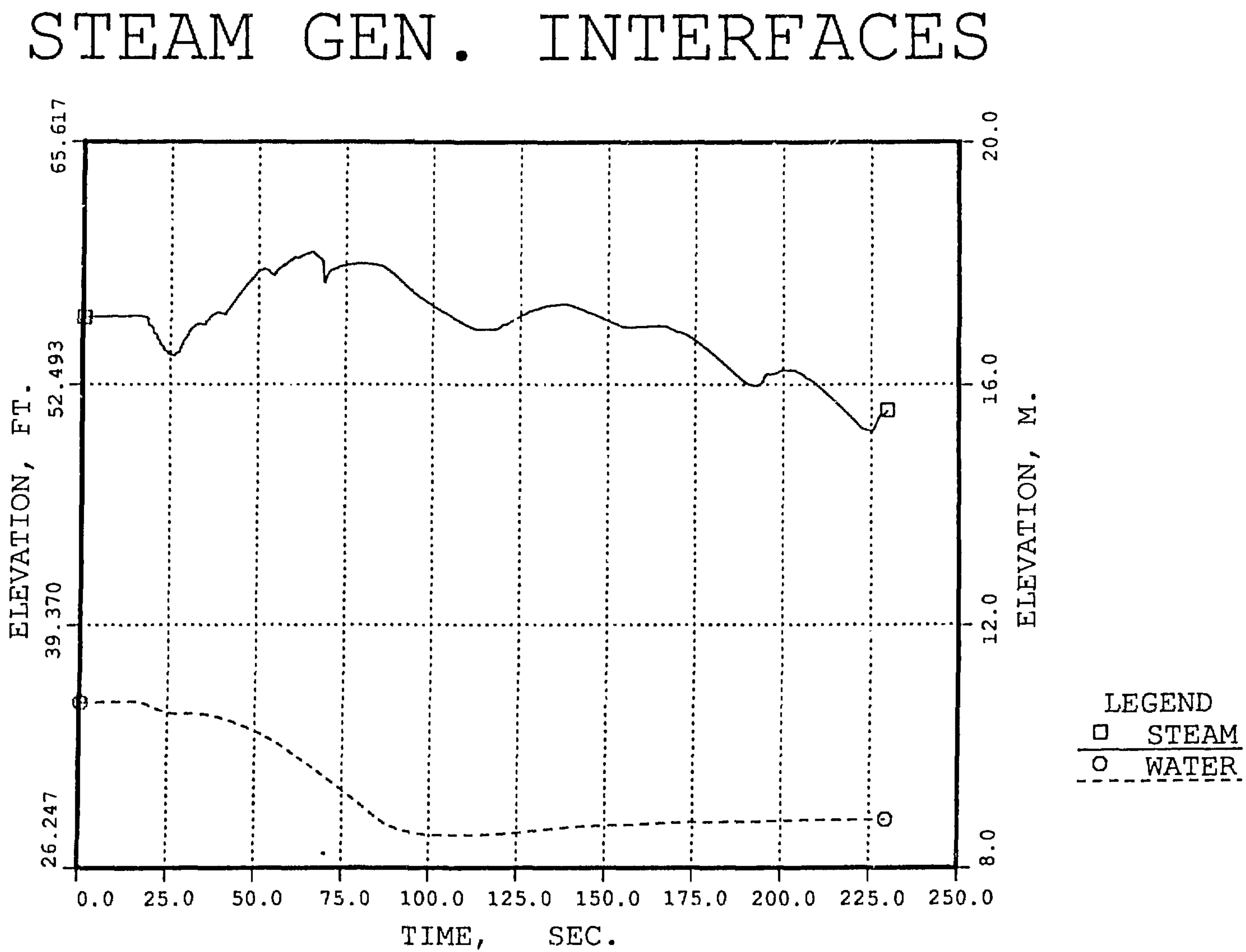


Figure 2


STEAM GEN. INTERFACES
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12.0
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ELEVATION, M.
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100.0
125.0
150.0
175.0
200.0
225.0
250.0
TIME, SEC.
LEGEND
STEAM
WATER

Figure 3